제 출 문

국토교통과학기술진흥원 귀하

‘국토교통기술촉진연구사업 슈퍼컴퓨터 기반의 3차원 수치모형을 이용한 자연형 만곡하천 내 수충부 보호를 위한 수제 설계기술 개발’ (연구개발 기간 : 2014. 7. 11~ 2016. 7. 10) 과제의 최종보고서 12부를 제출합니다.

2016. 8. 23.

주관연구기관명 : 한양대학교 산학협력단 (대표자) 안진호 (인)

주관연구기관책임자: 강석구

국토교통부소관 연구개발사업 운영규정 제38조에 따라 최종보고서 열람에 동의합니다.

보고서 요약서

<table>
<tr><td>과제 고유 번호</td><td>15CTAP-C077529-02</td><td>해당 단계
연구 기간</td><td>2014.07.11.
~ 2016.07.10.</td><td>단계구분</td><td>1/1
(해당단계)/(총단계)</td></tr>
<tr><td rowspan="2">연구사업명</td><td>중사업명</td><td colspan="4">국토교통기술촉진연구사업</td></tr>
<tr><td>세부사업명</td><td colspan="4">기초원천</td></tr>
<tr><td rowspan="2">연구과제명</td><td>대과제명</td><td colspan="4">없음</td></tr>
<tr><td>세부과제명</td><td colspan="4">슈퍼컴퓨터 기반의 3차원 수치모형을 이용한 자연형 만곡하천 내 수충부 보호를 위한 수제 설계기술 개발</td></tr>
<tr><td rowspan="2">연구책임자</td><td rowspan="2">강석구</td><td>해당단계
참여
연구원 수</td><td>총: 8 명
내부: 8 명
외부: 명</td><td>해당단계
연구개발비</td><td>정부:400,000천원
기업: 천원
정부 외: 천원
계:400,000천원</td></tr>
<tr><td>총 연구기간
참여
연구원 수</td><td>총: 8 명
내부: 8 명
외부: 명</td><td>총 연구개발비</td><td>정부:400,000천원
기업: 천원
정부 외: 천원
계:400,000천원</td></tr>
<tr><td>연구기관명 및
소속 부서명</td><td colspan="3">한양대학교 서울 공과대학 건설환경공학과</td><td colspan="2">참여기업명</td></tr>
<tr><td>국제공동연구</td><td colspan="3">상대국명:</td><td colspan="2">상대국 연구기관명:</td></tr>
<tr><td>위탁연구</td><td colspan="3">연구기관명:</td><td colspan="2">연구책임자: 강석구</td></tr>
<tr><td colspan="4">■ 문헌조사를 통해 하천에 설치된 수제가 하천 흐름에 미치는 영향에 대한 일반적인 지식을 습득함
■ 문헌조사를 통해 얻은 지식을 바탕으로 직선수로, 만곡수로에서 수리실험을 실시함
■ 문헌조사와 두 가지 수리실험을 통해 수제설계 시 하천 흐름에 미치는 영향이 큰 4가지 설계인자를 도출함
(수제길이, 수제높이, 수제각도, 하천만곡도)
■ 설계인자를 변화시켜가며 4가지의 기본하천 모형과 48가지의 수제가 설치된 하천의 수치모형실험 시나리오를 구축함
(수제길이/하천폭=0.25, 0.5, 수제높이/하천수심=0.5, 1, 수제각도=-30°, 0°, 30°, 하천곡률반지름/하천폭=2, 2.5)
■ 3차원 Navier-Stokes 방정식과 Level-set 방법을 지배방정식으로 하는 수치모델을 이용하고 슈퍼컴퓨터를 사용한 병렬연산기법으로 수치해석을 수행함
■ 수치해석 결과, 설계인자가 수제 주위를 흐르는 흐름특성(유속분포, 재순환영역길이) 및 난류흐름특성(난류에너지강도, 하상전단응력)에 미치는 영향을 분석함
■ 위에서 분석한 데이터를 바탕으로 설계인자와 수제 주위의 유동장과의 상관관계를 나타내는 도표를 제작함</td><td colspan="2">보고서 면수: 220 페이지</td></tr>
</table>

연구개발개요	■ 국내·외 홍수 피해사례에 관한 조사에 따르면, 제방 및 수공구조물의 파괴로 인한 인적 및 물적 피해가 심각하며, 그에 대한 여러 가지 대책 중 저비용으로 수충부를 반영구적으로 보호할 수 있는 수제 공법이 주목 받고 있음 ■ 수충부 보호 뿐 아니라 최근 하천복원 분야에서 수제 건설에 관한 수요가 급증하고 있음 ■ 수제설치는 하천형상, 하상지형, 3차원 흐름특성 등 국지적인 요인을 적용한 설계가 필수적이나, 국내의 수제 설치 사례가 충분치 않아 수제 설계에 있어 중요한 인자들에 관한 연구가 미흡한 실정임 ■ 기존 하천설계기준에 명시되어있는 수제 설계의 기준과 지침들은 일본과 유럽에서 제안된 경험공식이나 사례를 인용하고 있어 국내 상황에 맞지 않을뿐더러 해당 공식의 적용성이 체계적으로 검증된 사례가 없어 실제 수제 설계 시 필요한 하천만곡도와 그에 따른 수제의 제원(길이, 각도, 높이)에 관한 사항을 전혀 고려하지 못함 ■ 기존 대부분의 연구는 직선수로에 설치된 수제에 관한 것이며 만곡하천에 적용 가능한 설계 기준 또는 가이드라인은 국내·외를 통틀어 전무한 실정임 ■ 직선수로 상의 수제에 관한 연구 결과는 이차류의 고려가 필수적인 실제 만곡하천에서 직접적으로 적용하기에는 무리가 있음. 수제설치 후 수제역에서 발생하는 이차류 및 난류흐름을 정확히 예측하고 분석하기 위해서는 3차원 흐름측정 또는 해석이 필수적임 ■ 수리모형실험을 이용하여 만곡하천 내의 흐름을 측정하기 위해서는 다양한 만곡도와 하폭, 수심별로 각기 다른 형상의 개수로를 매 실험마다 제작할 필요가 있기 때문에 상당한 비용과 시간이 소요됨 ■ 이러한 문제를 극복하기 위하여 본 연구에서는 3차원 Navier-Stokes 방정식을 수치적으로 해석하는 3차원 수치모형을 사용하여 수제 주위의 3차원 흐름을 해석하여 그 결과분석을 통하여 수제 설계에 필요한 3차원 흐름특성에 관한 정보를 제공하고자 함 ■ 슈퍼컴퓨터 기반의 병렬연산을 이용하여 기존 3차원 수치모형이 갖는 한계점을 극복하여 수천만~수억 개의 격자망을 이용한 연산을 수행할 계획임 ■ 기존 국내·외의 수치모형을 활용한 연구 대부분이 1, 2차원 수심적분형모형이나 Flow3D와 같은 상용모형을 사용하였는데, 수심적분모형은 그 적용성이 매우 제한적이고 상용모형은 그 정확성이 체계적으로 검증된 바가 거의 없으나, 본 연구의 연구책임자에 의해 개발된 3차원 모형은 십여 건의 국제 SCI 학술지를 통하여 체계적으로 검증된 바가 있음
최종목표	■ 슈퍼컴퓨터 기반의 3차원 전산유체역학모형을 이용하여 다양한 가상의 수제 설치 시나리오에 대한 수치실험을 수행하고 이를 바탕으로 하천의 만곡도와 수제의 설치각도, 수제의 길이 및 간격에 관한 상호관계를 도출함 ■ 수제설계에 필요한 주요 인자들(하천만곡도, 수제간격, 수제길이, 수제높이 등)의 영향에 따른 수제 주위의 3차원 난류 흐름특성을 파악함
연구내용 및 범위	■ 성공적인 수제설계 관련 인자의 정립 및 주요 설계 인자들의 영향에 따른 수제 주위의 난류 흐름특성 파악을 위해서는 하천만곡도, 수제높이, 수제길이, 수제각도 등의 주요 인자들의 변화에 따른 다양 시나리오를 수립하고 각 시나리오 별 3차원 흐름특성을 파악하는 것이 필수적임 ■ 이와 같은 수십~수백 건에 달하는 시나리오에 대한 수리모형실험을 수행하여 이에 대한 3차원 정밀 유속장을 모두 취득하는 것은 현실적으로 불가능함 ■ 본 연구에서는 슈퍼컴퓨터 기반의 3차원 수치모형을 이용하여 약 40여 건의 대표적 시나리오에 대한 수치해석을 수행하고 이를 바탕으로 각 인자별 설계기준을 제시하고자 함

	■ 특히, 현재 하천설계기준에 제시되지 않은 하천 만곡도를 주요인자로 포함할 예정임 ■ 포함될 설계기준의 요소 및 인자는 다음과 같음 • 하천 만곡도에 따른 흐름변화에 관한 기준 • 단일 수제 각도에 따른 흐름변화에 관한 기준 • 단일 수제 하폭대비 길이 비에 따른 흐름변화에 관한 기준 • 수제의 높이에 따른 흐름변화에 관한 기준 ■ 주요 연구내용은 아래와 같음 1) 3차원 병렬 수치모형 구축 및 수리실험을 통한 검증 • 만곡하천 내의 3차원 흐름해석에 관한 국내·외 문헌조사 및 수치모델의 개선점에 관한 연구 • 3차원 흐름 지배방정식 및 경계조건에 관한 연구 • 3차원 수치모형의 병렬연산성능 향상에 관한 연구 • 직선하도와 만곡하도에서의 주요 설계인자에 대한 데이터베이스 구축 • 직선수로 내 수제에 관한 수리모형실험 및 3차원 유속장 취득 및 수치모형의 검증 • 만곡수로 상의 수제에 관한 수리모형실험 및 3차원 수치모형 검증 2) 하천 만곡도, 수제 설치각도, 길이 및 간격에 따른 수제주위 난류 흐름특성 • 하천 만곡도, 수제 높이, 수제 각도에 관한 수치모델링 시나리오 결정 (약 40건) • 시나리오별 3차원 정밀 수치해석 • 시나리오별 3차원 흐름특성 분석 및 하상 및 제방에 가해지는 전단응력 산정 • 하천 만곡도별 수제간의 최적 높이 및 각도, 길이에 관한 난류 흐름특성 파악
연구개발성과	■ 국내·외 최초로 직선하도 및 만곡하천 모두에서 활용 가능하도록 수제설계에 있어 중요한 인자(하천 만곡도, 수제설치 각도, 길이 및 간격 등)를 정립하고 각 인자에 따른 수제주위의 흐름변화를 파악함 ■ 국내 최초로 슈퍼컴퓨팅 기술을 활용하여 수공구조물 설계기준에 주요한 인자에 관한 연구를 통하여 새로운 연구 패러다임을 제시함 ■ 수제 주위의 3차원 정밀 유속장 정보를 제공함으로서 실무 수공기술자의 3차원 흐름특성에 관한 이해를 증진함 ■ 국내외 저명 학술지에 연구결과를 논문으로 게재하여 연구성과를 널리 홍보함 ■ 주요 인자별 3차원 흐름변화를 예측하여 하천별 맞춤 수제설계에 초석을 마련하고, 차후 효율적인 수충부 보호 및 수충부 파괴로 인한 제 2, 3차적 피해를 미연에 방지함 ■ 수행하는 연구를 통해 만곡하천의 흐름에 대한 기초지식 및 해석기술을 활용하여 차후 수제의 과다설계로 인한 경제적 손실을 방지함
연구개발성과의 활용계획 (기대효과)	■ 본 연구에서 수행하고자 하는 수제설계인자와 흐름특성 간의 관계에 관한 연구는 궁극적으로 수충부를 보호하여 다른 수공구조물에 직접적인 영향을 미치는 흐름의 속도를 저하시키고 흐름을 변화시켜 수충부 손실 또는 붕괴로 인한 제 2, 3차적 피해를 감소시키는데 있음. 따라서 본 연구에서 제시될 수제설계인자 간의 관계 및 인자들이 흐름에 미치는 영향은 차후 수제설계에 초석을 마련하고 이를 통해 홍수 시 제방의 피해와 이로 인해 발생되는 인명, 재산피해를 미연에 방지하고 장기적으로 제방보수 비용을 절감하여 국가건설예산 절감에 기여 할 수 있음 ■ 본 연구개발 결과는 국토교통부를 비롯한 하천관리를 수행하는 국가기관을 통해 자연하천 보호 및 하천정비, 복원사업에도 활용이 가능함

	■ 현재의 수제 설계기준은 그 내용이 모호하고 구체성이 떨어지므로 실제 설계 시 활용이 거의 불가능함. 본 연구에서 제안되는 연구결과를 바탕으로 차후 수제설계기준을 재정비하여 신규로 설치되는 수제의 뿐만 아니라 기존 수제의 설계 적정성 검토에 활용할 수 있음 ■ 신뢰성 있는 연구결과를 바탕으로 차후 수제설계기준이 확립될 경우 하천복원 사업에 적극 활용될 것으로 예상하며 특히 도시지역 내 소하천 하천복원에 사용될 경우 수제 주변 어류 서식처 및 식생의 자연적 조성이 가능함 ■ 본 연구에서 취득할 수제의 3차원 수리 특성에 관한 정보는 향후 생물, 화학적 수질 변화 및 어류서식처 변화 등에 관한 생태적 연구에 유용하게 사용될 수 있음 ■ 수제설계인자의 정립을 통해 과다설계로 인한 경제적 손실을 막고 친환경적인 소재로 수제 시공 능력을 제고할 수 있을 것으로 기대됨				
핵심어 (5개 이내)	수제	만곡하천	3차원 흐름	병렬연산	제방보호

〈 SUMMARY 〉

Research Motivation	■ According to an investigation on flood damage caused by hydraulic structure failure, loss of financial and human resources is severe. Therefore the semi-permanent construction method of spur dike which can protect the river with low cost obtains attention in the industry. ■ Recently, not only river protection but also river restoration demand the construction of spur dike. ■ It is necessary to consider local features such as, river shape, river bed topography, and three dimensional flow characteristics in an installation of the spur dike. However the lack of researches on spur dike interrupts to determine the critical parameters in the installation ■ Most of the guidelines in Korea refers empirical equations and criteria in Europe or Japan. However they are not applicable to the structures in Korea because Korea has unique hydrological and river characteristics as well as applicability of the empirical equations have not been proved with systematic approaches. As a result the equations do not consider the characteristics of spur dike, such as length, height, inclined angle, and sinuosity of a spur dike ■ Existing researches are only focused on spur dike in a straight flume so that there are no applicable guidelines for a meander river in the literature. ■ Results from the experiment in straight flume can not be applied in a meander river because they can not account for secondary flow which is distinct characteristics in meander river. Therefore three dimensional velocity measurement and analysis are essential to accurately predict effects of a spur dike in meander river. ■ It costs huge amount of time and money to conduct physical experiments of a meander river because it is necessary to build meander river models having diverse shapes for every experiment. ■ To overcome the limitations of physical experiment, this research is going to provide information of three dimensional flow characteristics in a meander river by employing three dimensional numerical model solving Navier-Stokes equation. ■ The numerical model utilizes hundreds of millions grids to overcome the limitations of a physical experiment with Message Passing Interface (MPI) ■ Most of the numerical models use one or two dimensional depth-averaged models or commercial model such as Flow3D. However depth-averaged model is applicable in limited conditions and the accuracy of the model has not been proved. The research employs three dimensional numerical model developed by director of this project and the accuracy and applicability of this numerical model have been demonstrated in SCI journal.
Research object	■ Conducting three dimensional numerical experiments based on super-computer with various dimensions of a spur dike and a meander river and figuring out the critical parameters in installation of a spur dike in a meander river. ■ Inducing the relation between the dimensions of a spur dike and a meander river and flow characteristics with the results of the numerical experiments.

Research content and scope	■ It is necessary to establish experiment scenarios which have different dimensions of a spur dike and a meander river, such as sinuosity of a river, length, height, and inclined angle of the spur dike to determine the effect on the turbulent flow characteristics around the spur dike. ■ It is infeasible to conduct a physical experiment collecting the three dimensional flow velocity for the scenarios. ■ This research conducts over 40 cases of representative numerical experiments and suggests the design criteria for each critical parameter. ■ Especially, this research includes the river sinuosity which has not been covered in river design criteria. ■ Critical parameters which are going to be included in design criteria is such below • Flow characteristics change according to river sinuosity • Flow characteristics change according to inclined angle in spur dike • Flow characteristics change according to spur dike length • Flow characteristics change according to spur dike height ■ Primary research contents are such below 1) Establishing three dimensional numerical experiment with parallel computing and validating the results from the numerical model with physical experiments • Investigating the analysis on three dimensional flow characteristic in a meander river and improvements of the numerical model • Studying the boundary conditions of governing equations in three dimensional flow • Examining on the improvements of calculation speed of the numerical model in the parallel computing • Setting up database of the design criteria for a straight river and a meander river • Carrying out physical experiment measuring three dimensional velocity components to validate the numerical model in a straight flume • Conducting physical experiment collecting three dimensional velocity components to validate the numerical model in a meander river 2) Turbulent flow characteristics around a spur dike depending on river sinuosity, inclined angle, length, and height of a spur dike • Determining 52 cases of representative numerical model scenarios depending on river sinuosity, inclined angle, length, and height of a spur dike • Conducting numerical analysis for each scenario • Analyzing three dimensional flow characteristics and determining shear stress acting on river bed and a spur dike • Investigating turbulent flow characteristics on optimized height, length, and inclined angle of a spur dike for each river sinuosity
Research Achievement	■ The first attempt to establish critical parameters which can be considered for both a straight and a meander river, and to investigate the effects of each parameter on the flow characteristics around a spur dike ■ Suggesting new paradigm for a hydraulic structure design by employing super-computing technology ■ Improving the understanding of the three dimensional flow characteristics around hydraulic structures by providing accurate three dimensional velocity components data

	■ Promoting the achievement of this research by publishing the paper in eminent journal with the result of this research ■ Establishing the foundation of the spur dike design fitting in the unique river characteristic by predicting the flow characteristics around the hydraulic structures and preventing the damage by the failure of the hydraulic structures in advance with effective way ■ Avoiding economical loss by over deign of the hydraulic structures with the results of this research
Expected Contribution	■ The purpose of this research is protecting the vulnerable region in hydraulic structures and minimizing damage caused by collapse of hydraulic structure by better understanding the effects of the critical parameters on the turbulent flow characteristics around the structure. Therefore the relation among the parameters and the effects of the parameters on the flow provides the foundation of a safe spur dike design. Also it helps to prevent casualties and economical loss caused by the failure of the hydraulic structure in advance and to cut the government's construction budget by decreasing the maintenance cost for the structure ■ The results can be applied in river protection, river maintenance, and river restoration project by the institution supervising rivers ■ Existing design criteria is are too vague to be applied in real life. Therefore the design criteria can be modified with the results of this research and the criteria can be applied in a newly constructed spur dike as well as in review of the safety of the existing spur dikes ■ When the design criteria is modified with the reliable results in this research, the results are going to be applied in river restoration which can create habitat for fish and plant around a river ■ The information obtained in this research can be utilized in ecological research around a river including change of water quality and biological species dwelling near a river ■ The results in this research helps to construct spur dike with more efficient ways preventing over design and economical loss

Keywords	Groyne	Meandering River	Three-dimensional flow	Parallel Computing	River Bank Stabilization

< Contents >

Chapter 1. Research motivation ····· 11
1. Research object
2. Research necessity
3. Research scope
Chapter 2. Investigation of previous researches on spur dike ····· 13
1. Past researches in Korea
2. Prior researches abroad
3. Distinction of this project compared previous researches
Chapter 3. Research content and achievement ····· 15
1. 1st year
1) Determination of the critical parameters
2) Physical experiment
(1) Experiment on a spur dike in a meander river model
(2) Experiment on a spur dike in a straight flume
3) Modification of numerical model with the results from physical experiment
4) Establishment of scenarios for the numerical experiments
2. 2nd year
1) Numerical experiment results
2) Analysis of numerical experiment results
(1) Recirculation attachment length
(2) Velocity distribution
(3) Turbulence intensity
(4) Bed shear stress
3) Deduction of critical parameters
Chapter 4. Research plan and expected contribution ····· 209
1. Plan
1) 1st year
2) 2nd year
2. Expected contribution
Chapter 5. Applicability of the research results ····· 210
Chapter 6. Newly known technology abroad during the research ····· 211
Chapter 7. Security level of the research achievement ····· 213
1. Classification of the security level
2. Reason
Chapter 8. Registered equipment in the system ····· 214
Chapter 9. Safety eduction in the laboratory ····· 215
Chapter 10. Representative performance ····· 216
Chapter 11. The others ····· 217
Chapter 12. References ····· 218

〈 목 차 〉

제1장. 연구개발과제의 개요 ····· 11
1. 연구개발 목적
2. 연구개발의 필요성
3. 연구개발 범위
제2장. 국내외 기술 개발 현황 ····· 13
1. 수제와 관련한 국내 기술개발현황
2. 수제와 관련한 국외 기술개발현황
3. 연구 결과가 국내외 기술 개발 현황에서 차지하는 위치
제3장. 연구 수행 내용 및 성과 ····· 15
1. 1차년도
1) 설계인자 설정
2) 수리모형실험
(1) 만곡수로 수제 수리모형 실험
(2) 직선수로 수제 수리모형 실험
3) 수리모형실험 결과에 따른 수치모형 개선
4) 수치모형실험 시나리오 구축
2. 2차년도
1) 수치해석 결과
2) 수치해석 결과분석
(1) 재순환영역길이(recirculation attachment length)
(2) 유속분포
(3) 난류흐름강도
(4) 바닥전단응력
3) 주요설계인자 도출 및 정립
제4장. 목표 달성도 및 관련 분야 기여도 ····· 209
1. 목표달성도
1) 1차년도
2) 2차년도
2. 관련 분야 기여도
제5장. 연구개발성과의 활용 계획 ····· 210
제6장. 연구 과정에서 수집한 해외 과학기술 정보 ····· 211
제7장. 연구개발성과의 보안등급 ····· 213
1. 보안등급의 분류
2. 결정사유
제8장. 국가과학기술종합정보시스템에 등록한 연구시설 · 장비 현황 ····· 214
제9장. 연구개발과제 수행에 따른 연구실 등의 안전 조치 이행 실적 ····· 215
제10장. 연구개발과제의 대표적 연구 실적 ····· 216
제11장. 기타 사항 ····· 217
제12장. 참고 문헌 ····· 218

제1장. 연구개발과제의 개요

1. 연구개발 목적

- 본 연구에서는 3차원 Navier-Stokes 방정식을 수치적으로 계산하는 3차원 수치모형을 사용하여 수제 주위의 3차원 흐름을 해석하고 결과분석을 통하여 수제 설계에 필요한 3차원 흐름특성에 관한 정보를 제공하고자 함
- 슈퍼컴퓨터 기반의 병렬연산을 이용하여 기존 3차원 수치모형이 갖는 한계점을 극복하여 수천만~수억 개의 격자망을 이용한 연산을 수행함
- 기존 국내·외의 수치모형을 활용한 연구 대부분이 1, 2차원 수심적분형모형이나 Flow3D와 같은 상용모형을 사용하였는데, 수심적분모형은 그 적용성이 매우 제한적이고 상용모형은 그 정확성이 체계적으로 검증된 바가 거의 없으나, 본 연구의 연구책임자에 의해 개발된 3차원 모형은 십여 건의 국제 SCI 학술지를 통하여 체계적으로 검증된 바가 있음
- 슈퍼컴퓨터 기반의 3차원 전산유체역학모형을 이용하여 다양한 가상의 수제 설치 시나리오에 대한 수치실험을 수행하고 이를 바탕으로 하천의 만곡도와 수제의 설치각도, 수제의 길이 및 높이에 관한 상호관계를 도출함
- 수제설계에 필요한 주요 인자들(하천만곡도, 수제간격, 수제길이, 수제각도 등)의 영향에 따른 수제 주위의 3차원 난류 흐름특성을 파악함

2. 연구개발의 필요성

- 국내·외 홍수 피해사례에 관한 조사에 따르면, 제방 및 수공구조물의 파괴로 인한 인적 및 물적 피해가 심각하며, 그에 대한 여러 가지 대책 중 저비용으로 수충부를 반영구적으로 보호할 수 있는 수제 공법이 주목 받고 있음
- 수충부 보호 뿐 아니라 최근 하천복원 분야에서 수제 건설에 관한 수요가 급증하고 있음
- 수제설치는 하천형상, 하상지형, 3차원 흐름특성 등 국지적인 요인을 적용한 설계가 필수적이나, 국내의 수제 설치 사례가 충분치 않아 수제 설계에 있어 중요한 인자들에 관한 연구가 미흡한 실정임
- 기존 하천설계기준에 명시되어있는 수제 설계의 기준과 지침들은 일본과 유럽에서 제안된 경험공식이나 사례를 인용하고 있어 국내 상황에 맞지 않을뿐더러 해당 공식의 적용성이 체계적으로 검증된 사례가 없어 실제 수제 설계 시 필요한 하천만곡도와 그에 따른 수제의 제원(길이, 각도, 높이)에 관한 사항을 전혀 고려하지 못함
- 기존 대부분의 연구는 직선수로에 설치된 수제에 관한 것이며 만곡하천에 적용 가능한 설계 기준 또는 가이드라인은 국내·외를 통틀어 전무한 실정임
- 수리모형실험을 이용하여 만곡하천 내의 흐름을 측정하기 위해서는 다양한 만곡도와 하폭, 수심별로 각기 다른 형상의 개수로를 매 실험마다 제작할 필요가 있기 때문에 상당한 비용과 시간이 소요됨
- 직선수로 상의 수제에 관한 연구 결과는 이차류의 고려가 필수적인 실제 만곡하천에서 직접적으로 적용하기에는 무리가 있음. 수제설치 후 수제역에서 발생하는 이차류 및 난류흐름을 정확히 예측하고 분석하기 위해서는 3차원 흐름 측정 또는 해석이 필수적임

3. 연구개발 범위

■ 성공적인 수제설계 관련 인자의 정립 및 주요 설계 인자들의 영향에 따른 수제 주위의 난류 흐름특성 파악을 위해서는 하천만곡도, 수제간격, 수제길이, 수제각도 등의 주요 인자들의 변화에 따른 다양한 시나리오를 수립하고 각 시나리오 별 3차원 흐름특성을 파악하는 것이 필수적임

■ 이와 같은 수십 건에 달하는 시나리오에 대한 수리모형실험을 수행하여 이에 대한 3차원 정밀 유속장을 모두 취득하는 것은 현실적으로 불가능함

■ 본 연구에서는 슈퍼컴퓨터 기반의 3차원 수치모형을 이용하여 약 50여 건의 대표적 시나리오에 대한 수치해석을 수행하고 이를 바탕으로 각 인자별 설계인자를 정립함으로써 설계기준을 제시하고자 함

■ 특히, 현재 하천설계기준에 제시되지 않은 하천 만곡도를 주요인자로 포함할 예정임

■ 포함될 설계기준의 요소 및 인자는 다음과 같음

- 하천 만곡도에 따른 흐름변화에 관한 기준
- 단일 수제 각도에 따른 흐름변화에 관한 기준
- 단일 수제 하폭대비 길이 비에 따른 흐름변화에 관한 기준
- 단일 수제 높이에 따른 흐름변화에 관한 기준

■ 주요 연구내용은 아래와 같음

1) 3차원 병렬 수치모형 구축 및 수리실험과의 비교를 통한 검증

- 만곡하천 내의 3차원 흐름해석에 관한 국내·외 문헌조사 및 수치모델의 개선점에 관한 연구
- 3차원 흐름 지배방정식 및 경계조건에 관한 연구
- 3차원 수치모형의 병렬연산성능 향상에 관한 연구
- 직선하도와 만곡하도에서의 주요 설계인자에 대한 데이터베이스 구축
- 직선수로 내 수제에 관한 수리모형실험 및 3차원 유속장 취득 및 수치모형의 검증
- 만곡수로 상의 수제에 관한 수리모형실험 및 3차원 수치모형 검증

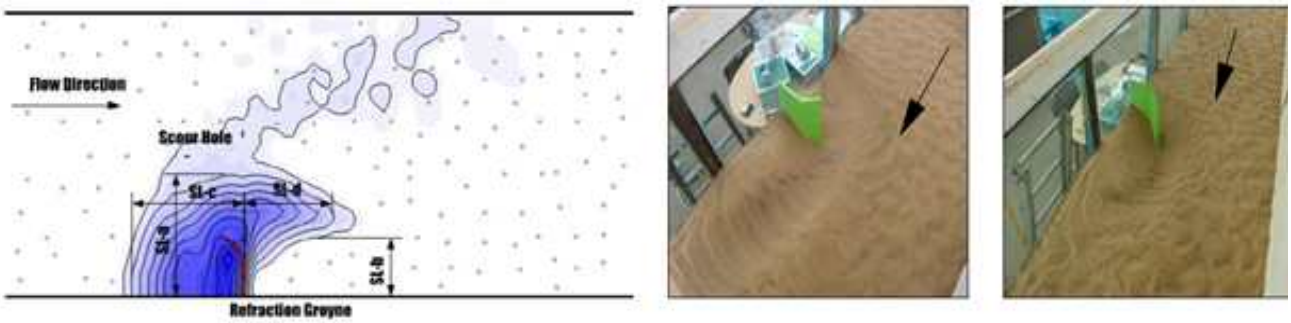
2) 하천 만곡도, 수제 설치각도, 길이 및 높이에 따른 수제주위 난류 흐름특성

- 하천 만곡도, 수제 간격, 수제 각도, 수제 길이에 관한 수치모델링 시나리오 결정 (약 50건)
- 시나리오별 3차원 정밀 수치해석 수행
- 시나리오별 3차원 흐름특성 분석 및 하상 및 제방에 가해지는 전단응력 산정
- 하천 만곡도별 수제 높이 및 각도, 길이에 관한 난류 흐름특성 파악

제2장. 국내외 기술 개발 현황

1. 수제와 관련한 국내 기술개발현황

건설부 국립건설시험소(1987)는 남한강 본류와 달천의 합류점에서 제방안정공법의 하나로서 수제(횡수제와 평행수제)를 제시하여 1/80의 고정상 및 이동상 수리모형실험을 수행하였다. 연구결과, 수제가 없는 경우 만곡 외측의 세굴이 심하게 나타나나 수제가 설치된 경우에는 유심선이 수로의 중앙으로 이동하여 세굴이 둔화되는 경향을 보이는 것으로 나타났다. 강준구 외(2006, 2009)는 LSPIV(Large Scale Particle Image Velocimetry) 기법을 사용한 실험을 통하여 직각 수제의 설치 간격에 따른 흐름특성을 분석하였다 (그림1).



<그림1> 세굴영역 측정인자 및 굴절수제 하상변동 실험 (강준구 외, 2009)

수제는 배치에 따라 횡수제, 평행수제 그리고 혼합형 수제로 분류할 수 있는데, 여홍구 외(2007, 2008)는 혼합형 수제로 분류되는 수제형상들 중 L형 수제를 정의하고 수제 팔이 하류로 향하는 배치에 의해 발생하는 흐름특성에 관한 실험적 연구를 수행하였다 (그림2). 또한 안선복 외(2008)는 2차원 수치모의를 이용해 수제 설치 간격에 따른 흐름특성 분석을 하였다.

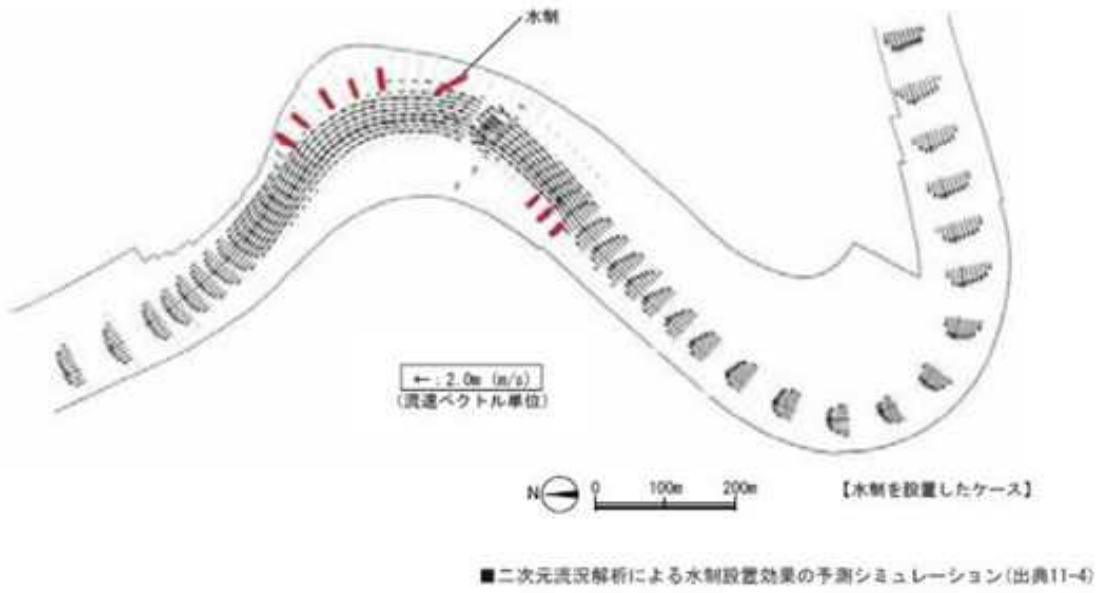


<그림2> L형 수제 설치모습 및 LSPIV를 이용한 측정 (여홍구 외, 2008)

2. 수제와 관련한 국외 기술개발현황

일본에서는 수제를 홍수로 인해 유실된 호안을 복원하는데 사용하여 수제가 홍수방어 구조물의 역할을 하도록 활용하였다. 그 사례로 2005년 일본토목학회 디자인상을 수상한 일본의 코요시강은 설계 초부터 2차원 유황해석을 실시하여 수제 설치 전·후의 흐름 상황을 공학적으로 예측하였다 (그림3). 중국에서는 기존의 설치사례를 분석하고 수리실험 등을 통해 수제설계 기술에 관한 이론을 정립하였으며, 특히 <항도정치공정기술규범>에서는 선박운행을 위한 수제 설치시 수제의 횡단면 경사, 수제 두부 설계 및 천단부의 폭, 수제와 호안의 연결부에 관한 기준을 제시하였다. 이를 통해 1975년 후아이강에 수제 8기를 배치하여 수제와 수제 사이에 토사 퇴적을 유도하여 하안을 보호하고 선박운행을 위한 수심을 확보 하였다. 미국은 1980년대 초

미국 아이오와 대학 수리연구실에서 Odgaard의 실험연구를 시작으로 수제의 한 형태인 베인(vane)에 관한 연구 및 기술개발이 이뤄지고 있는데, 이는 베인을 설치하여 발생되는 이차류로 하여금 만곡하천의 외측제방에 토사퇴적을 유도하여 세굴로 인한 제방유실을 보호하는 기술이다. 실제로 Nishnabotna 강에 베인을 시공한 후, 약 50 %의 하상 횡단경사가 감소하였고 수충부(제방) 부근 유속이 10-20 % 가량 감소한 것으로 알려져 있다.



■二次元流況解析による水制設置効果の予測シミュレーション(出典11-4)

<그림3> 2차원 유황해석 (일본국토교통성, 2008)

미육군 공병 수로시험소(U. S. Army Engineer Waterways Experiment Station)의 Copeland(1983)는 만곡부에서 호안 보호공으로서 불투과 횡수제의 효과를 평가하고 검증하였으며, 이와 관련된 인자로 길이-간격비, 설치각도, 수제의 기부에서 보호공의 영향 등을 설정하였다. 미국 연방도로국(FHWA, 1985)은 모형 시험, 문헌조사 및 현장조사에 기초한 연구를 통해 수제의 설계에 있어 길이와 투과성을 다루고, 투과율이 35 % 이하인 경우와 80 % 이상인 경우에 대해 각각 다른 설계를 제안하였다. Sukhodolov 외(2002)는 독일 Elbe강(그림 6b)에 설치된 횡수제에 대한 현장측정으로 수제의 길이와 수제간의 간격이 수제역 내의 흐름에 영향을 미치는 요인으로 정의하였다. McCoy 외(2008)는 LES(Large Eddy Simulation)를 이용하여 두 개의 연속되는 직각 수제 주변에서 발생하는 말굽와(horseshoe vortex, HV)에 관한 연구를 수행하였으며, 이를 통하여 수제 주변의 수리 특성을 정량적으로 설명 할 수 있음을 보여주었다. Duan(2009)은 수리실험에서 micro-ADV를 사용하여 두께 4mm의 얇은 단일 직각 수제 주변에서의 흐름특성 및 난류강도 등을 측정하여 직각 수제 주변 흐름특성을 다방면에서 정량적인 수치로 제시하였다. Yu 외(2010)는 수치모형을 사용하여 직각 수제 주변의 흐름에 대하여 실험자료와 연계하여 비교 및 분석하였다.

3. 연구 결과가 국내외 기술 개발 현황에서 차지하는 위치

직선수로에 비해 만곡하천 수제역에서의 흐름은 수직, 수평 방향으로 단정할 수 없는 복잡한 구조를 가지고 있다. 하지만 현재까지 국내의 실험·연구 사례들은 이차류가 고려되지 않은 직선수로에서 얻어진 결과들이므로 자연형 만곡하천 설계 적용에 쉽지 않다는 문제가 있다. 또한, 앞서 기술한 국내·외 대부분의 기존 연구들은 단순히 실험결과를 나열하는 수준에 그치고 있어 실제 수제 주위의 3차원 흐름특성(수로 부 유속증가, 수제역 와류현상)에 대한 자료를 제시하지는 못하고 있다. 본 연구 결과는 3차원 정밀 수치 모형을 이용하여 만곡수로 상의 수제 주위의 흐름을 해석하여 3차원 흐름 특성을 분석하였다.

제3장. 연구 수행 내용 및 성과

1. 1차년도

1) 설계인자 설정

■ 만곡도와 만곡의 개수: 국내 국가하천 및 지방하천 내 만곡하천을 대상으로 산정한 만곡도(=0.43~2.84)이며 이를 토대로 한 건설기술연구원의 실험수로는 사행도 1.75에 해당하는 단일 만곡 수로이다. 사행하천은 단일만곡수로와는 달리 만곡부가 교호적으로 나타나기 때문에 하천의 흐름특성을 파악하기에는 어려움이 있다. 선행된 연구에 따르면 사행도는 대개 1.0~2.0 이내에서 수행되었으며 만곡부가 교호부로 나타나는 수로의 경우 첫 번째 만곡에서 생성된 이차류는 다음 만곡부에서도 이어지며 이로 인해 종방향 유속분포에 영향을 미친다. 이차류의 경우, 직선수로와 만곡수로에서 모두 나타나지만 만곡수로의 경우 원심력에 의해 이차류가 추가적으로 발생하며 이로 인해 흐름 분포가 왜곡되어 유사이동, 하상, 하안 침식 등 매우 큰 영향을 미친다.

■ 수제길이: 수제의 길이는 제방 부근의 유속을 감소시키거나 역흐름을 생성시켜 흐름을 지연시키지만 수로의 통수능을 감소시키기 때문에 본류(main channel)의 유속을 증가시킨다. 따라서 여홍구 외(2005)는 단일 수제의 경우 본류영역의 최대유속이 평균유속의 2배 이상이 되지 않도록 수제길이는 수로 폭의 20~25% 이내로 설정하는 것이 바람직하다고 제안하였다.

■ 수제각도: 현재까지 직선수로에서 수제의 각도 변화에 의한 영향에 관한 연구는 있었지만 만곡수로에서 수제의 각도에 의한 흐름장의 변화에 관한 연구는 없었다. 이러한 이유에서 만곡하천에서 수제의 각도 변화에 따른 효과에 관한 연구를 수행하였다.

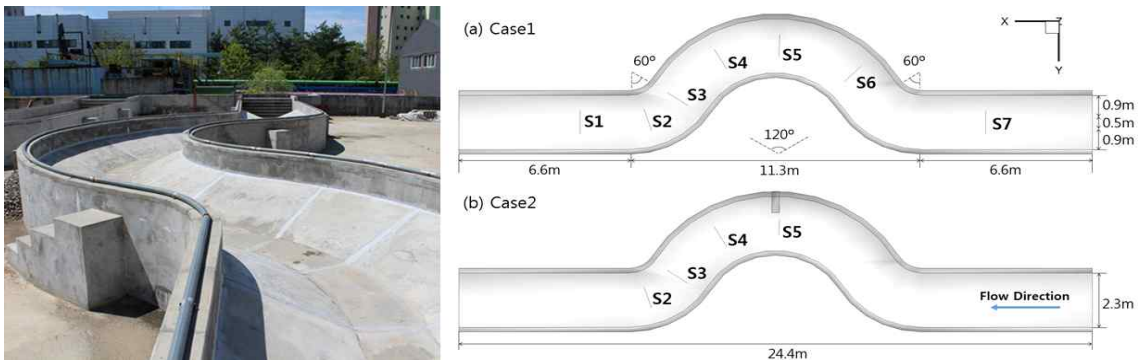
■ 수제높이: 수제의 높이는 유속차를 증가시키거나 수위차를 발생시켜 수위가 설치되지 않은 단면 쪽으로 유속을 증가시키기 때문에 강한 이차류를 발생시킨다. 따라서 하천설계기준·해설(2009)에서는 평행수제는 평균저수위보다 0.5m정도 높게 설치하는 것이 효과적이라고 제안하였다.

1) 수리모형실험

(1) 만곡수로 수제 수리모형실험

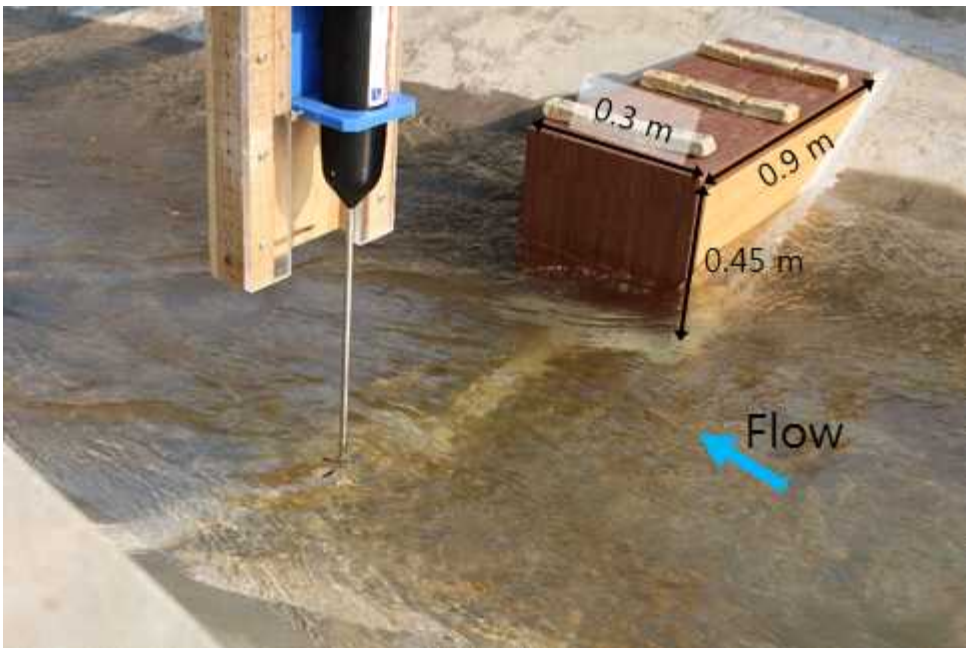
■ 실험 수로 및 조건

한국건설기술연구원에 위치한 전체 하폭 2.3 m, 흐름 방향 길이 24.4 m, 수로경사 2%인 콘크리트 만곡수로에서 실험을 실시하였다. 주 흐름방향에 수직인 단면은 저변 폭 0.5 m 비탈면 폭 각각 0.9 m인 사다리꼴 형상으로 연직방향과 수평방향 비탈경사는 1:2로 제작되었다 (그림4). 수로의 만곡부는 총 길이 11.2 m로 상·하류의 직선부와 60°로 연결되며, 중심각은 120°, 중심부의 곡률반경은 3.5 m로, 이는 사행도 1.75에 해당되는 값이다.



<그림4> 만곡수로 전경과 실험 수로

수제가 설치되지 않은 경우를 Case1, 설치된 경우를 Case2로 표기하였다. 실험 측정 단면은 Case1을 기준으로 상·하류 직선부에 각각 1 단면, 만곡부에 5 단면을 선정하여 하류 단면부터 시작하여 S1~S7으로 명명하였다. Case2의 경우, 수제 형 수리구조물 설치에 따른 흐름변화가 예상되는 S2~S5의 4개 단면에 대해서만 측정을 실시하였다. 실험은 0.13 m^3/s의 단일 유량조건에 대해 실시하였으며 상류에 위치한 단면 S7에서 측정된 유속값을 흐름단면적에 관하여 적분하여 측정된 유량값을 재검증하였다. 단면 S1이후에 위치한 수로 하단에는 포인트게이지를 설치하여 하류수위를 측정하였다. 하류수심은 0.25 m로 유지하였으며, 이를 기준으로 산정된 Case1의 수면기울기는 $S_f=7.85\times10^{-4}$, 평균 유속은 U=0.53 m/s이다. 평균수심과 평균유속에 근거하여 산정한 프루드수(Fr)와 레이놀즈수(Re)는 각각 0.34, 1.24×10^5이다. Case2에서 설치한 수제형 수리구조물의 경우, 높이 0.45 m 두께 0.3 m 하폭 방향 길이 0.9 m로 사면에서의 굴곡을 고려하여 목재로 제작하였으며 만곡부 우안에 설치하였다 (그림4). 실험에서 사용한 평균수심 0.250m에 대한 수면에서의 하폭은 1.5 m이며, 이에 대한 수제길이 비는 약 0.33이다 (그림 5).



<그림5> 만곡부 정점에 설치된 수제

■ 유속측정

Nortek사의 Vectrino-Ⅱ 초음파유속계(Acoustic Doppler Velocimeter)를 이용하여 3차원 유속을 측정하였다. 선행 연구에 따르면 Vectrino-Ⅱ는 기기 중심부로부터 50-55 mm 떨어진 구간에서 점 유속에 대한 가장 높은 정확도를 보이며 이를 제외한 구간에서는 이에 멀어질수록 오차가 점점 더 크게 발생한다. 따라서 정확도를 높이고자 1 mm 간격을 설정하여 총 31개의 측

점 중 위에서부터 16번째 측점에 해당하는, 즉 유속계의 하단부로부터 55 mm 아래에 위치한 유속을 이용하였다. 이때, 각각의 탐침을 통해 10 MHz의 반사된 신호를 최대 100 Hz의 샘플링 주파수로 데이터를 수집한다. 유속계는 수면에 수직으로 고정된 상태에서 단면을 측정할 수 있도록 그림 2와 같이 거치대를 이용하여 설치하였으며, 거치대는 하폭방향(y) 및 수심방향(z)으로 위치를 조정할 수 있게 하였다. 그림 3과 같이 측정된 횡방향과 수심방향은 각각 주수로 폭(B=0.5 m)과 평균수심(H=0.25 m)으로 무차원화하여 나타냈다. 각 단면의 횡방향에 대해서는 중심(y/B=0.0 지점)을 기점으로 하여 6 cm 간격으로 좌우 48 cm까지(y/B=±0.96 지점) 측정하였으며 수심방향은 수심의 변화에 따라 3~4 cm 간격으로 나누어, 총 65 개 지점의 유속을 측정하였다. 이때, 수심방향의 간격은 수면에서부터 하상까지 측정 가능한 범위를 모두 포함하는 z/H=0.28~0.84를 고려하여 등간격으로 나눈 것이며, 그림 3에서 나타낸 65개의 점은 측점에 해당하는 곳을 표시한 것이다. 유속계의 샘플링 주파수를 100 Hz로 설정하여 5분간 약 30,000개의 유속 데이터를 각 지점에서 취득하였고, 수충부에 해당하는 사면흐름(단면의 양 끝단)에 대해서는 와류 및 이차류의 영향을 고려하여 약 6~7분간 자료를 수집하였다. 일반적으로 유속계를 이용한 측정에서는 기기의 측정 유속 범위를 초과하거나 하상 및 벽면으로부터 반사된 과거의 신호(pulse)로 인해 간헐적인 스파이크(spike)가 생기는데, 이러한 스파이크를 줄이기 위해 Parsheh et al. (2010)가 제안한 PST(phase-space-thresholding) 기법을 후처리과정에 이용하여 데이터의 정확도와 신뢰도를 높였다.



<그림6> 단면 내 측점의 위치

(2) 직선수로 수제 수리모형실험

■ 실험 수로 및 조건

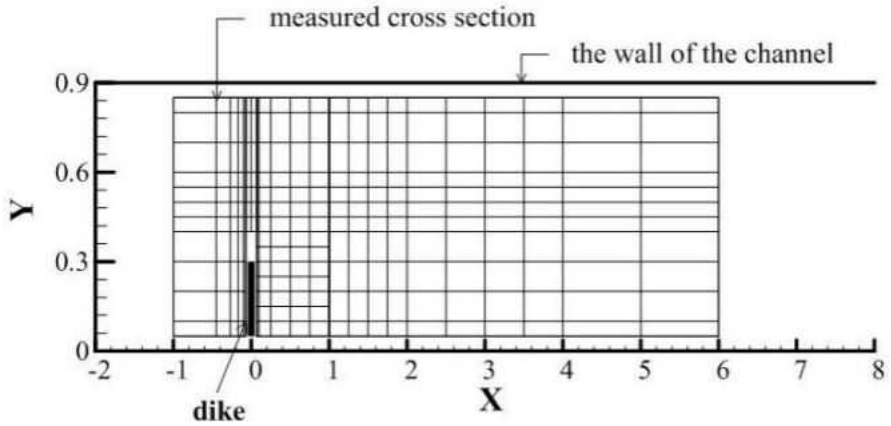


<그림7> 직선 수로

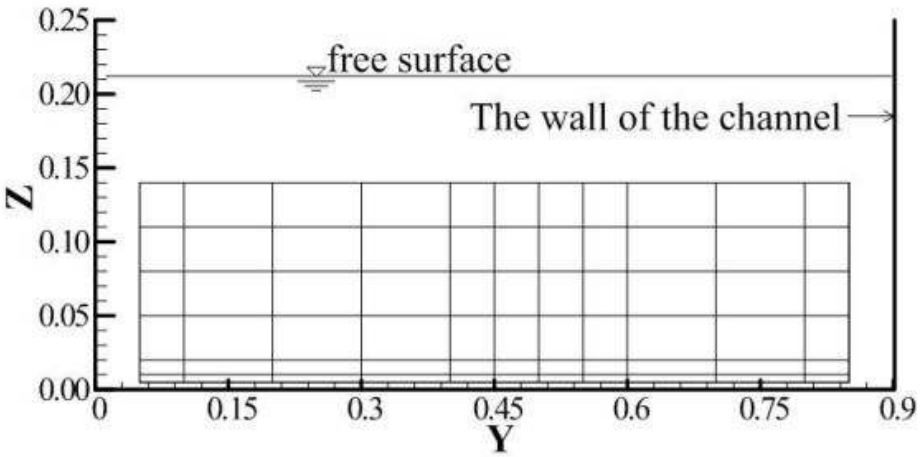
[표1] 실험 case별 유입흐름 조건

	Froude 수	유량(/s)	평균유속(m/s)	수심(m)
case1	0.100	0.0278	0.1443	0.214
case2	0.185	0.0528	0.2704	0.217

한양대학교에 위치한 폭 0.9 m, 높이 0.4 m, 길이 18 m 의 직선수로에서 Froude수가 각각 0.100, 0.185인 조건(각각 case1, case2)에서 수제 실험을 수행하였다. 각 case의 유입 흐름 조건은 [표1]에서 확인할 수 있다. 수제는 0.3×0.4×0.04 m의 크기이고 아크릴로 제작되었으며 하나의 수제만을 이용하여 실험하였다. 수제는 흐름 방향으로 9m 지점에서 우안에 직각방향으로 설치되었다. 만곡수로실험과 같이 Nortek사의 Vectrino-Ⅱ 초음파유속계(Acoustic Doppler Velocimeter)를 이용하여 3차원 유속을 측정하였다. 유속계는 수면에 수직으로 고정된 상태에서 단면을 측정할 수 있도록 그림과 같이 거치대를 이용하여 설치하였으며, 거치대는 하폭방향(y) 및 수심방향(z)으로 위치를 조정할 수 있게 하였다 (그림7). 측점은 y=0.05~0.85 m 구간에서 12개 지점(단, x=0.07~1.00 m 구간은 15개 지점), z축 방향으로는 z=0.005~0.14 m 구간에서 7개 지점을 유속 측정 지점으로 채택하여 총 1,946개 지점을 대상으로 유속을 측정하였다 (그림8). 각 측점에서 유속 분포를 고려하여 5~10분 동안 100Hz의 주파수로 샘플링하여 약 3만~6만 개의 유속 측정값을 수집하였고 측정 시 발생하는 노이즈는 Parshes et al.(2010)이 제안한 방법으로 제거하여 분석에 사용한 유속 측정값의 정확도와 신뢰도를 높였다.



(a) X-Y 평면



(b) Y-Z 평면

<그림8> 직선수로 내 측점의 위치

실험결과, Froude수에 상관없이 평균 유속 분포는 비슷하게 나타났지만 무차원 최대 난류응력과 무차원 최대 바닥전단응력은 Froude수가 클수록 크게 나타나는 경향을 보였다. 자세한 실험결과는 '수제 주위의 난류 특성 변화에 대한 실험연구'(2016년 수자원학회논문집 8월호)에 기술되어있다.

3)수리모형실험 결과에 따른 수치모형 개선

시나리오별 수제 부근의 3차원 수치모의 전에 기존 수치모형의 검증이 우선적으로 필요하다. 3차원 수치모의 결과 복잡한 유속장이 발생하는 수제 부근에서 수리모형 실험 결과와 오차가 발생하는 부분이 있었고 수치모델이 수렴하는데 오랜 시간이 걸린다는 것을 알 수 있었다. 기존 수치모형을 개선시키기 위해 수제길이를 L이라고 하였을 때 수제 앞쪽으로 L만큼, 수제 뒤쪽으로 3L만큼 격자망을 3~4배 촘촘히 되도록 개선하여 복잡한 유속장을 세밀하게 분석할 수 있게 하였고 계산 속도를 높일 수 있었다. 그리고 각각의 수치모형 case별로 약 200만개의 격자를 설정하여 m, cm단위의 미시적인 유속장 분석을 가능하게 하였다.

4) 수치모형실험 시나리오 구축

case	수제각도 (°)	하천곡률반지름비 (하천곡률반지름/ 하천폭)	수제길이비 (수제길이/ 하천폭)	수제높이비 (수제높이/ 하천수심)	하천만곡도
1	·	2.5	·	·	1.072
2	·	2	·	·	1.072
3	·	2.5	·	·	1.222
4	·	2	·	·	1.222
5	-30	2	0.25	0.5	1.072
6					1.222
7				1	1.072
8					1.222
9			0.5	0.5	1.072
10					1.222
11				1	1.072
12					1.222
13		2.5	0.25	0.5	1.072
14					1.222
15				1	1.072
16					1.222
17			0.5	0.5	1.072
18					1.222
19				1	1.072
20					1.222
21	0	2	0.25	0.5	1.072
22					1.222
23				1	1.072
24					1.222
25			0.5	0.5	1.072
26					1.222
27				1	1.072
28					1.222
29		2.5	0.25	0.5	1.072
30					1.222
31				1	1.072
32					1.222
33			0.5	0.5	1.072
34					1.222
35				1	1.072
36					1.222

37	+30	2	0.25	0.5	1.072
38					1.222
39				1	1.072
40					1.222
41			0.5	0.5	1.072
42					1.222
43				1	1.072
44					1.222
45		2.5	0.25	0.5	1.072
46					1.222
47				1	1.072
48					1.222
49			0.5	0.5	1.072
50					1.222
51				1	1.072
52					1.222

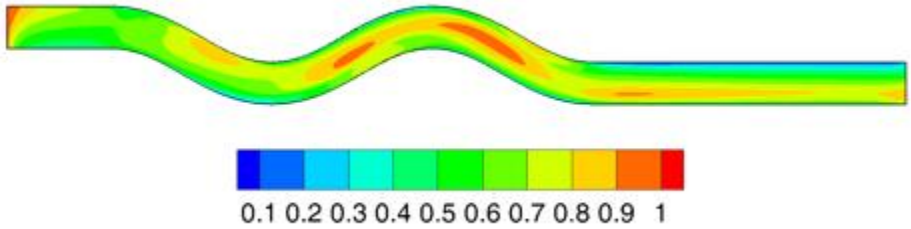
총 4가지의 수제 설계인자 (수제각도, 수제길이, 수제높이, 하천만곡도)에 의한 수치모델링 시나리오 구축하였고 기본 하천 수치모델링 4가지(case1~4)와 수제설치된 모델링(case5~52)에 대해 수치모의 하였다.

2. 2차년도

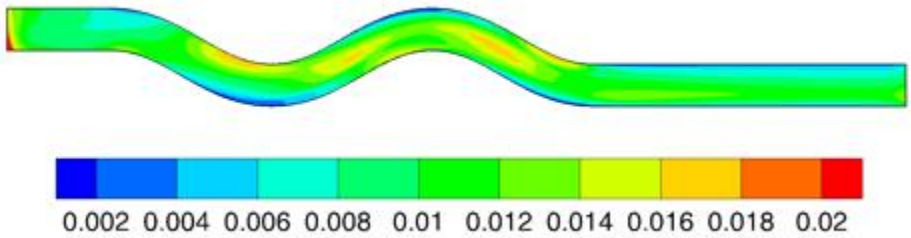
1) 수치해석 결과 (R: 하천곡률반지름, θ: 하천각도, α: 수제각도 l: 수제길이, h: 하천수심)

case1 (bottom/R=25/ =30 /l=2.5/h=0.5)

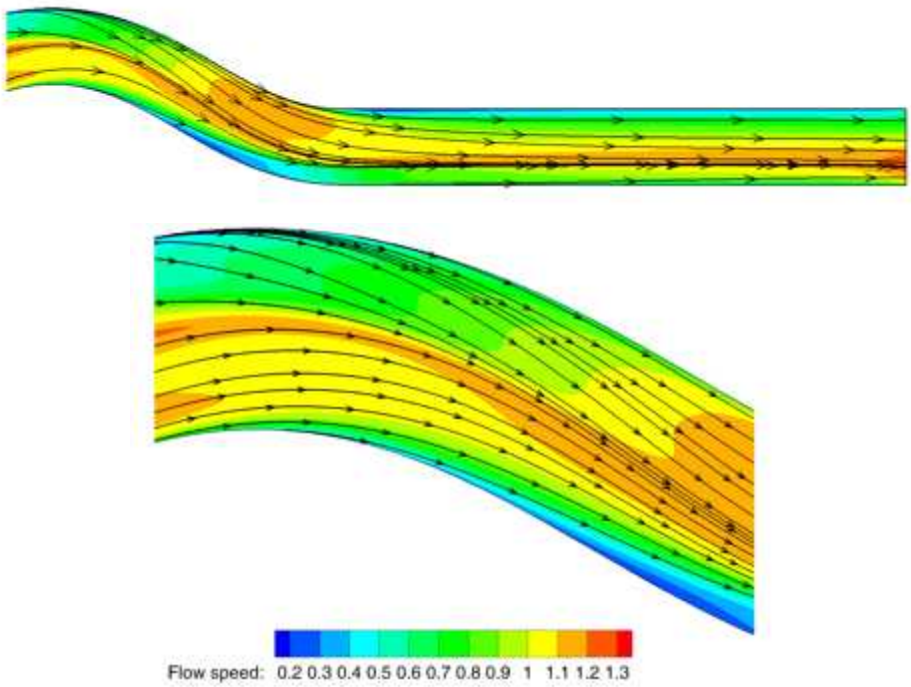
Flow speed



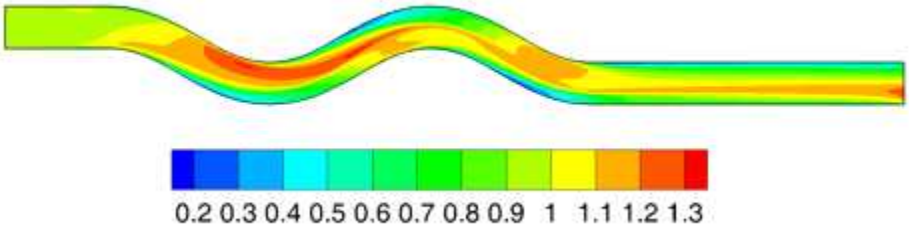
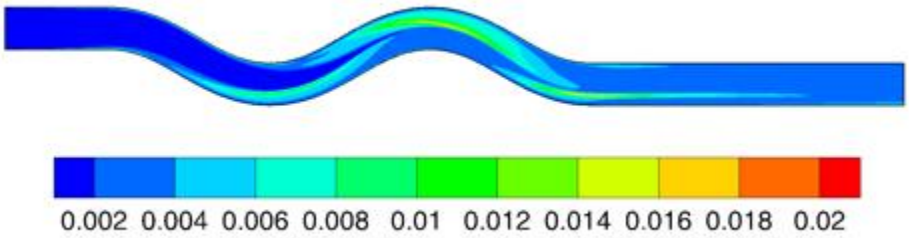
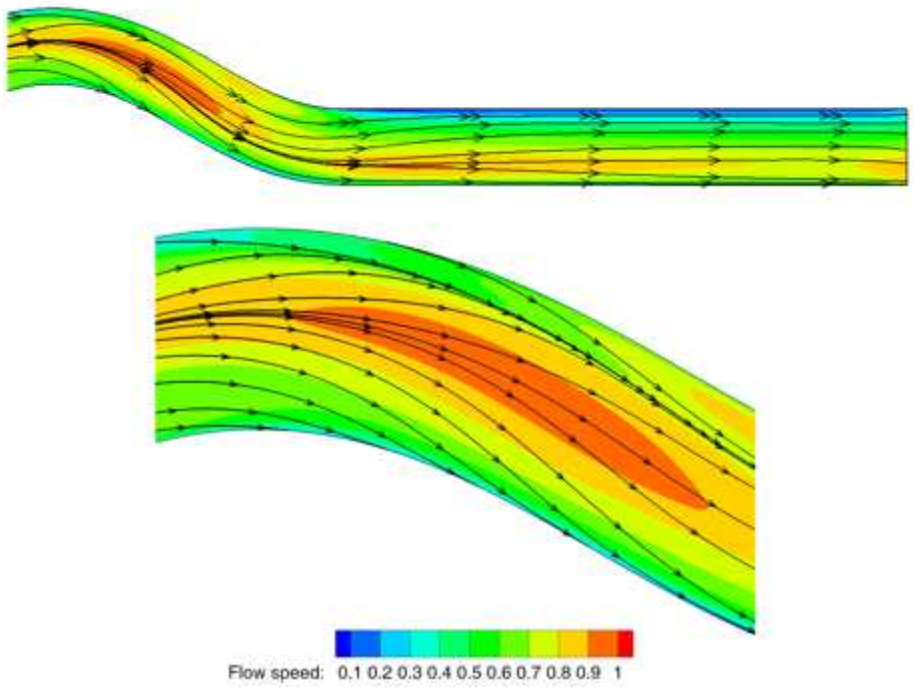
Turbulent kinetic energy (TKE)

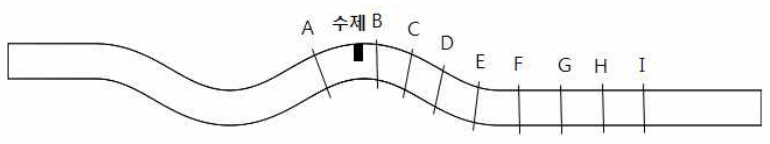
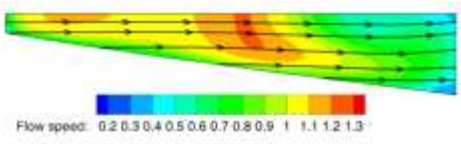
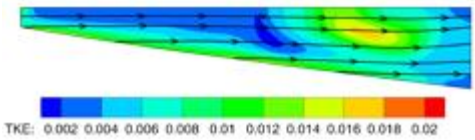
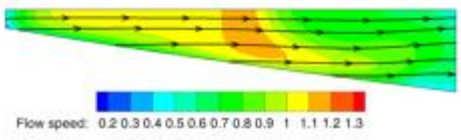
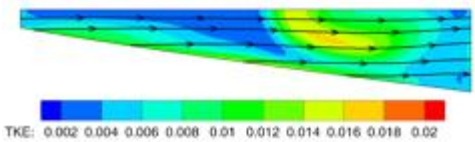
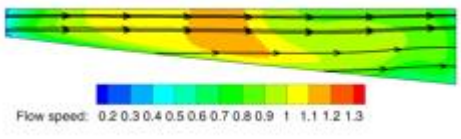
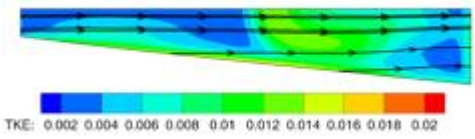
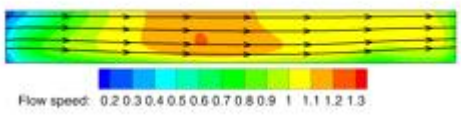
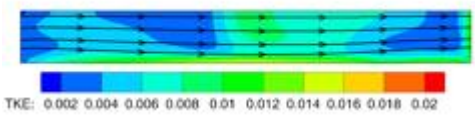
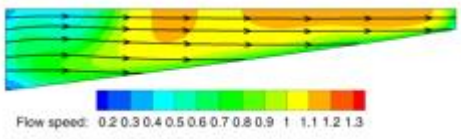
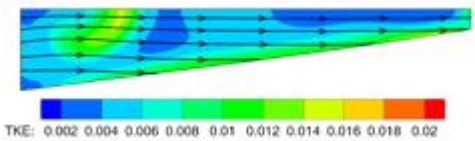
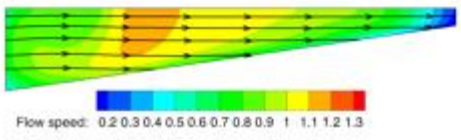
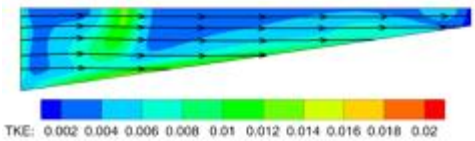
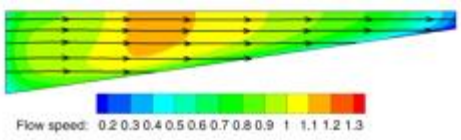
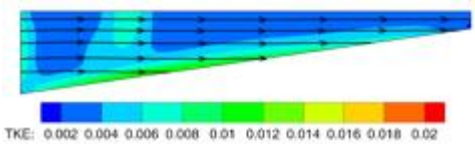
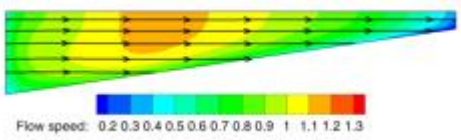
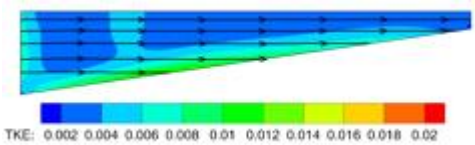


Recirculation



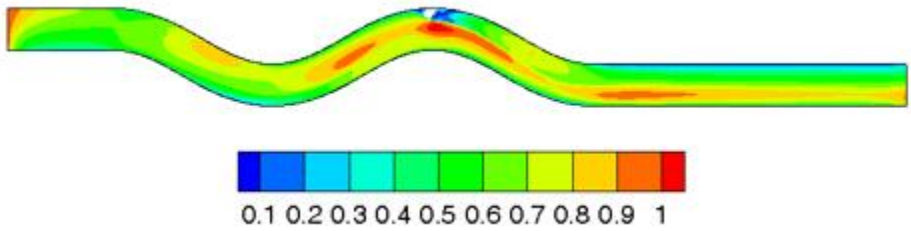
recirculation (X)

case1 (top/R=25/ =30 /l=2.5/h=0.5)
Flow speed

Turbulent kinetic energy (TKE)

Recirculation
 recirculation (X)

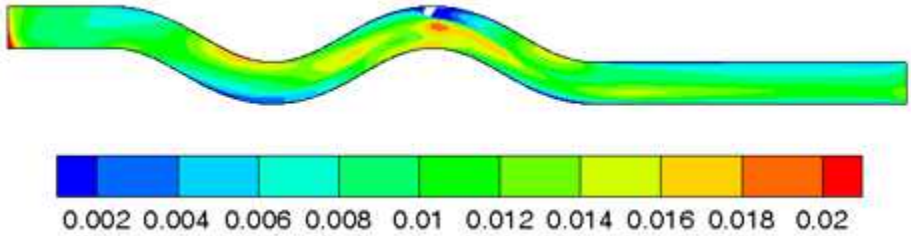
위치	case1 (bottom/R=25/ =30° /l=2.5/h=0.5)	
	secondary flow	
		
A		
B		
C		
D		
F		
G		
H		
I		

case13 (bottom/R=25/ =30/α=-30/l=2.5/h=0.5)

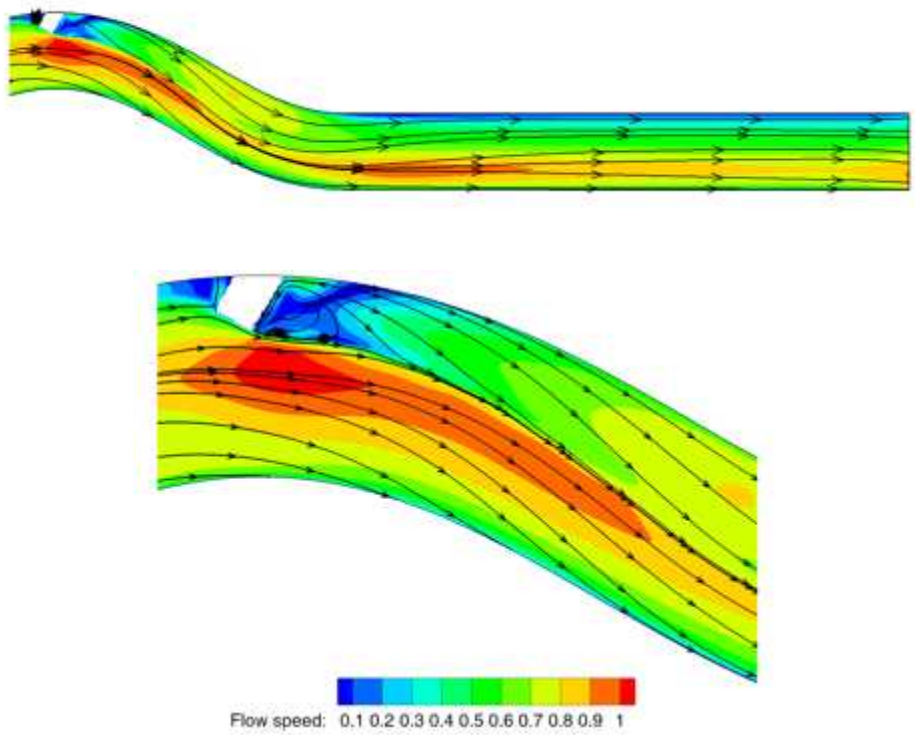
Flow speed



Turbulent kinetic energy (TKE)



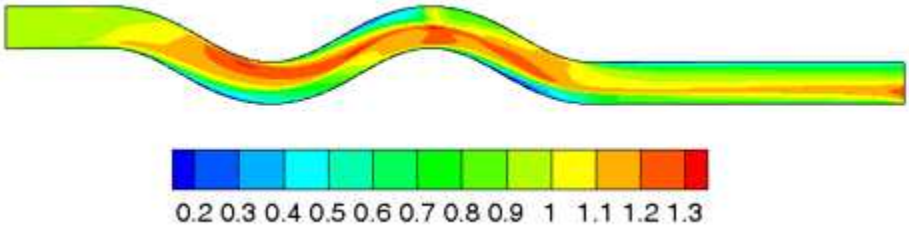
Recirculation



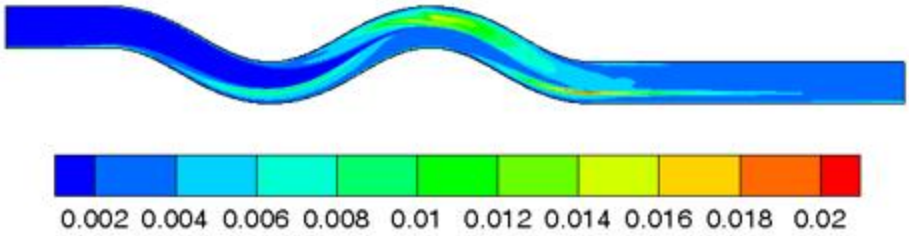
Normalized recirculation length : 0.3289

case13 (top/R=25/ =30/α=-30/l=2.5/h=0.5)

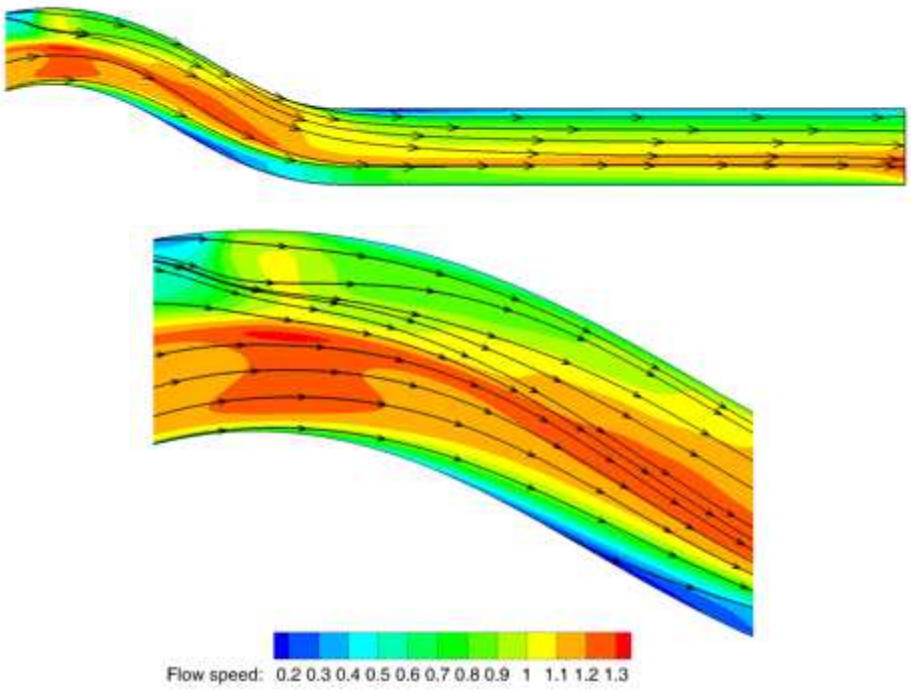
Flow speed



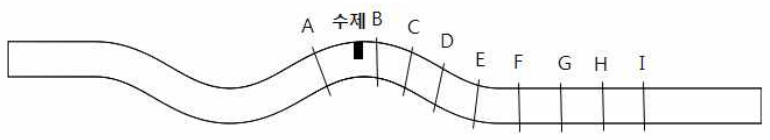
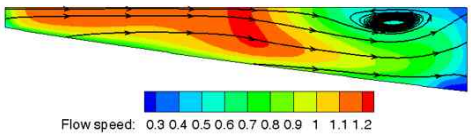
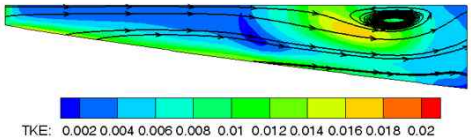
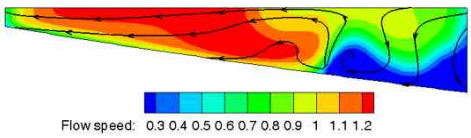
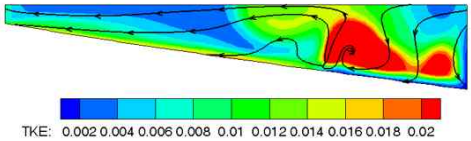
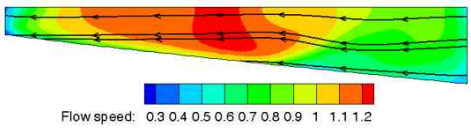
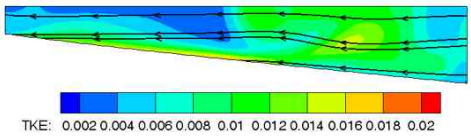
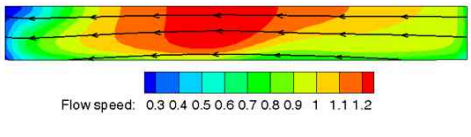
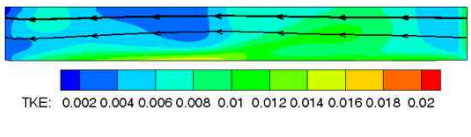
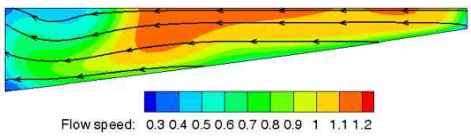
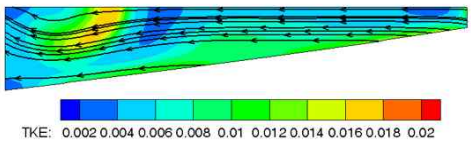
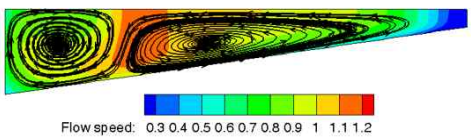
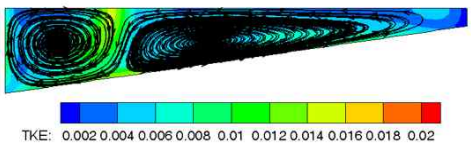
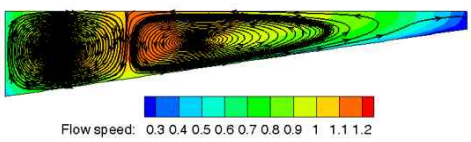
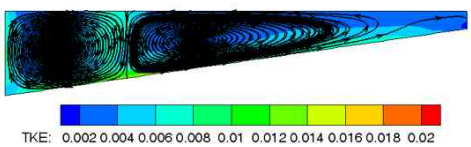
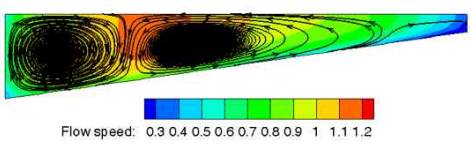
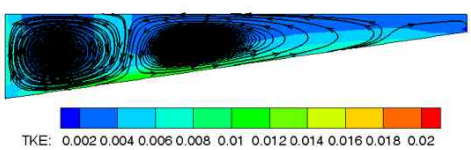
Turbulent kinetic energy (TKE)



Recirculation

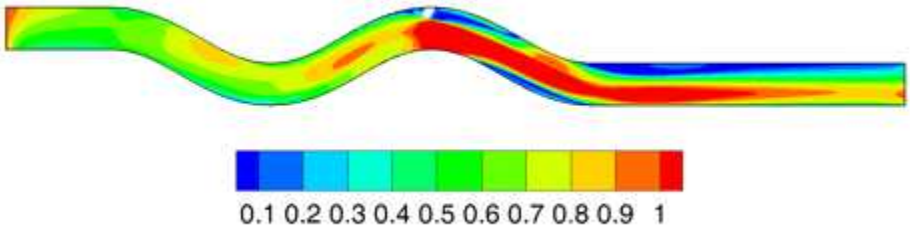


recirculation (X)

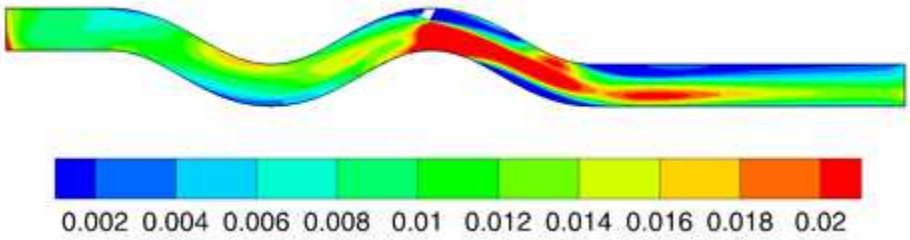
위치	case13 (R=25/ =30/α=-30/l=2.5/h=0.5)	
	secondary flow	
		
A		
B		
C		
D		
F		
G		
H		
I		

case15 (bottom/R=25/ =30/α=-30/l=2.5/h=1)

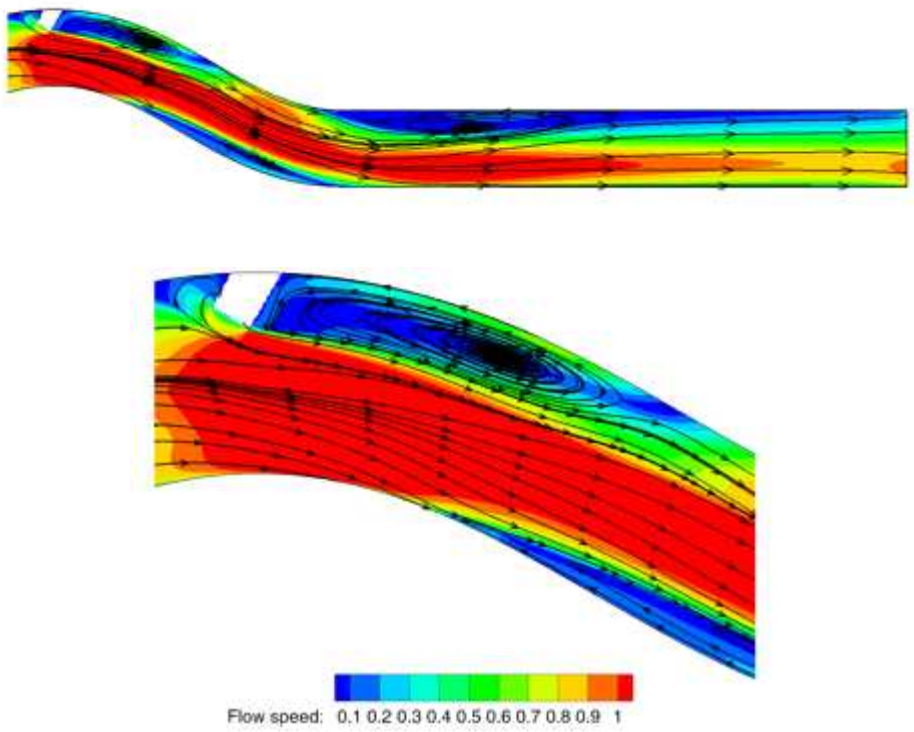
Flow speed



Turbulent kinetic energy (TKE)



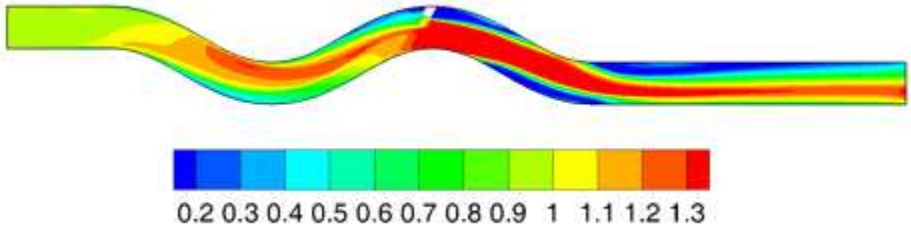
Recirculation



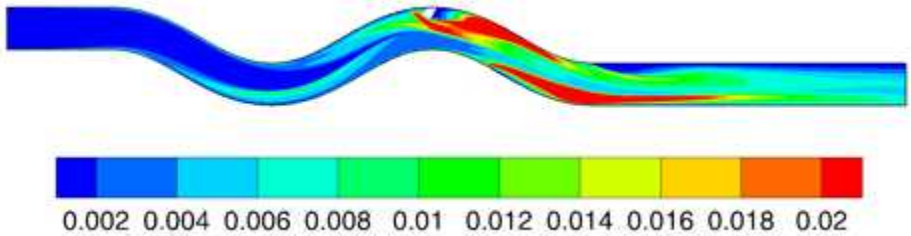
Normalized recirculation length : 1.6906

case15 (top/R=25/ =30/α=-30/l=2.5/h=1)

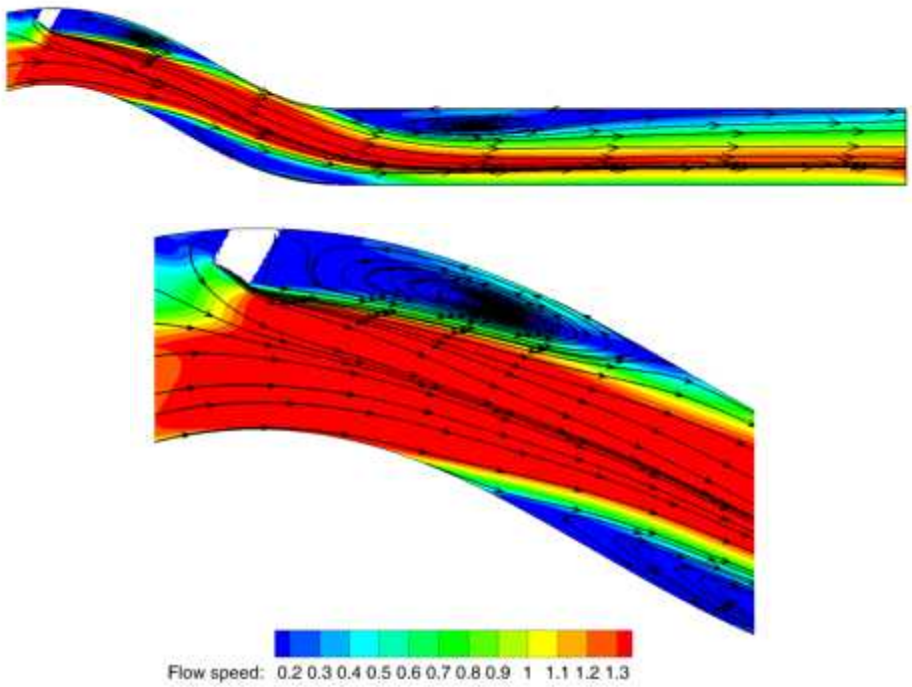
Flow speed



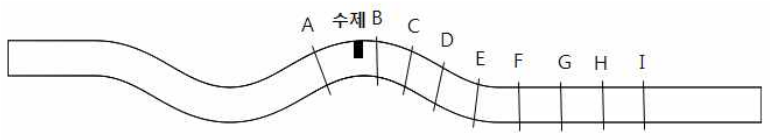
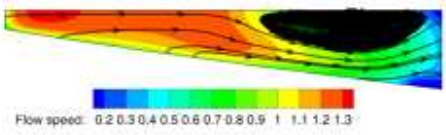
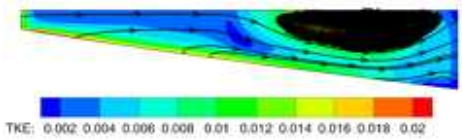
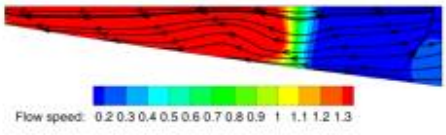
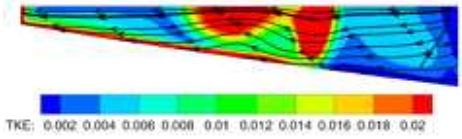
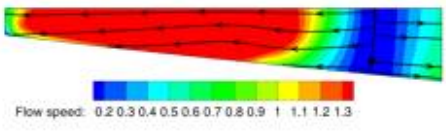
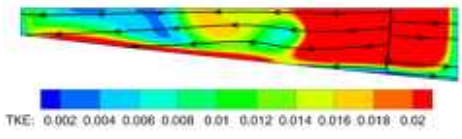
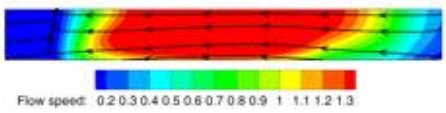
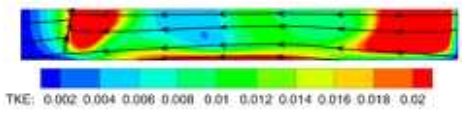
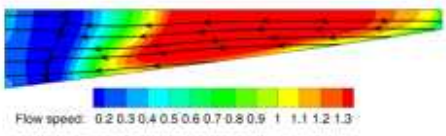
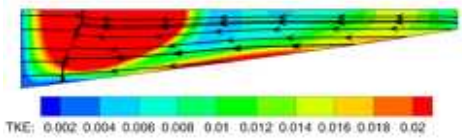
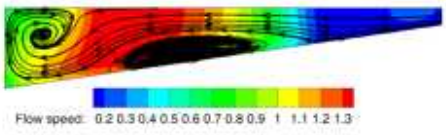
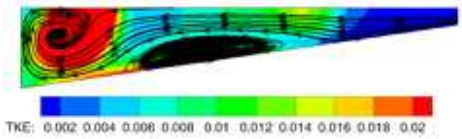
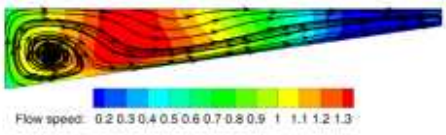
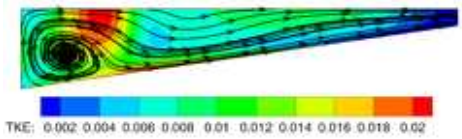
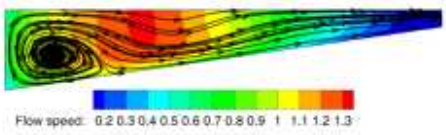
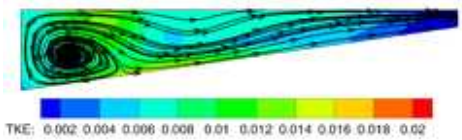
Turbulent kinetic energy (TKE)

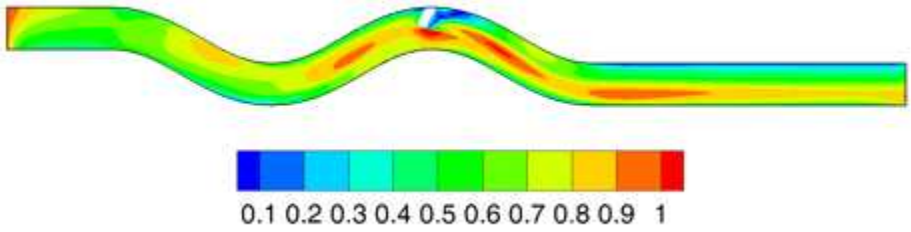
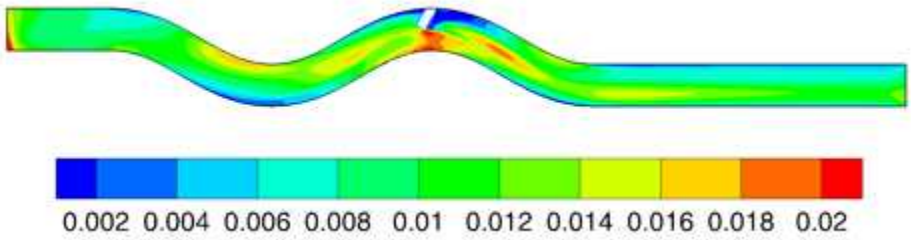
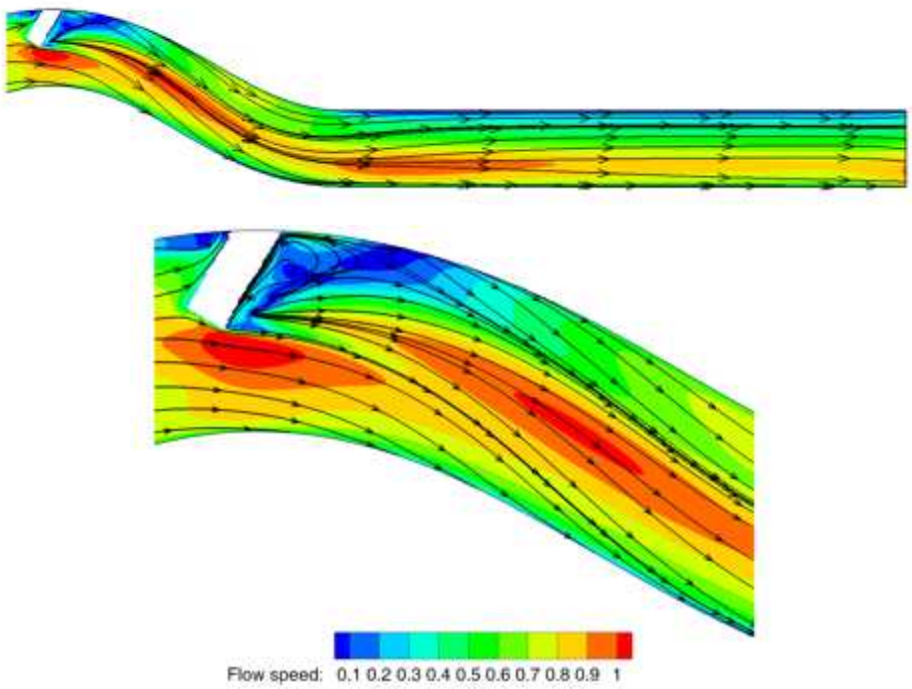


Recirculation



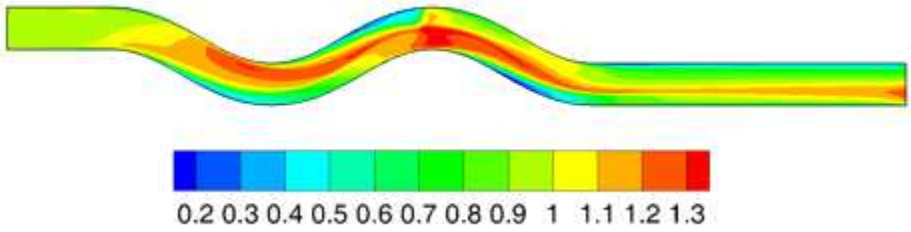
Normalized recirculation length : 1.7657

위치	case15 (R=25/ =30/α=-30/l=2.5/h=1)	
	secondary flow	
		
A		
B		
C		
D		
F		
G		
H		
I		

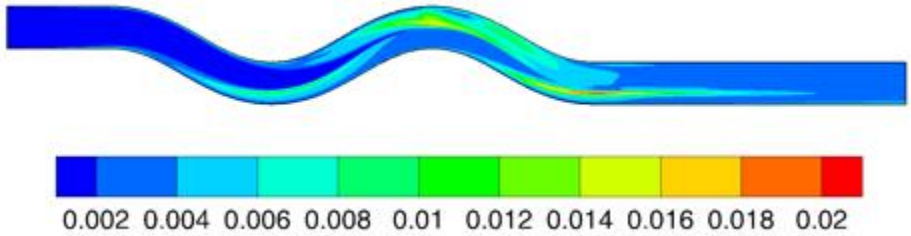
case17 (bottom/R=25/ =30/α=-30/l=5/h=0.5)
Flow speed

Turbulent kinetic energy (TKE)

Recirculation
 Normalized recirculation length : 0.4846

case17 (top/R=25/ =30/α=-30/l=5/h=0.5)

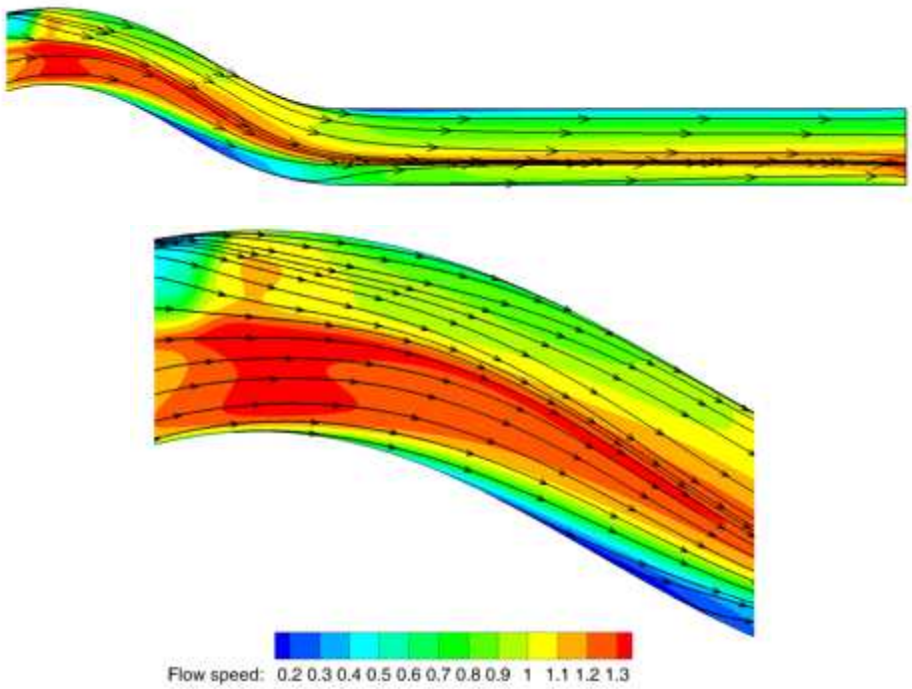
Flow speed



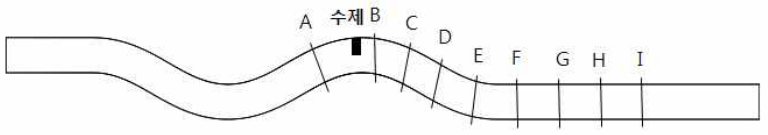
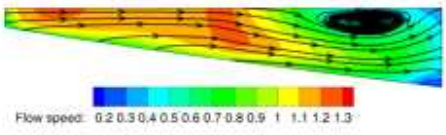
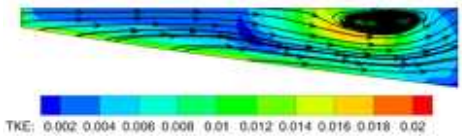
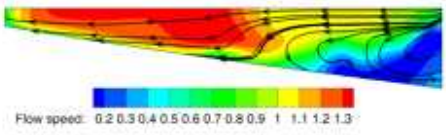
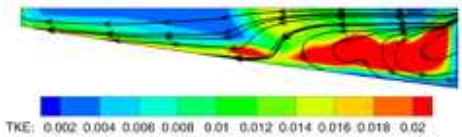
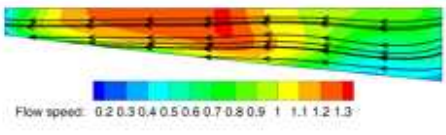
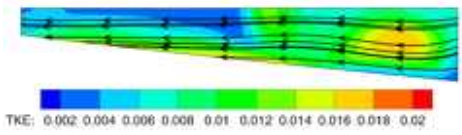
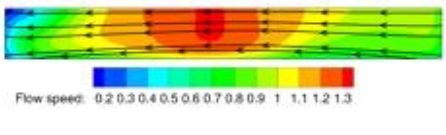
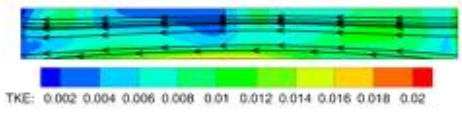
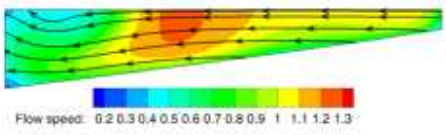
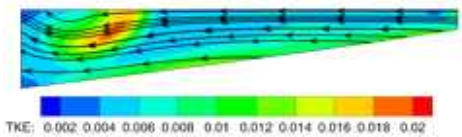
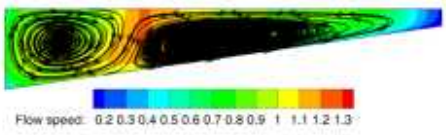
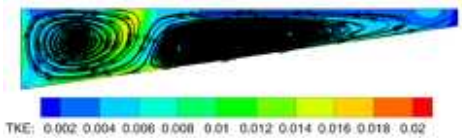
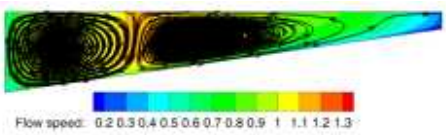
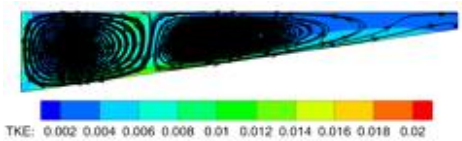
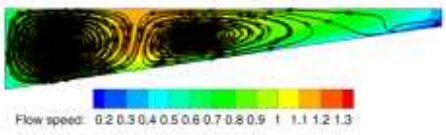
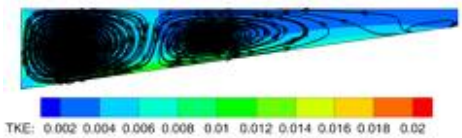
Turbulent kinetic energy (TKE)

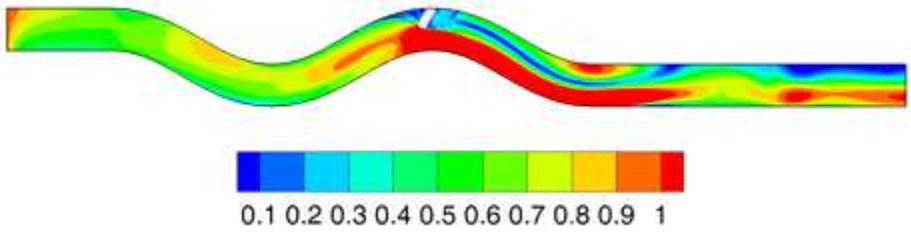
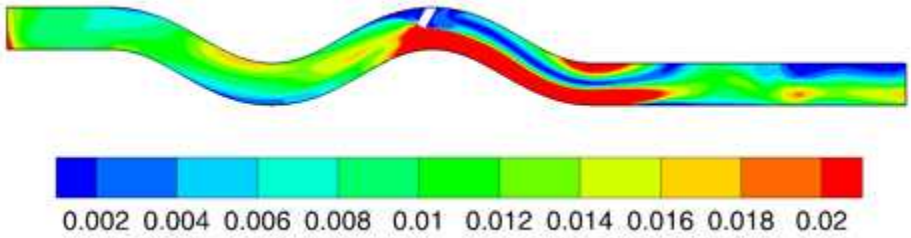
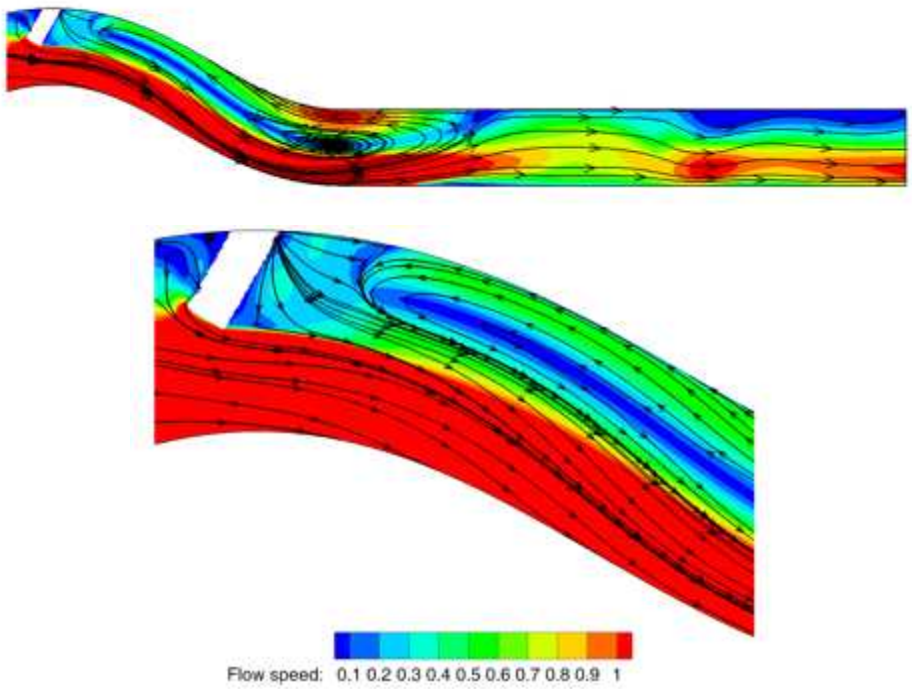


Recirculation



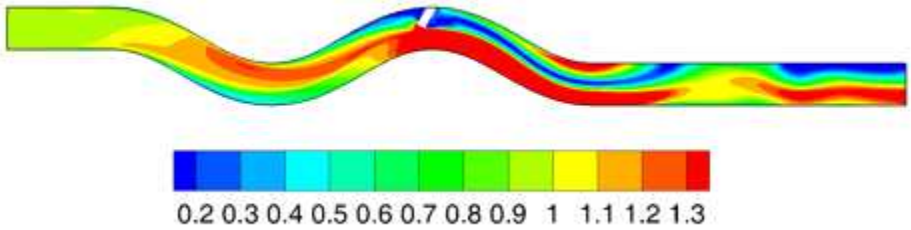
recirculation (X)

위치	case17 (R=25/ =30/α=-30/l=5/h=0.5)	
	secondary flow	
		
A		
B		
C		
D		
F		
G		
H		
I		

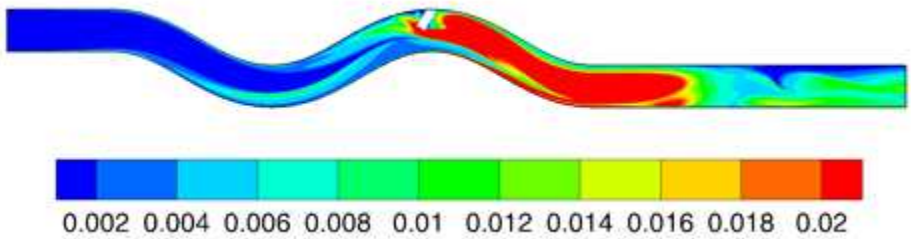
case19 (bottom/R=25/ =30/α=60/l=5/h=1)
Flow speed

Turbulent kinetic energy (TKE)

Recirculation
 Normalized recirculation length : 0.5163

case19 (top/R=25/ =30/α=-30/l=5/h=1)

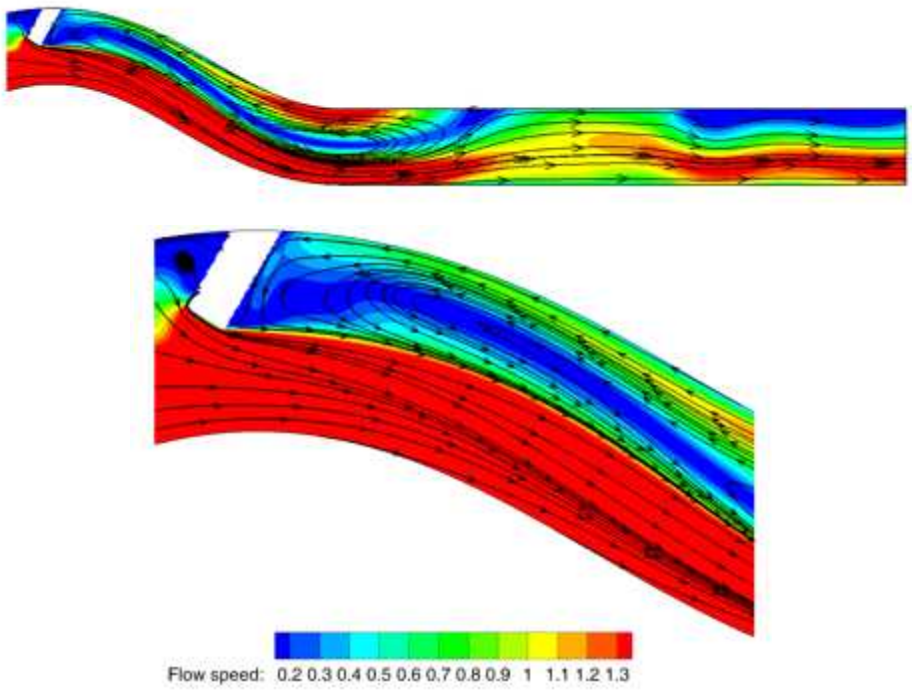
Flow speed



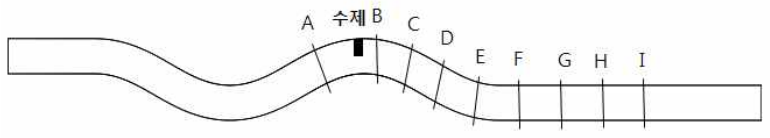
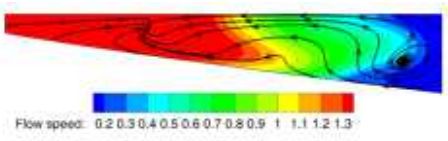
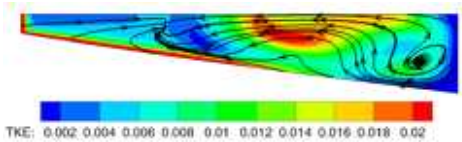
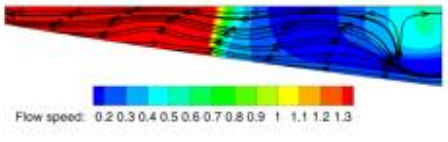
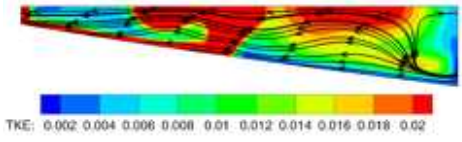
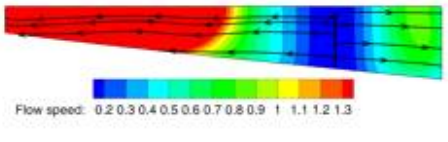
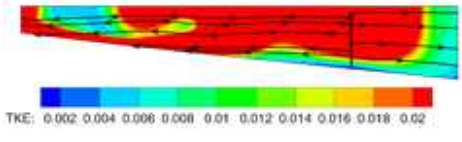
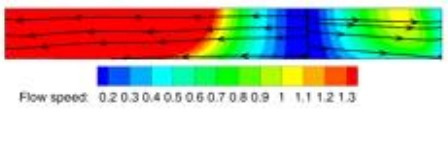
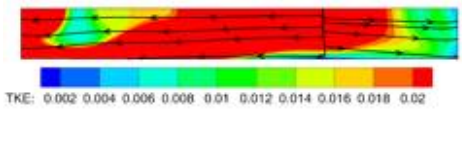
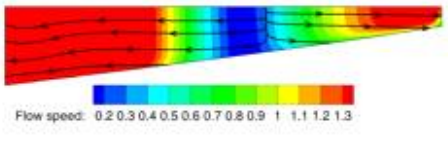
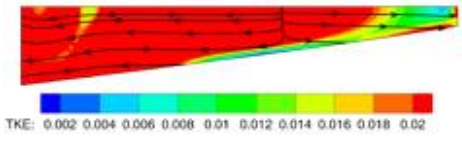
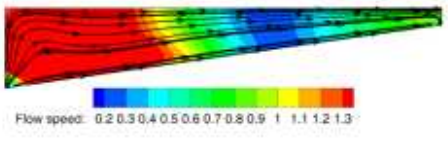
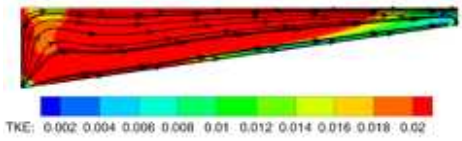
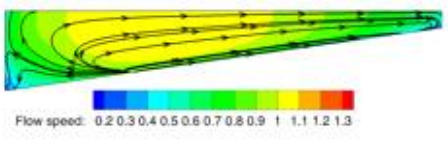
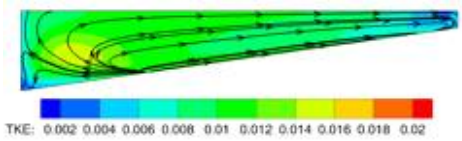
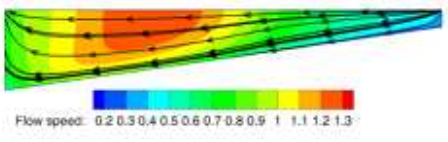
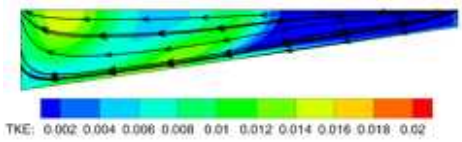
Turbulent kinetic energy (TKE)

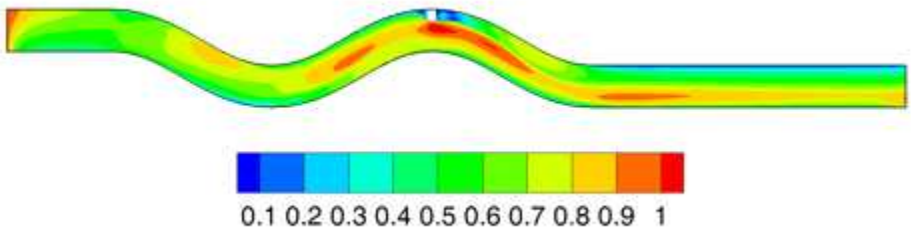
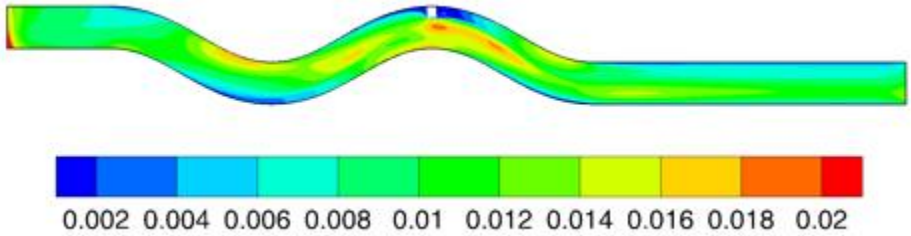
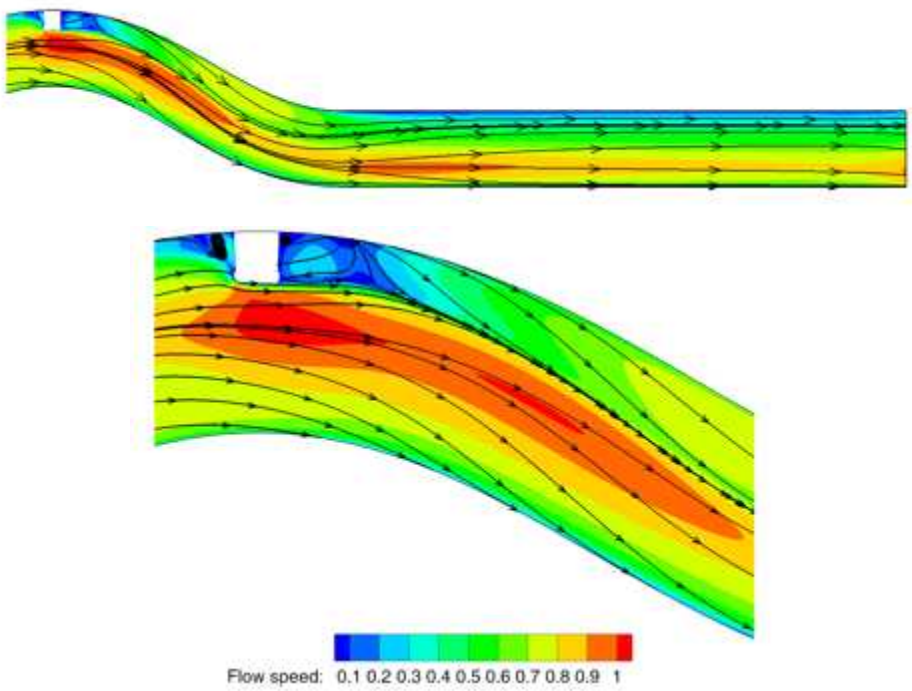


Recirculation



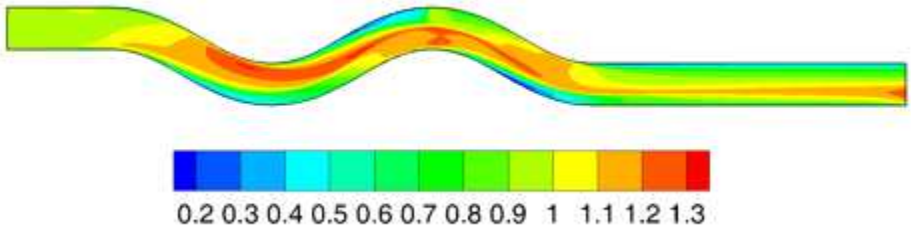
Normalized recirculation length : 5.5557

위치	case19 (R=25/ =30/α=-30/l=5/h=1)	
	secondary flow	
		
A		
B		
C		
D		
F		
G		
H		
I		

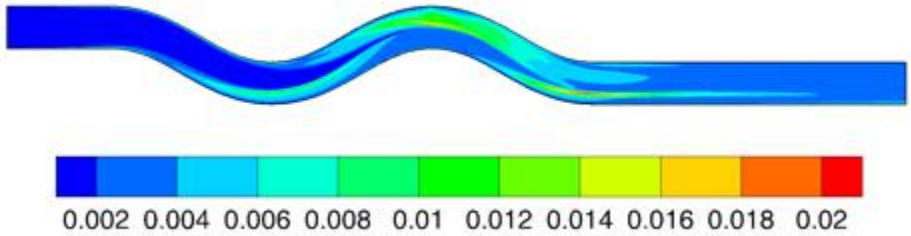
case29 (bottom/R=25/ =30/α=0/l=2.5/h=0.5)
Flow speed

Turbulent kinetic energy (TKE)

Recirculation
 Normalized recirculation length : 0.3624

case29 (top/R=25/ =30/α=0/l=2.5/h=0.5)

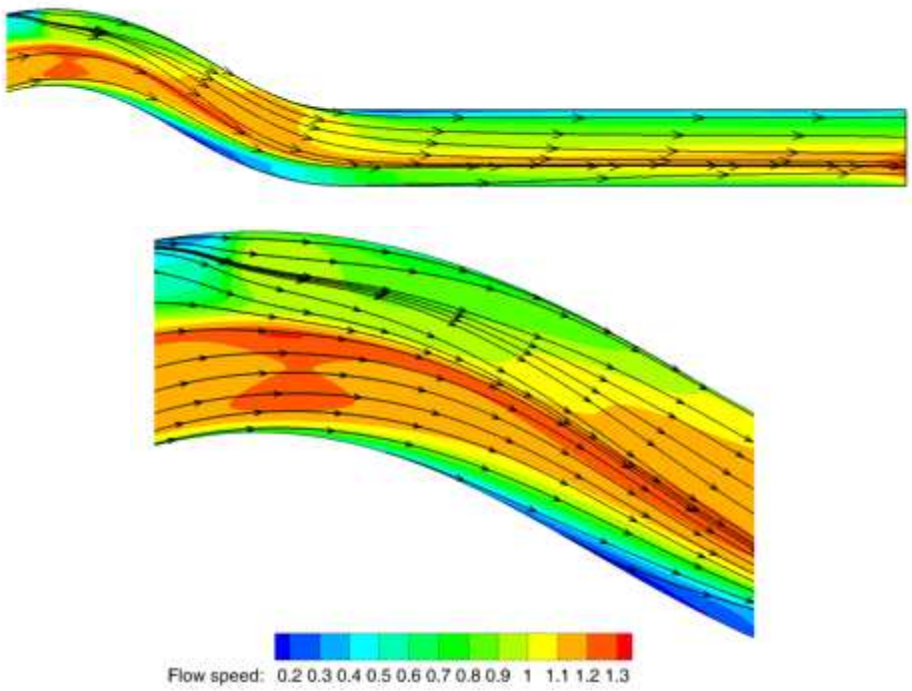
Flow speed



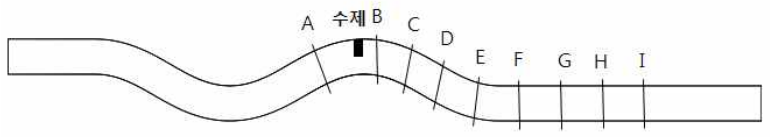
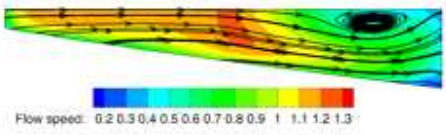
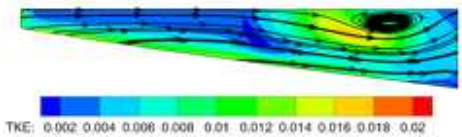
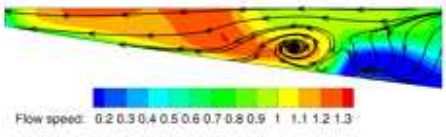
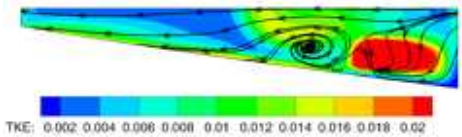
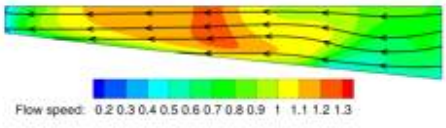
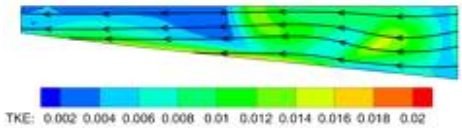
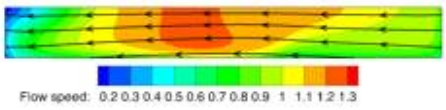
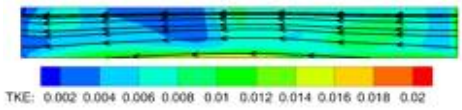
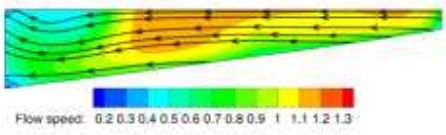
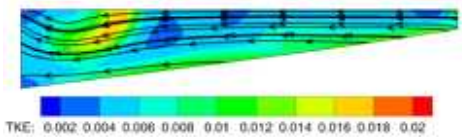
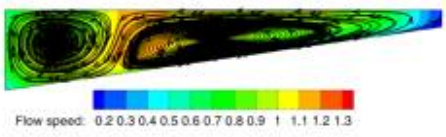
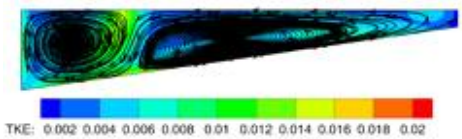
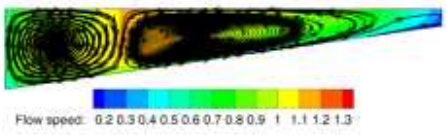
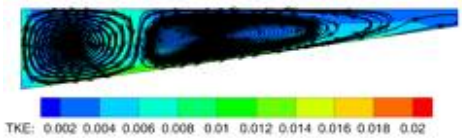
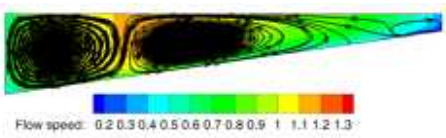
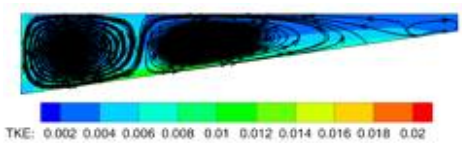
Turbulent kinetic energy (TKE)



Recirculation

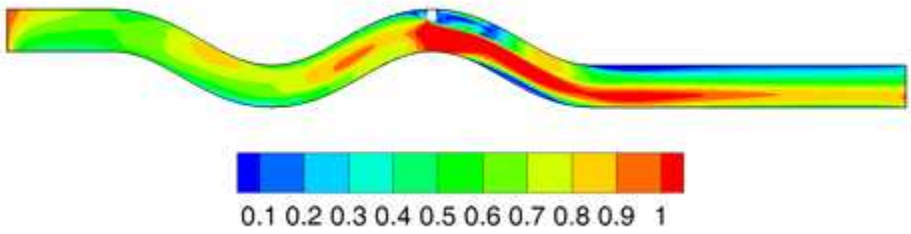


recirculation (X)

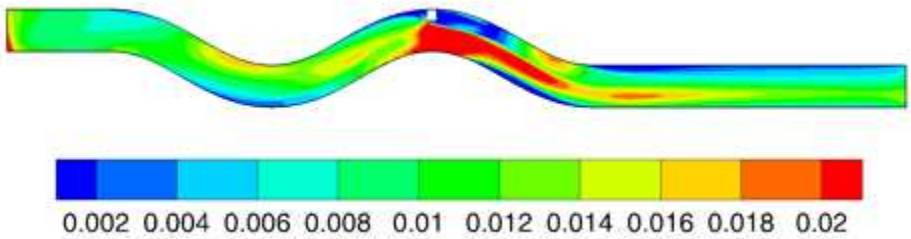
위치	case29 (R=25/ =30/α=0/l=2.5/h=0.5)	
	secondary flow	
		
A		
B		
C		
D		
F		
G		
H		
I		

case31 (bottom/R=25/ =30/α=0/l=2.5/h=1)

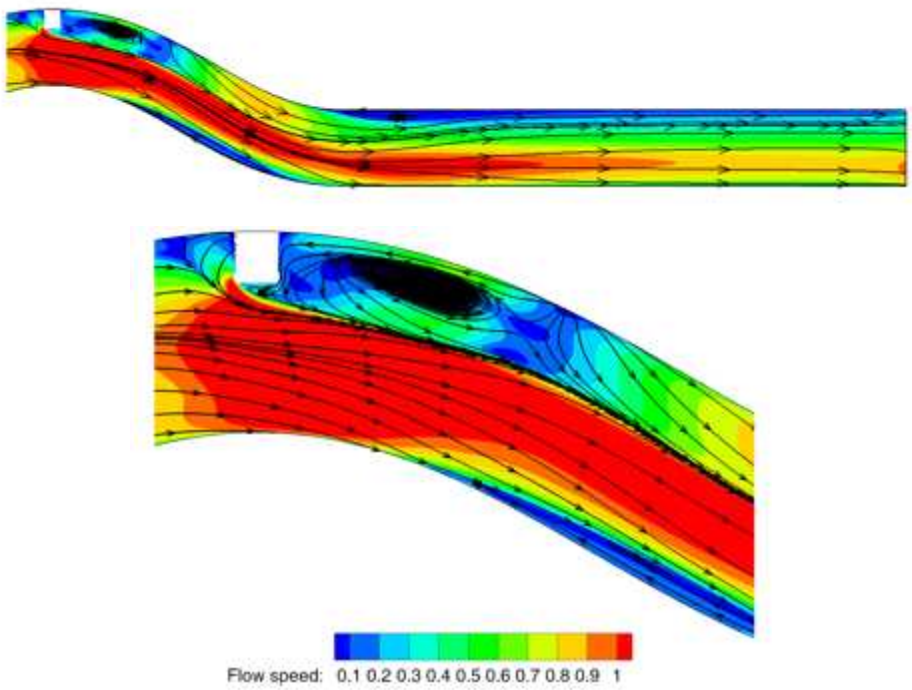
Flow speed



Turbulent kinetic energy (TKE)



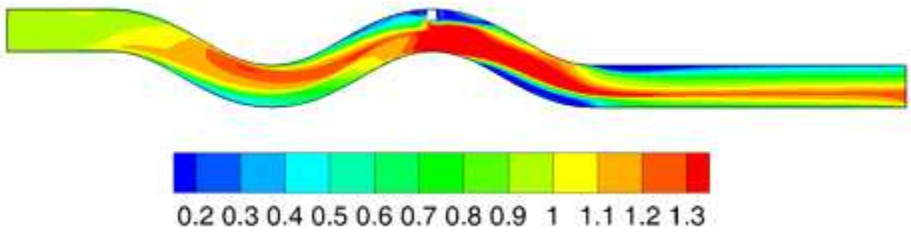
Recirculation



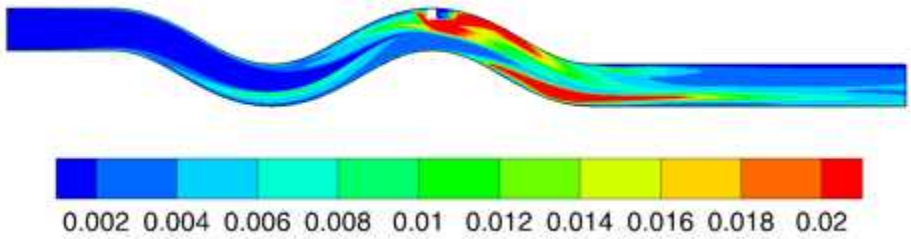
Normalized recirculation length : 1.3809

case31 (top/R=25/ =30/α=0/l=2.5/h=1)

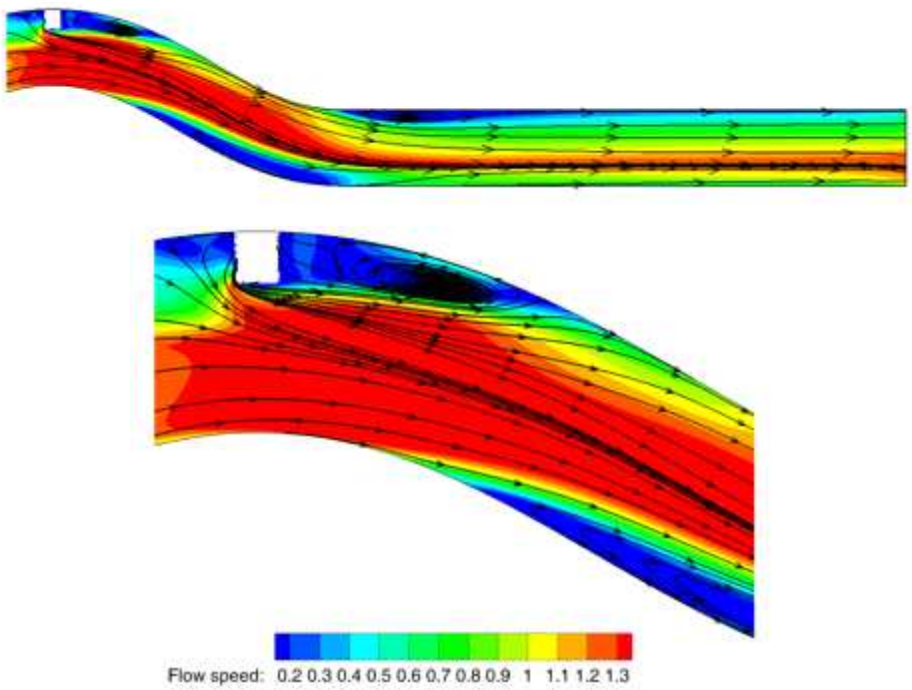
Flow speed



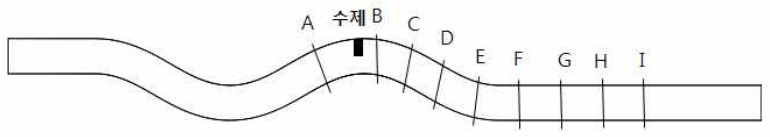
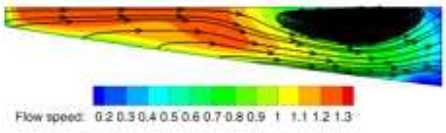
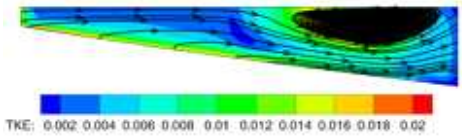
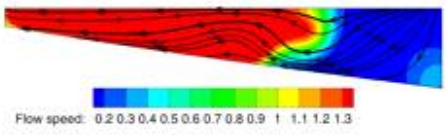
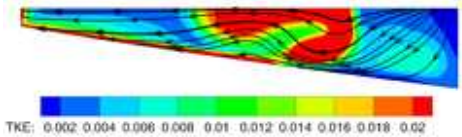
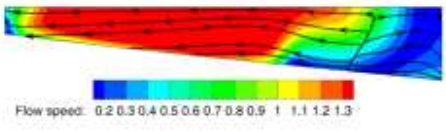
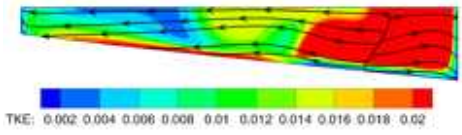
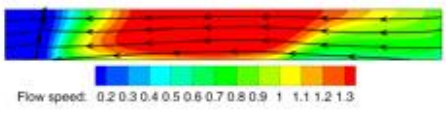
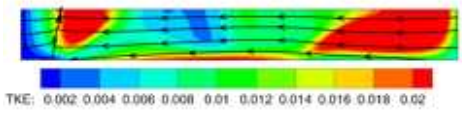
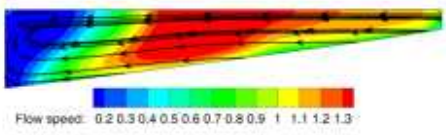
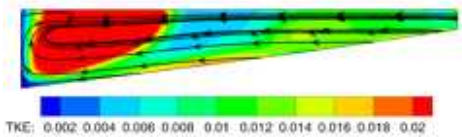
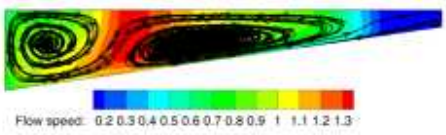
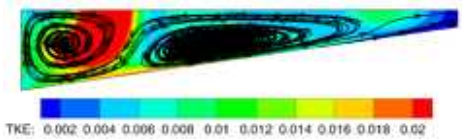
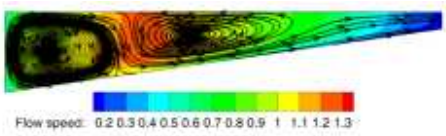
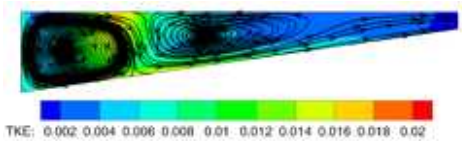
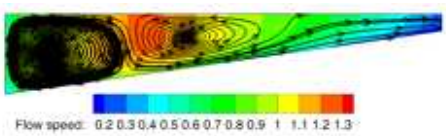
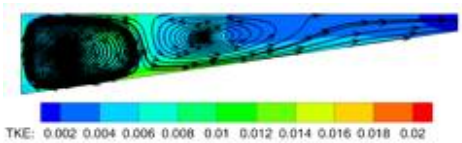
Turbulent kinetic energy (TKE)



Recirculation

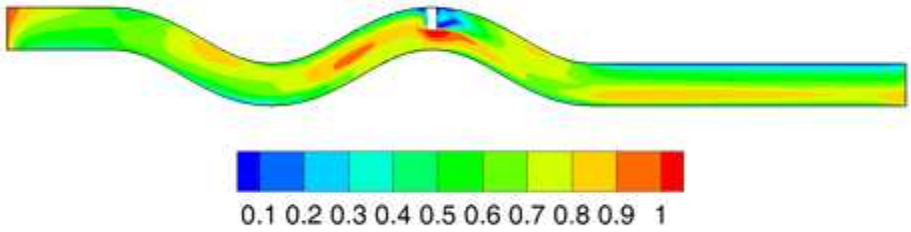


Normalized recirculation length : 1.2044

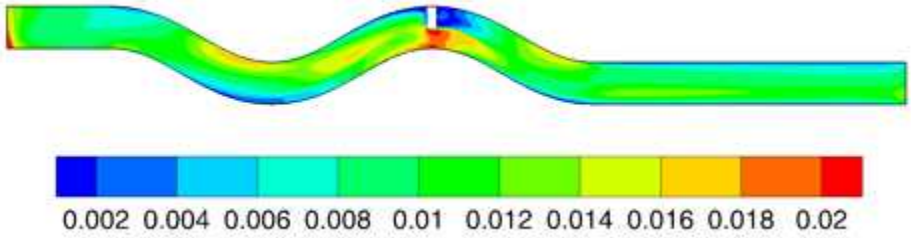
위치	case31 (top/R=25/ =30/α=0/l=2.5/h=1)	
	secondary flow	
		
A		
B		
C		
D		
F		
G		
H		
I		

case33 (bottom/R=25/ =30/α=0/l=5/h=0.5)

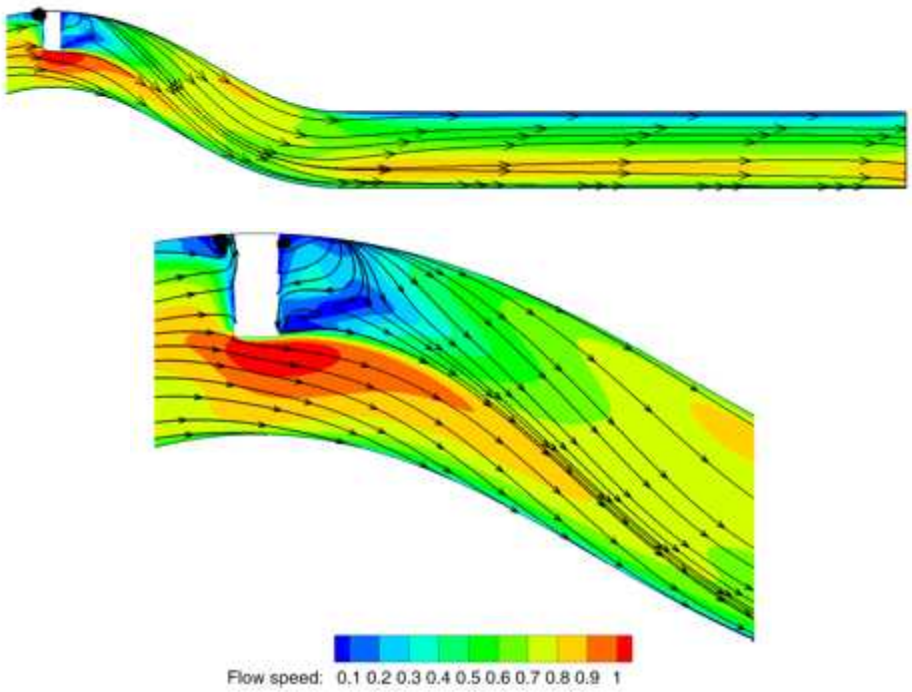
Flow speed



Turbulent kinetic energy (TKE)



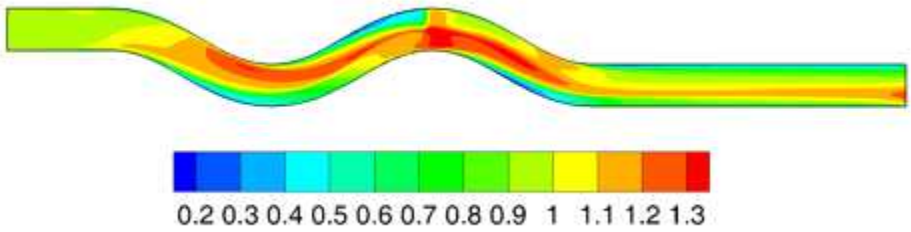
Recirculation



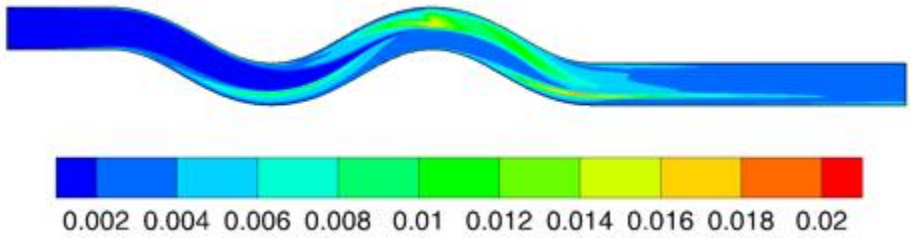
Normalized recirculation length : 0.4076

case33 (top/R=25/ =30/α=0/l=5/h=0.5)

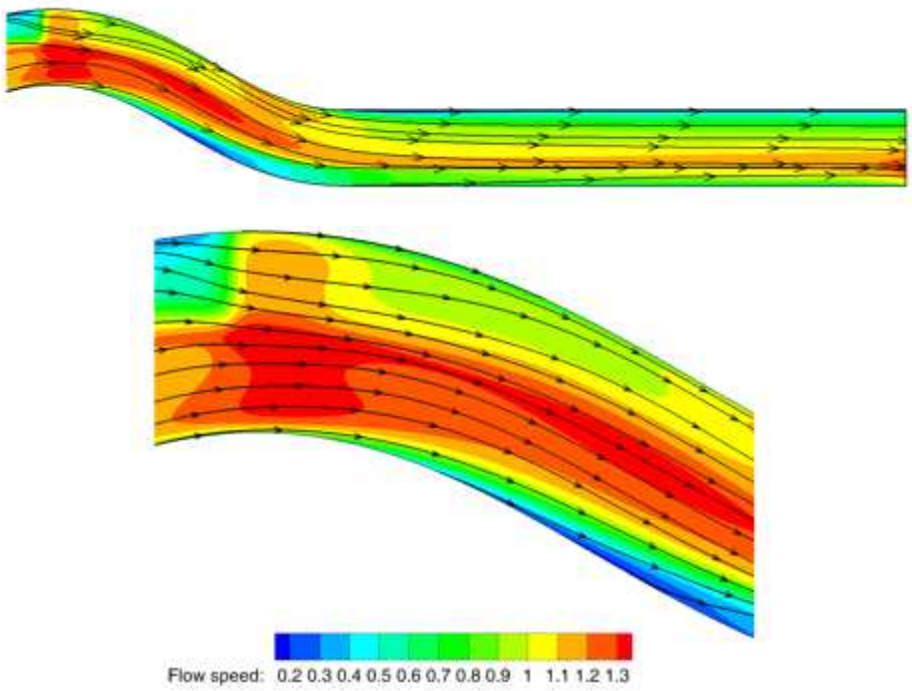
Flow speed



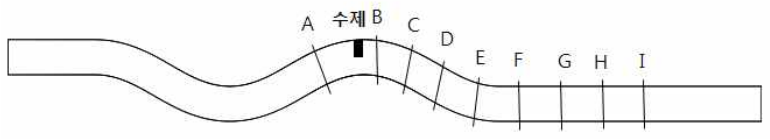
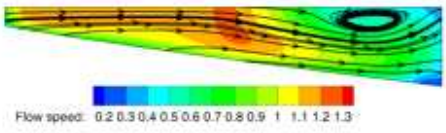
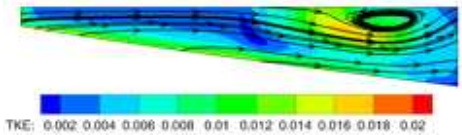
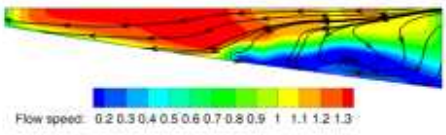
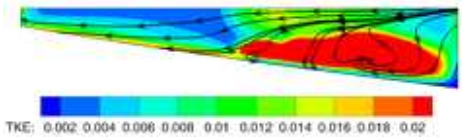
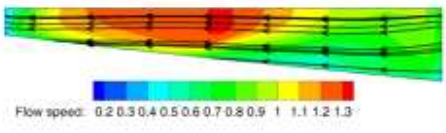
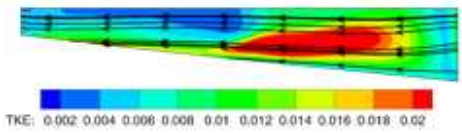
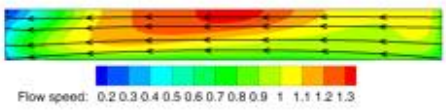
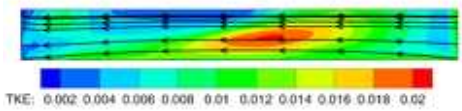
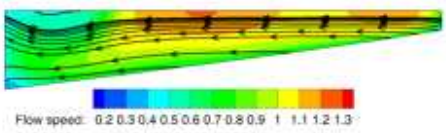
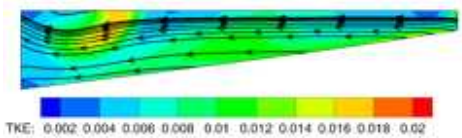
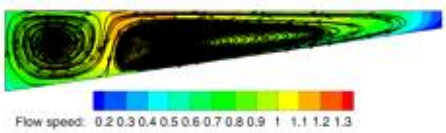
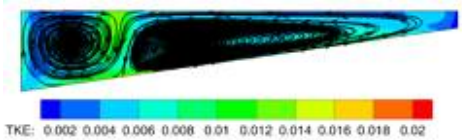
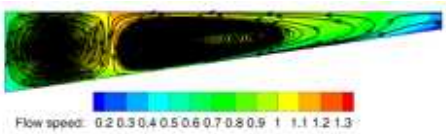
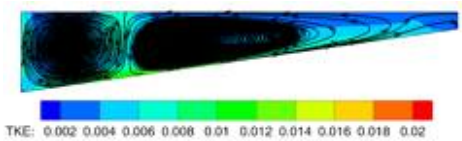
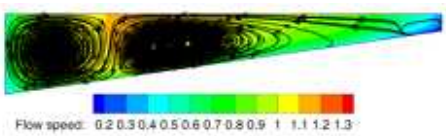
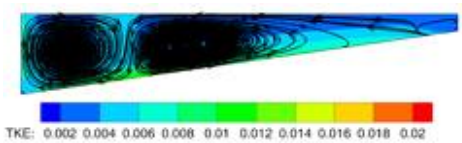
Turbulent kinetic energy (TKE)

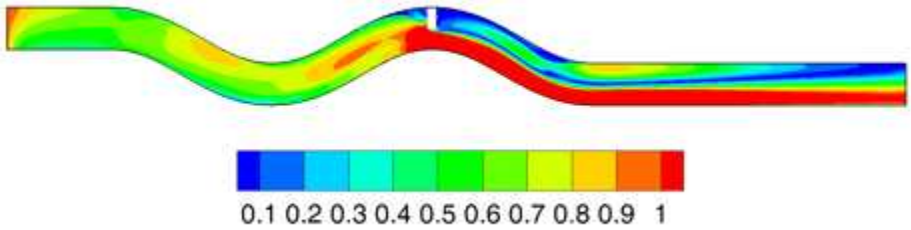
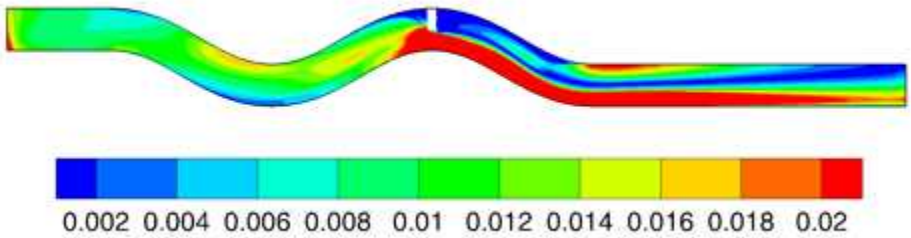
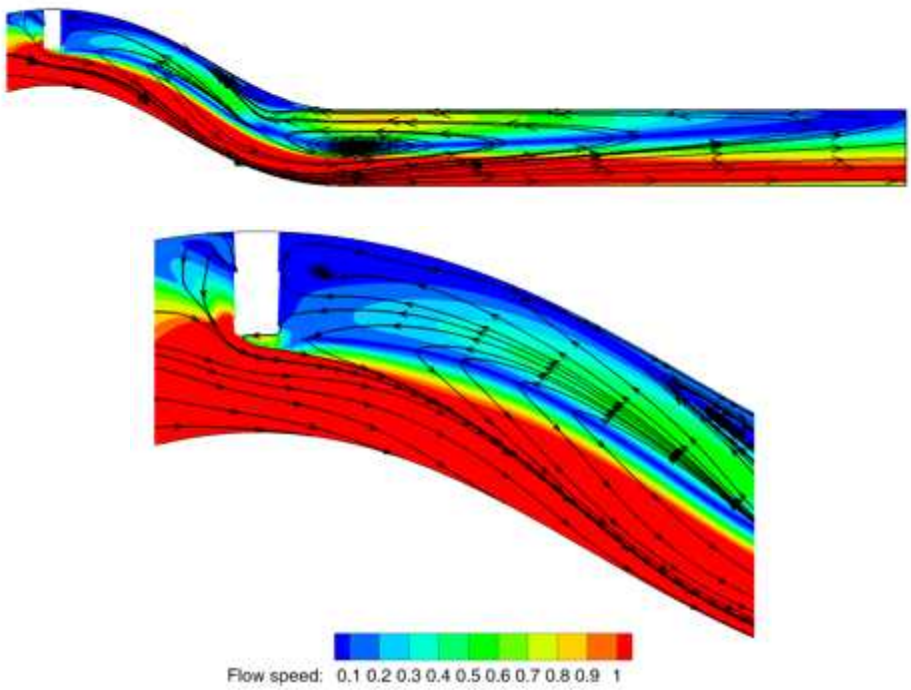


Recirculation



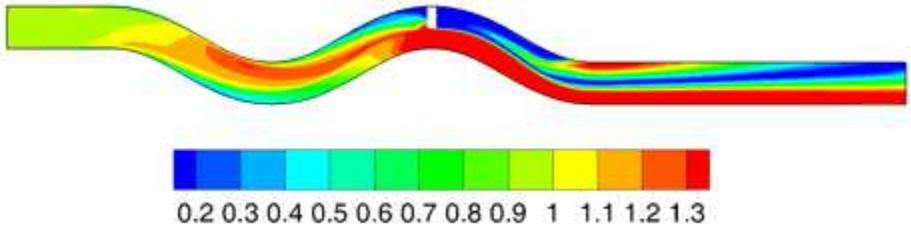
recirculation (X)

위치	case33 (R=25/ =30/α=0/l=5/h=0.5)	
	secondary flow	
		
A		
B		
C		
D		
F		
G		
H		
I		

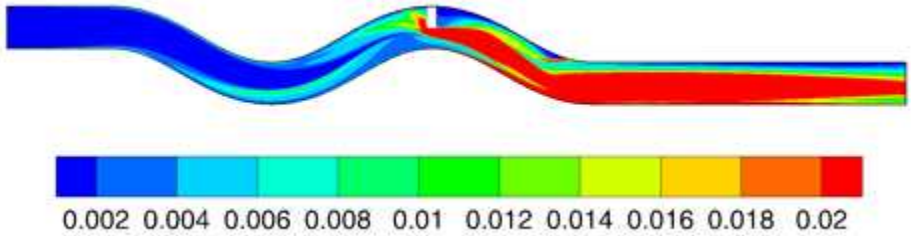
case35 (bottom/R=25/ =30/α=0/l=5/h=1)
Flow speed

Turbulent kinetic energy (TKE)

Recirculation
 Normalized recirculation length : 11.0458

case35 (top/R=25/ =30/α=0/l=5/h=1)

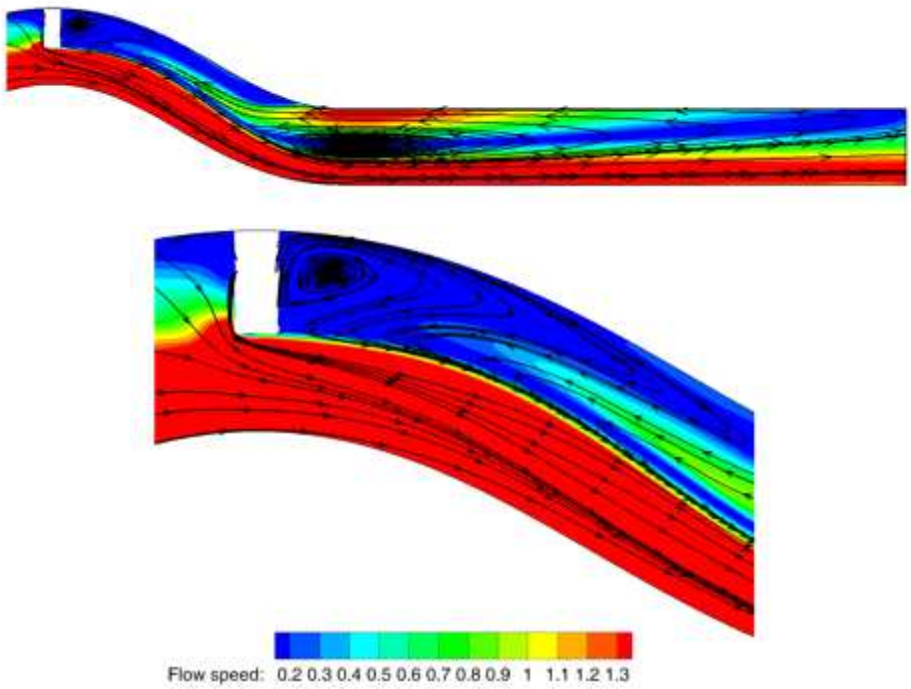
Flow speed



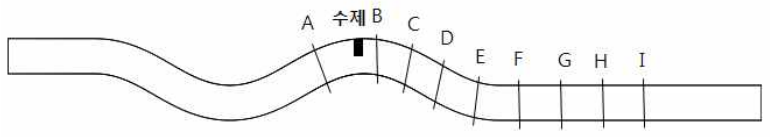
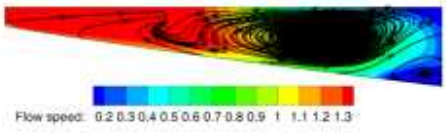
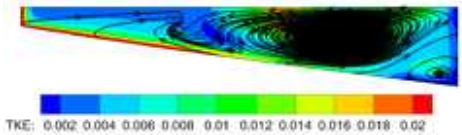
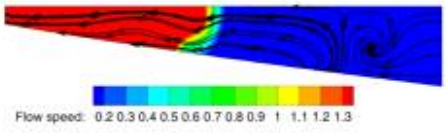
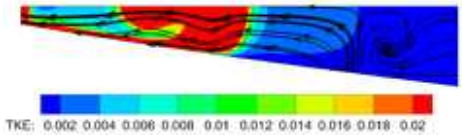
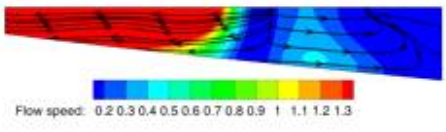
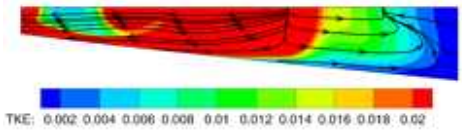
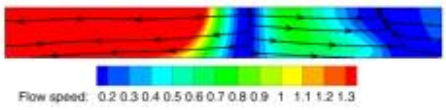
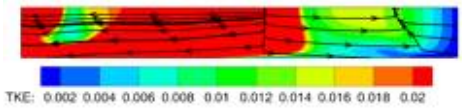
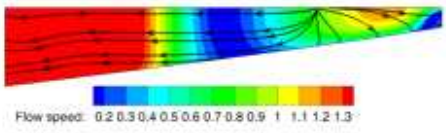
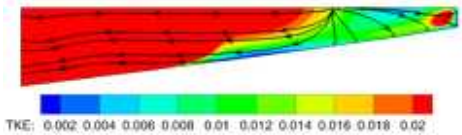
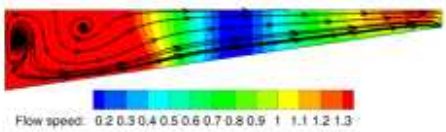
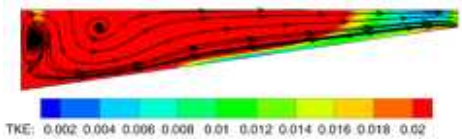
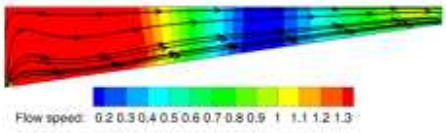
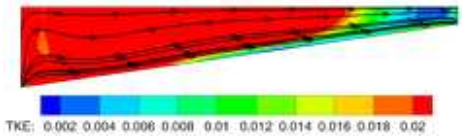
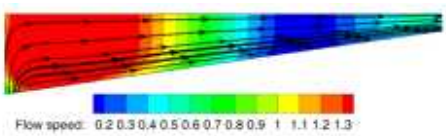
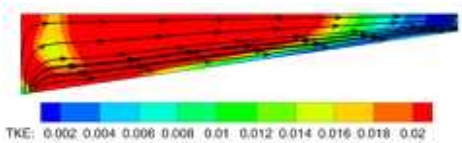
Turbulent kinetic energy (TKE)

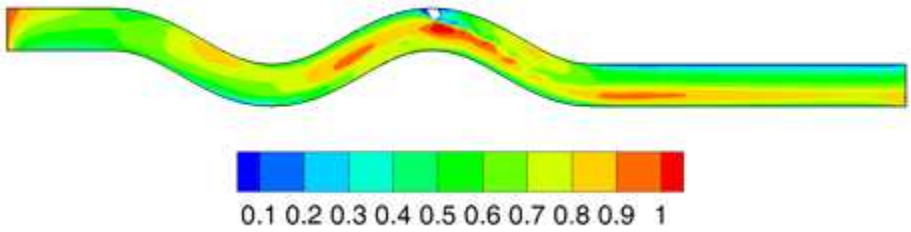
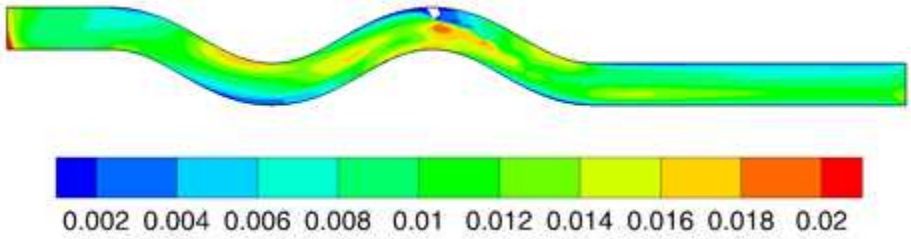
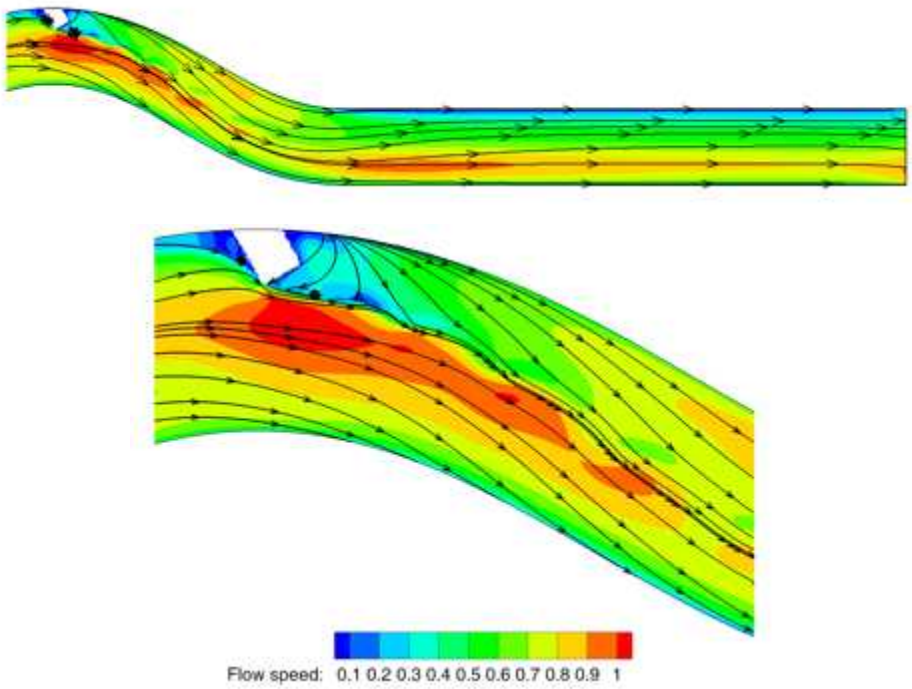


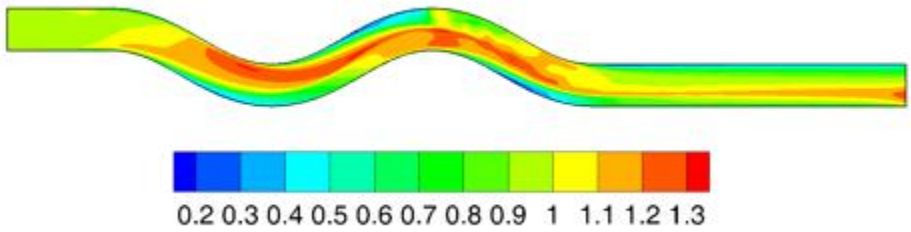
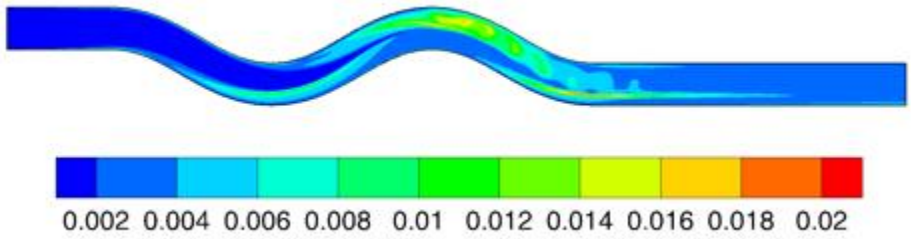
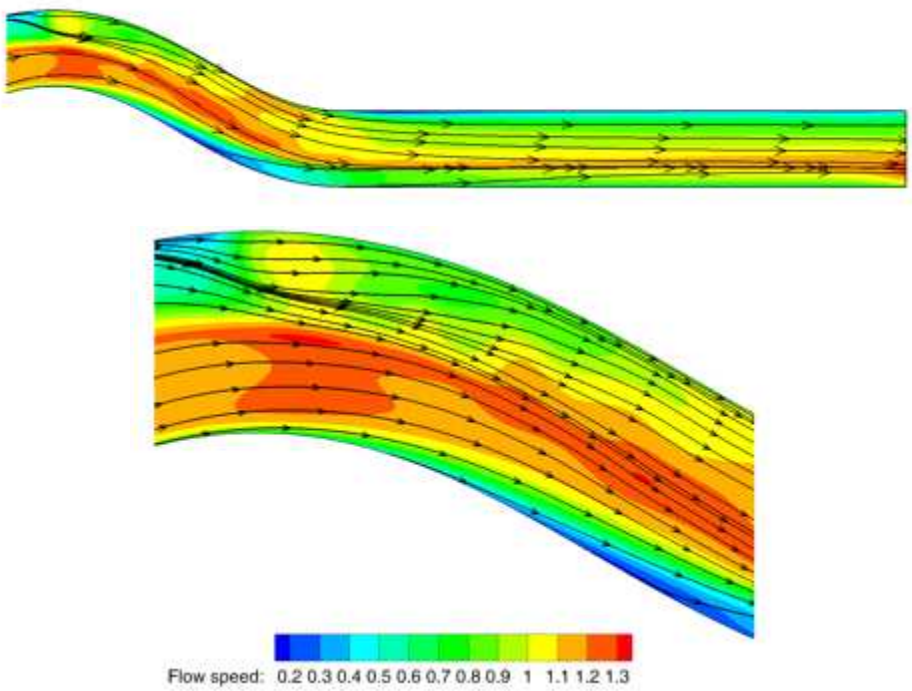
Recirculation

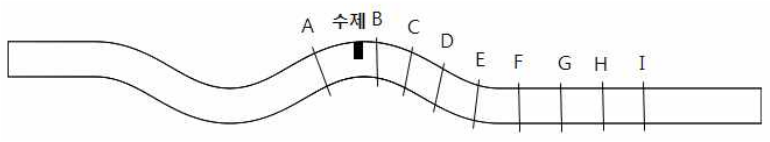
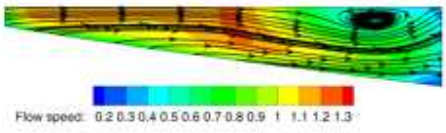
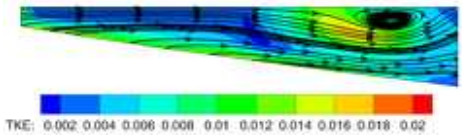
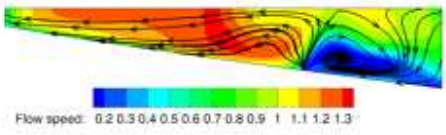
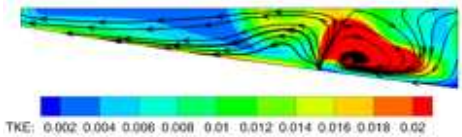
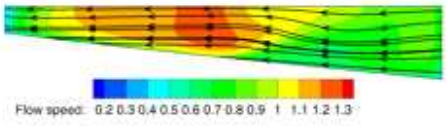
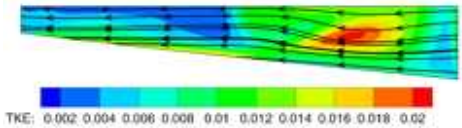
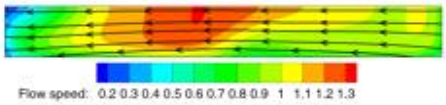
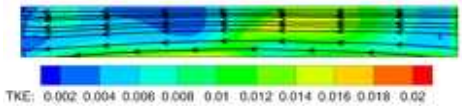
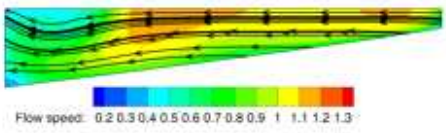
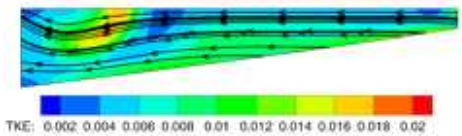
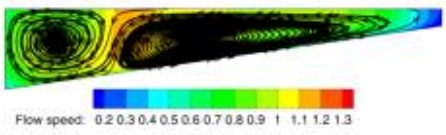
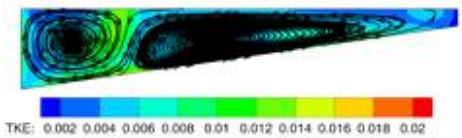
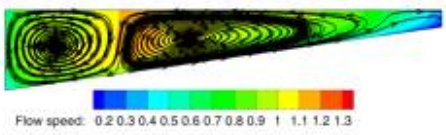
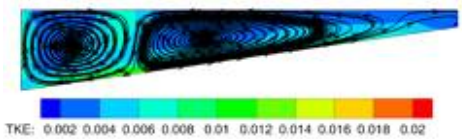
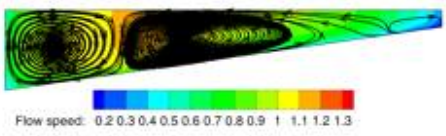
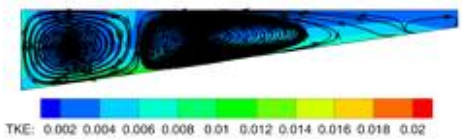


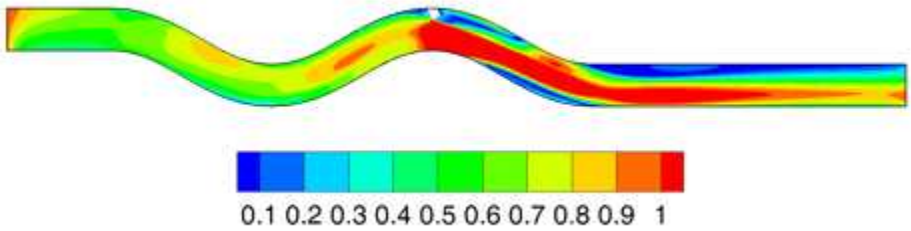
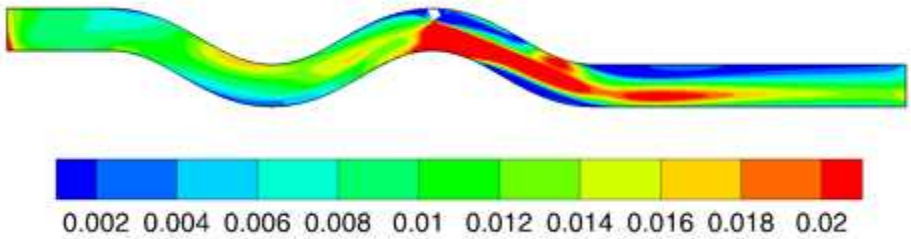
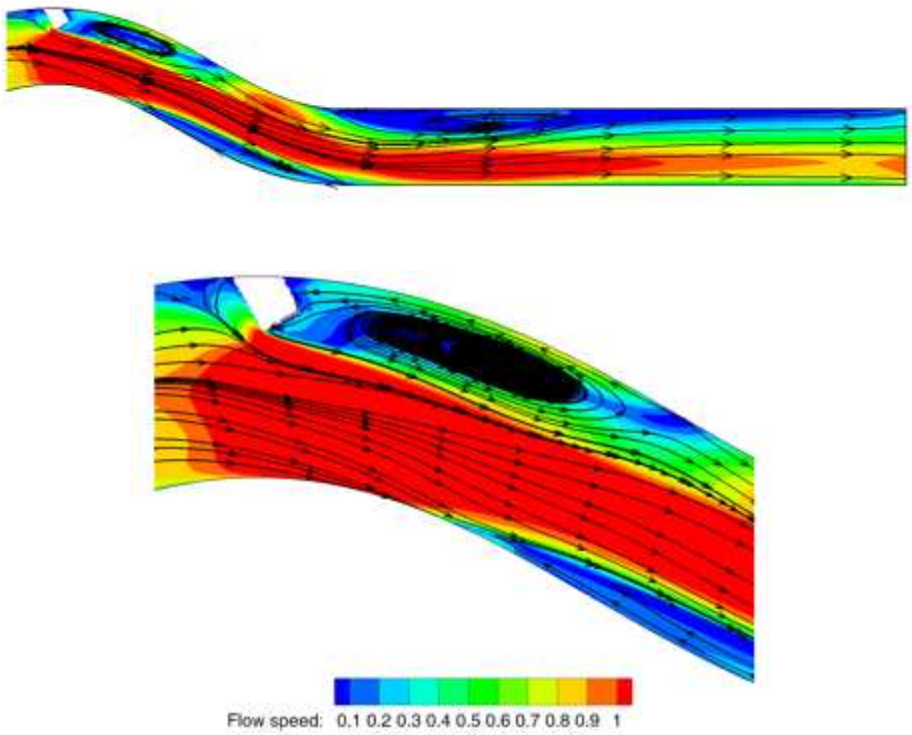
Normalized recirculation length : 11.0459

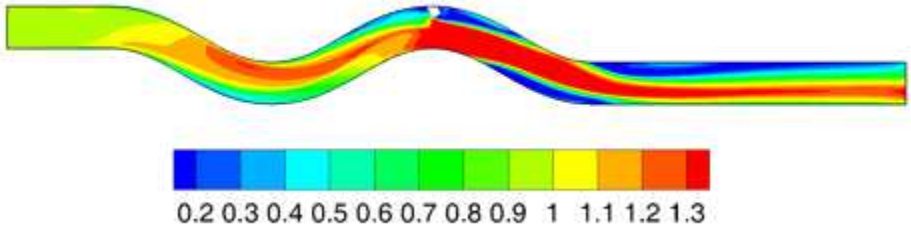
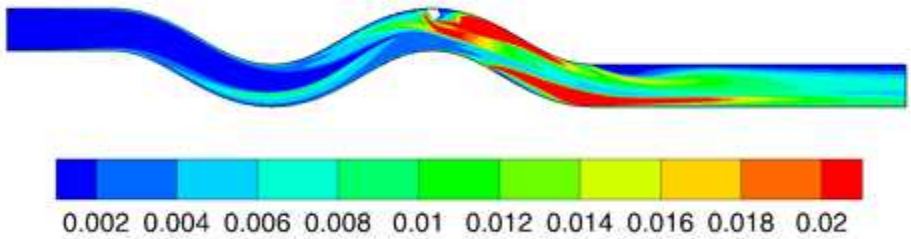
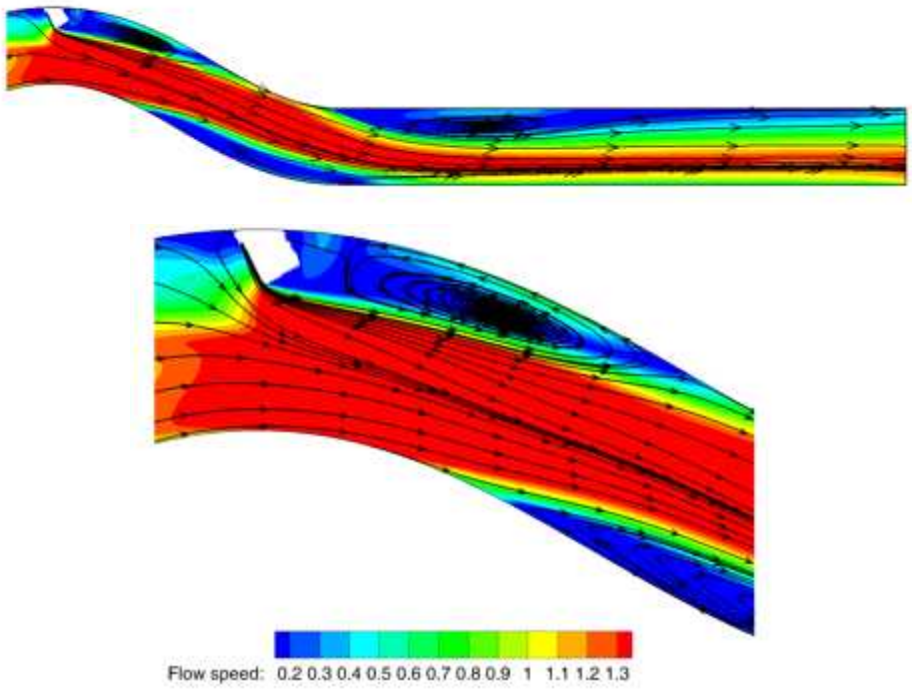
위치	case35 (R=25/ =30/α=0/l=5/h=1)	
	secondary flow	
		
A		
B		
C		
D		
F		
G		
H		
I		

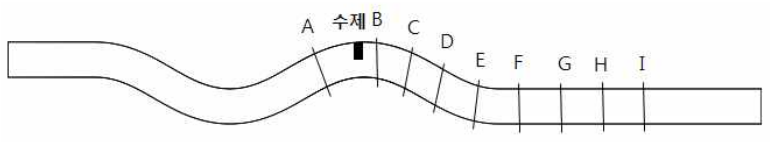
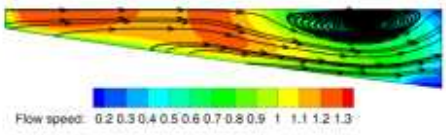
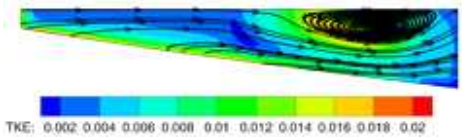
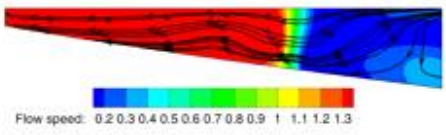
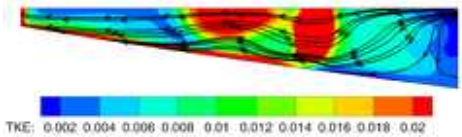
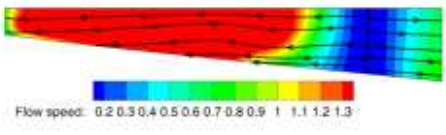
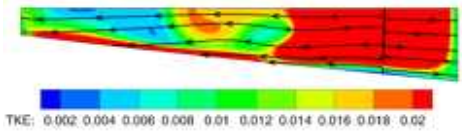
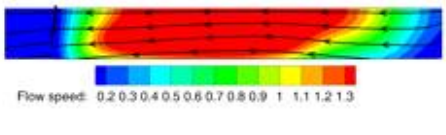
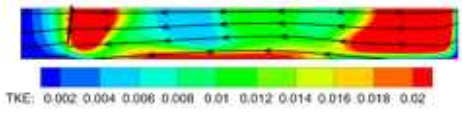
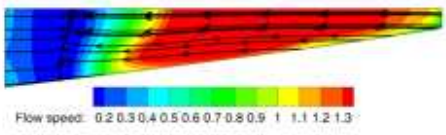
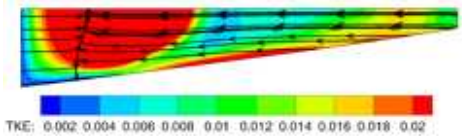
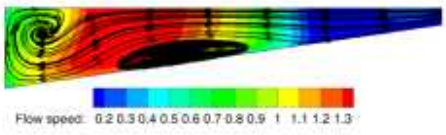
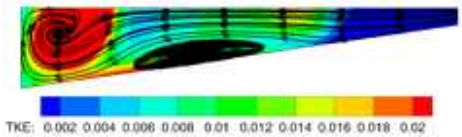
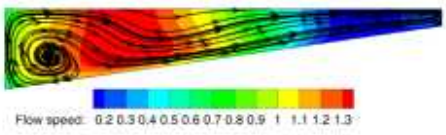
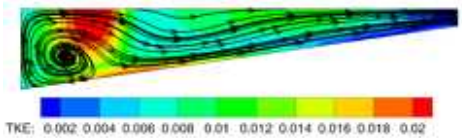
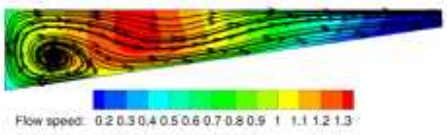
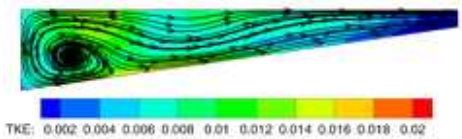
case45 (bottom/R=25/ =30/α=+30/l=2.5/h=0.5)
Flow speed

Turbulent kinetic energy (TKE)

Recirculation
 Normalized recirculation length : 0.3941

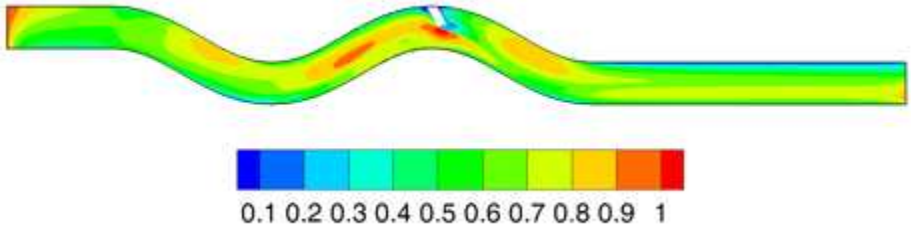
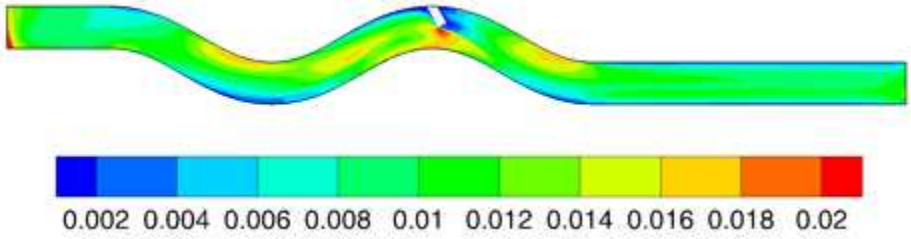
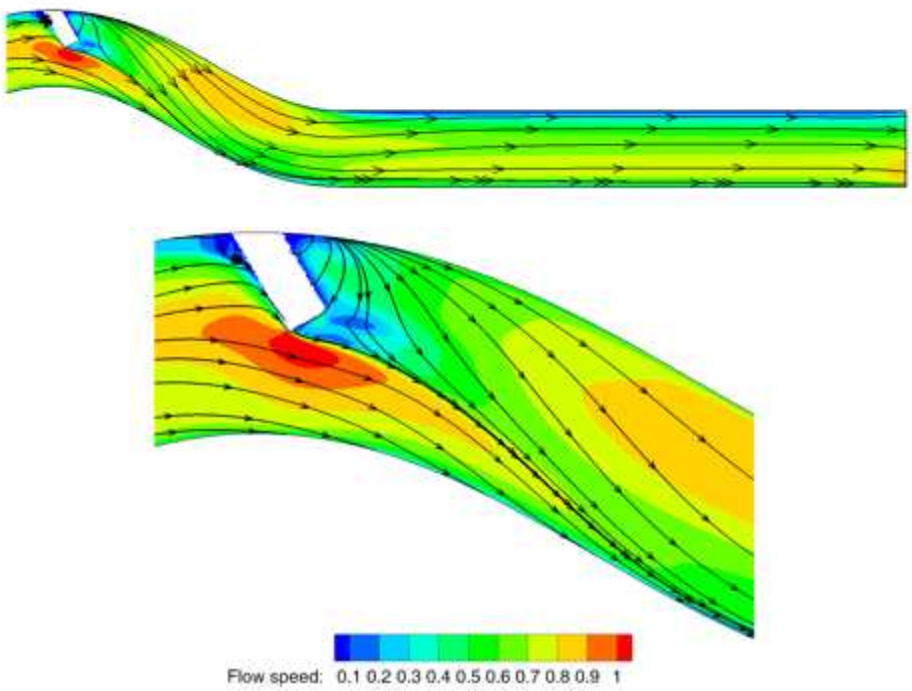
case45 (top/R=25/ =30/α=+30/l=2.5/h=0.5)
Flow speed

Turbulent kinetic energy (TKE)

Recirculation
 recirculation (X)

위치	case45 (R=25/ =30/α=+30/l=2.5/h=0.5)	
	secondary flow	
		
A		
B		
C		
D		
F		
G		
H		
I		

case47 (bottom/R=25/ =30/α=+30/l=2.5/h=1)
Flow speed

Turbulent kinetic energy (TKE)

Recirculation
 Normalized recirculation length : 1.9604

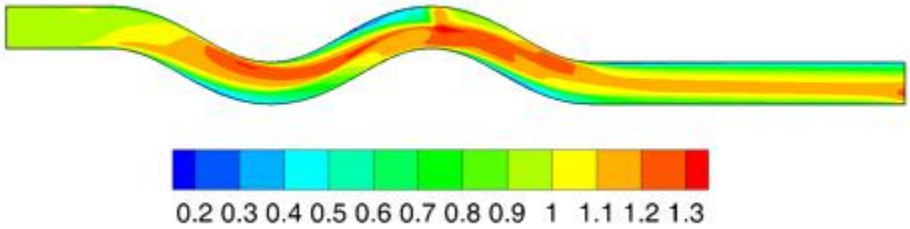
case47 (top/R=25/ =30/α=+30/l=2.5/h=1)
Flow speed

Turbulent kinetic energy (TKE)

Recirculation
 Normalized recirculation length : 1.9000

위치	case47 (R=25/ =30/α=+30/l=2.5/h=1)	
	secondary flow	
		
A		
B		
C		
D		
F		
G		
H		
I		

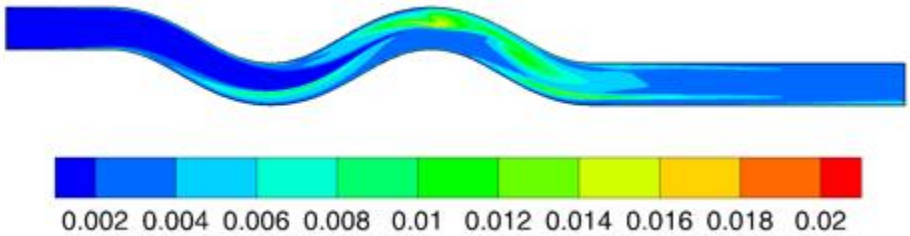
case49 (bottom/R=25/ =30/α=+30/l=5/h=0.5)
Flow speed

Turbulent kinetic energy (TKE)

Recirculation
 Normalized recirculation length : 0.4303

case49 (top/R=25/ =30/α=+30/l=5/h=0.5)

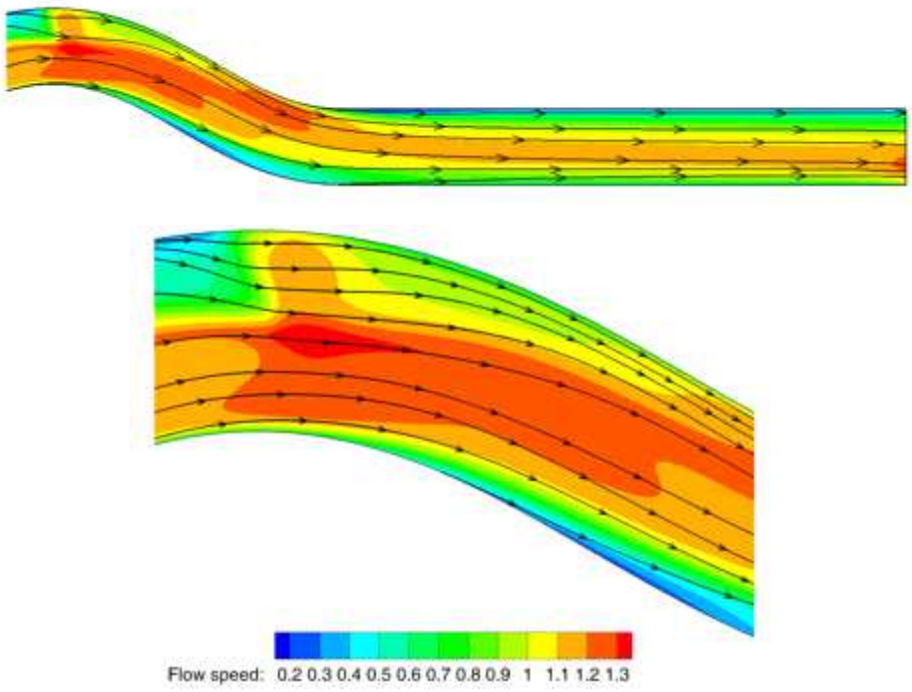
Flow speed



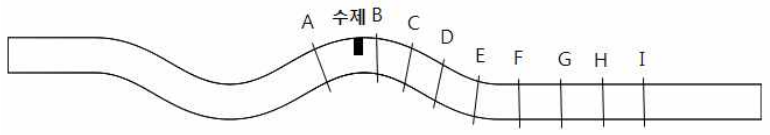
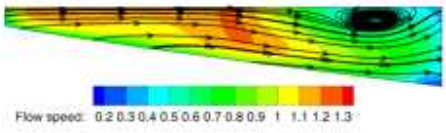
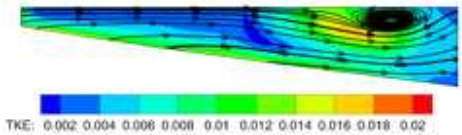
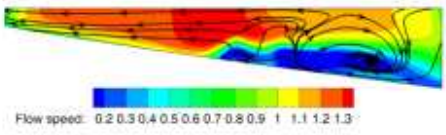
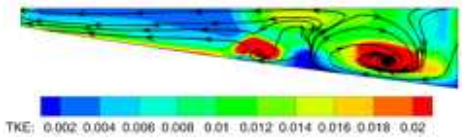
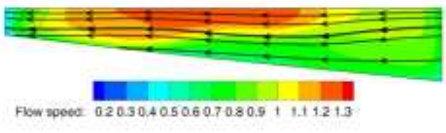
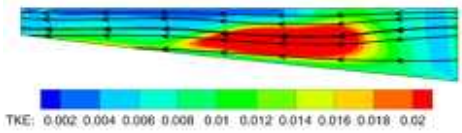
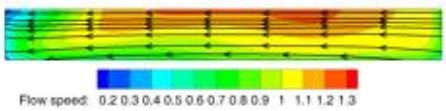
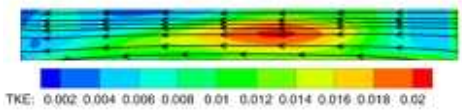
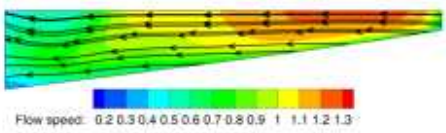
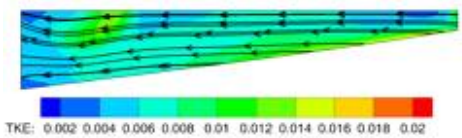
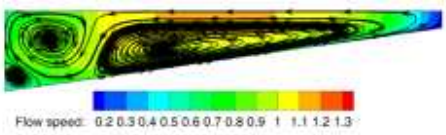
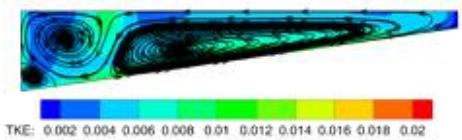
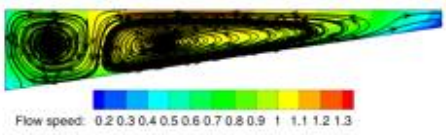
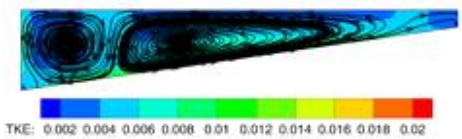
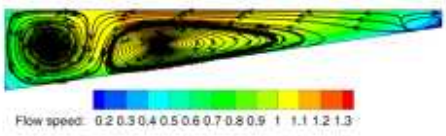
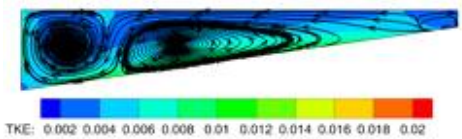
Turbulent kinetic energy (TKE)



Recirculation

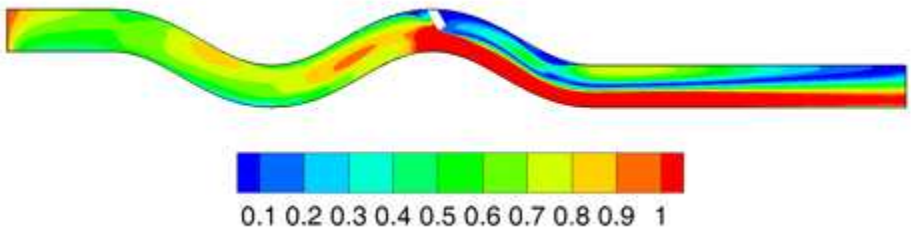


recirculation (X)

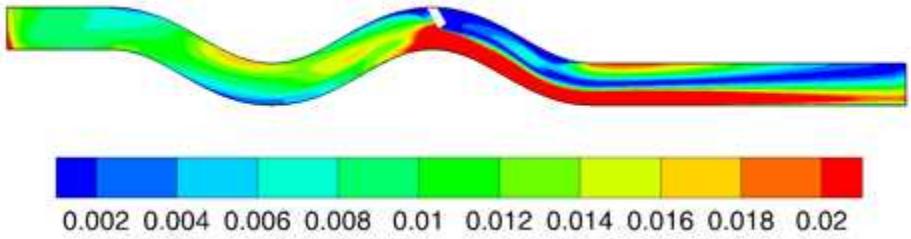
위치	case49 (R=25/ =30/α=+30/l=5/h=0.5)	
	secondary flow	
		
A		
B		
C		
D		
F		
G		
H		
I		

case51 (bottom/R=25/ =30/α=+30/l=5/h=1)

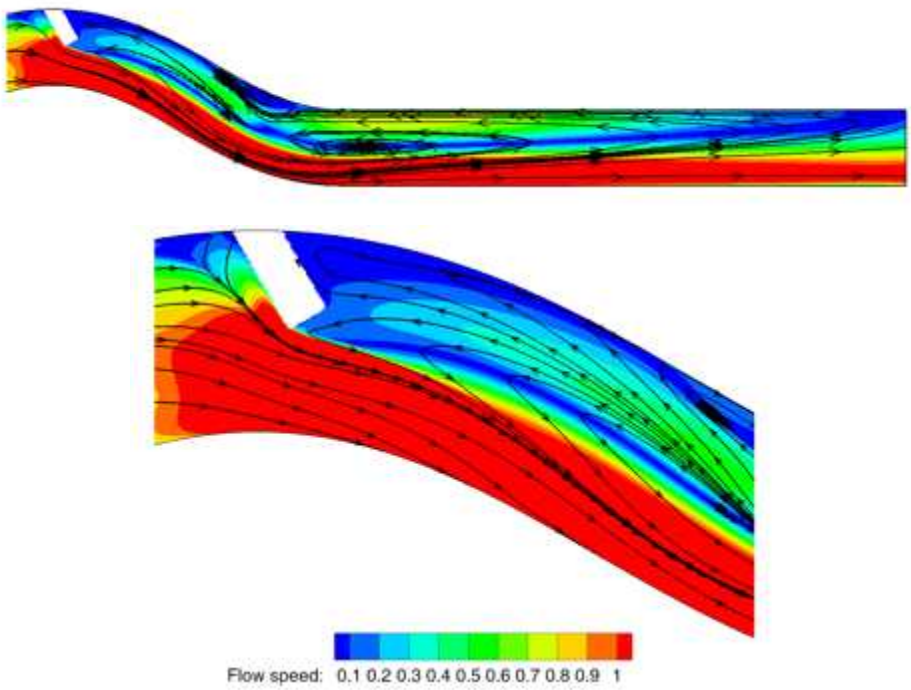
Flow speed



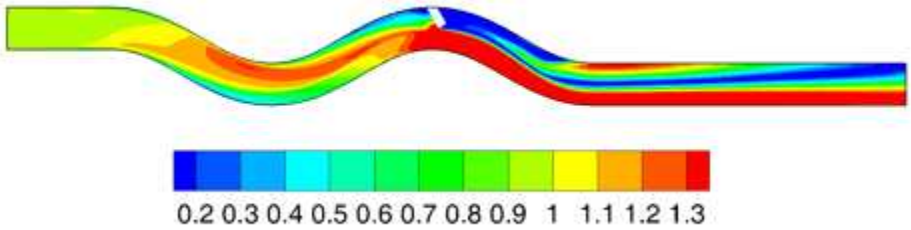
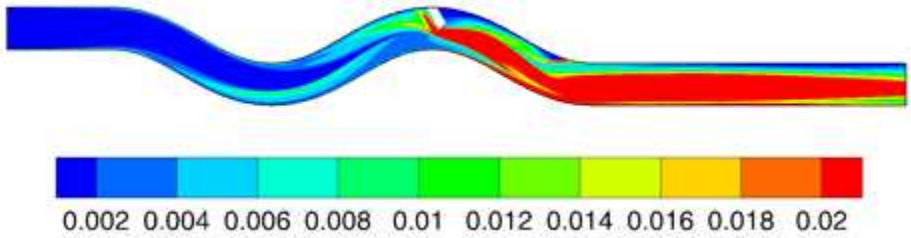
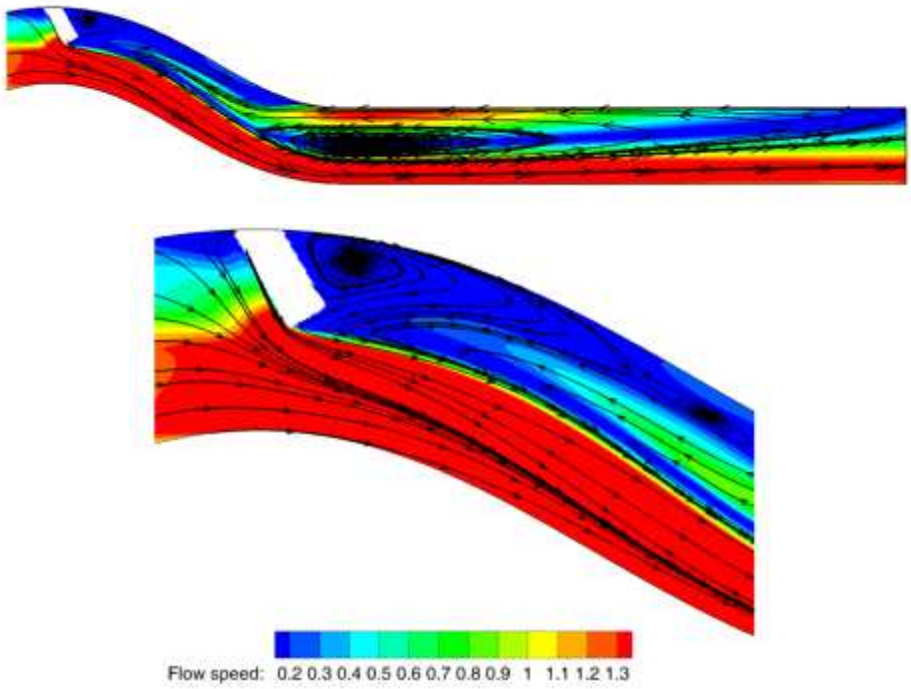
Turbulent kinetic energy (TKE)

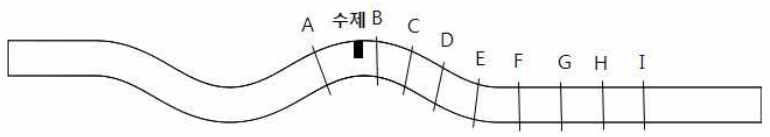
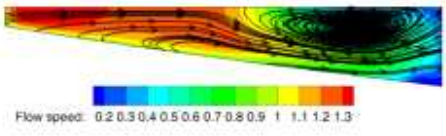
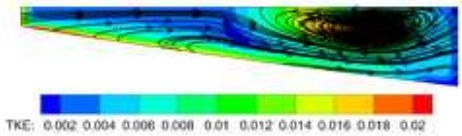
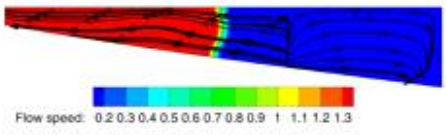
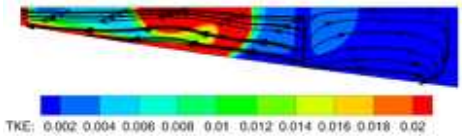
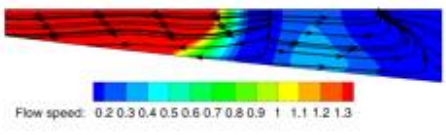
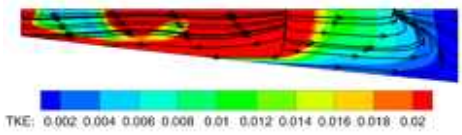
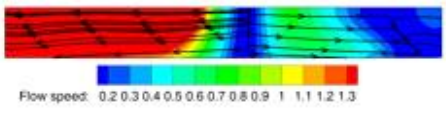
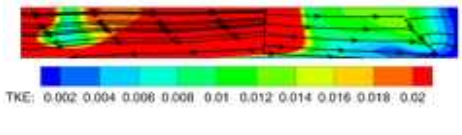
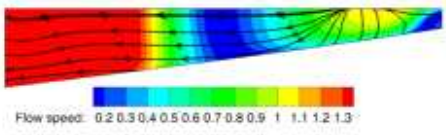
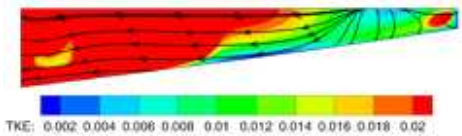
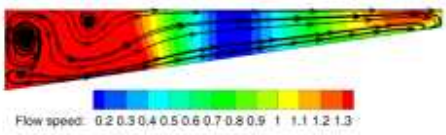
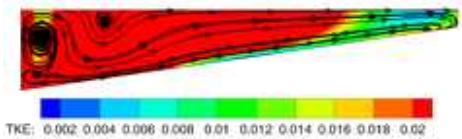
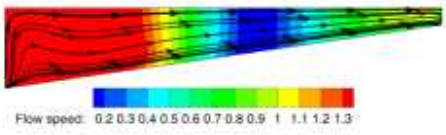
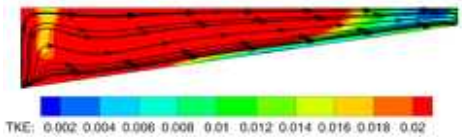
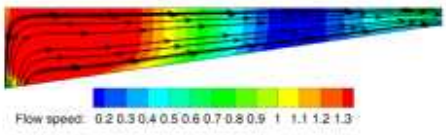
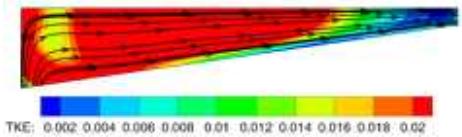


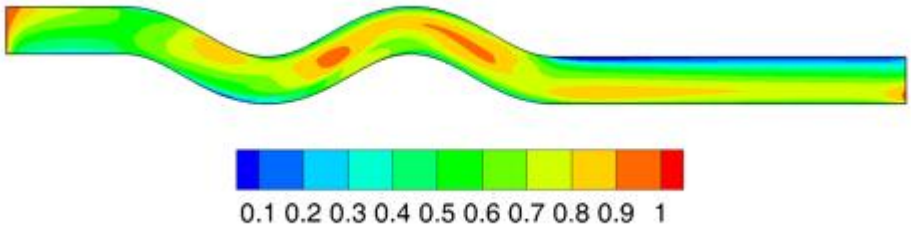
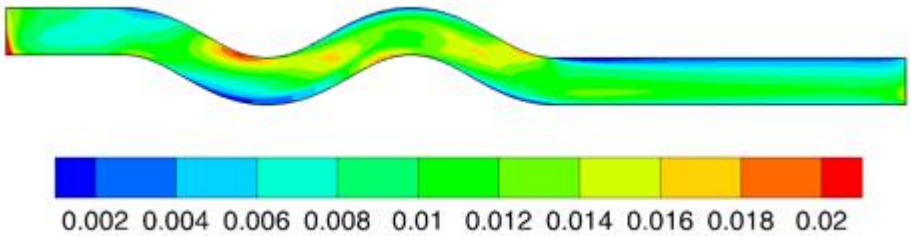
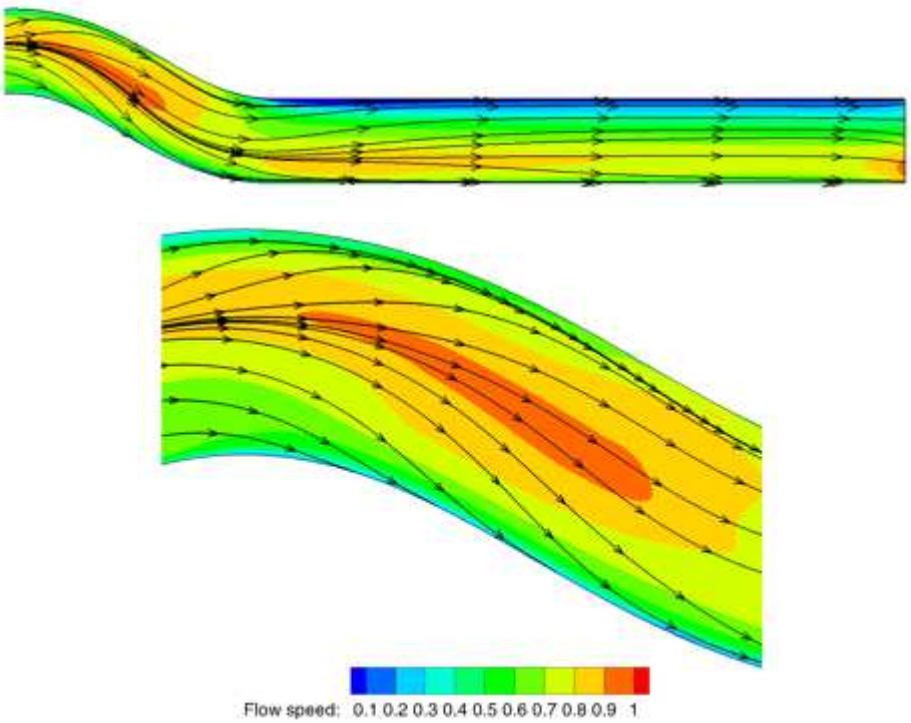
Recirculation



Normalized recirculation length : 11.1184

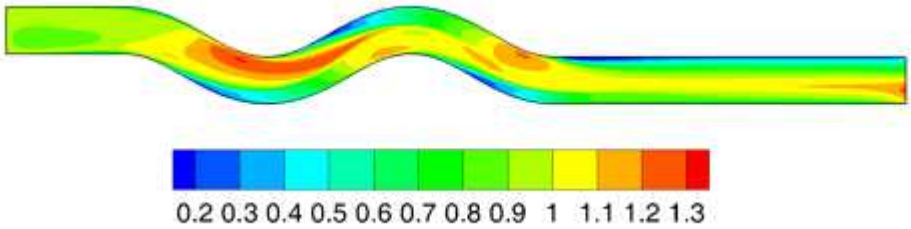
case51 (top/R=25/ =30/α=+30/l=5/h=1)
Flow speed

Turbulent kinetic energy (TKE)

Recirculation
 Normalized recirculation length : 11.1048

위치	case51 (R=25/ =30/α=+30/l=5/h=1)	
	secondary flow	
		
A		
B		
C		
D		
F		
G		
H		
I		

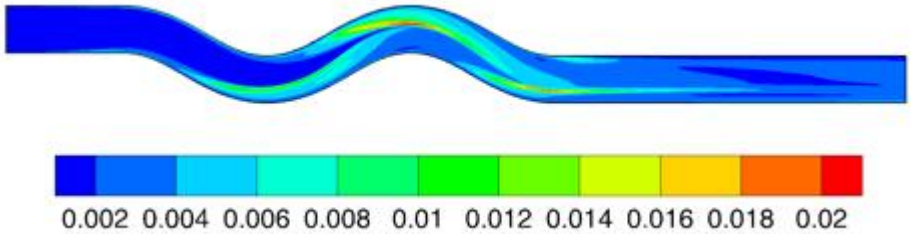
case2 (bottom/R=20/ =30° /l=2.5/h=0.5)
Flow speed

Turbulent kinetic energy (TKE)

Recirculation
 recirculation (X)

case2 (top/R=20/ =30° /l=2.5/h=0.5)

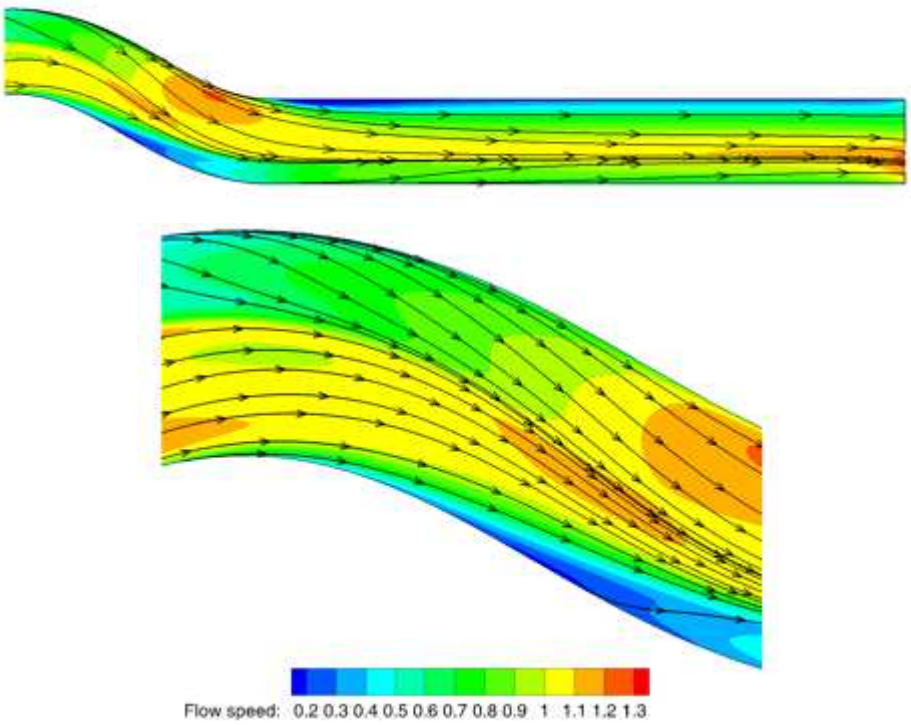
Flow speed



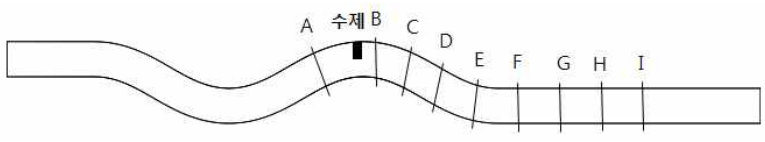
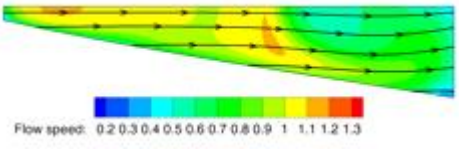
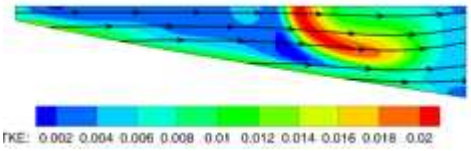
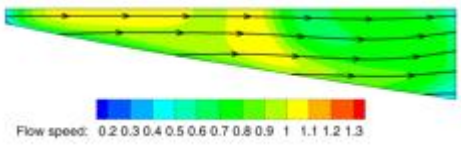
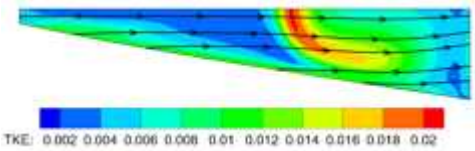
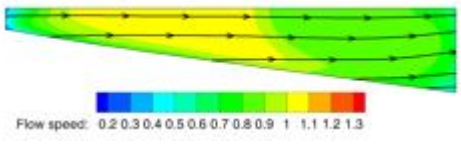
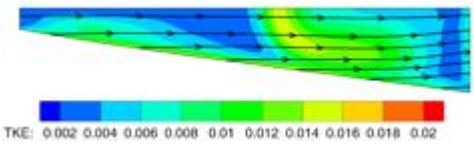
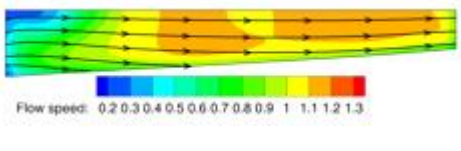
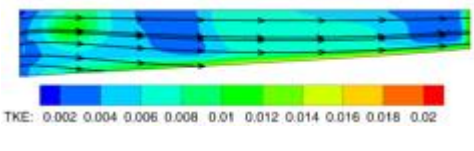
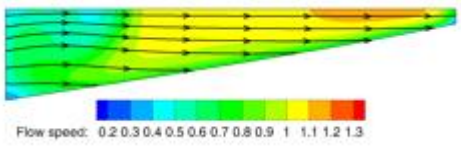
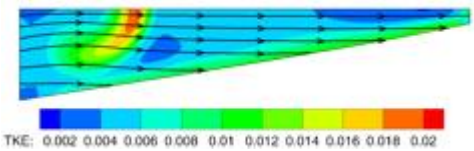
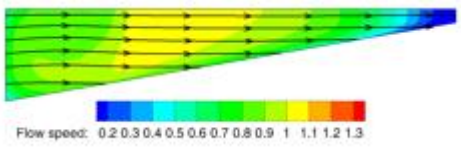
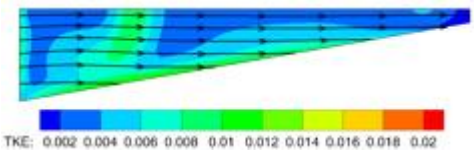
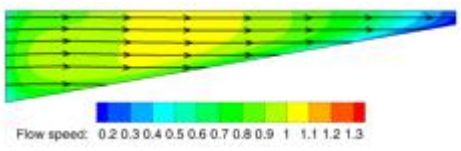
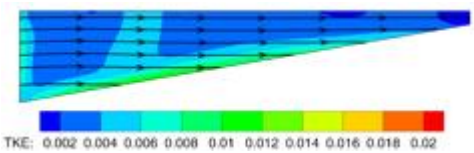
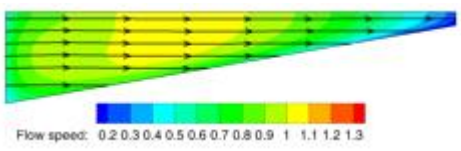
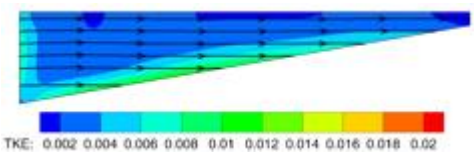
Turbulent kinetic energy (TKE)

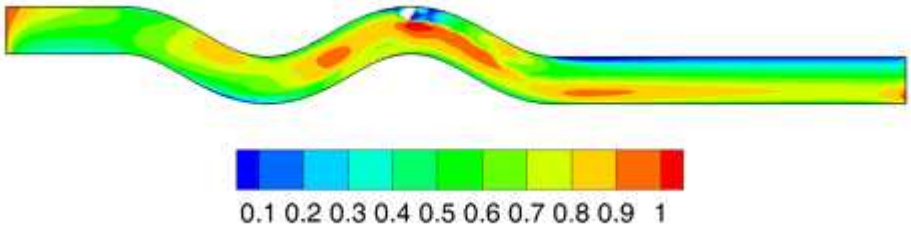
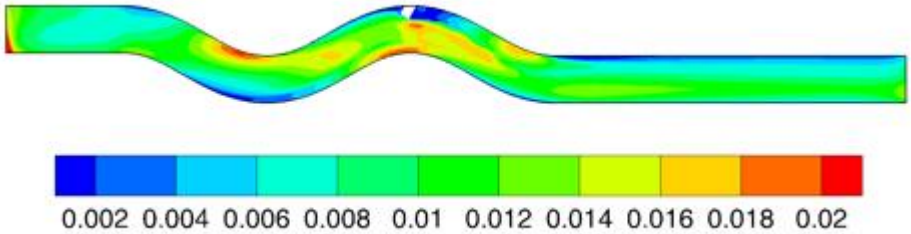
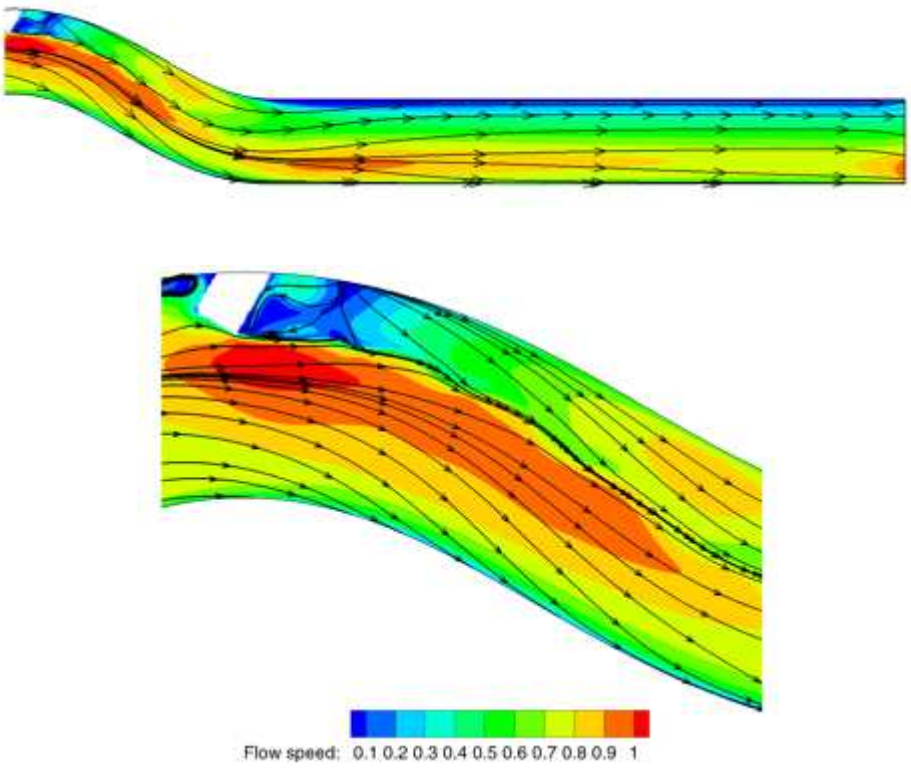


Recirculation



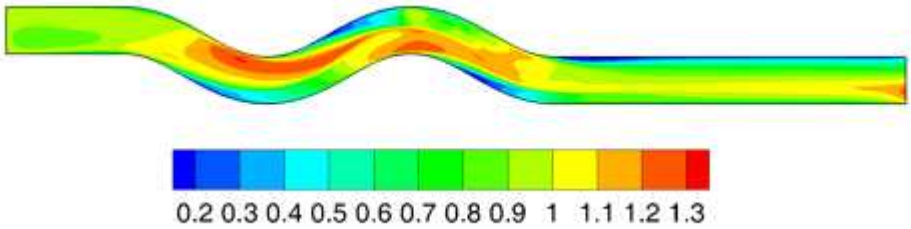
recirculation (X)

위치	case2 (R=20/ =30 /l=2.5/h=0.5)	
	secondary flow	
		
A		
B		
C		
D		
F		
G		
H		
I		

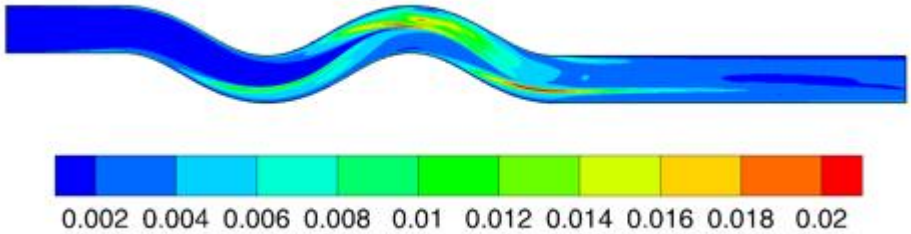
case5 (bottom/R=20/ =30/α=-30/l=2.5/h=0.5)
Flow speed

Turbulent kinetic energy (TKE)

Recirculation
 Normalized recirculation length : 0.3355

case5 (top/R=20/ =30/α=-30/l=2.5/h=0.5)

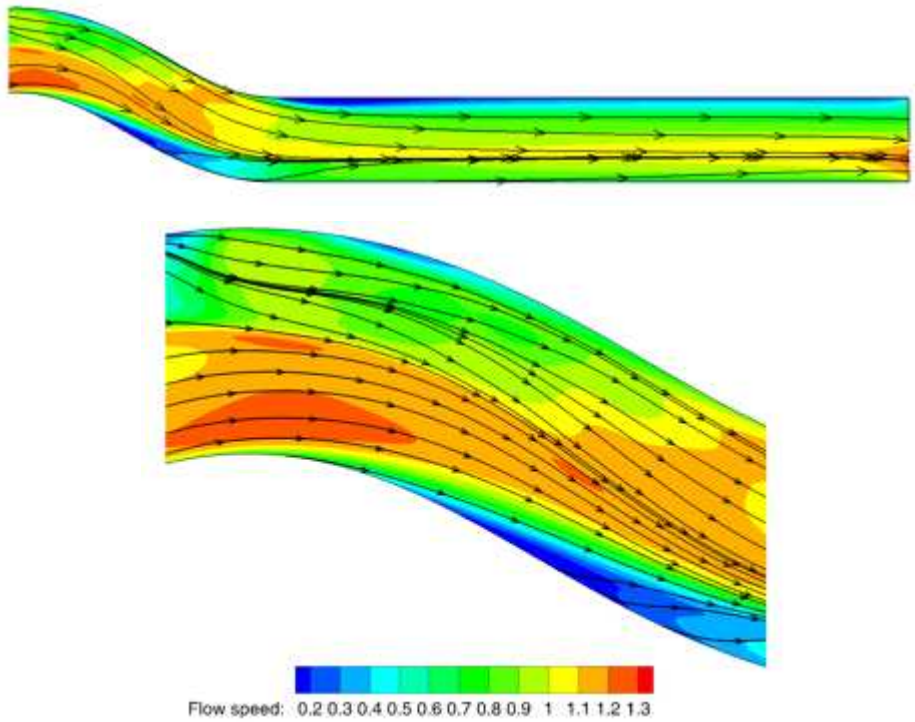
Flow speed



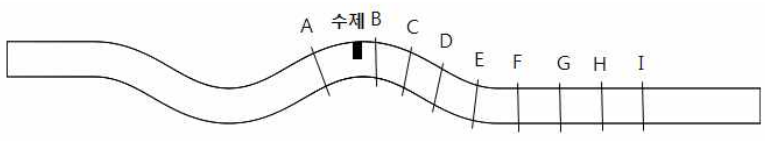
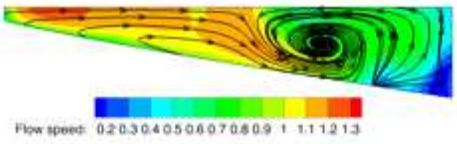
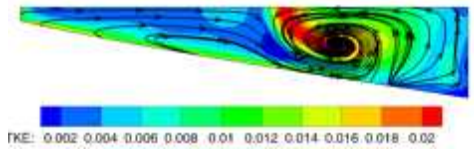
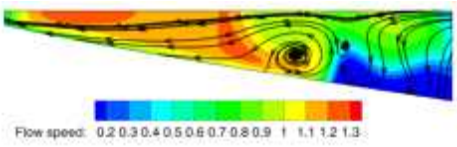
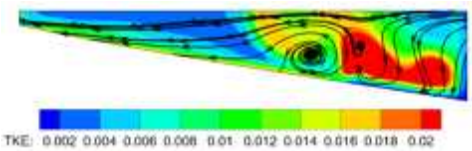
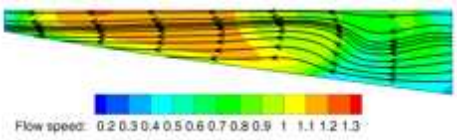
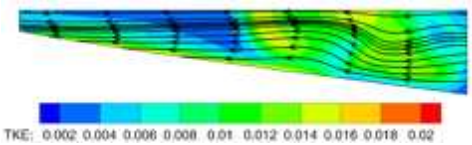
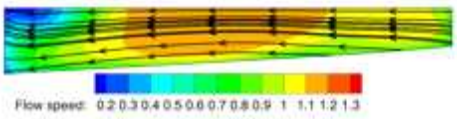
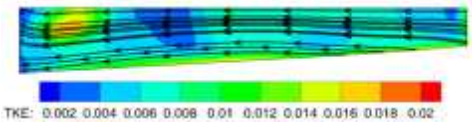
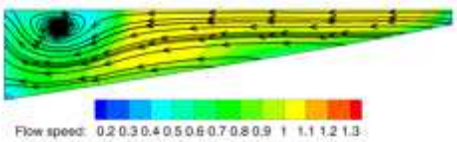
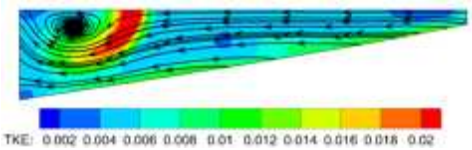
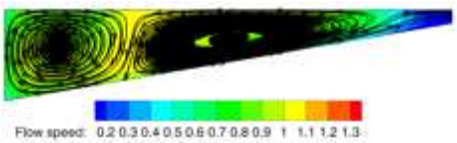
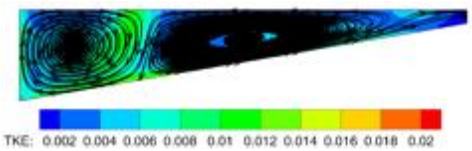
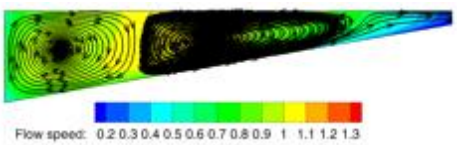
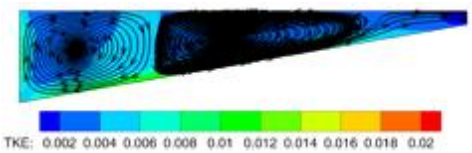
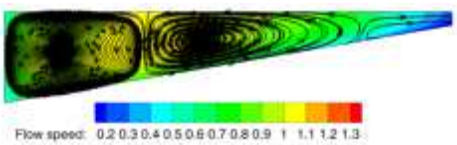
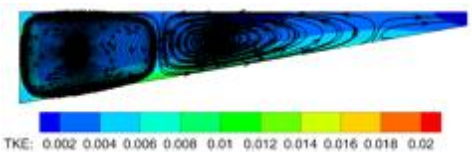
Turbulent kinetic energy (TKE)



Recirculation

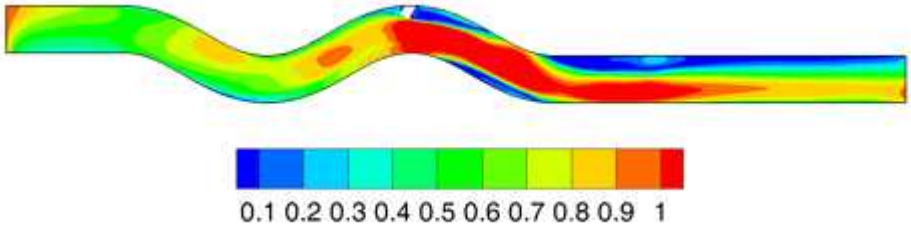


recirculation (X)

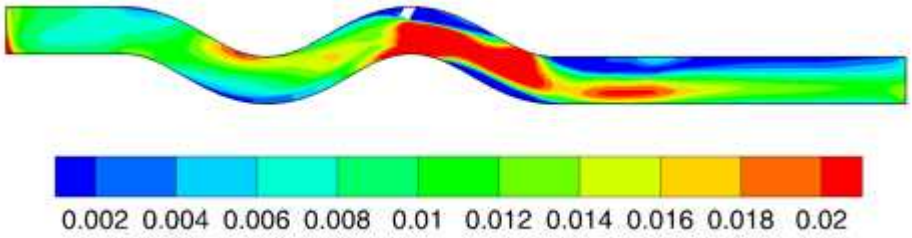
위치	case5 (R=20/ =30/α=-30/l=2.5/h=0.5) secondary flow	
		
A		
B		
C		
D		
F		
G		
H		
I		

case7 (bottom/R=20/ =30/α=-30/l=2.5/h=1)

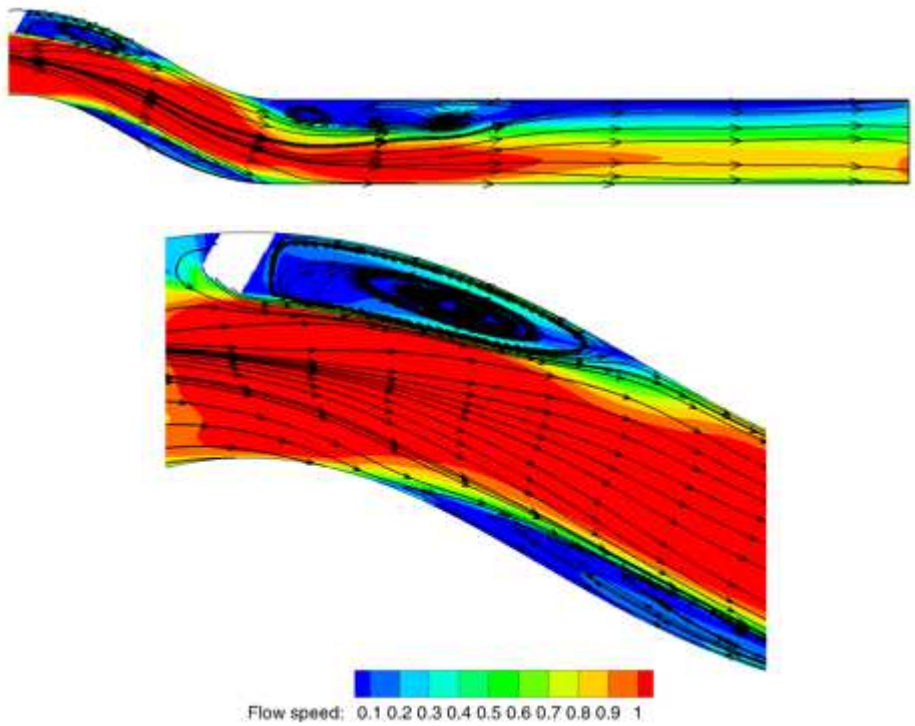
Flow speed



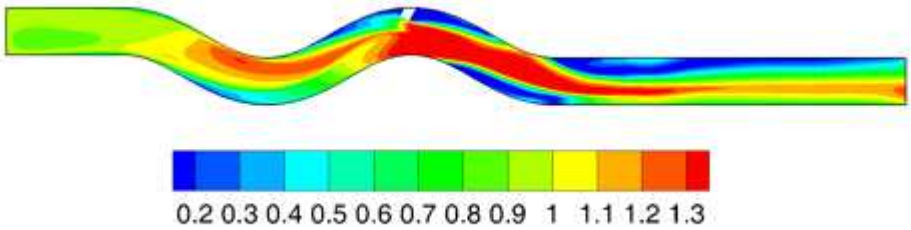
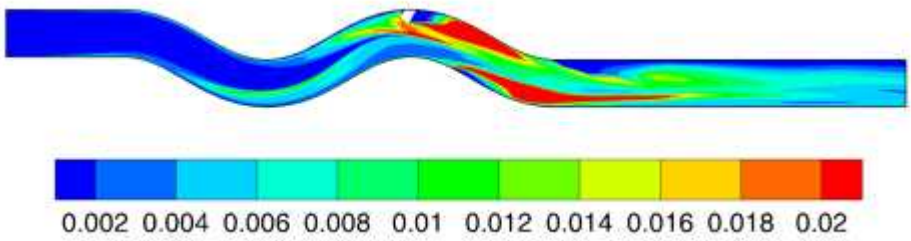
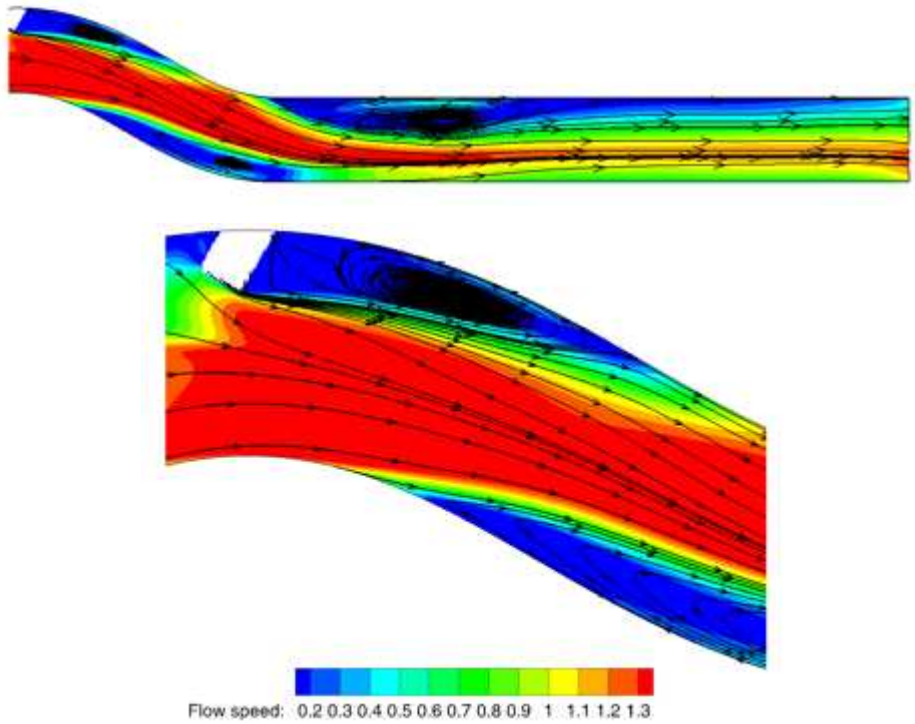
Turbulent kinetic energy (TKE)

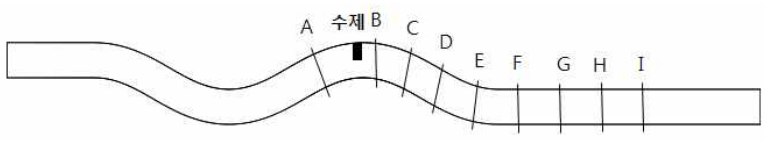
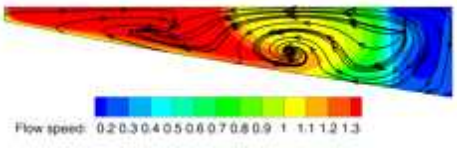
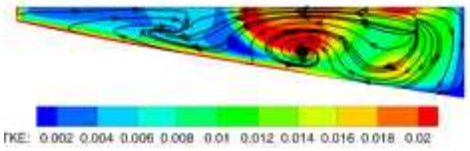
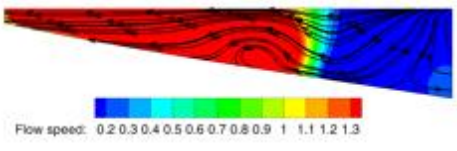
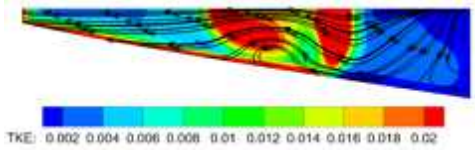
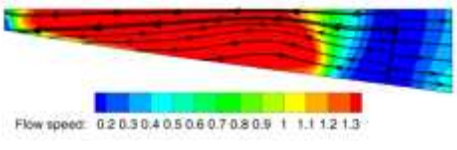
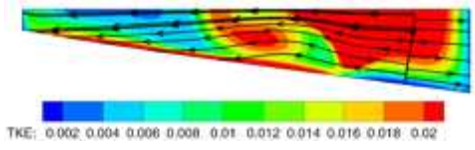
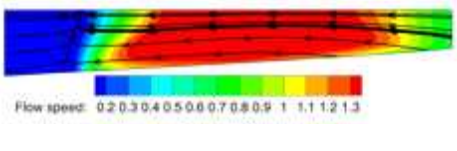
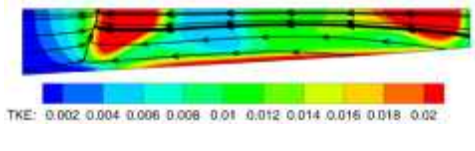
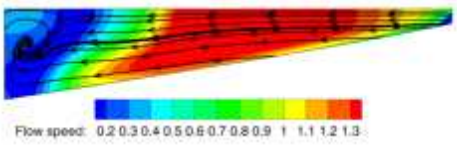
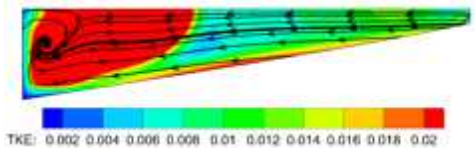
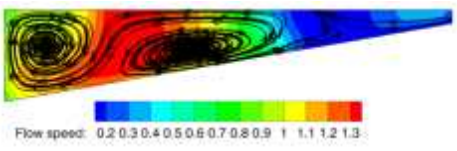
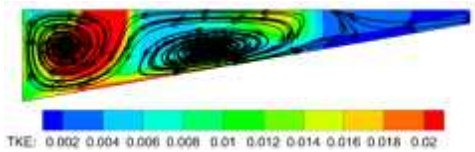
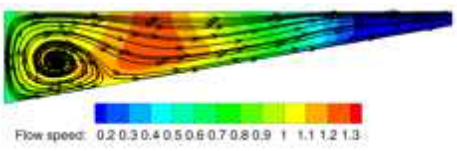
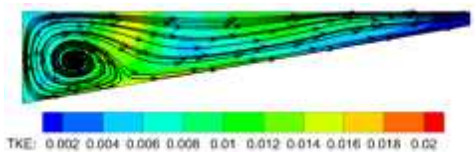
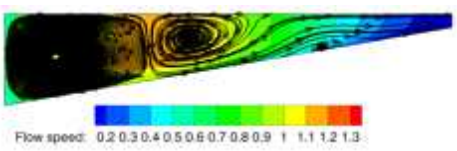
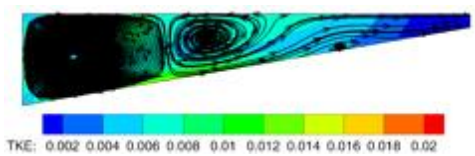


Recirculation



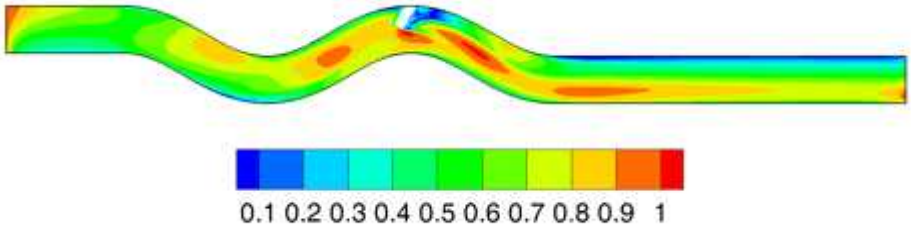
Normalized recirculation length : 1.5276

case7 (top/R=20/ =30/α=-30/l=2.5/h=1)
Flow speed

Turbulent kinetic energy (TKE)

Recirculation
 Normalized recirculation length : 1.4915

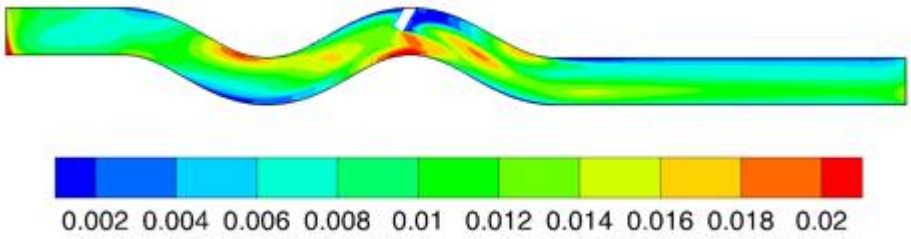
위치	case7 (R=20/ =30/α=-30/l=2.5/h=1)	
	secondary flow	
		
A		
B		
C		
D		
F		
G		
H		
I		

case9 (bottom/R=20/ =30/α=-30/l=5/h=0.5)

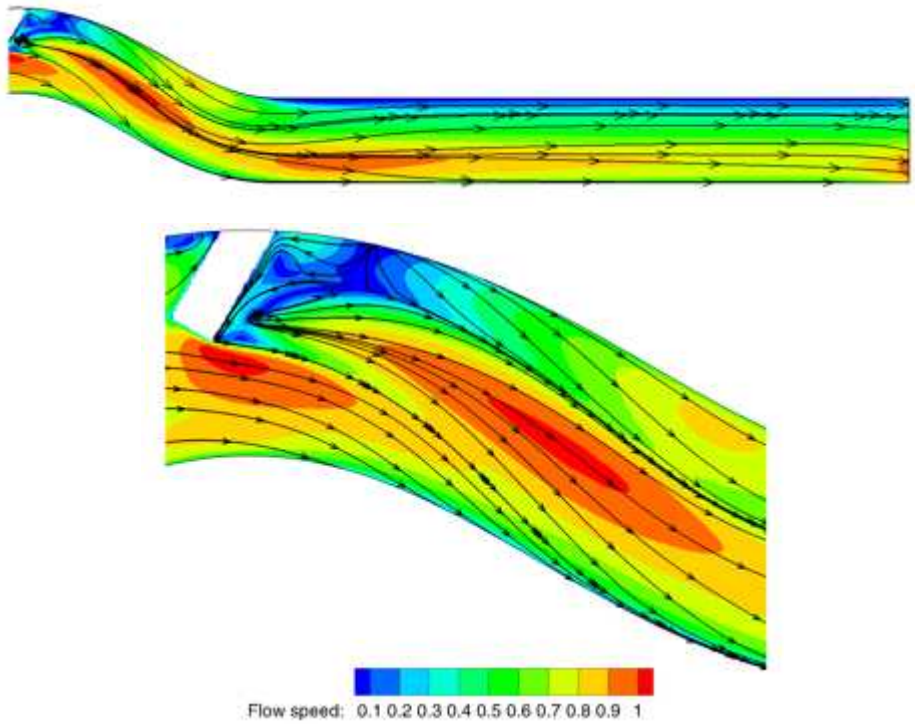
Flow speed



Turbulent kinetic energy (TKE)



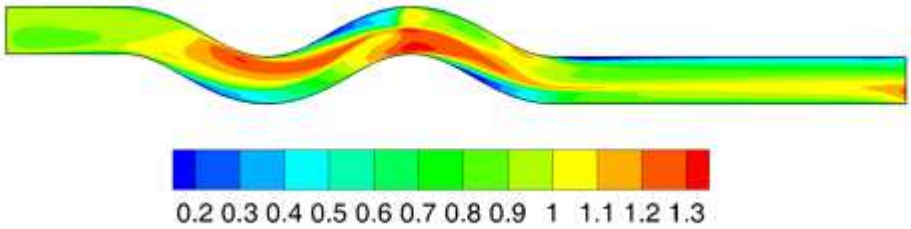
Recirculation



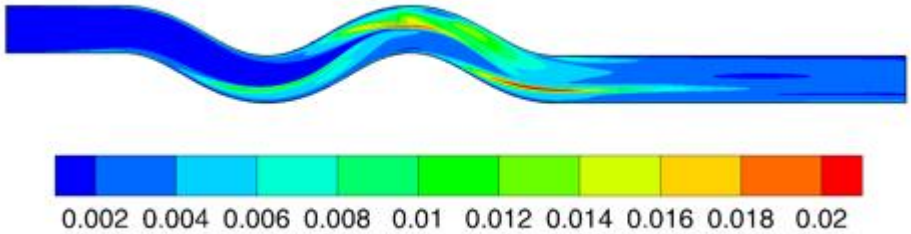
Normalized recirculation length : 0.4366

case9 (top/R=20/ =30/α=-30/l=5/h=0.5)

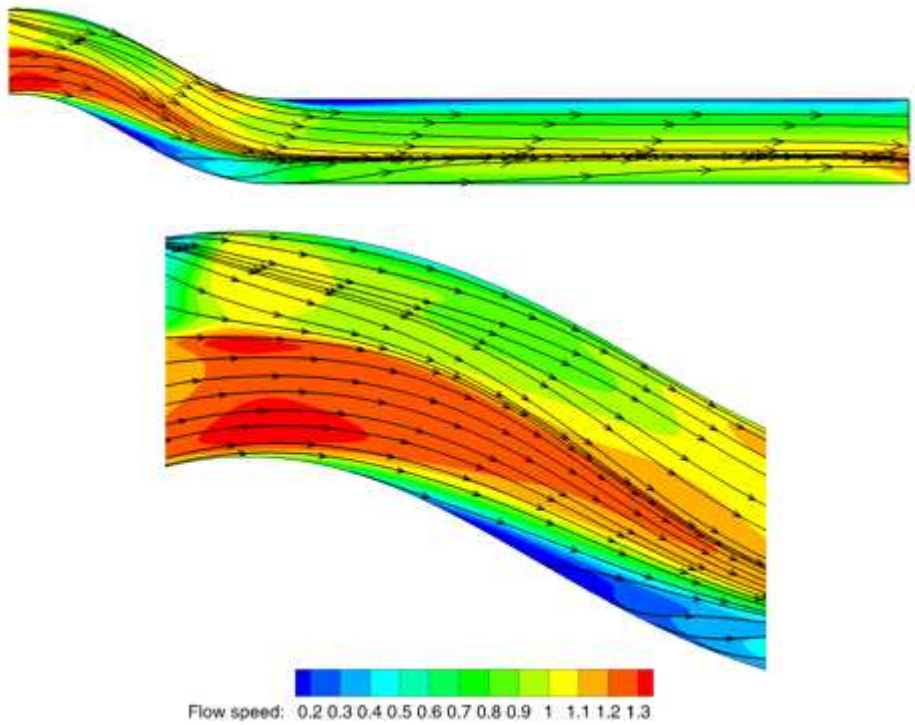
Flow speed



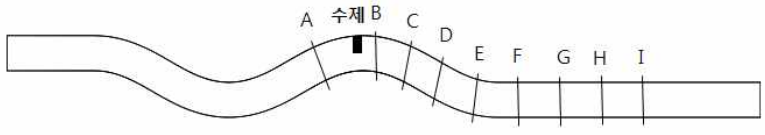
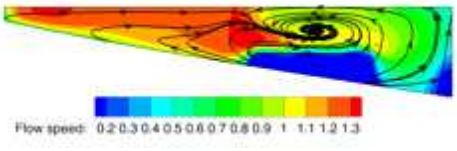
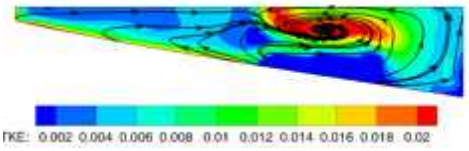
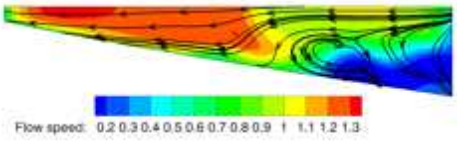
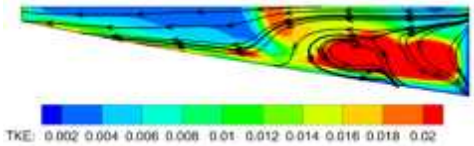
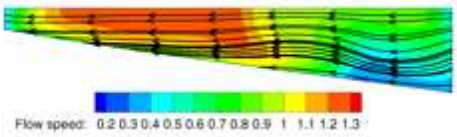
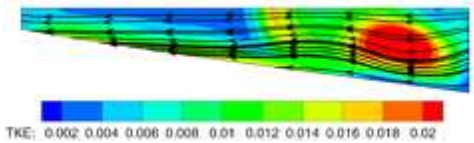
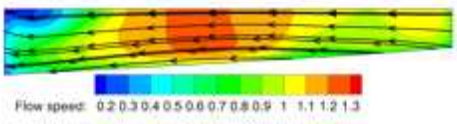
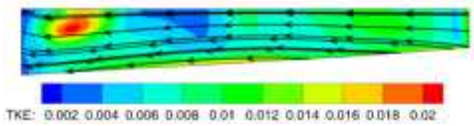
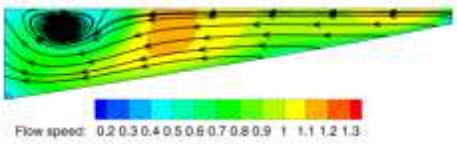
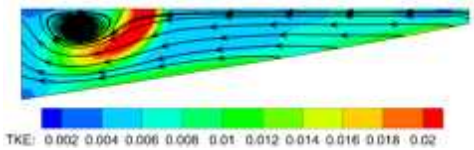
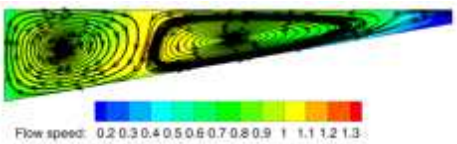
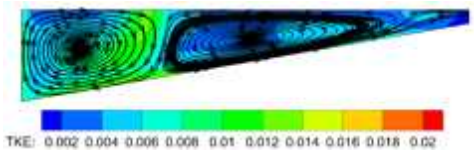
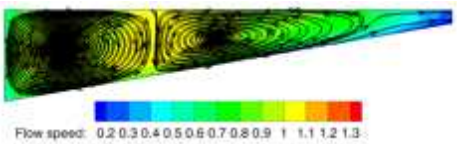
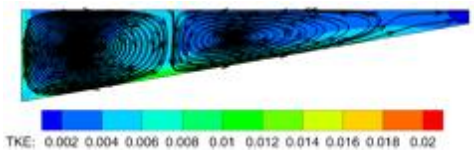
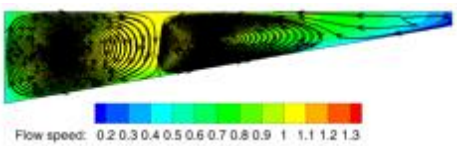
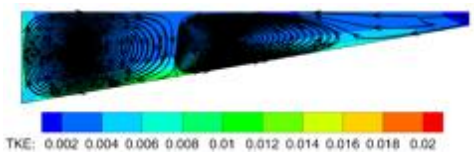
Turbulent kinetic energy (TKE)

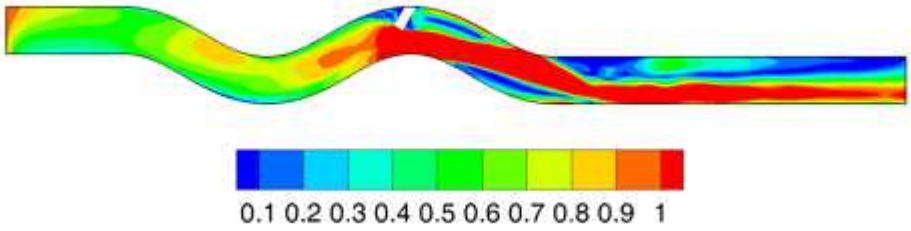
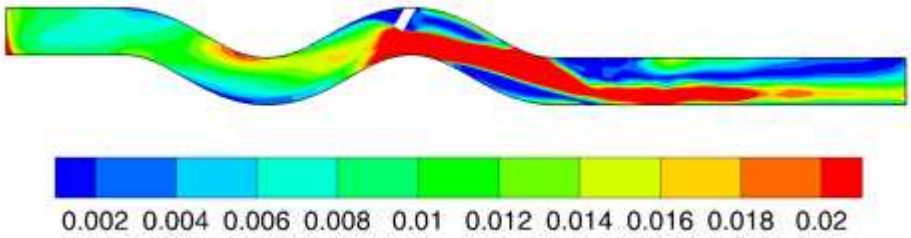
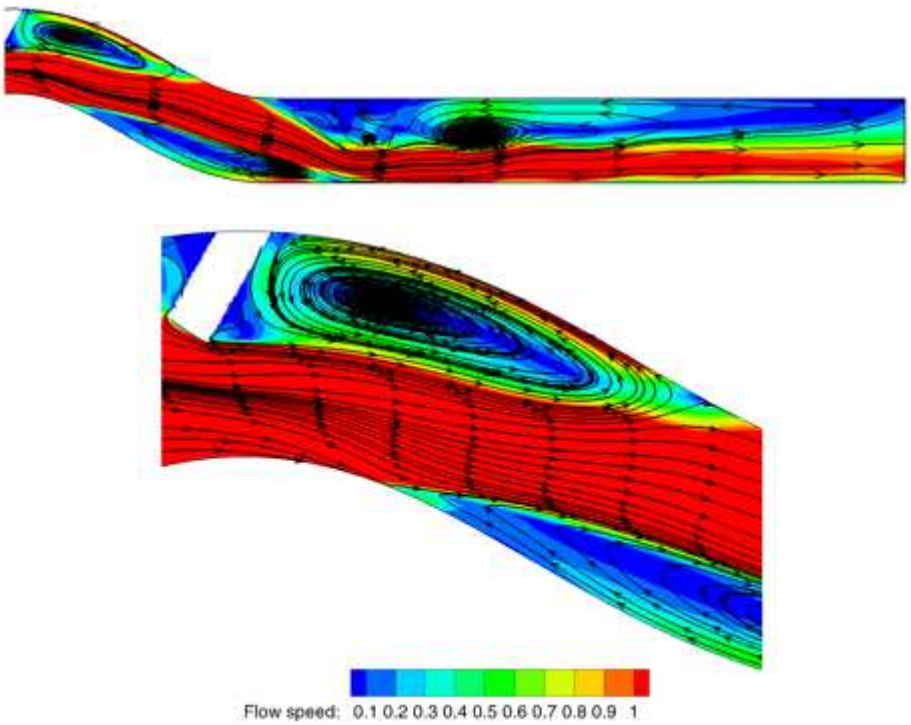


Recirculation



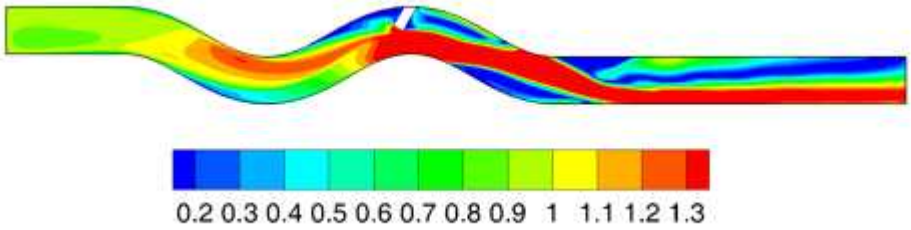
recirculation (X)

위치	case9 (R=20/ =30/α=-30/l=5/h=0.5)	
	secondary flow	
		
A		
B		
C		
D		
F		
G		
H		
I		

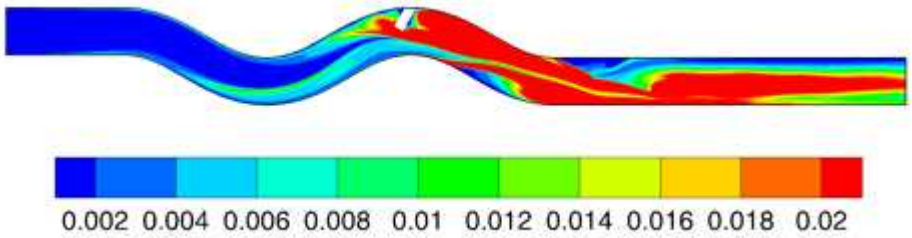
case11 (bottom/R=20/ =30/α=-30/l=5/h=1)
Flow speed

Turbulent kinetic energy (TKE)

Recirculation
 Normalized recirculation length : 1.8798

case11 (top/R=20/ =30/α=-30/l=5/h=1)

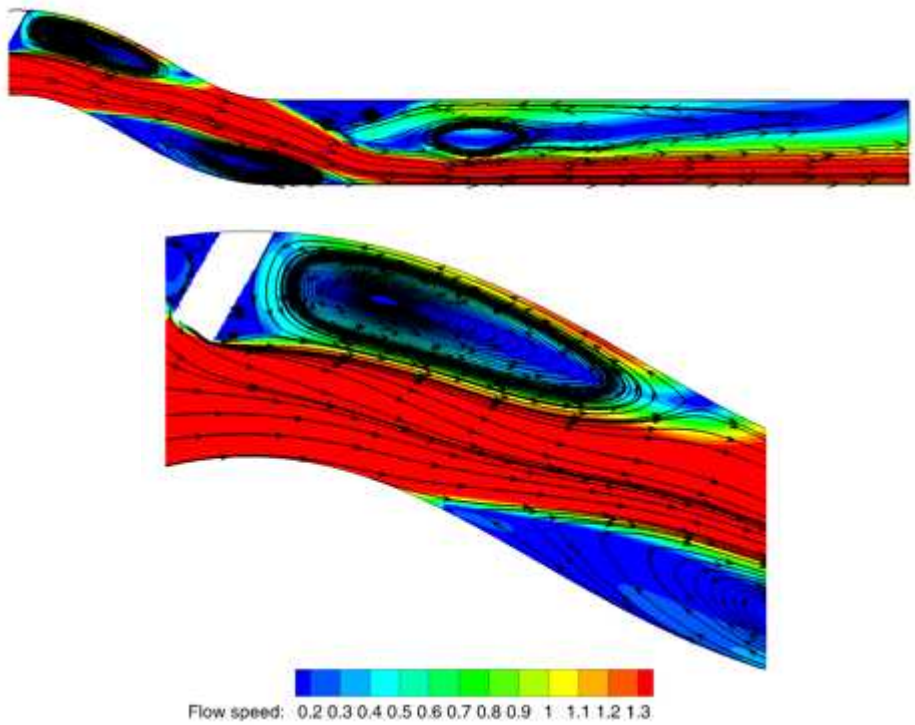
Flow speed



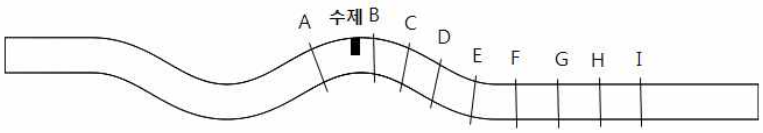
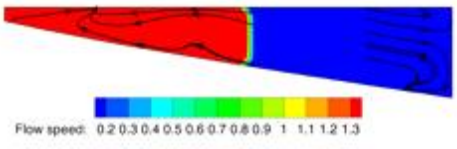
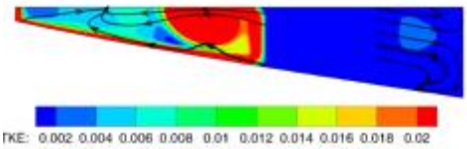
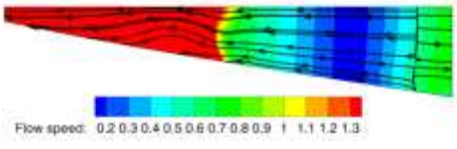
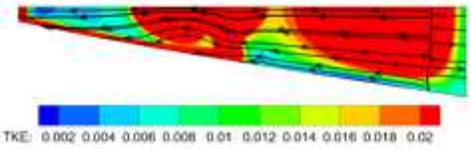
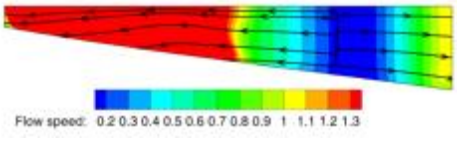
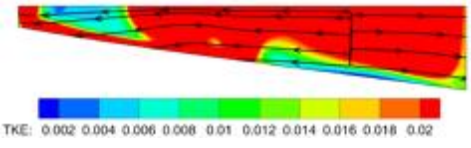
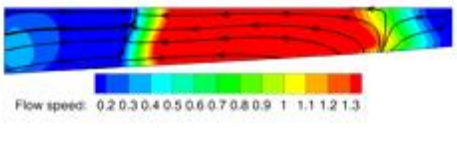
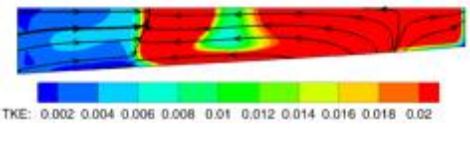
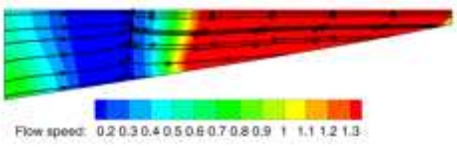
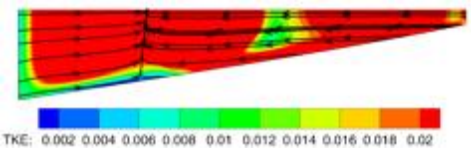
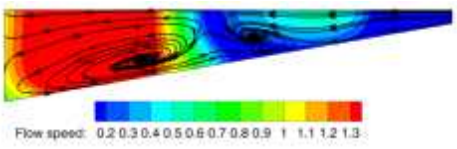
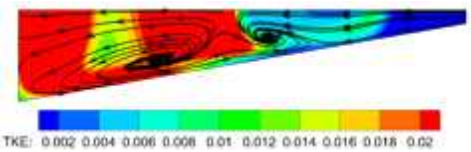
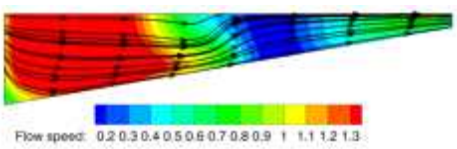
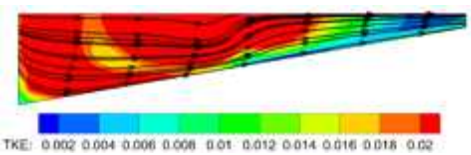
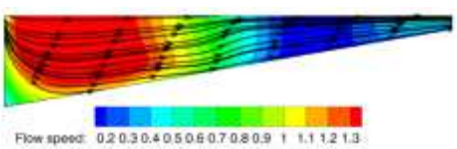
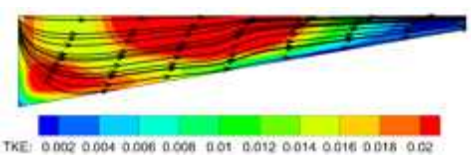
Turbulent kinetic energy (TKE)



Recirculation

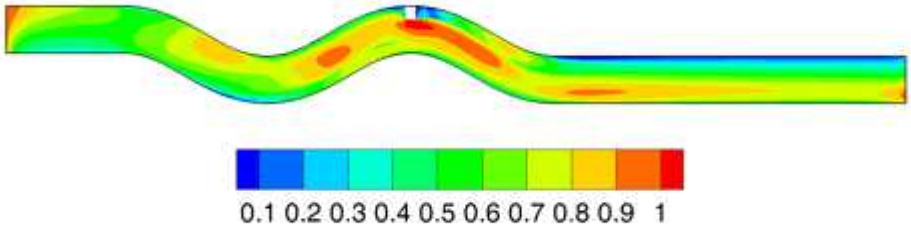


Normalized recirculation length : 1.8838

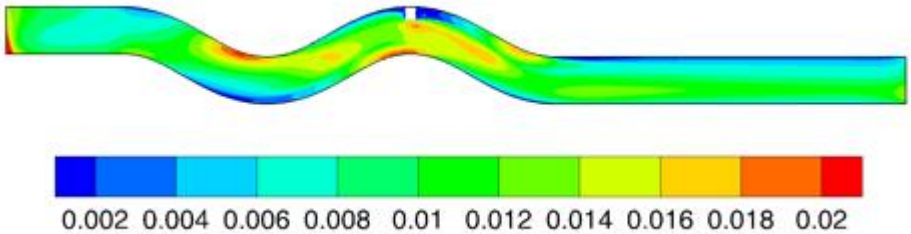
위치	case11 (R=20/ =30/α=-30/l=5/h=1)	
	secondary flow	
		
A		
B		
C		
D		
F		
G		
H		
I		

case21 (bottom/R=20/ =30/α=0/l=2.5/h=0.5)

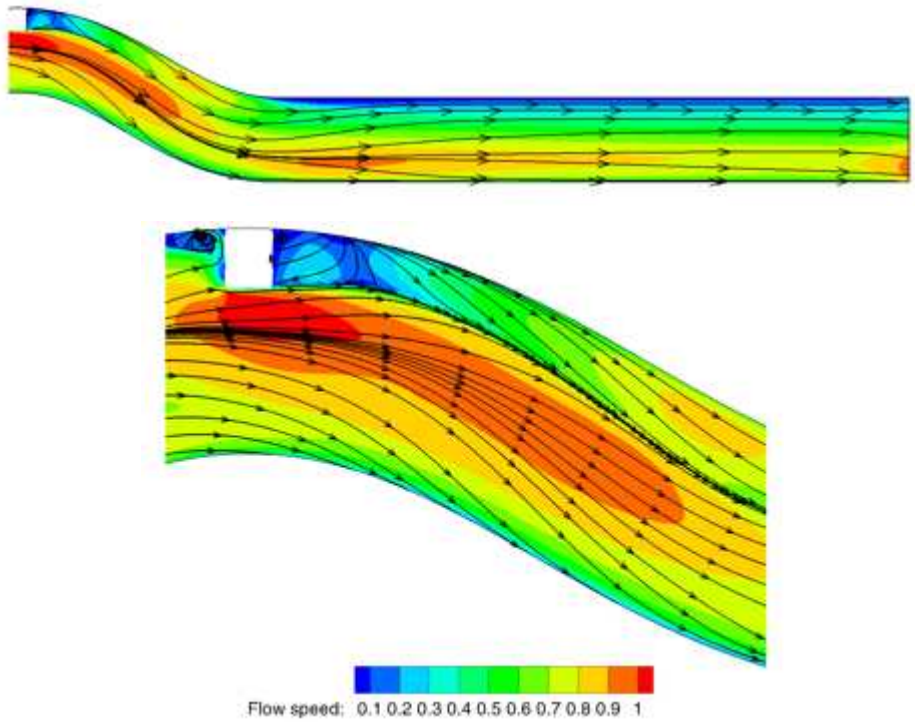
Flow speed



Turbulent kinetic energy (TKE)



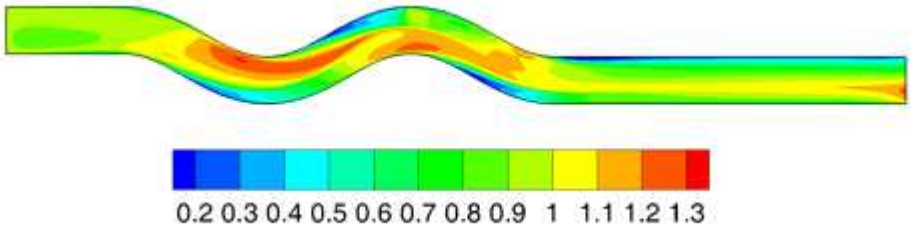
Recirculation



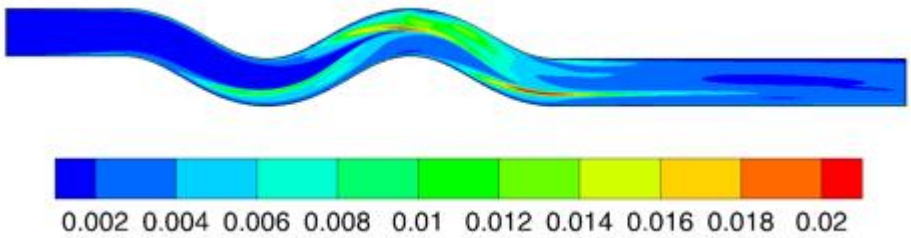
Normalized recirculation length : 0.3598

case21 (bottom/R=20/ =30/α=0/l=2.5/h=0.5)

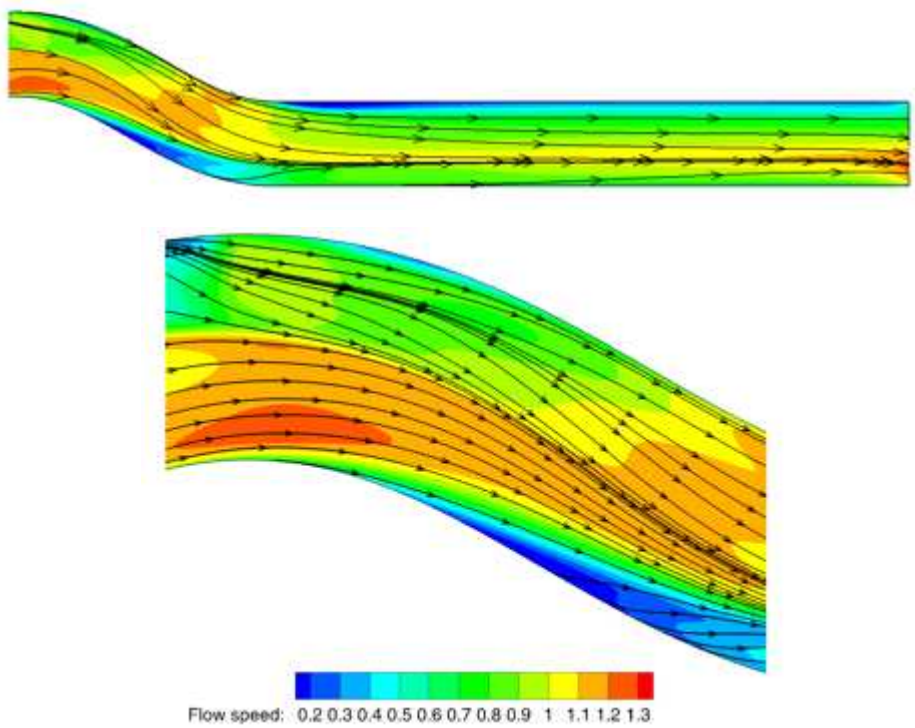
Flow speed



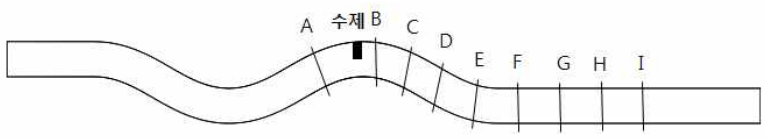
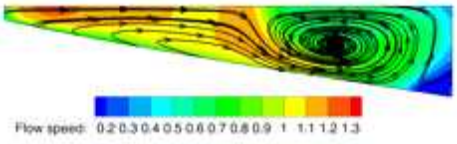
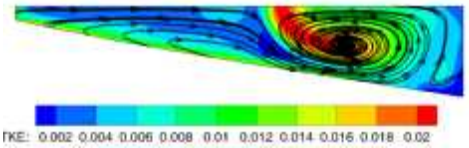
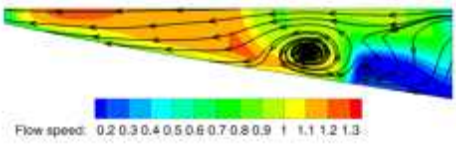
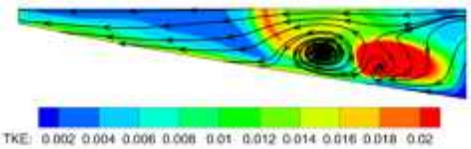
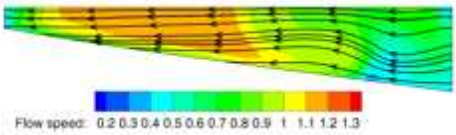
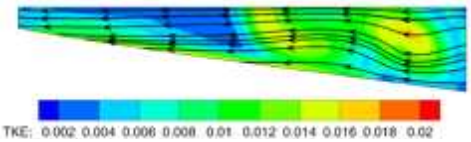
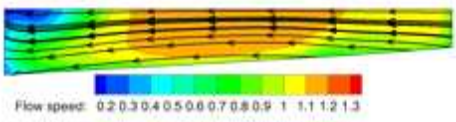
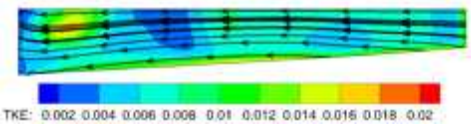
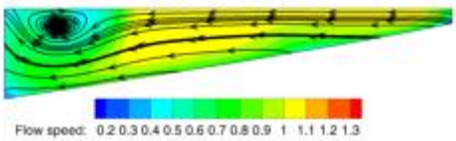
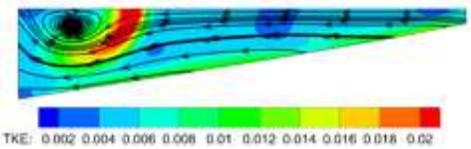
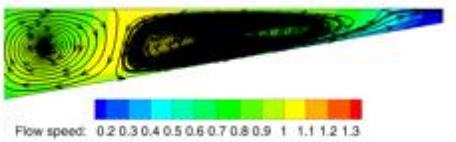
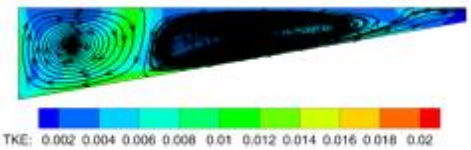
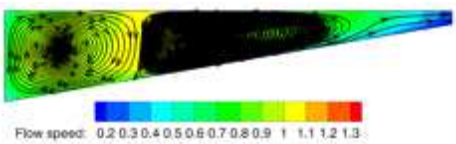
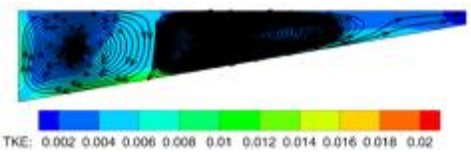
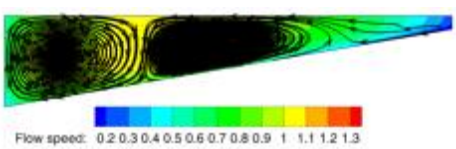
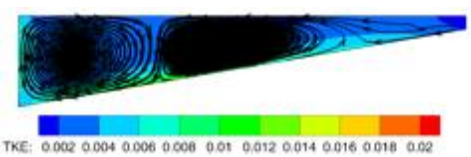
Turbulent kinetic energy (TKE)



Recirculation

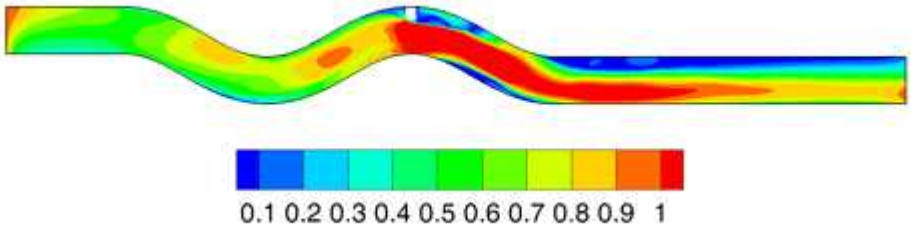


recirculation (X)

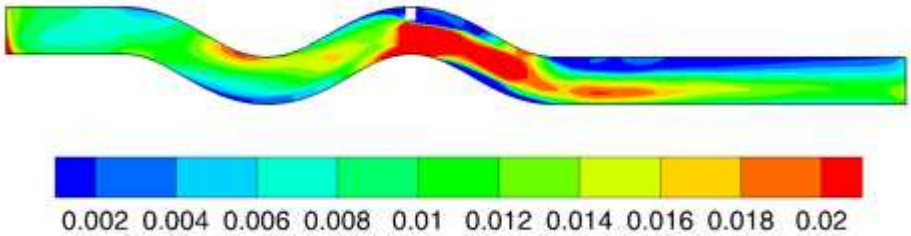
위치	case21 (bottom/R=20/ =30/α=0/l=2.5/h=0.5)	
	secondary flow	
		
A		
B		
C		
D		
F		
G		
H		
I		

case23 (bottom/R=20/ =30/α=0/l=2.5/h=1)

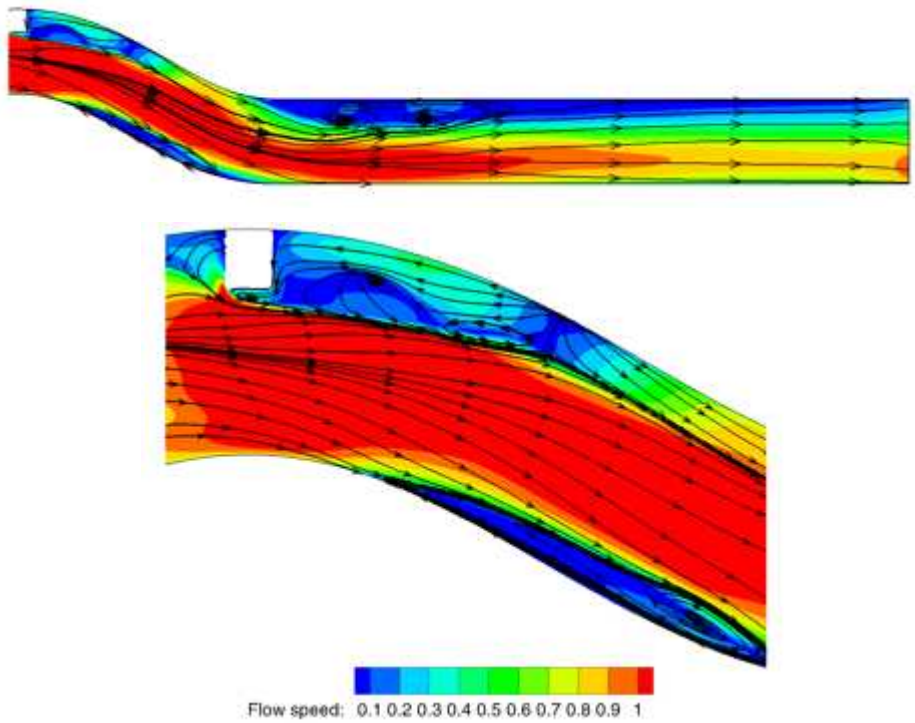
Flow speed



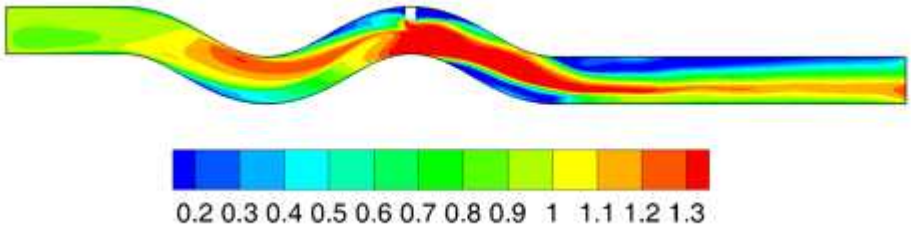
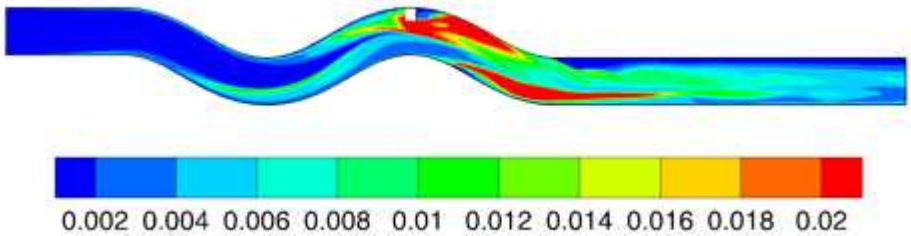
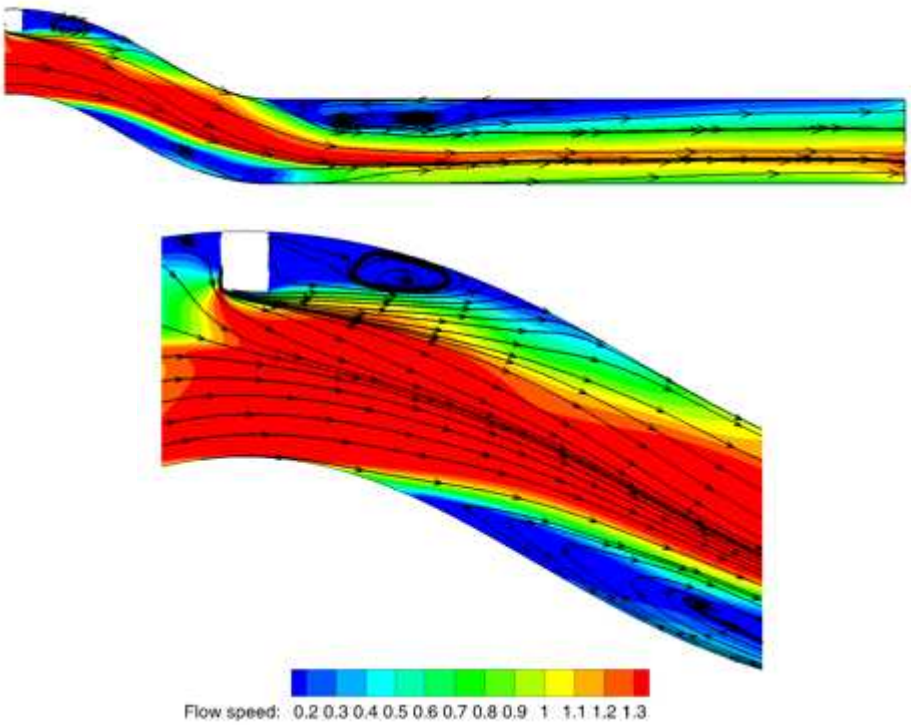
Turbulent kinetic energy (TKE)

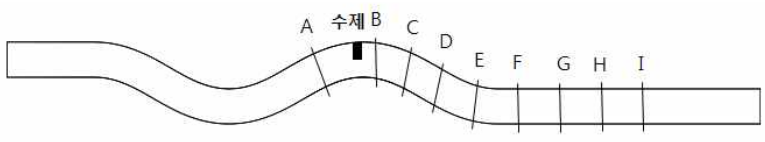
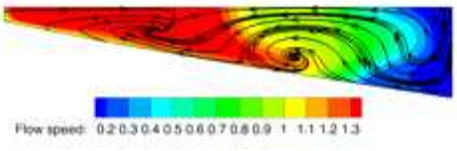
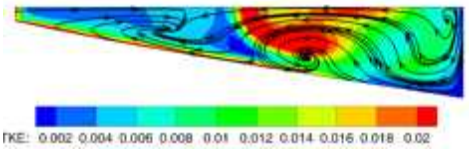
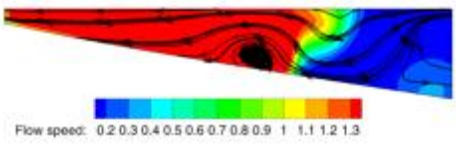
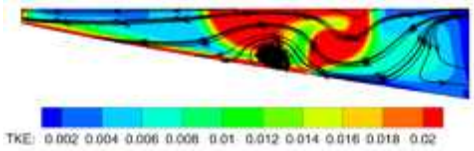
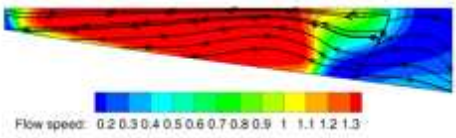
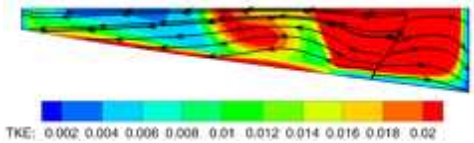
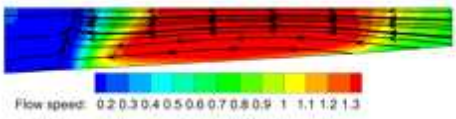
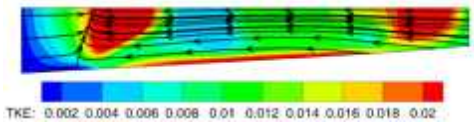
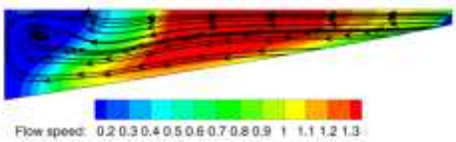
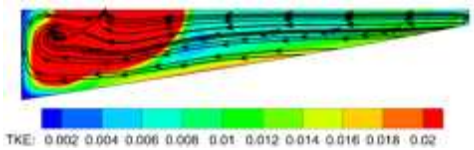
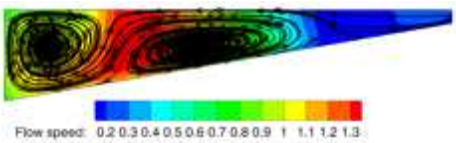
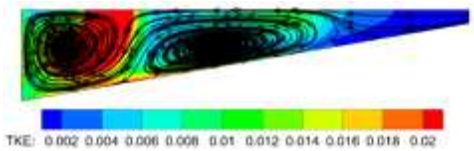
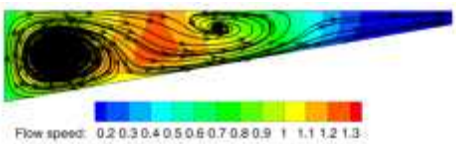
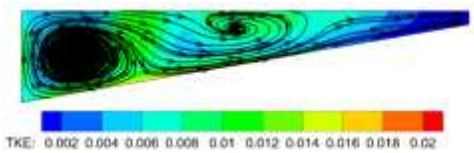
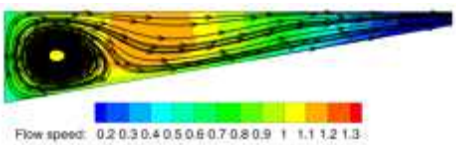
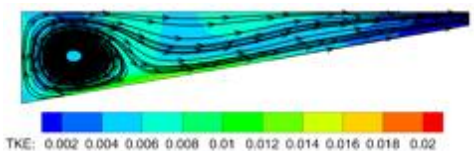


Recirculation



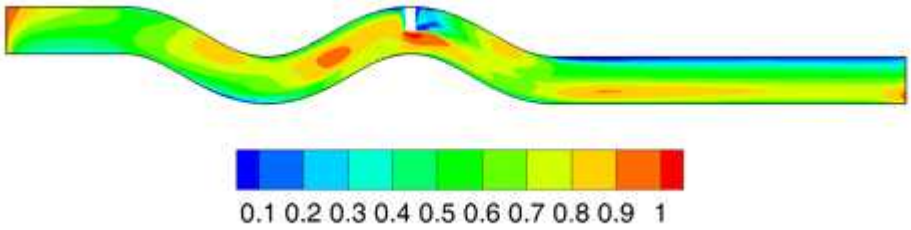
Normalized recirculation length : 1.2734

case23 (top/R=20/ =30/α=0/l=2.5/h=1)
Flow speed

Turbulent kinetic energy (TKE)

Recirculation
 Normalized recirculation length : 0.9298

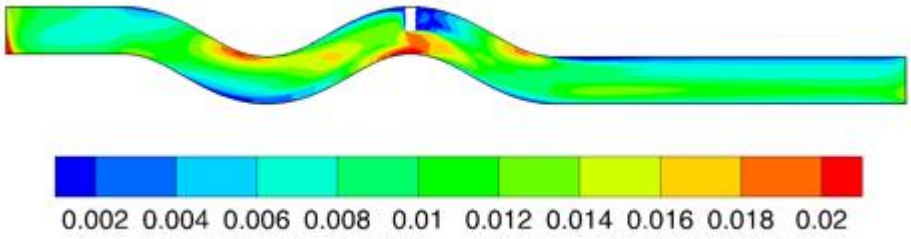
위치	case23 (R=20/ =30/α=0/l=2.5/h=1)	
	secondary flow	
		
A		
B		
C		
D		
F		
G		
H		
I		

case25 (bottom/R=20/ =30/α=0/l=5/h=0.5)

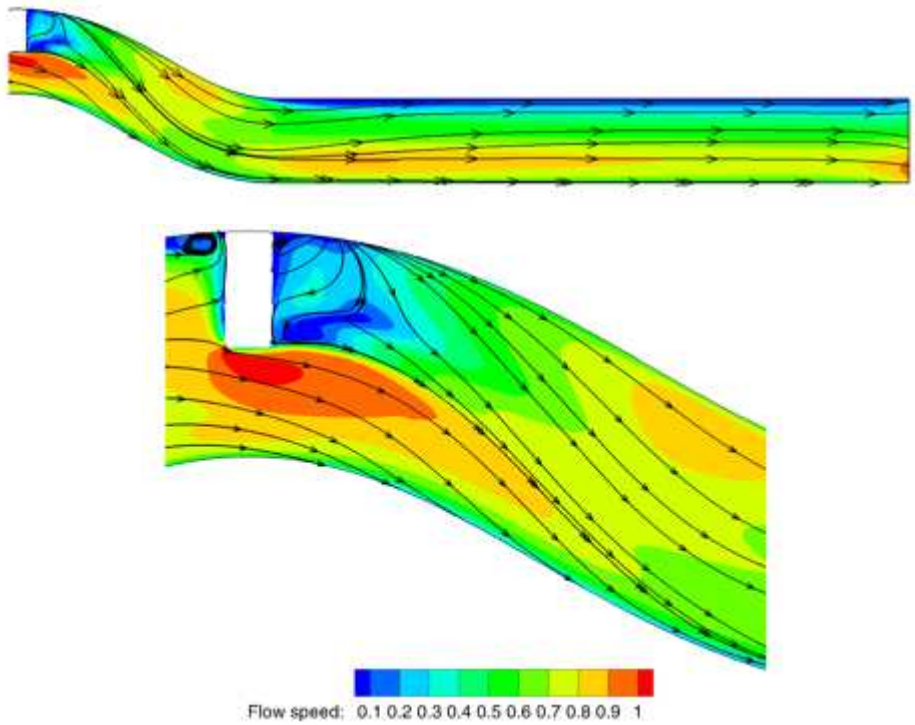
Flow speed



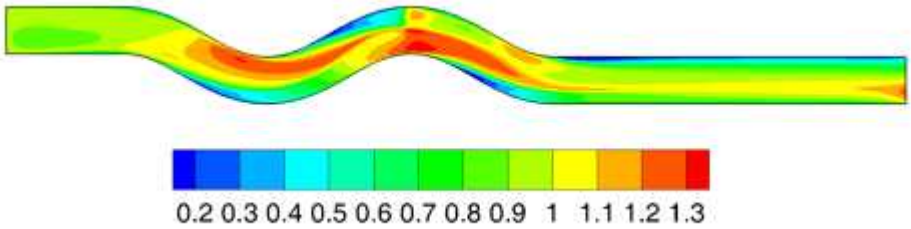
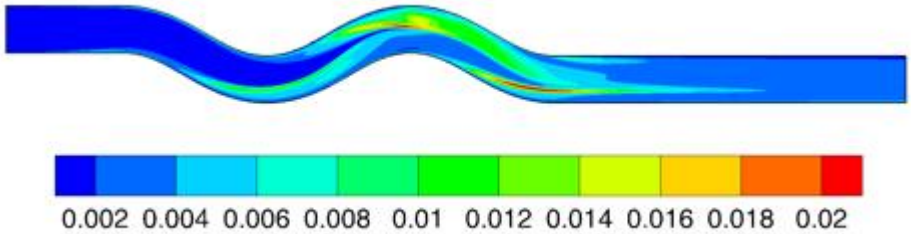
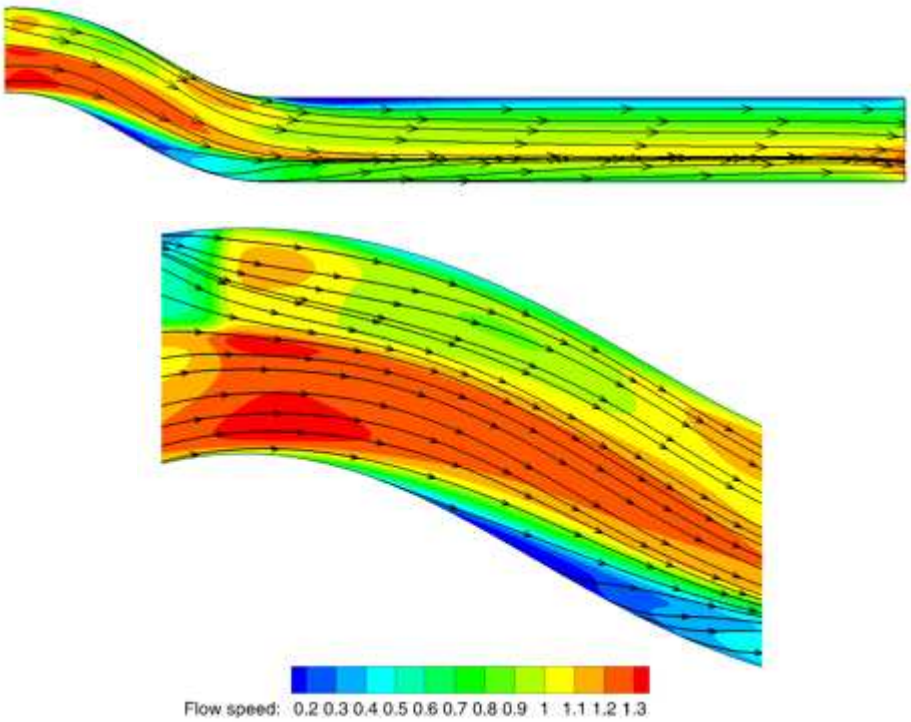
Turbulent kinetic energy (TKE)

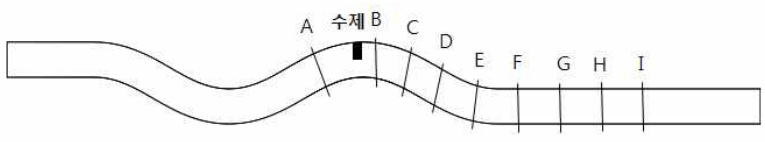
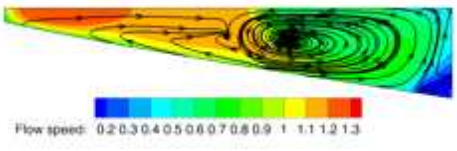
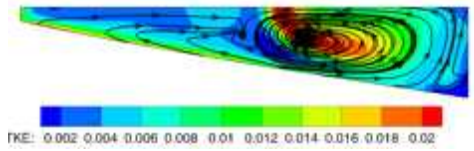
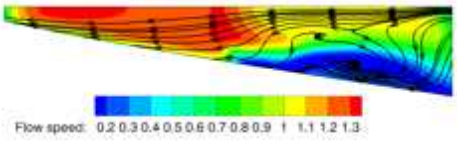
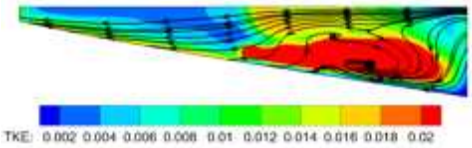
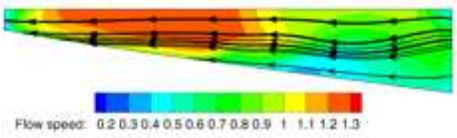
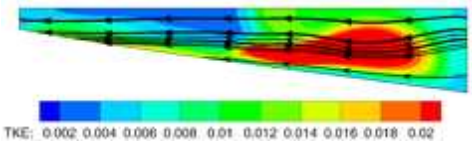
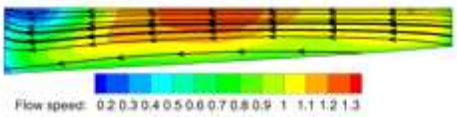
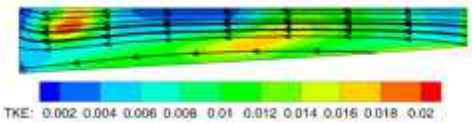
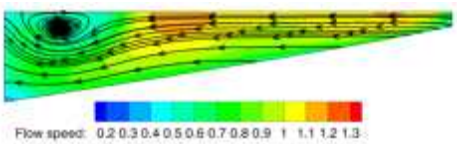
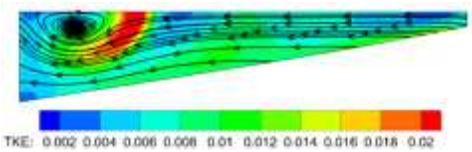
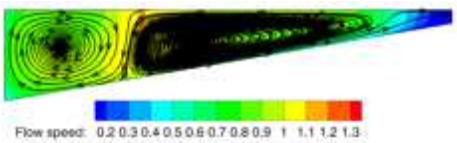
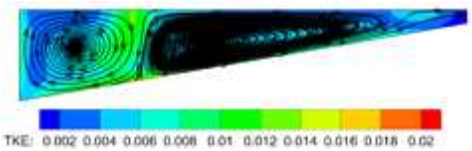
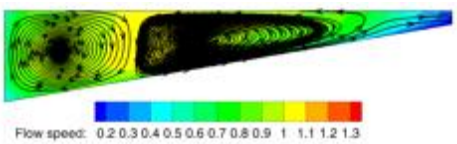
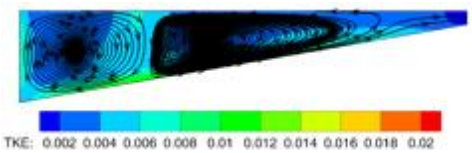
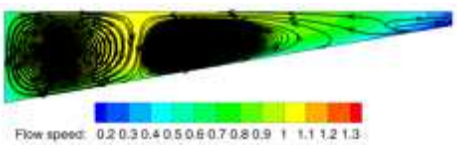
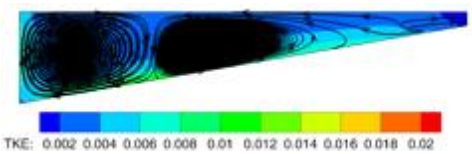


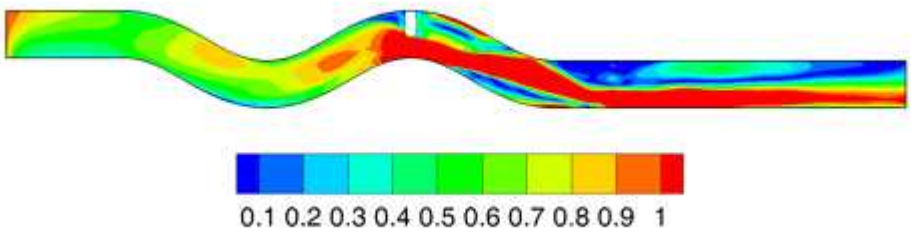
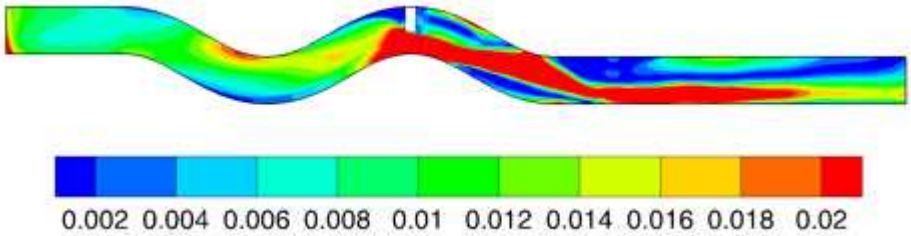
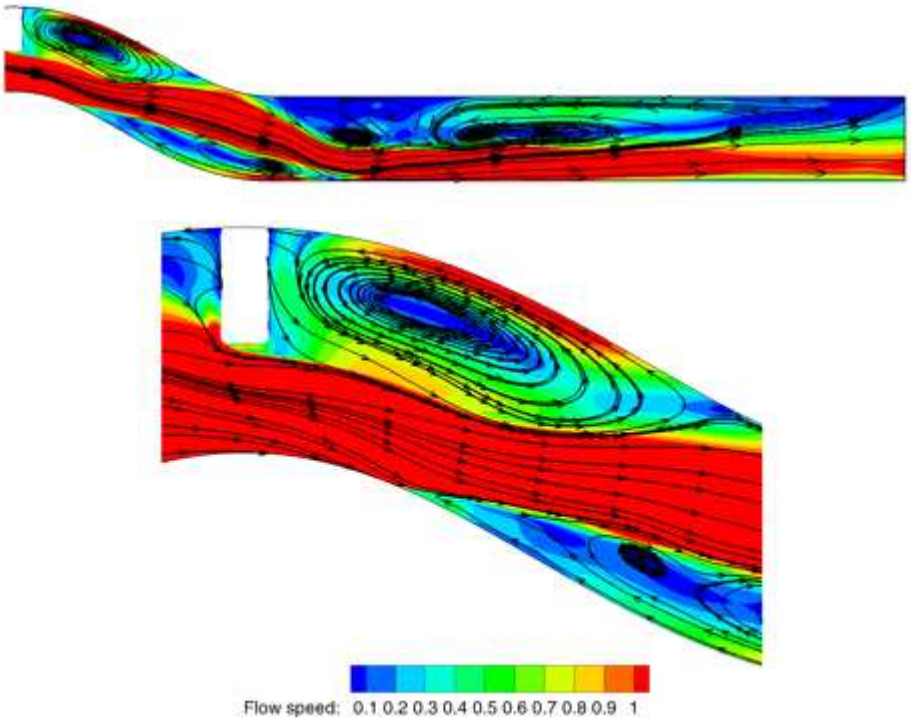
Recirculation



Normalized recirculation length : 0.3921

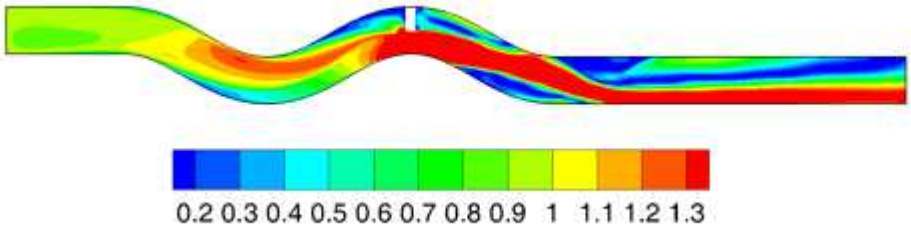
case25 (top/R=20/ =30/α=0/l=5/h=0.5)
Flow speed

Turbulent kinetic energy (TKE)

Recirculation
 recirculation (X)

위치	case25 (R=20/ =30/α=0/l=5/h=0.5)	
	secondary flow	
		
A		
B		
C		
D		
F		
G		
H		
I		

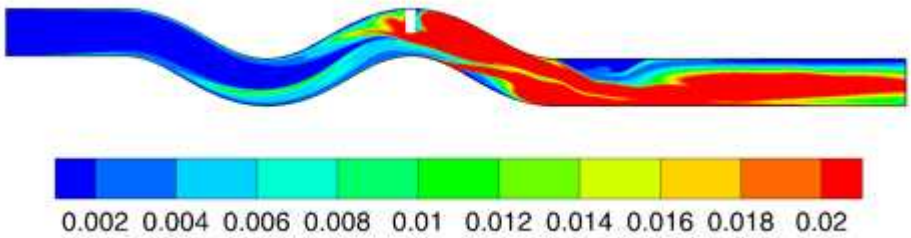
case27 (bottom/R=20/ =30/α=0/l=5/h=1)
Flow speed

Turbulent kinetic energy (TKE)

Recirculation
 Normalized recirculation length : 2.0011

case27 (top/R=20/ =30/α=0/l=5/h=1)

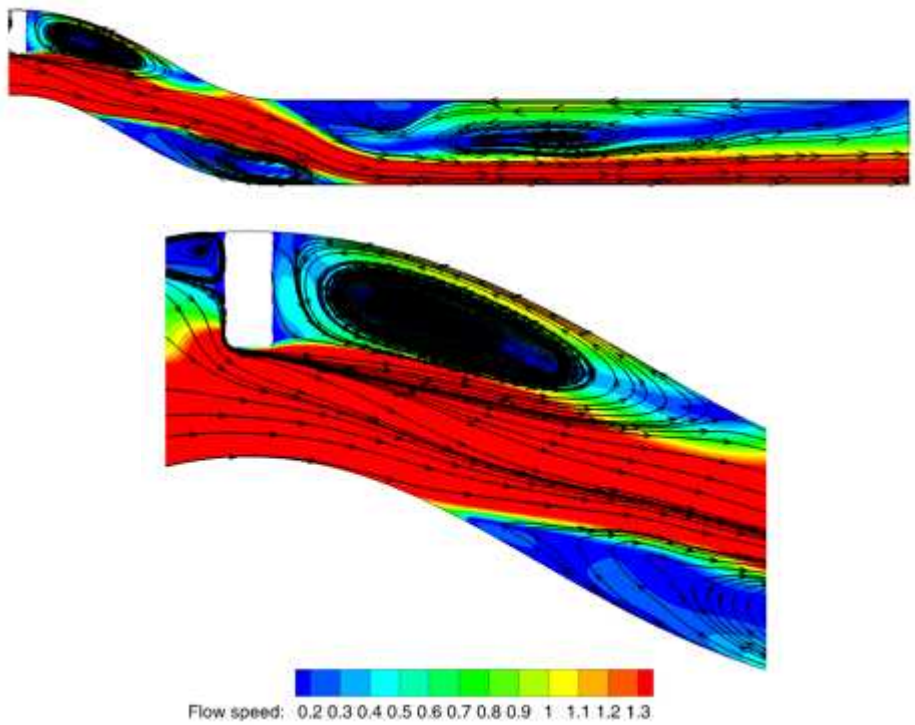
Flow speed



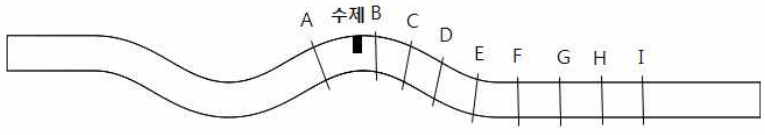
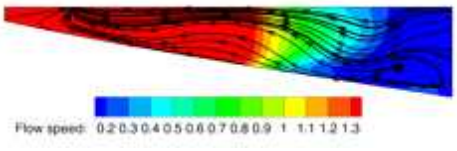
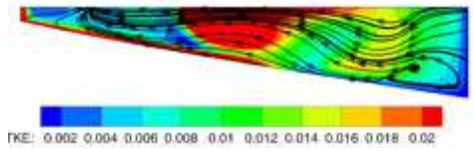
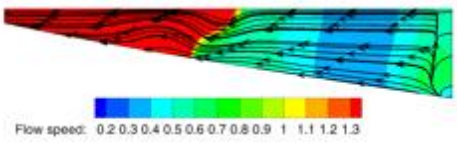
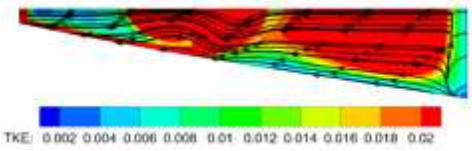
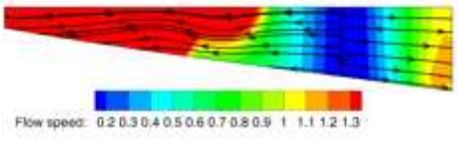
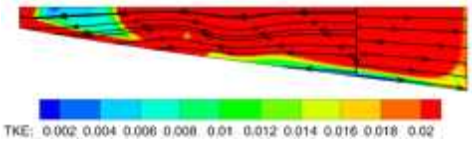
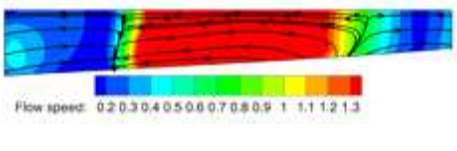
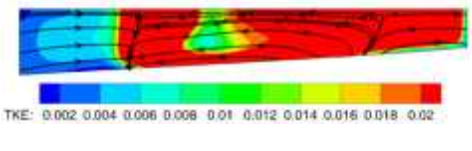
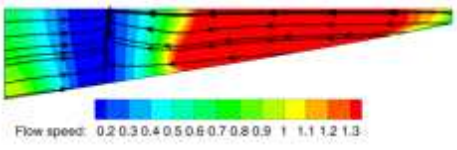
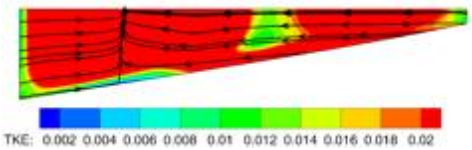
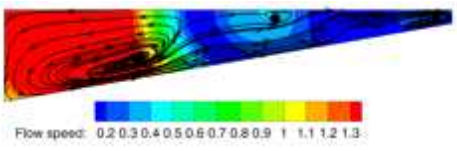
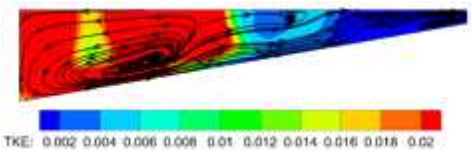
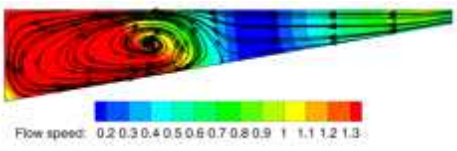
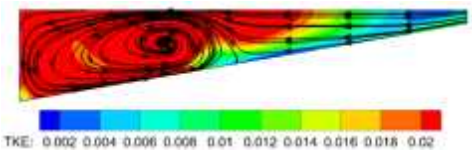
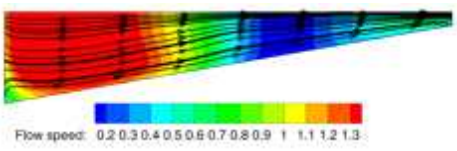
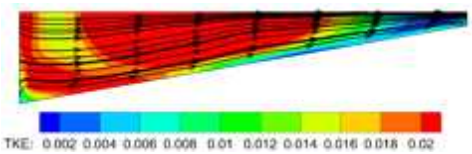
Turbulent kinetic energy (TKE)



Recirculation

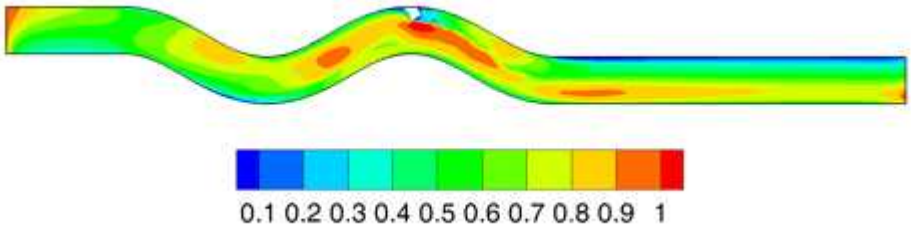


Normalized recirculation length : 1.9687

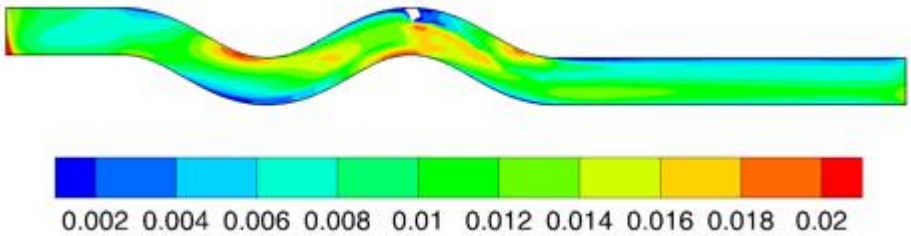
위치	case27 (R=20/ =30/α=0/l=5/h=1)	
	secondary flow	
		
A		
B		
C		
D		
F		
G		
H		
I		

case37 (bottom/R=20/ =30/α=+30/l=2.5/h=0.5)

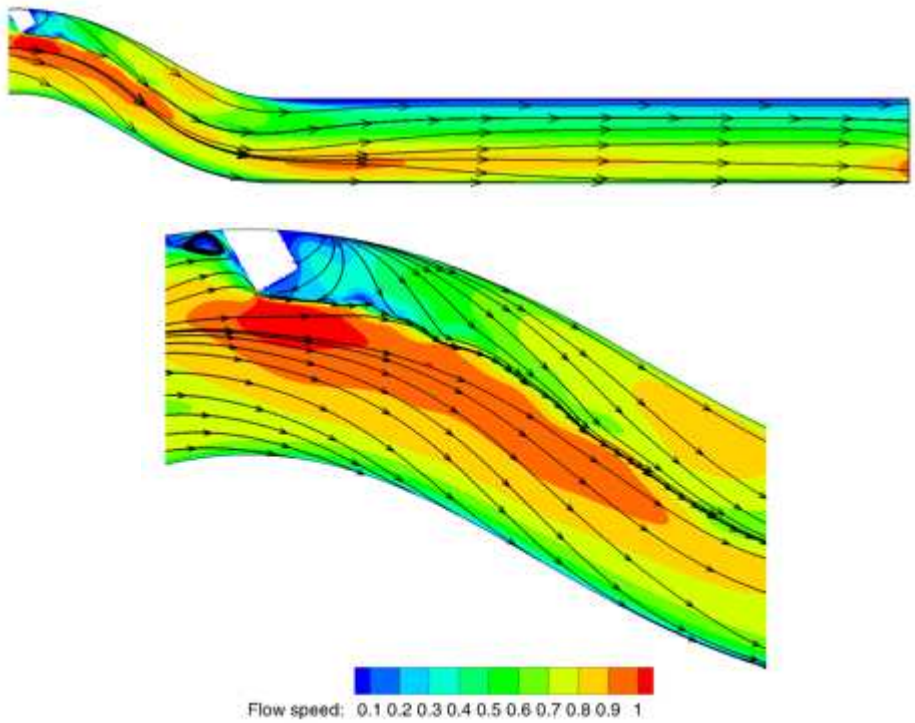
Flow speed



Turbulent kinetic energy (TKE)



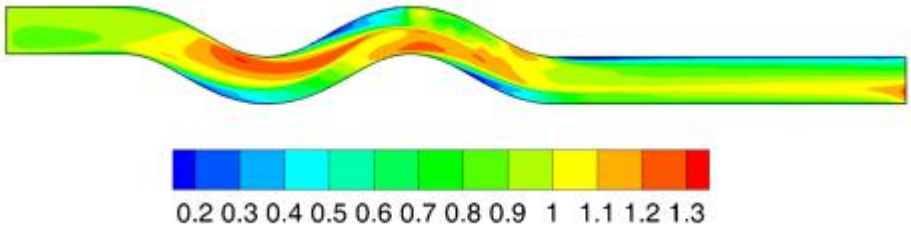
Recirculation



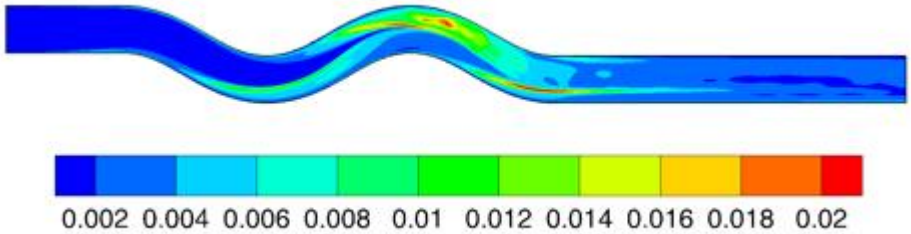
Normalized recirculation length : 0.3760

case37 (top/R=20/ =30/α=+30/l=2.5/h=0.5)

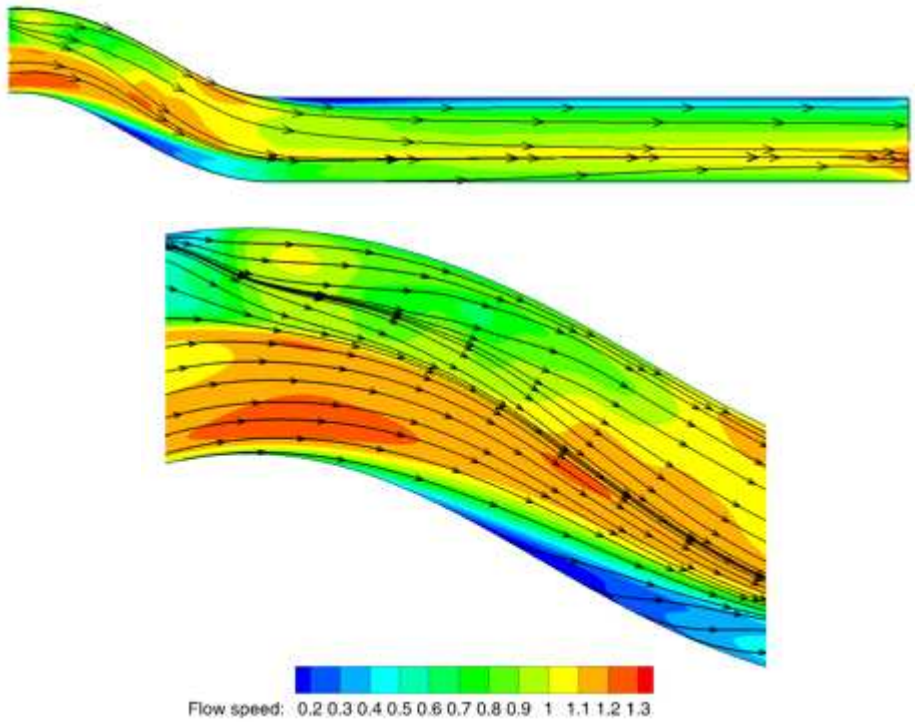
Flow speed



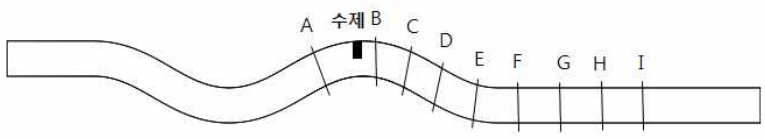
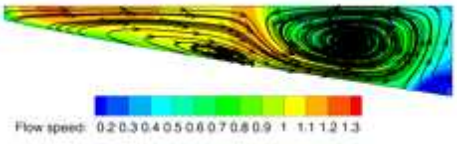
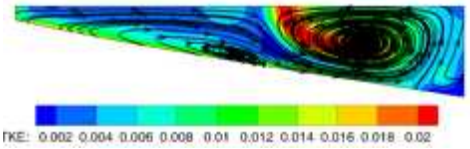
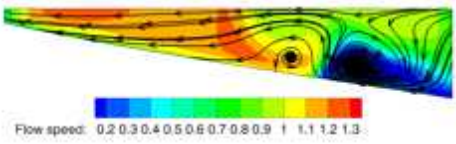
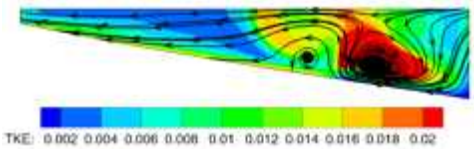
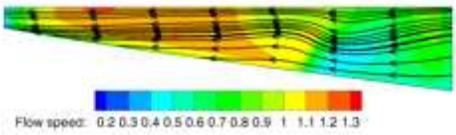
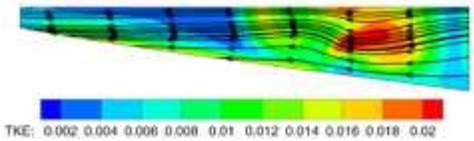
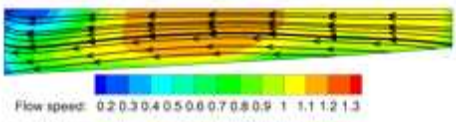
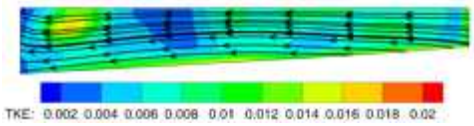
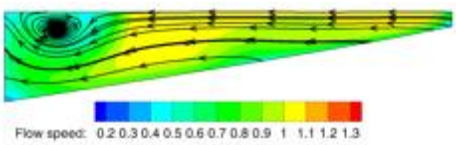
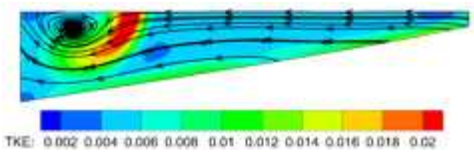
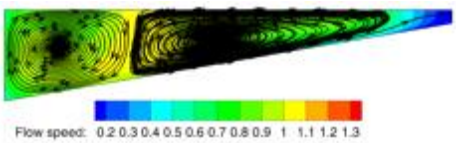
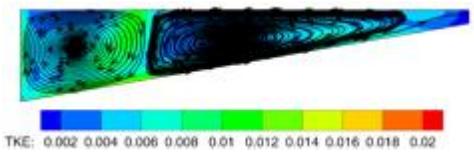
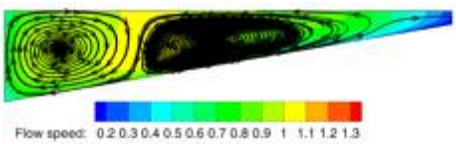
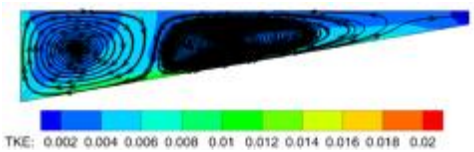
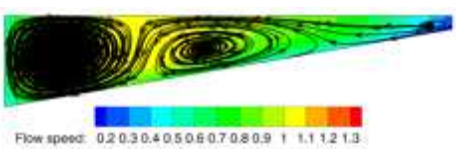
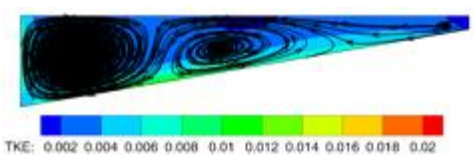
Turbulent kinetic energy (TKE)

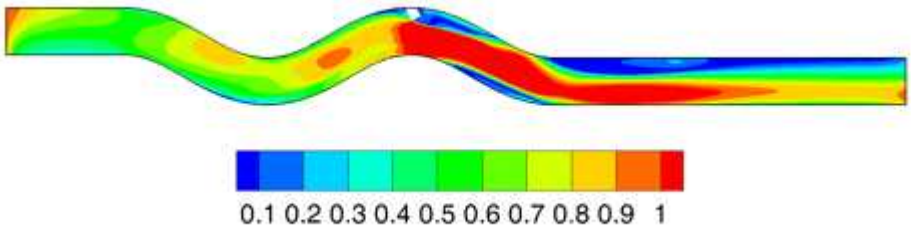
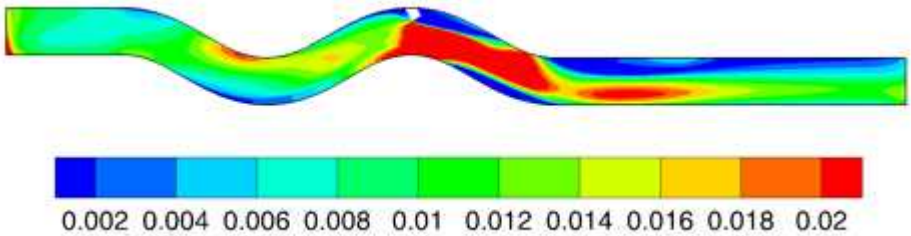
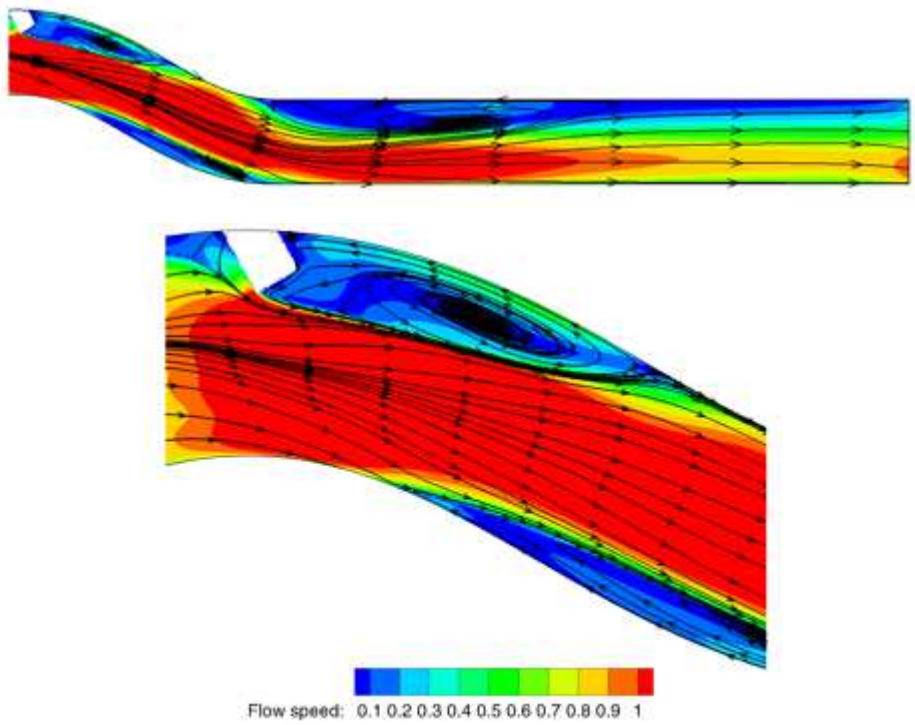


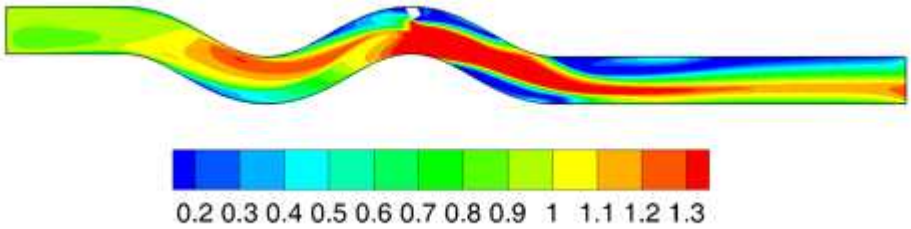
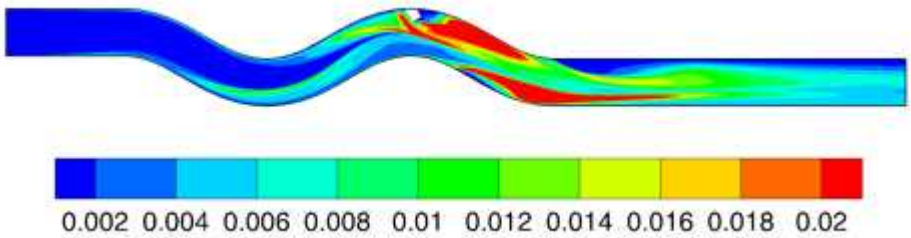
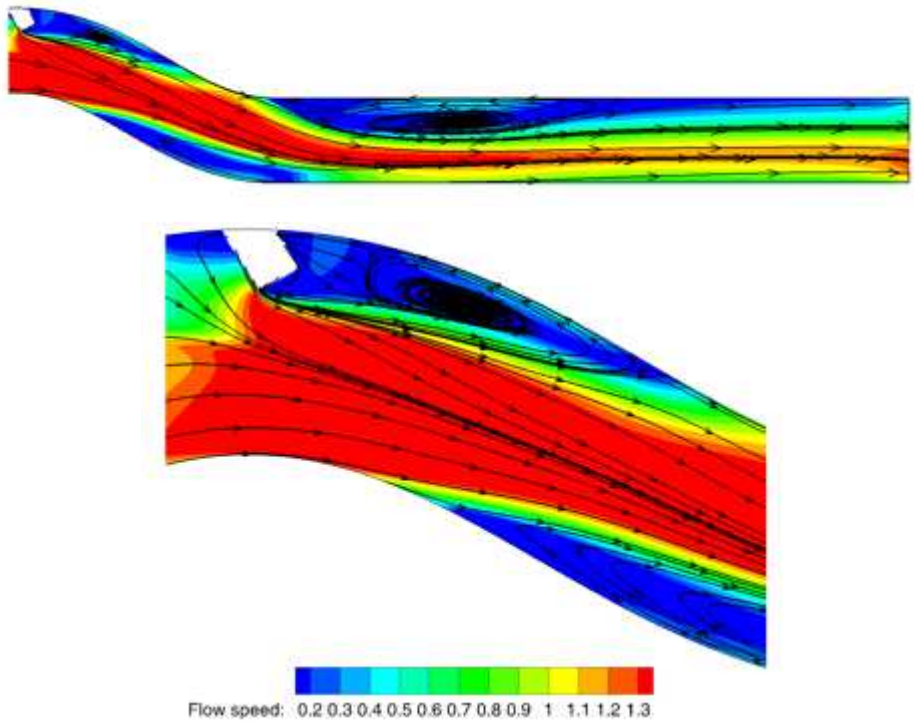
Recirculation

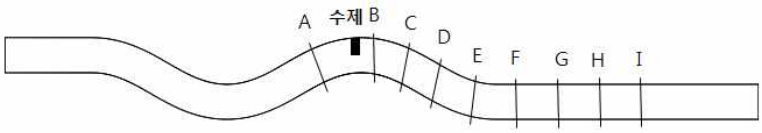
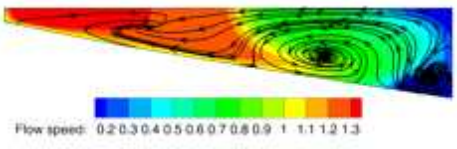
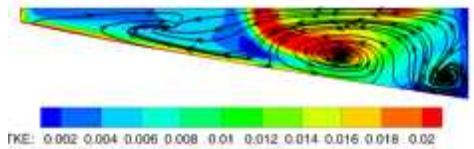
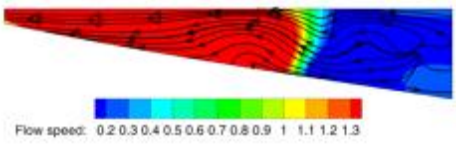
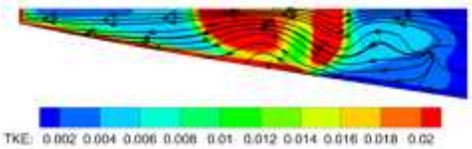
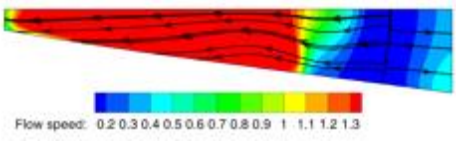
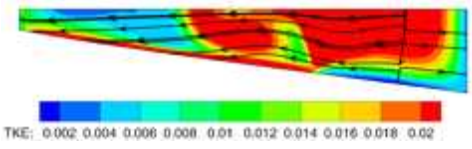
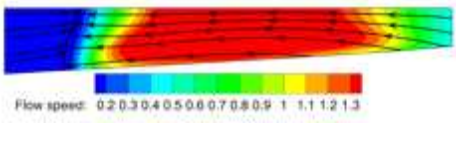
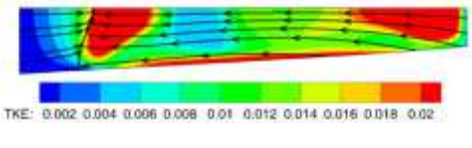
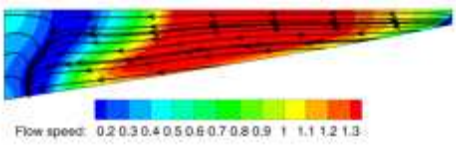
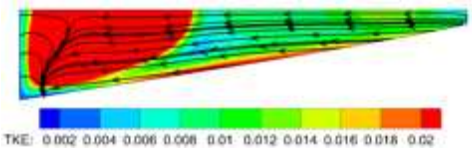
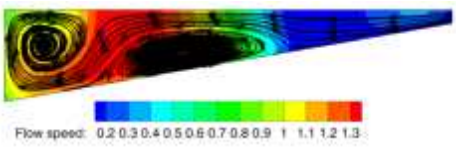
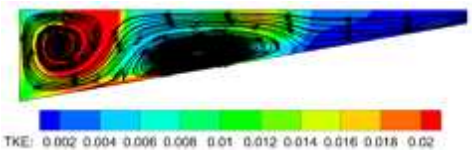
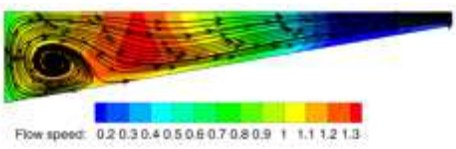
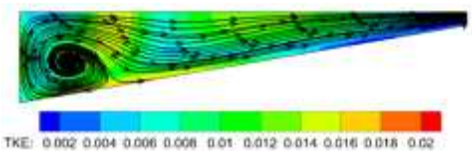
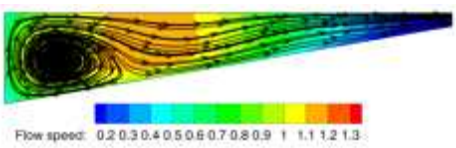
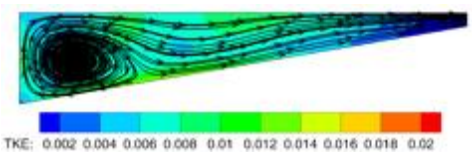


recirculation (X)

위치	case37 (R=20/ =30/α=+30/l=2.5/h=0.5)	
	secondary flow	
		
A		
B		
C		
D		
F		
G		
H		
I		

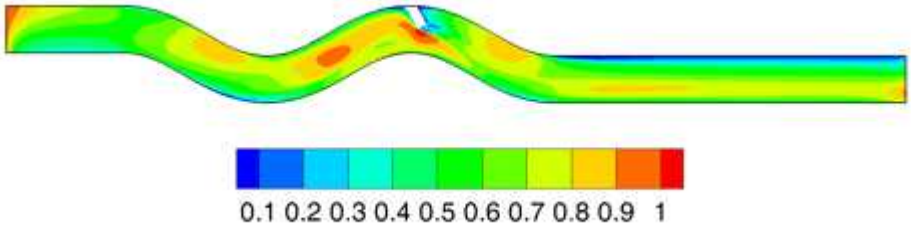
case39 (bottom/R=20/ =30/α=+30/l=2.5/h=1)
Flow speed

Turbulent kinetic energy (TKE)

Recirculation
 Normalized recirculation length : 1.6800

case39 (top/R=20/ =30/α=+30/l=2.5/h=1)
Flow speed

Turbulent kinetic energy (TKE)

Recirculation
 Normalized recirculation length : 1.6580

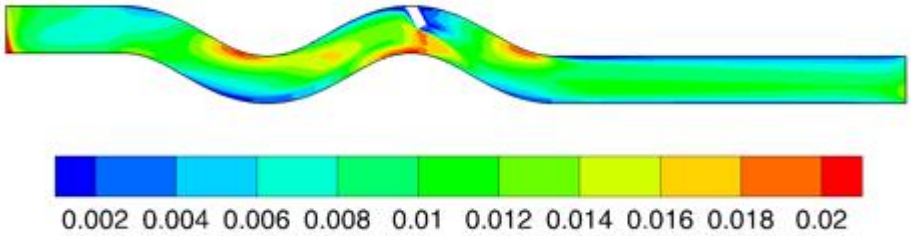
위치	case39 (R=20/ =30/α=+30/l=2.5/h=1)	
	secondary flow	
		
A		
B		
C		
D		
F		
G		
H		
I		

case41 (bottom/R=20/ =30/α=+30/l=5/h=0.5)

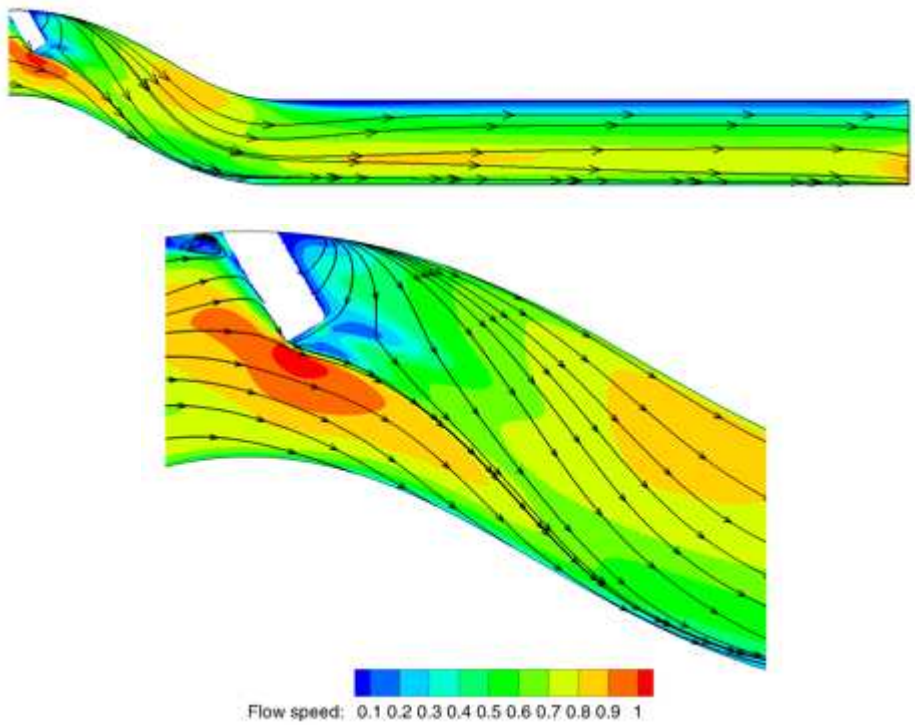
Flow speed



Turbulent kinetic energy (TKE)



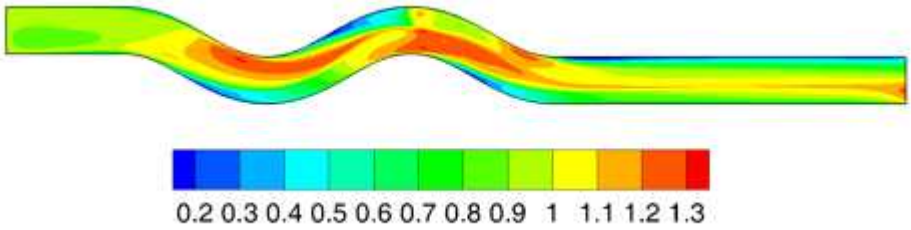
Recirculation



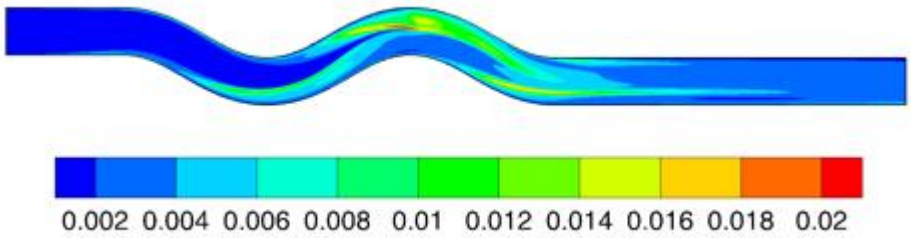
Normalized recirculation length : 0.4123

case41 (top/R=20/ =30/α=+30/l=5/h=0.5)

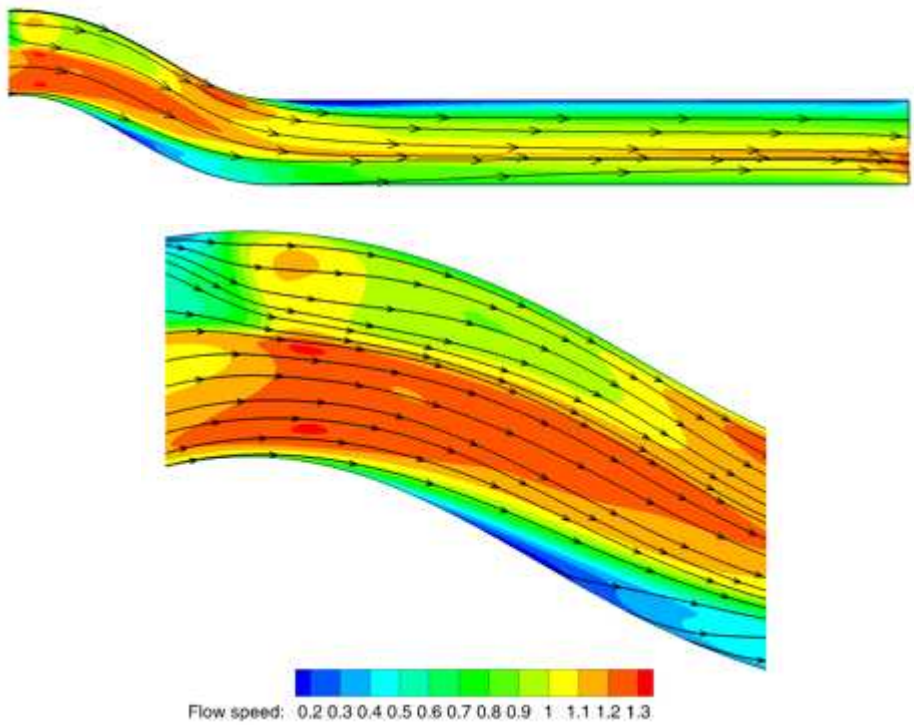
Flow speed



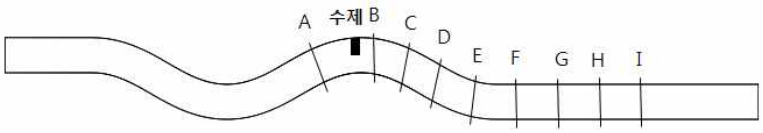
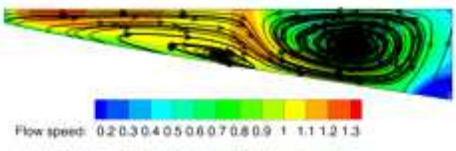
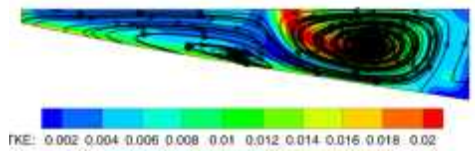
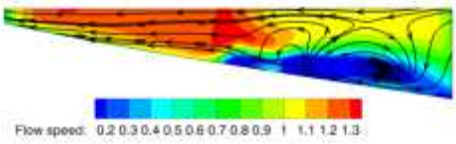
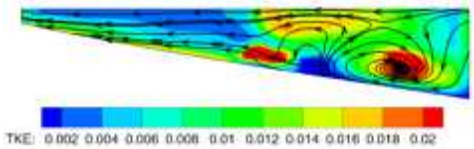
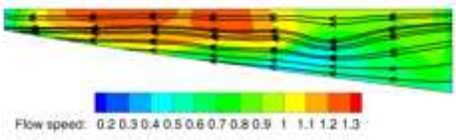
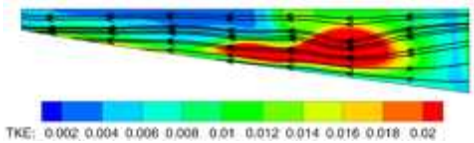
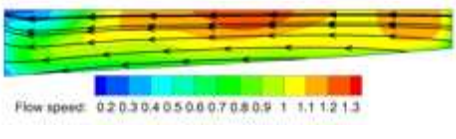
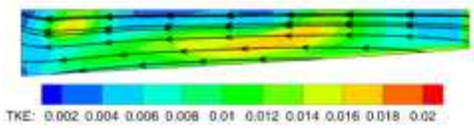
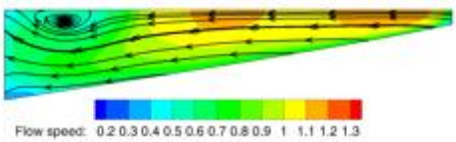
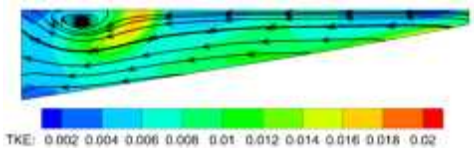
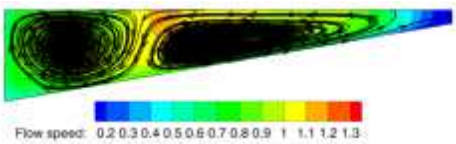
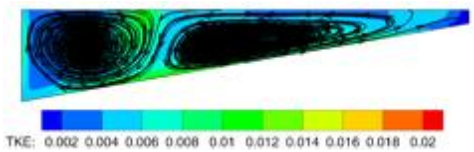
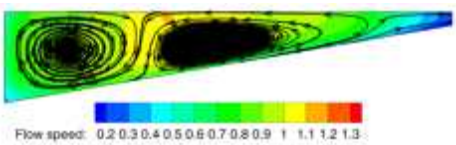
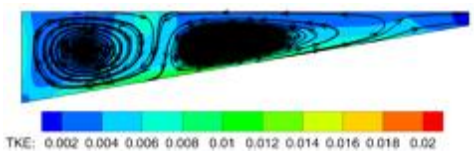
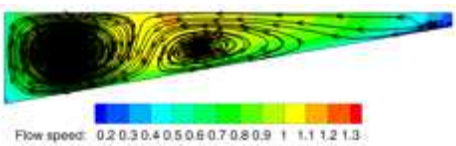
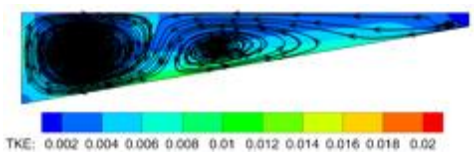
Turbulent kinetic energy (TKE)



Recirculation

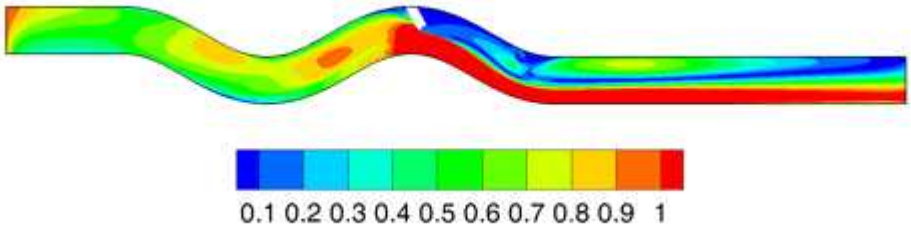


recirculation (X)

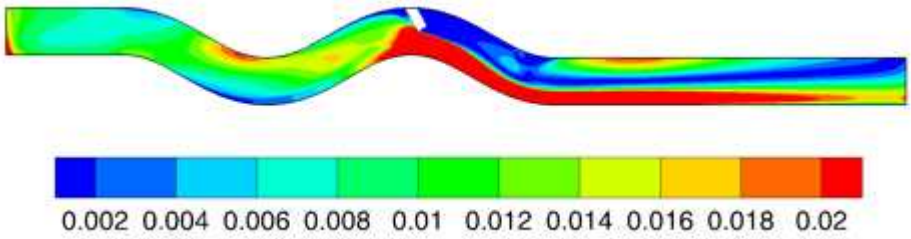
위치	case41 (R=20/ =30/α=+30/l=5/h=0.5)	
	secondary flow	
		
A		
B		
C		
D		
F		
G		
H		
I		

case43 (bottom/R=20/ =30/α=+30/l=5/h=1)

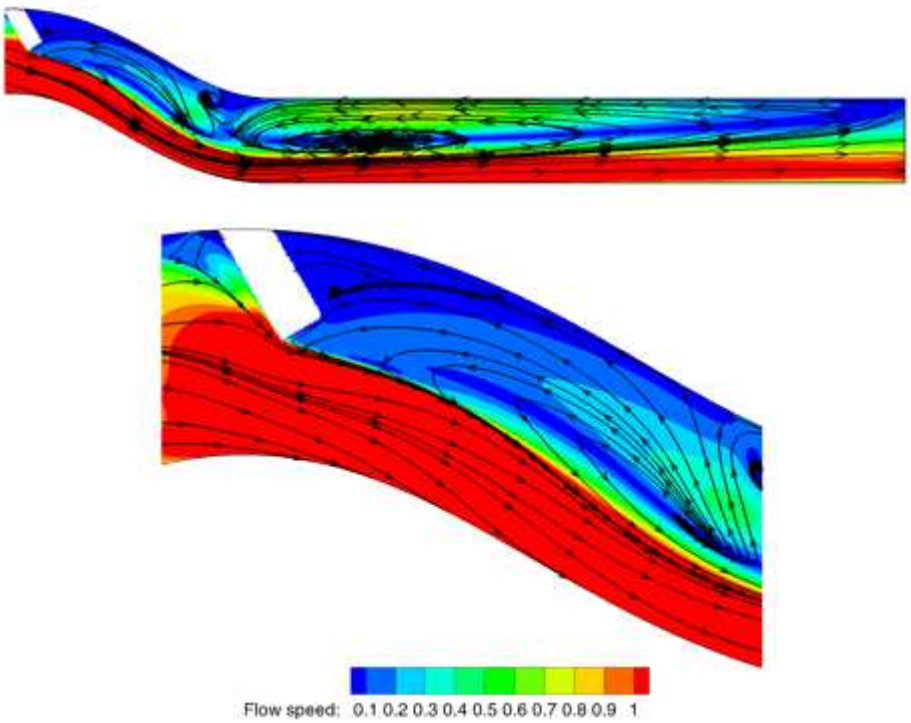
Flow speed



Turbulent kinetic energy (TKE)



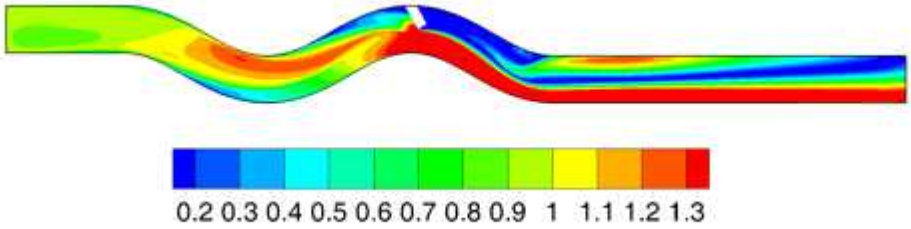
Recirculation



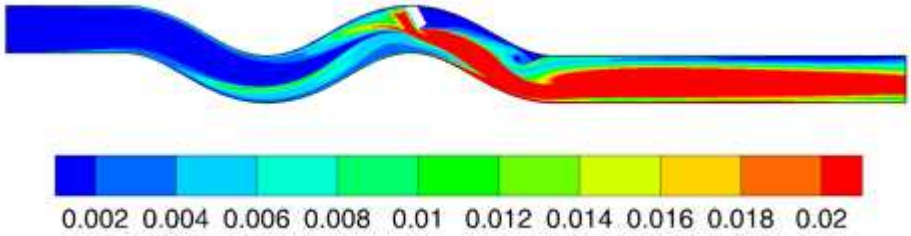
Normalized recirculation length : 10.2720

case43 (top/R=20/ =30/α=+30/l=5/h=1)

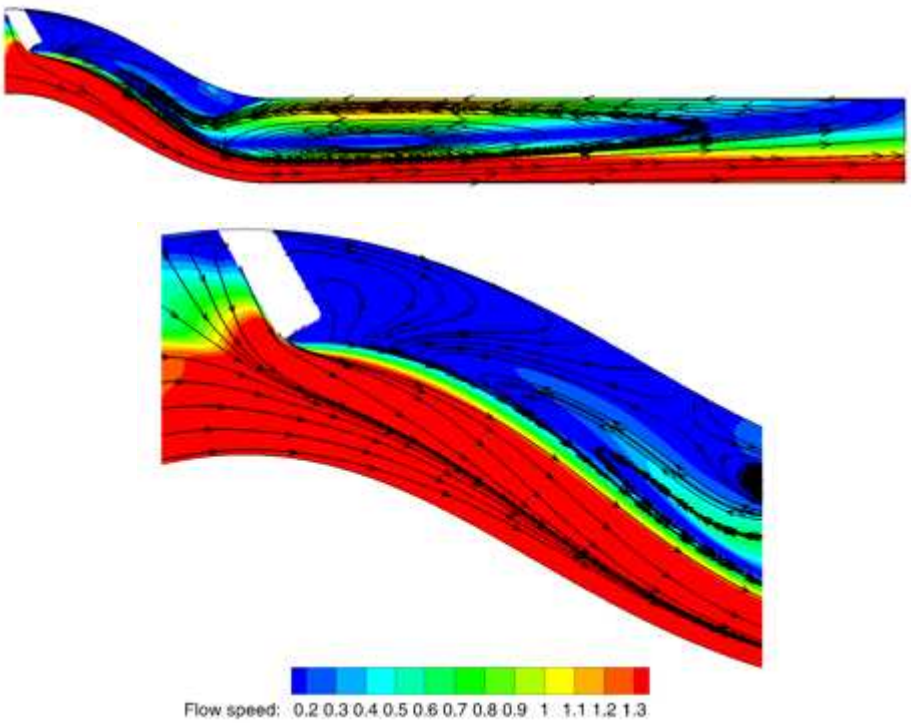
Flow speed



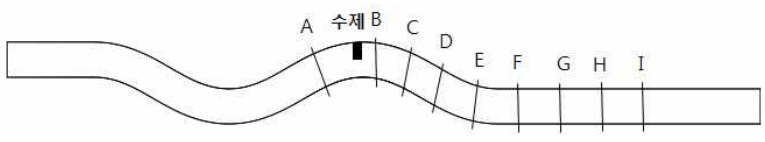
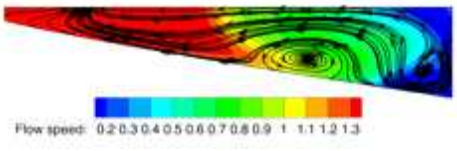
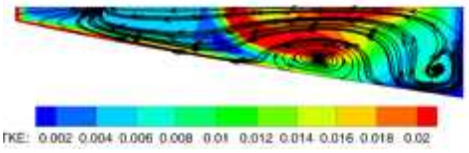
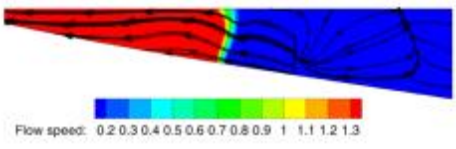
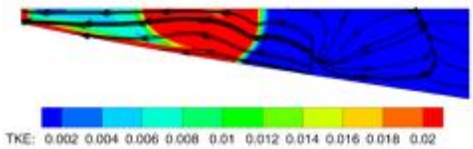
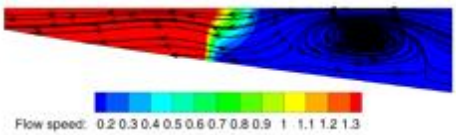
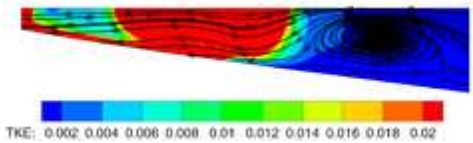
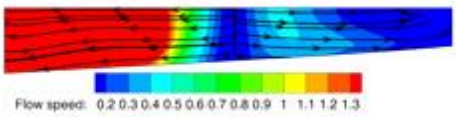
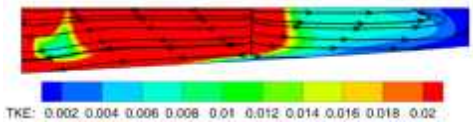
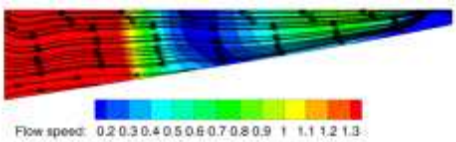
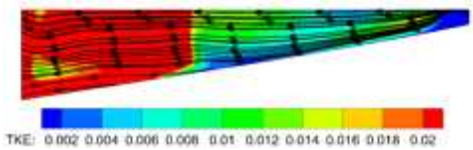
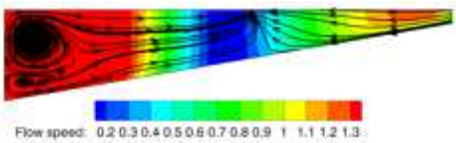
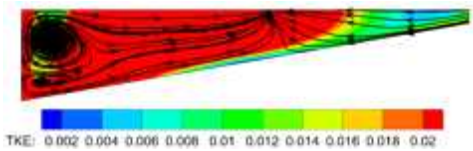
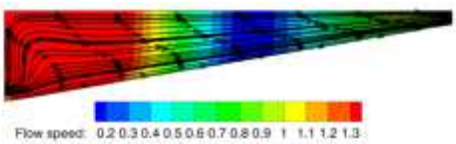
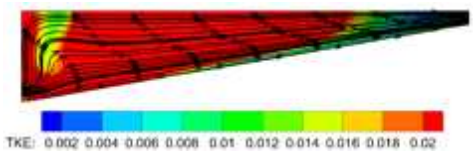
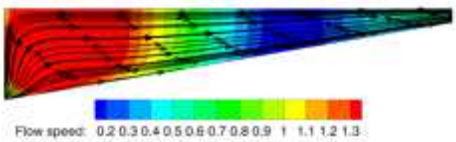
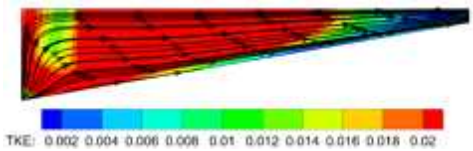
Turbulent kinetic energy (TKE)

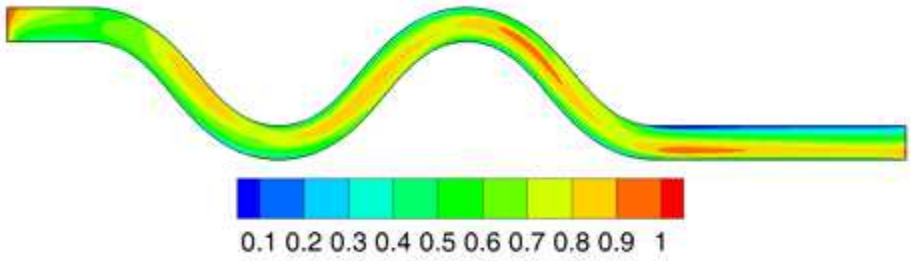
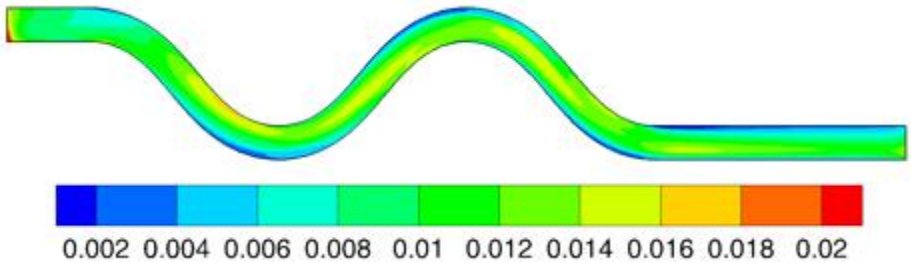
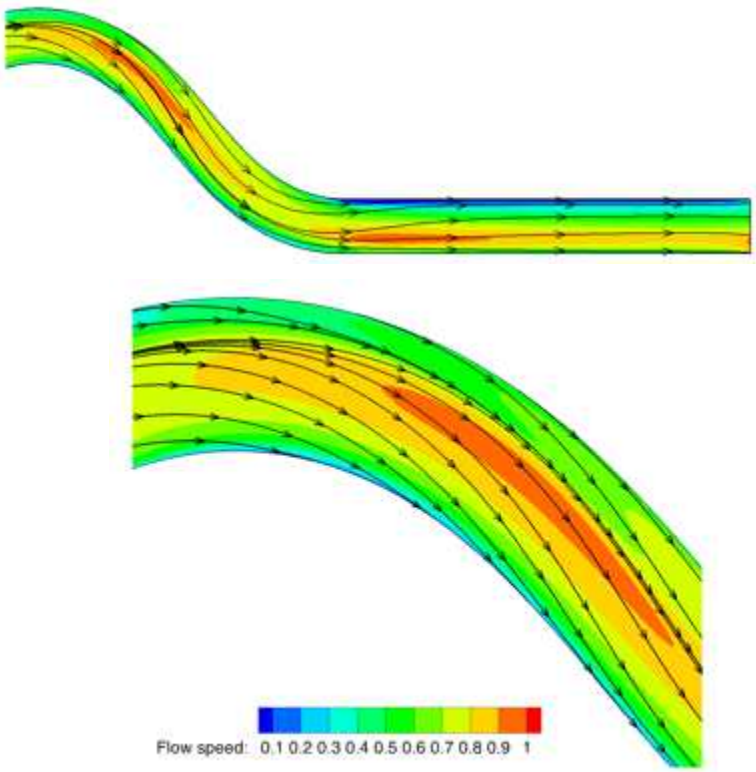


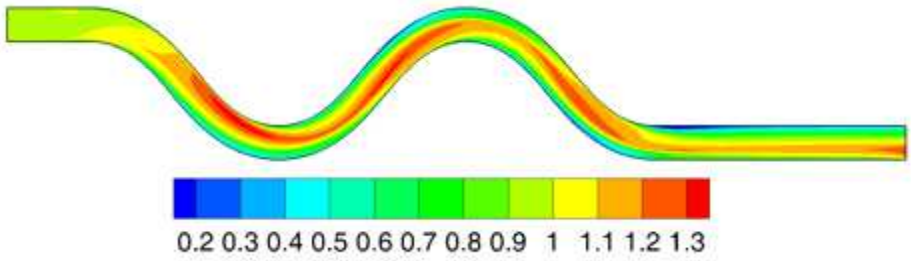
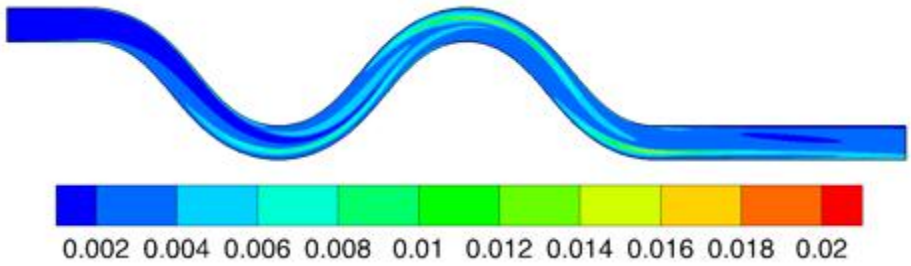
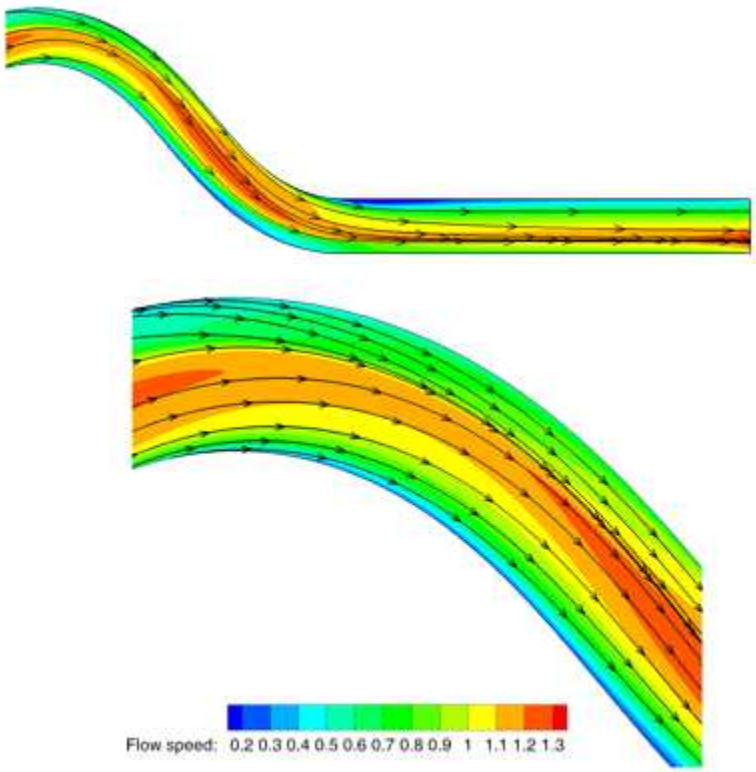
Recirculation

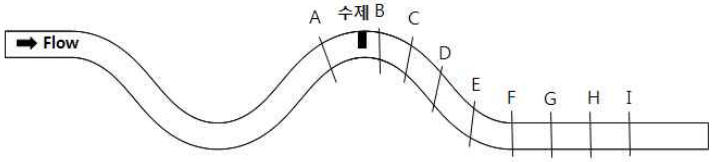
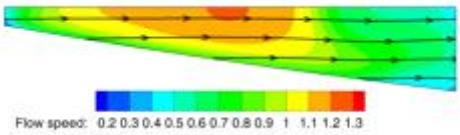
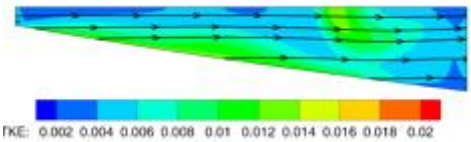
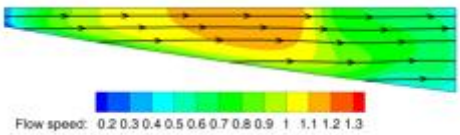
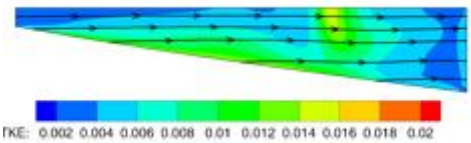
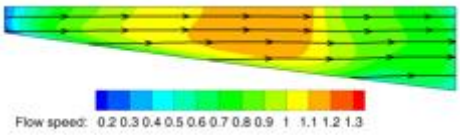
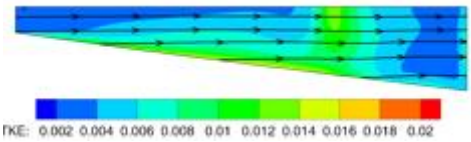
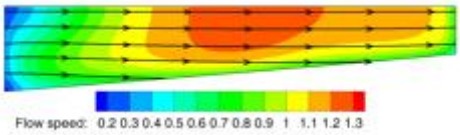
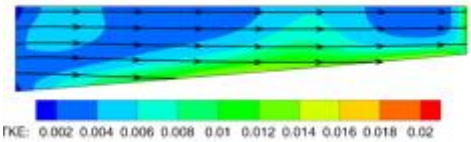
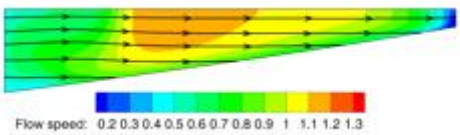
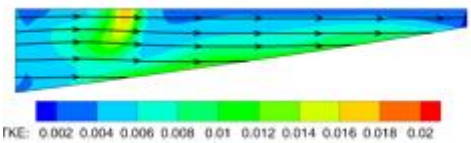
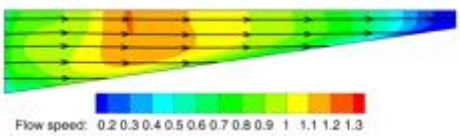
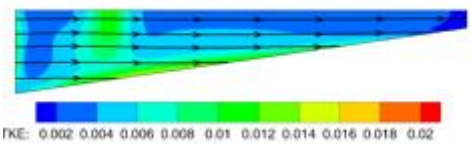
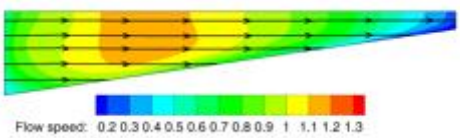
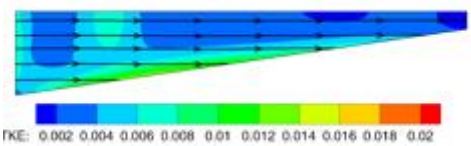
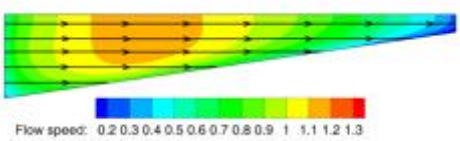
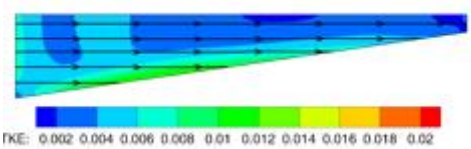


Normalized recirculation length : 10.2680

위치	case43 (R=20/ =30/α=+30/l=5/h=1)	
	secondary flow	
		
A		
B		
C		
D		
F		
G		
H		
I		

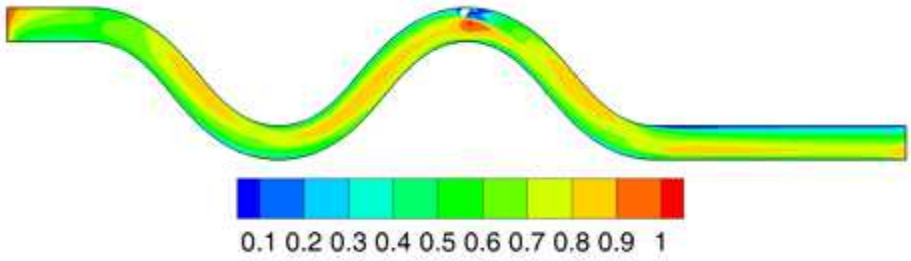
case3 (bottom/R=25/ =50/l=2.5/h=0.5)
Flow speed

Turbulent kinetic energy (TKE)

Recirculation
 recirculation (X)

case3 (top/R=25/ =50/l=2.5/h=0.5)
Flow speed

Turbulent kinetic energy (TKE)

Recirculation
 recirculation (X)

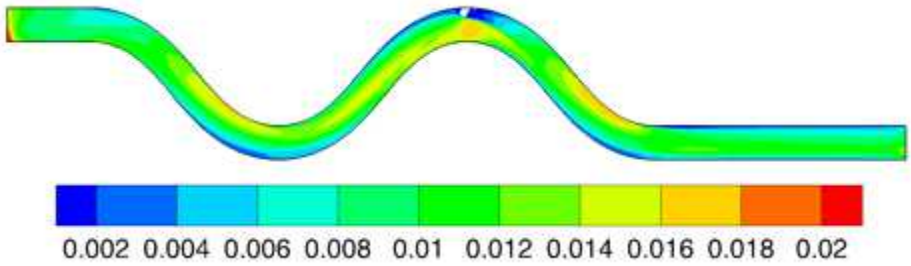
위치	case3 (R=25/ =50/l=2.5/h=0.5)	
	secondary flow	
		
A		
B		
C		
D		
F		
G		
H		
I		

case14 (bottom/R=25/ =50/α=-30/l=2.5/h=0.5)

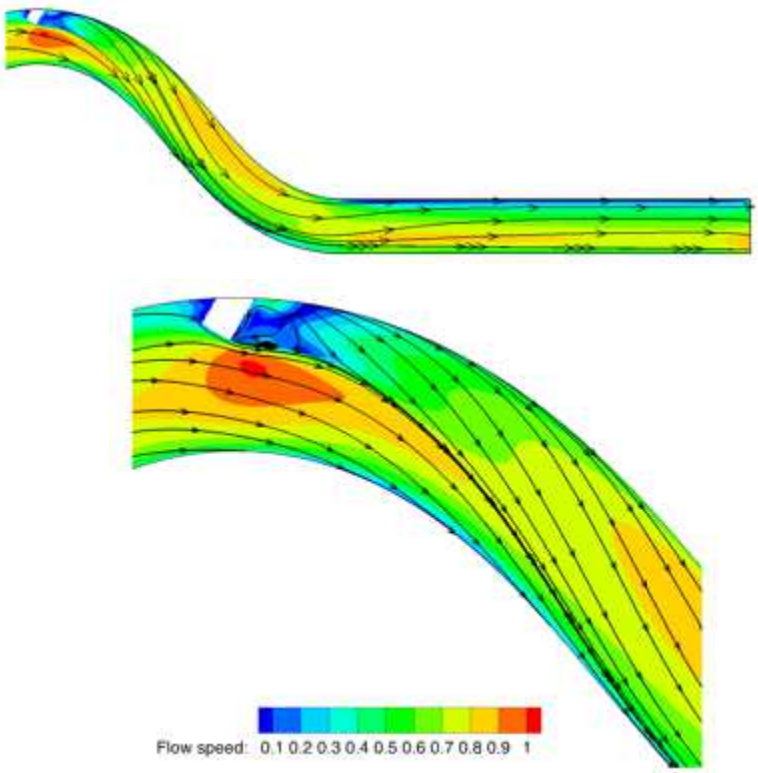
Flow speed



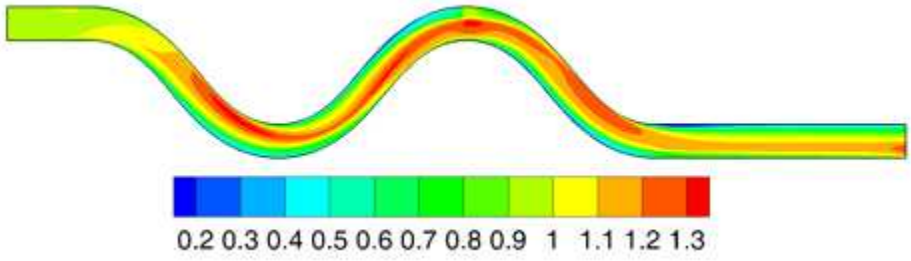
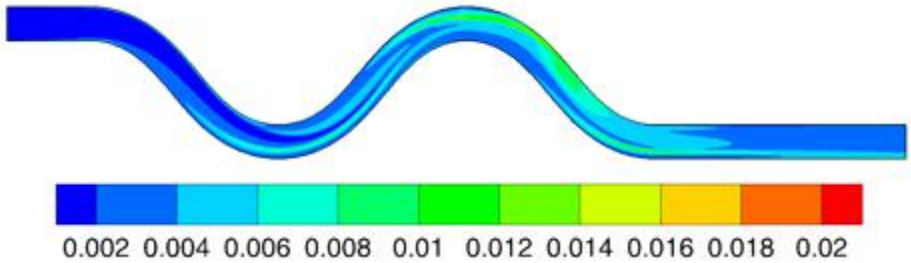
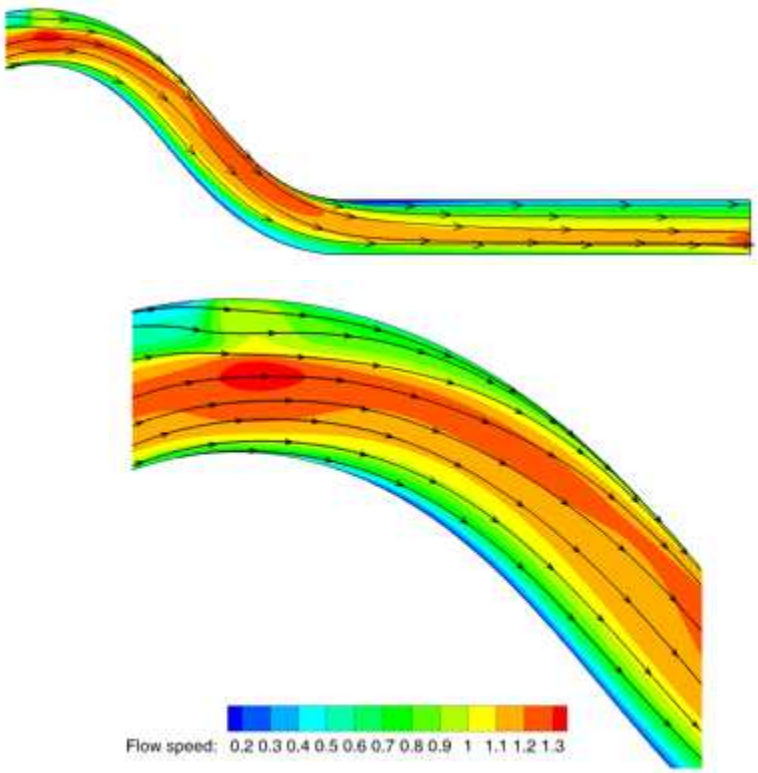
Turbulent kinetic energy (TKE)

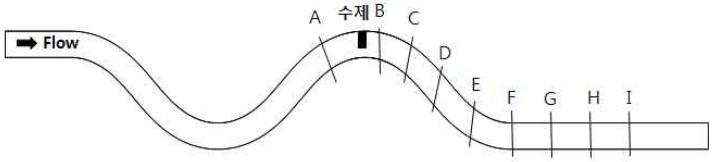
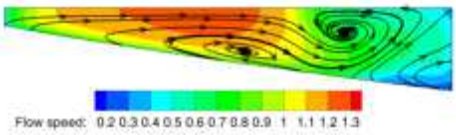
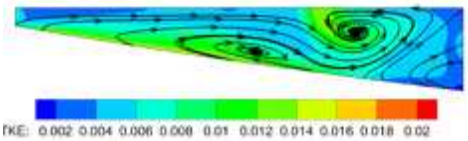
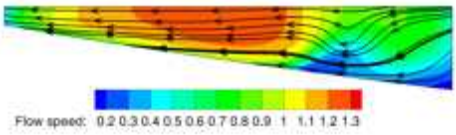
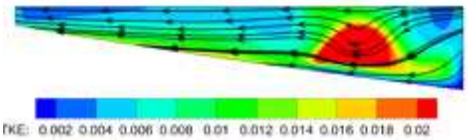
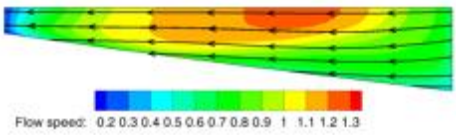
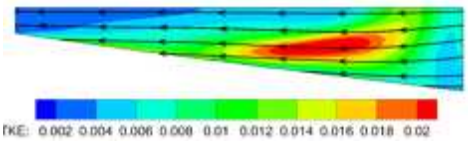
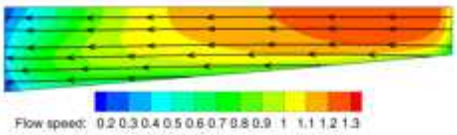
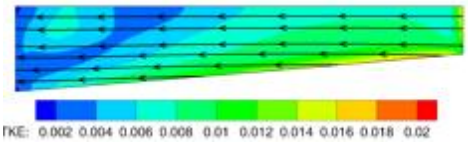
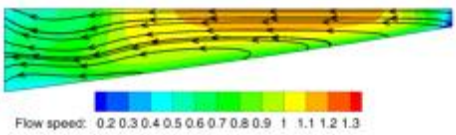
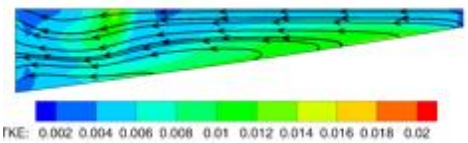
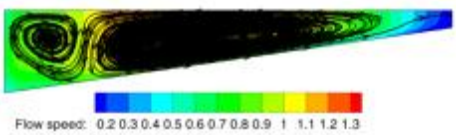
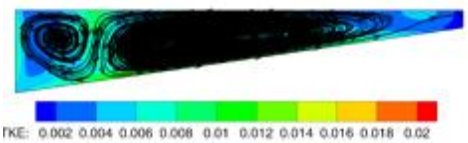
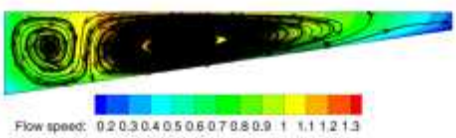
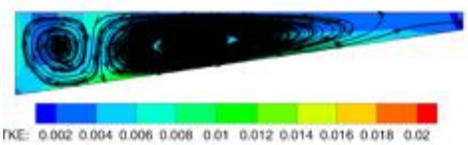
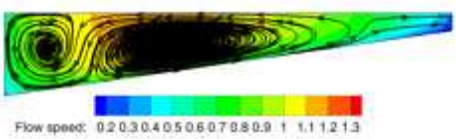
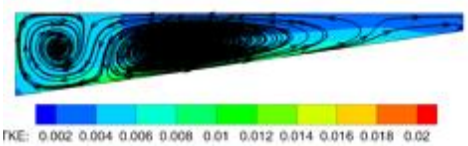


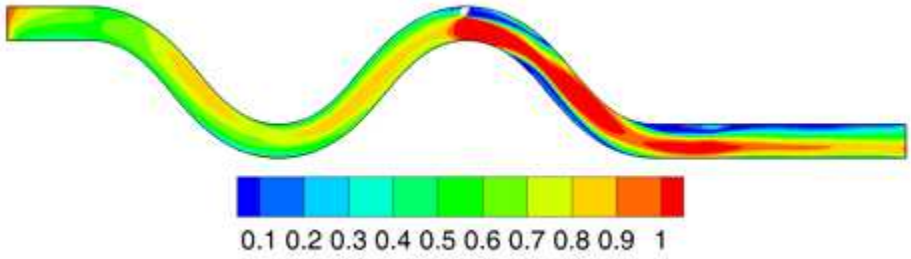
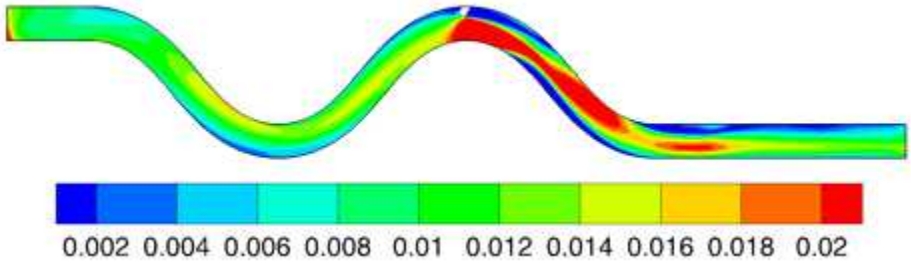
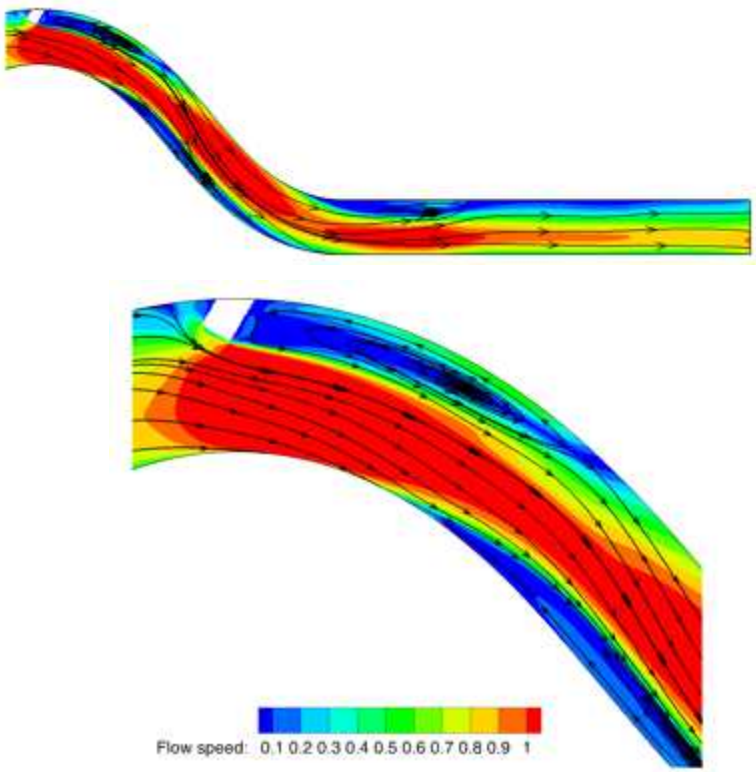
Recirculation

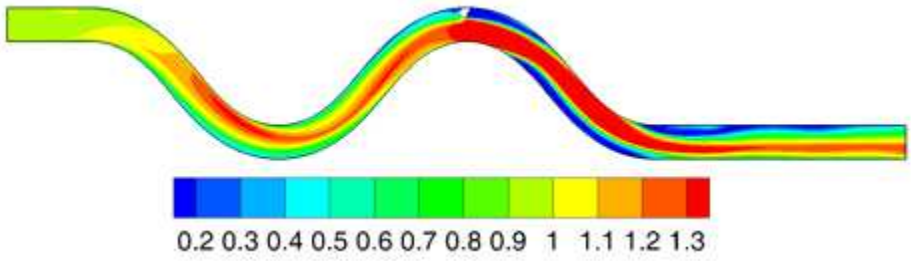
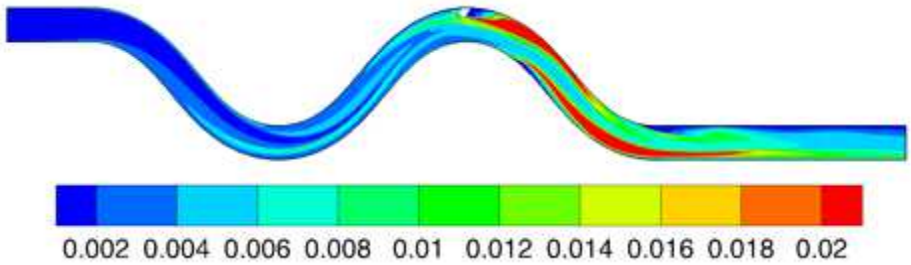
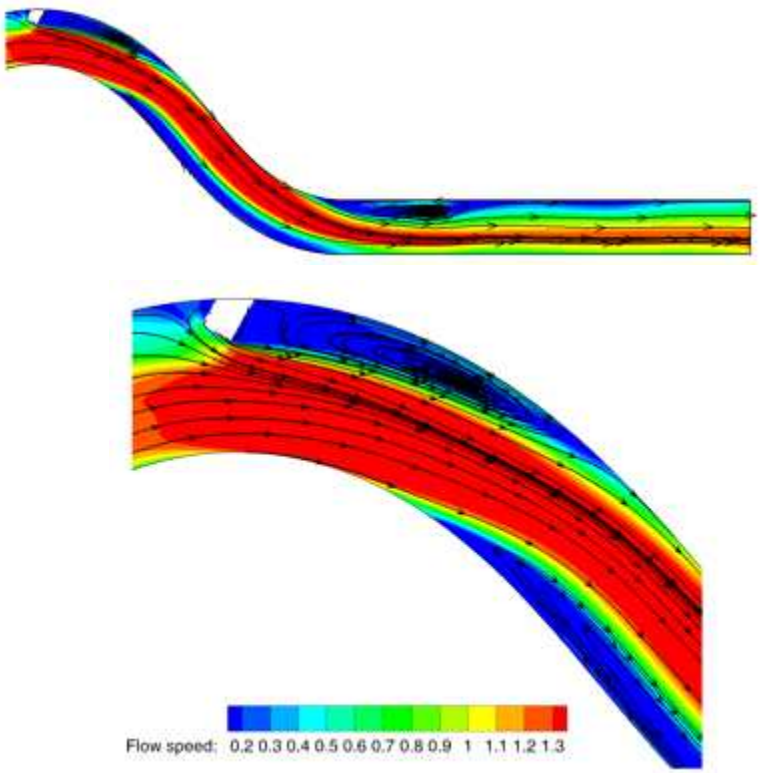


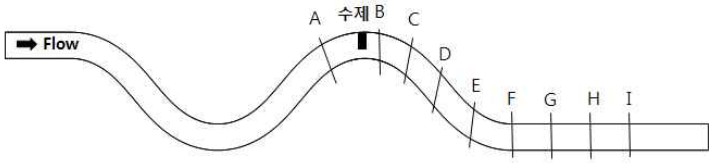
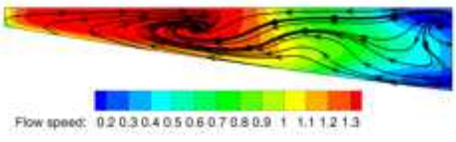
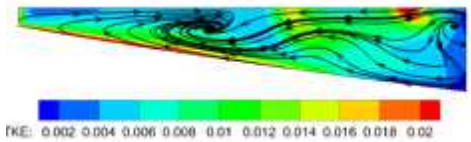
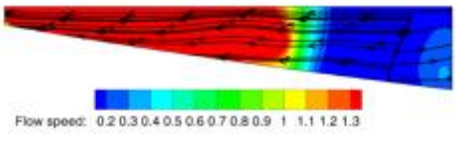
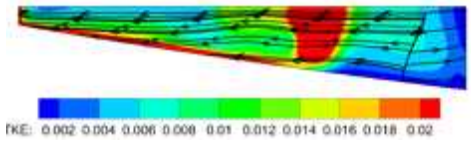
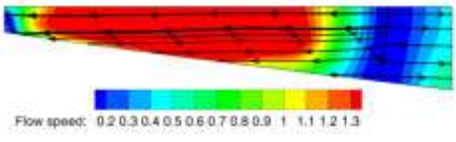
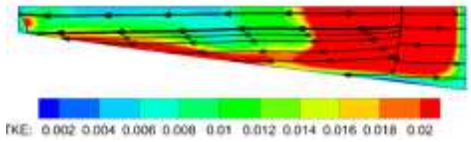
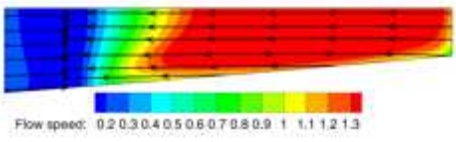
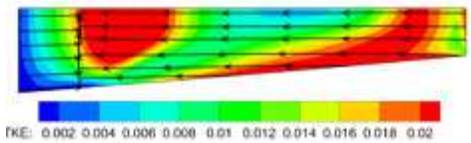
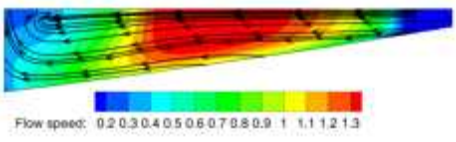
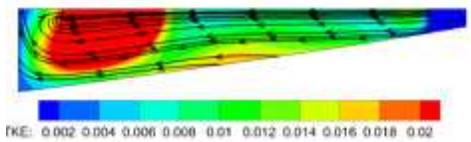
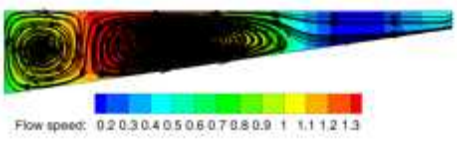
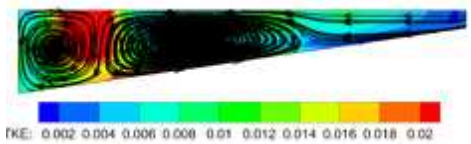
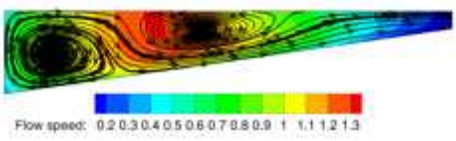
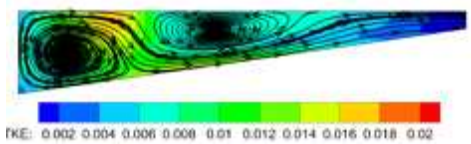
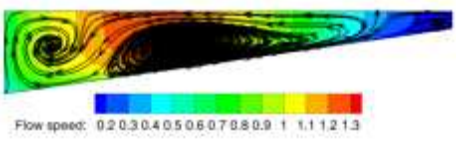
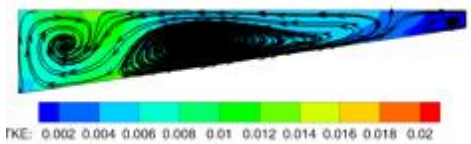
Normalized recirculation length : 0.3757

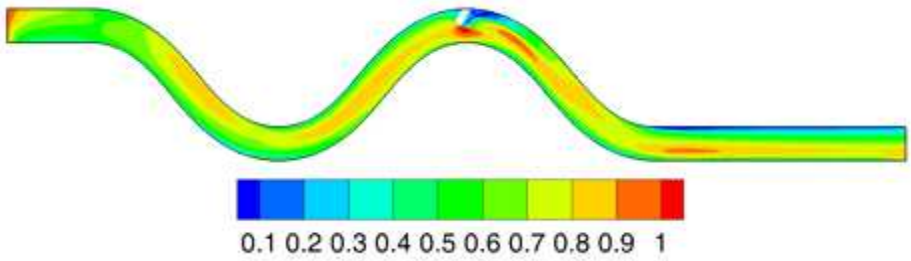
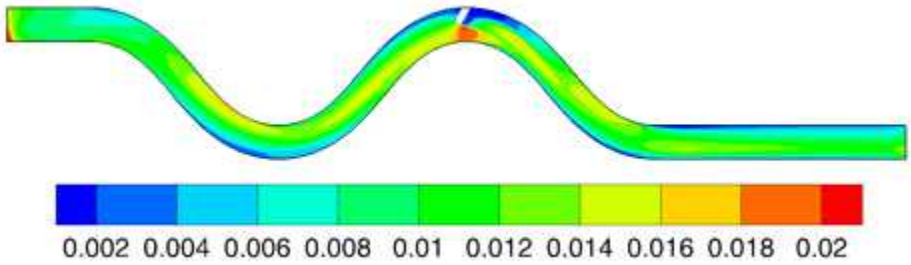
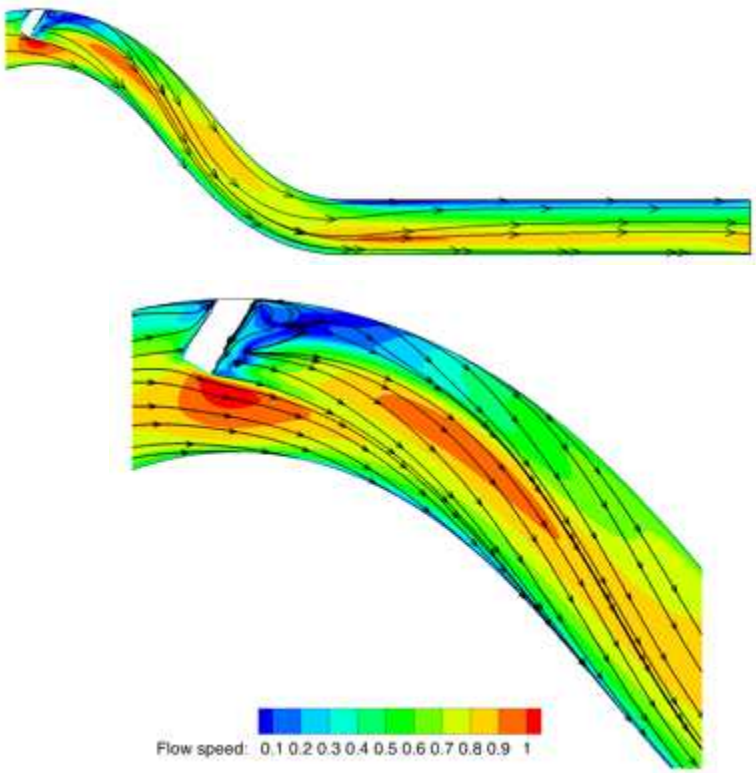
case14 (top/R=25/ =50/α=-30/l=2.5/h=0.5)
Flow speed

Turbulent kinetic energy (TKE)

Recirculation
 recirculation (X)

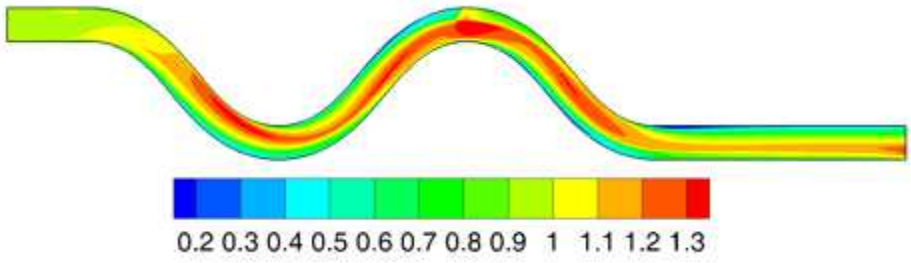
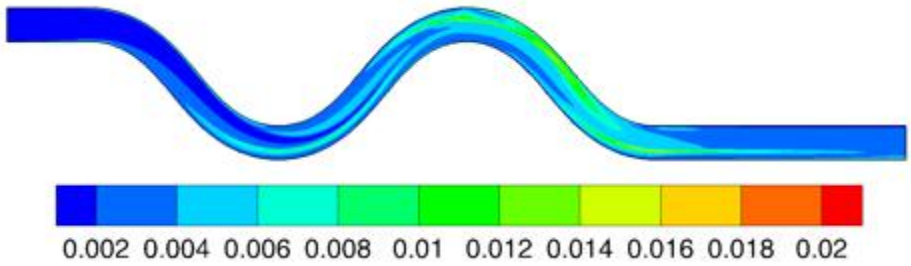
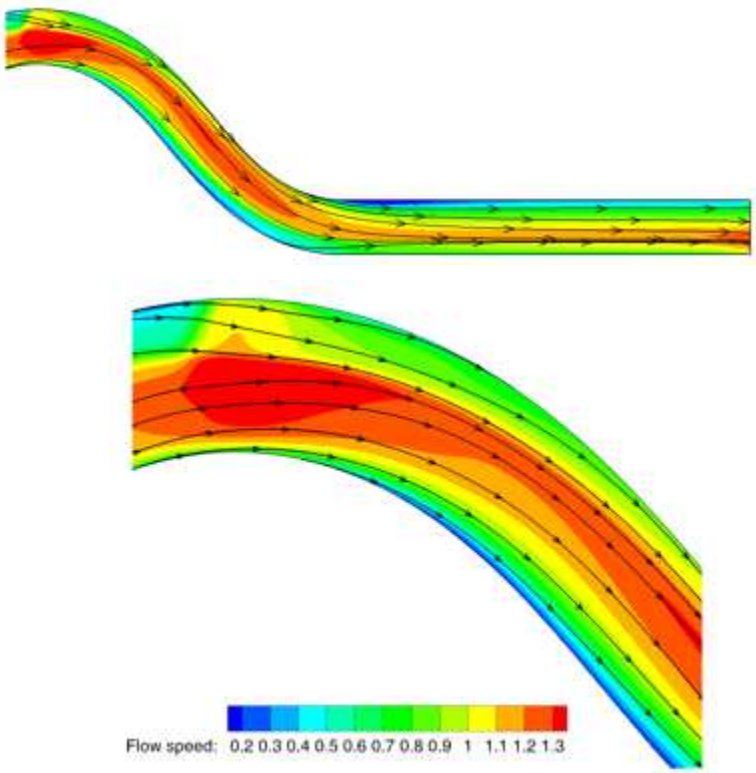
위치	case14 (R=25/ =50/α=-30/l=2.5/h=0.5)	
	secondary flow	
		
A		
B		
C		
D		
F		
G		
H		
I		

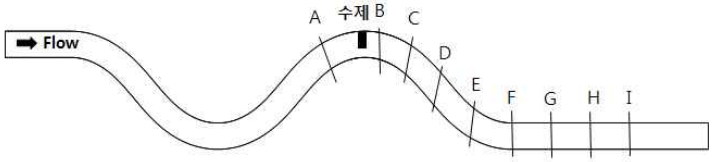
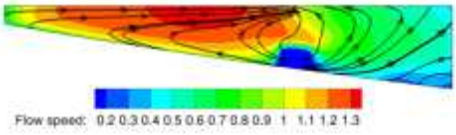
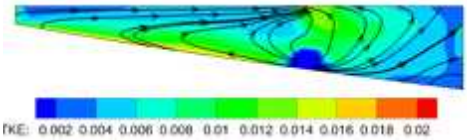
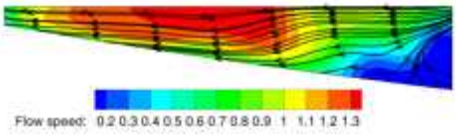
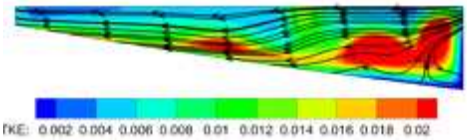
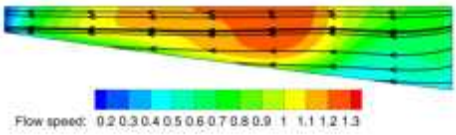
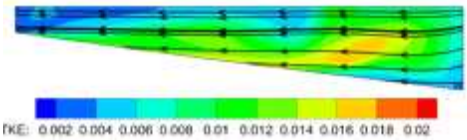
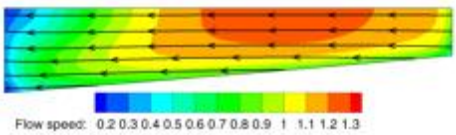
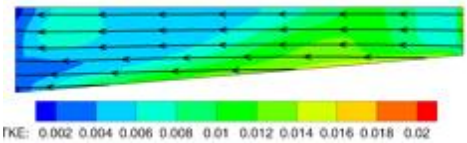
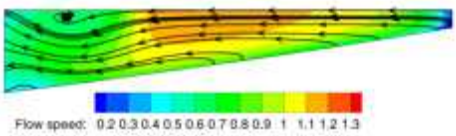
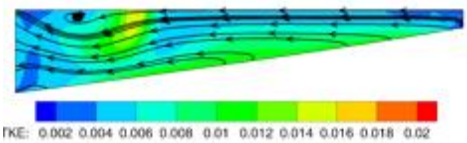
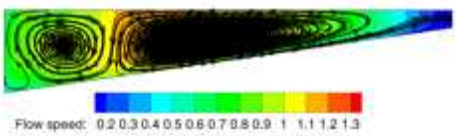
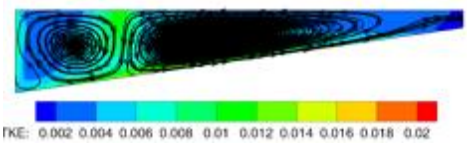
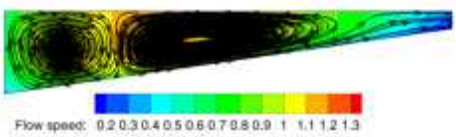
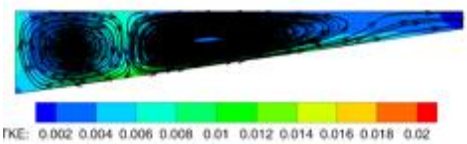
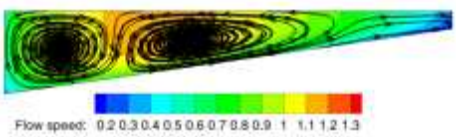
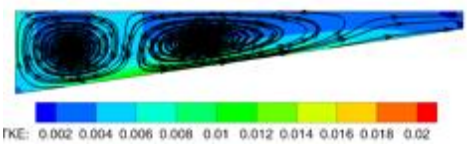
case16 (bottom/R=25/ =50/α=-30/l=2.5/h=1)
Flow speed

Turbulent kinetic energy (TKE)

Recirculation
 Normalized recirculation length : 2.3052

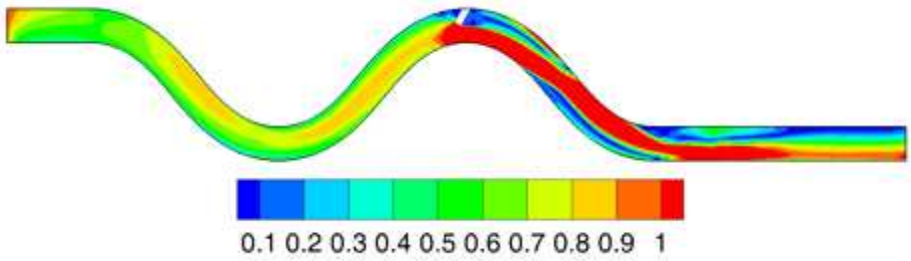
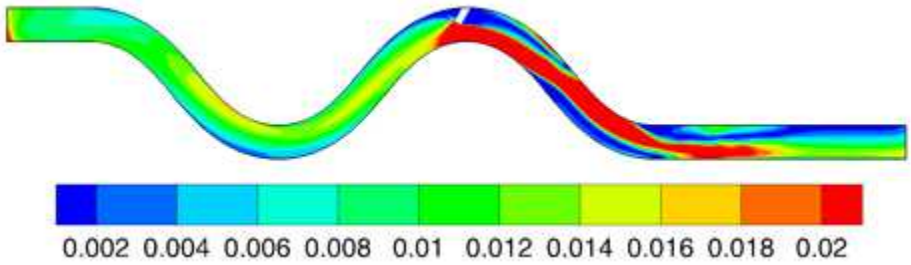
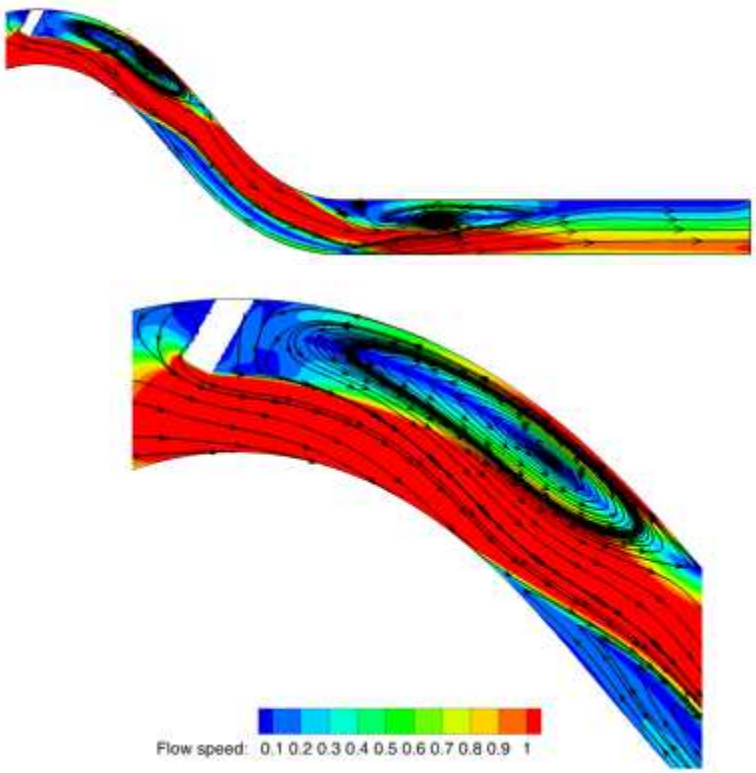
case16 (top/R=25/ =50/α=-30/l=2.5/h=1)
Flow speed

Turbulent kinetic energy (TKE)

Recirculation
 Normalized recirculation length : 2.1561

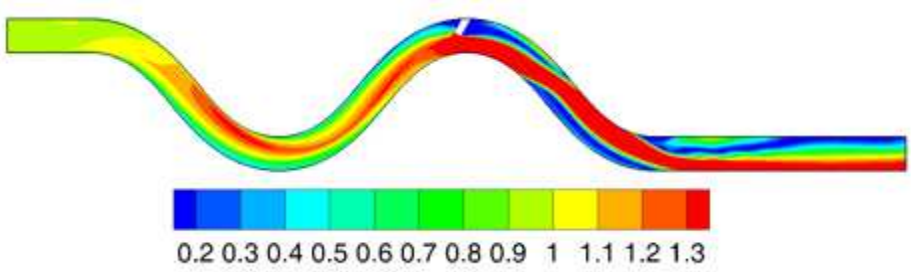
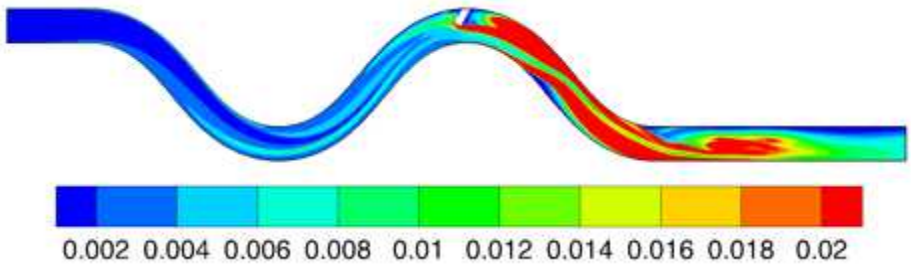
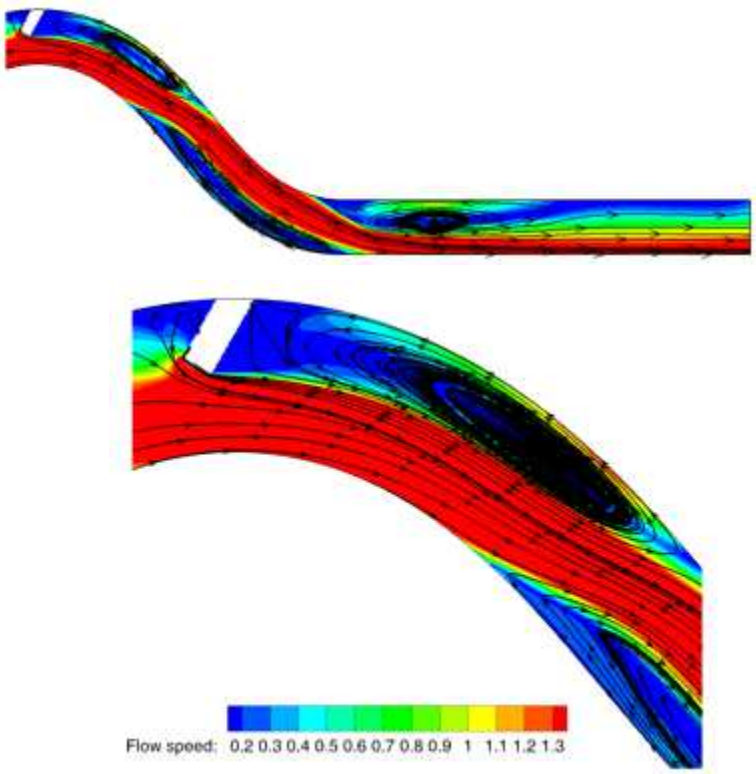
위치	case16 (R=25/ =50/α=-30/l=2.5/h=1)	
	secondary flow	
		
A		
B		
C		
D		
F		
G		
H		
I		

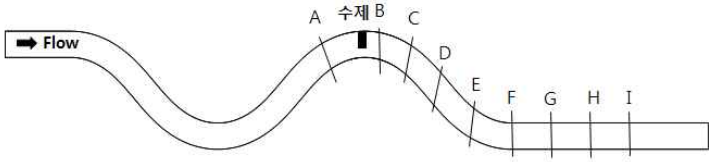
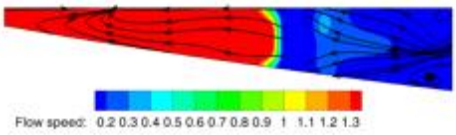
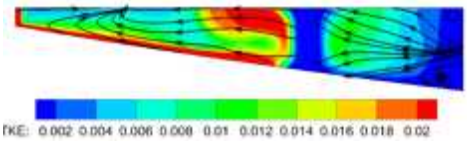
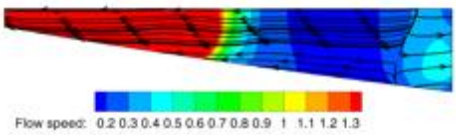
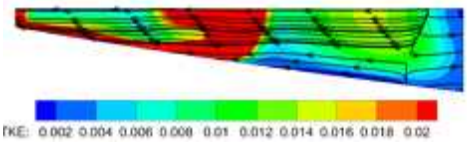
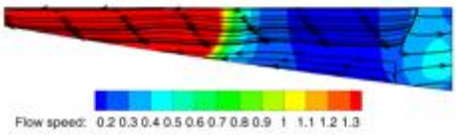
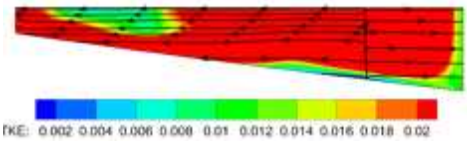
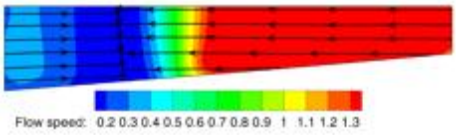
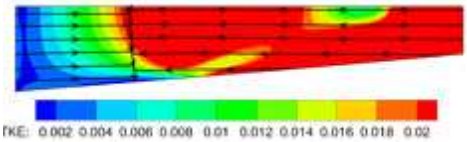
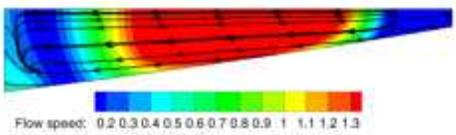
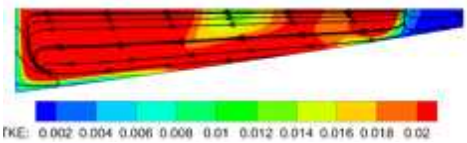
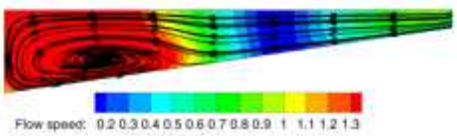
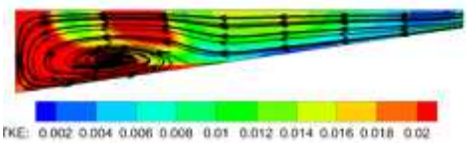
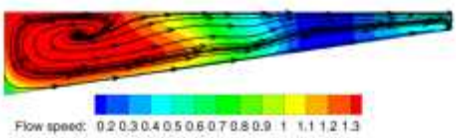
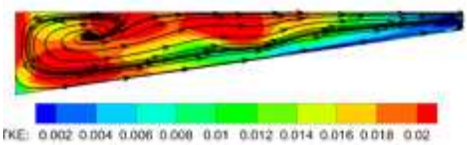
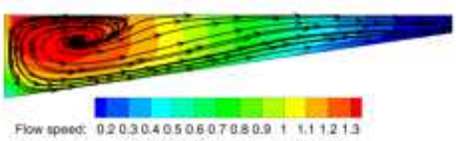
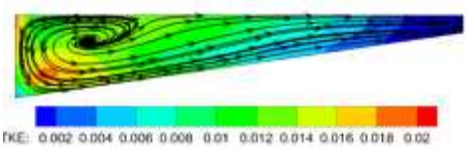
case18 (bottom/R=25/ =50/α=-30/l=5/h=0.5)
Flow speed

Turbulent kinetic energy (TKE)

Recirculation
 Normalized recirculation length : 0.6348

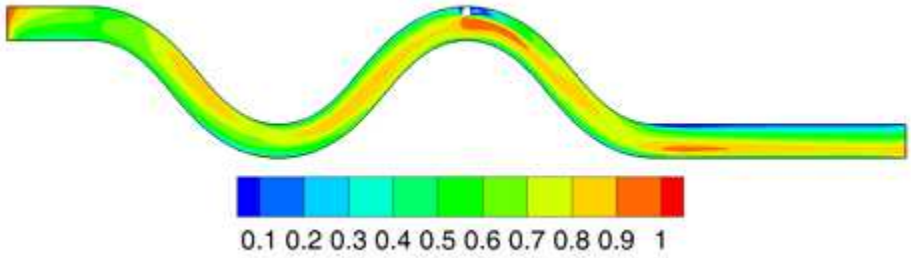
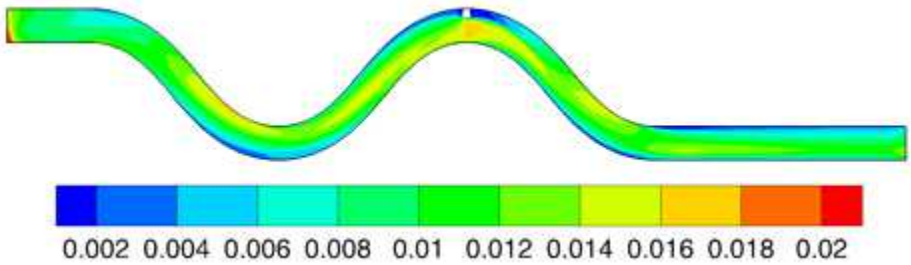
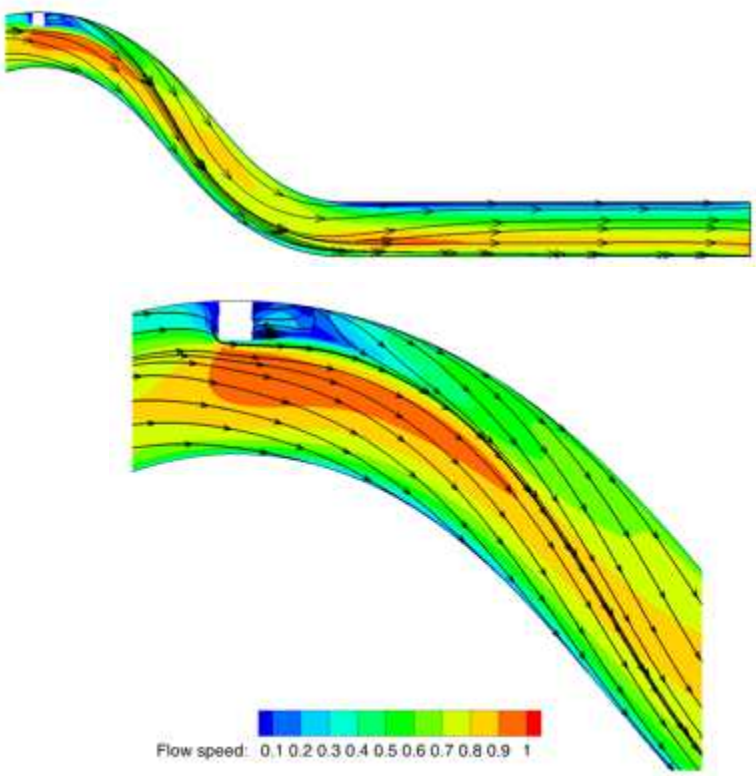
case18 (top/R=25/ =50/α=-30/l=5/h=0.5)
Flow speed

Turbulent kinetic energy (TKE)

Recirculation
 recirculation (X)

위치	case18 (R=25/ =50/α=-30/l=5/h=0.5)	
	secondary flow	
		
A		
B		
C		
D		
F		
G		
H		
I		

case20 (bottom/R=25/ =50/α=-30/l=5/h=1)
Flow speed

Turbulent kinetic energy (TKE)

Recirculation
 Normalized recirculation length : 2.9267

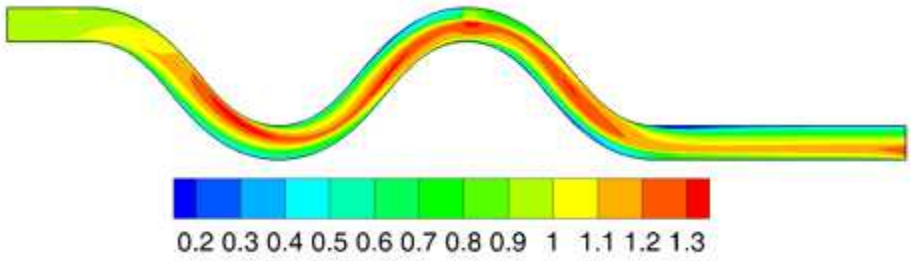
case20 (top/R=25/ =50/α=-30/l=5/h=1)
Flow speed

Turbulent kinetic energy (TKE)

Recirculation
 Normalized recirculation length : 2.8636

위치	case20 (R=25/ =50/α=-30/l=5/h=1)	
	secondary flow	
		
A		
B		
C		
D		
F		
G		
H		
I		

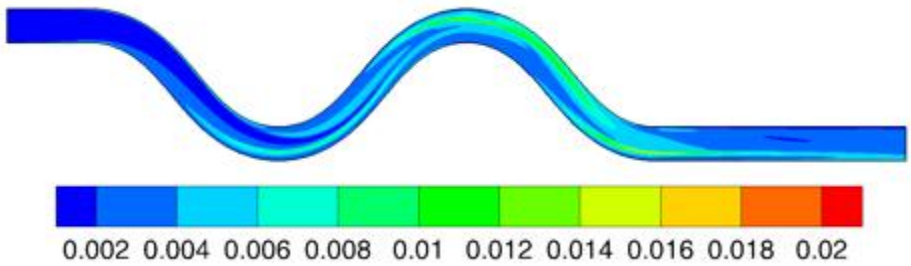
case30 (bottom/R=25/ =50/α=0/l=2.5/h=0.5)
Flow speed

Turbulent kinetic energy (TKE)

Recirculation
 Normalized recirculation length : 0.4460

case30 (top/R=25/ =50/α=0/l=2.5/h=0.5)

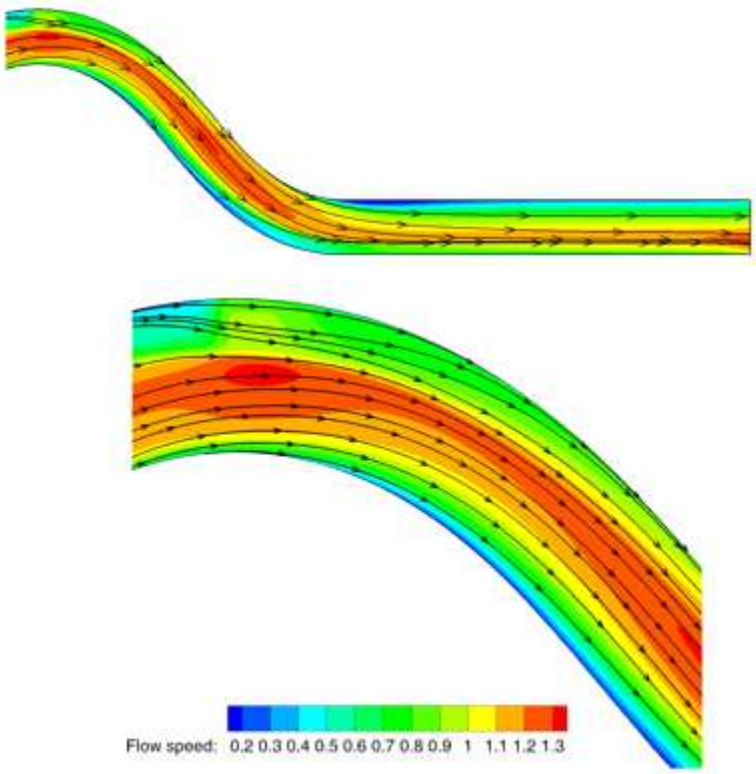
Flow speed



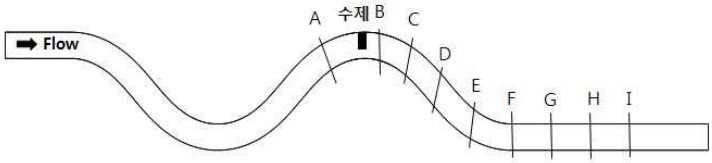
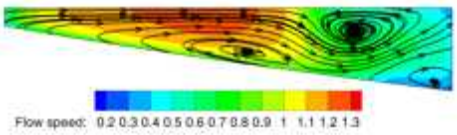
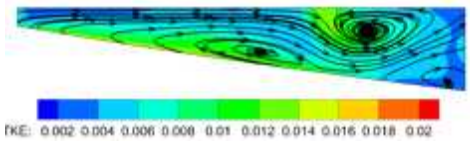
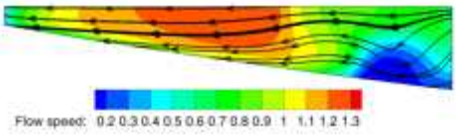
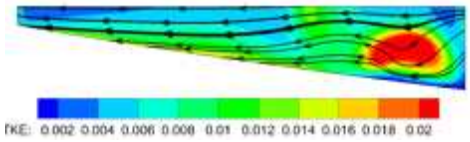
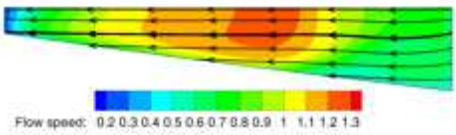
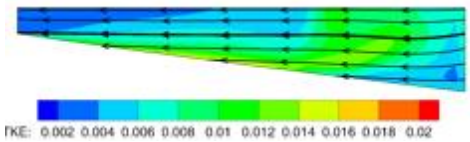
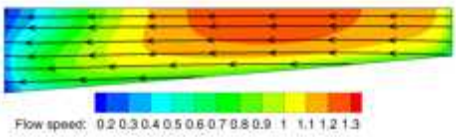
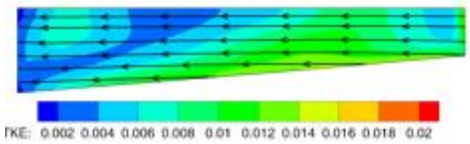
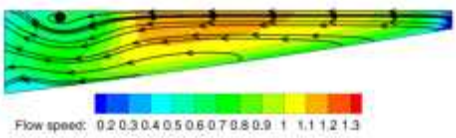
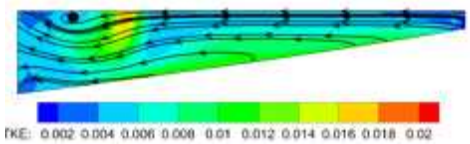
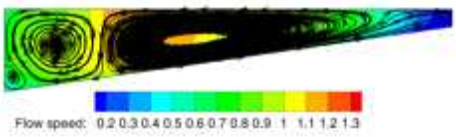
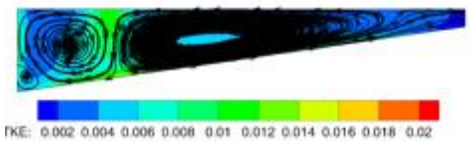
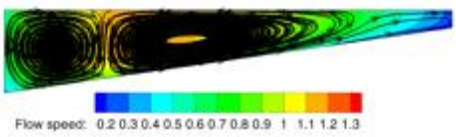
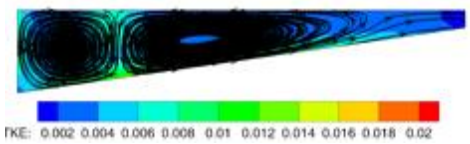
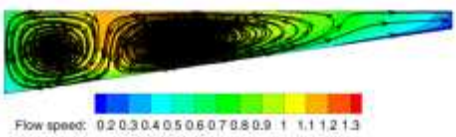
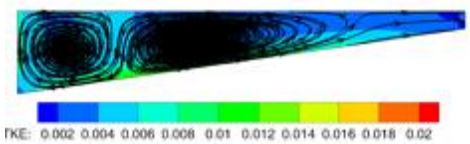
Turbulent kinetic energy (TKE)

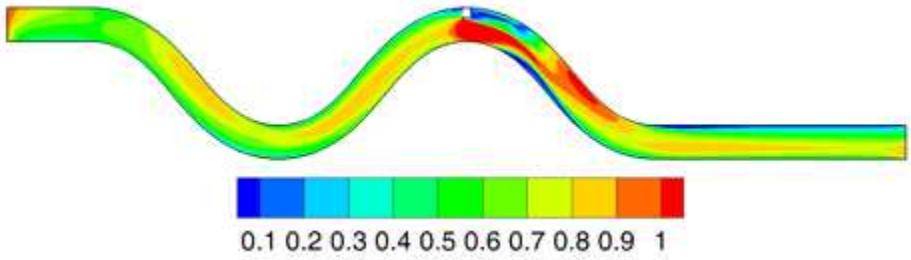
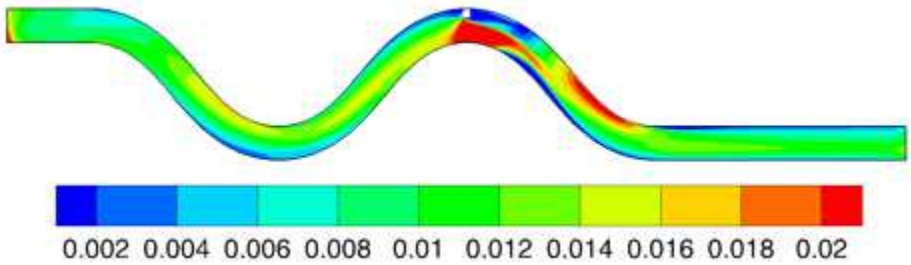
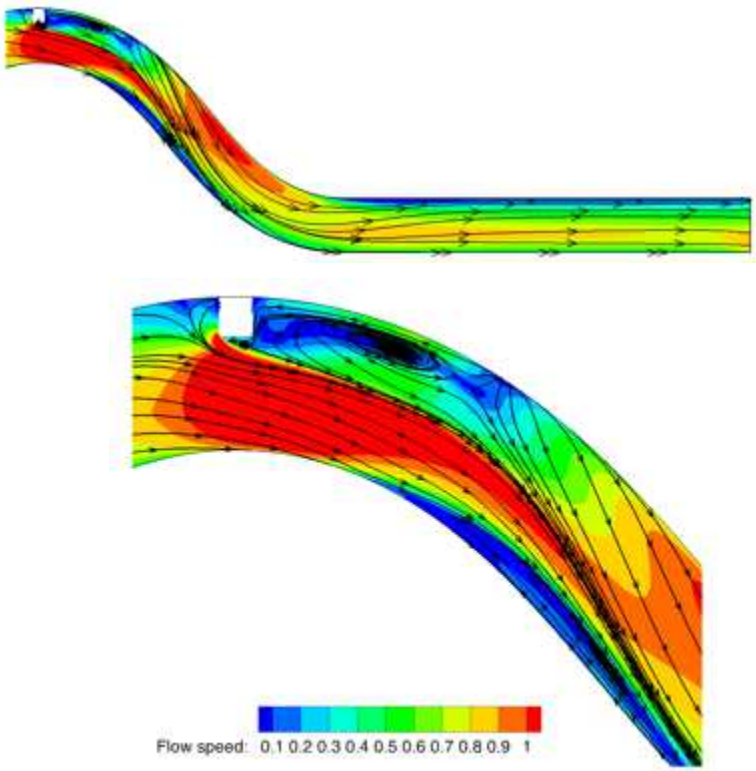


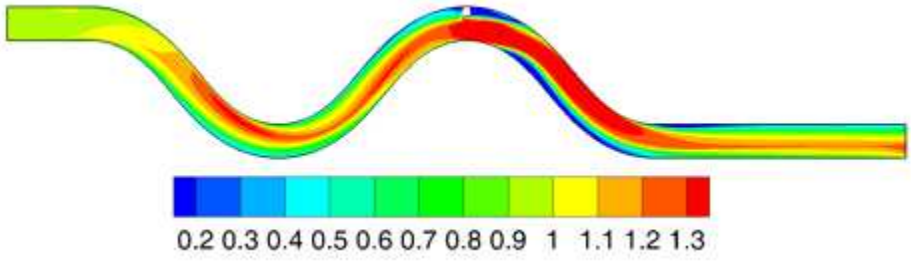
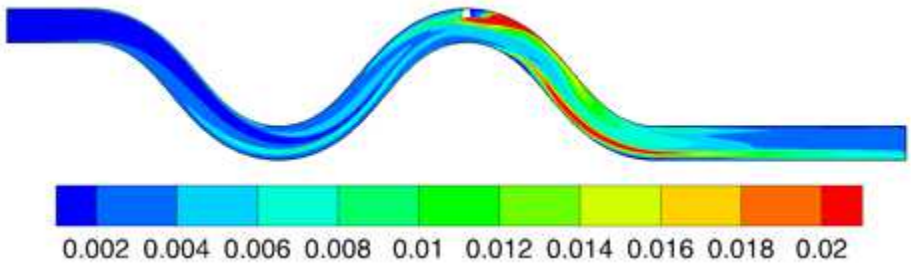
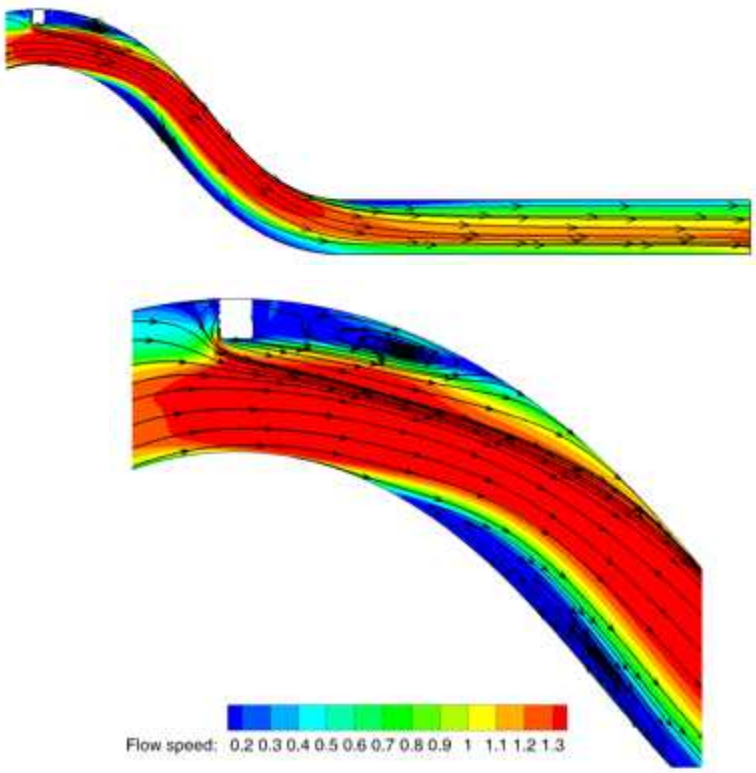
Recirculation

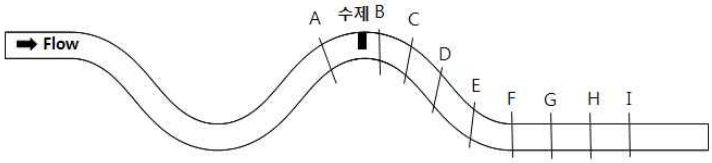
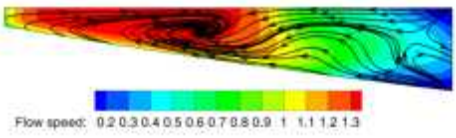
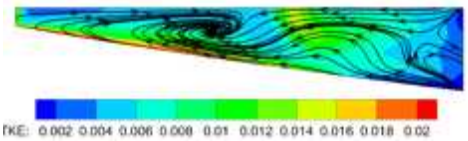
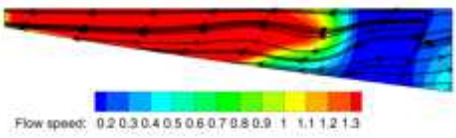
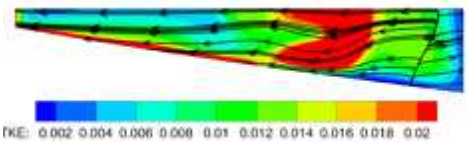
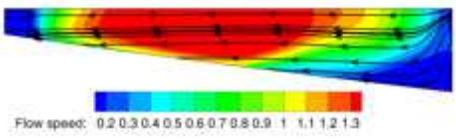
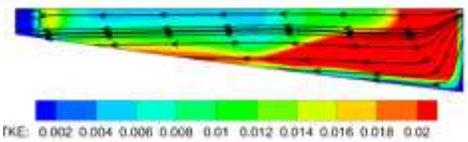
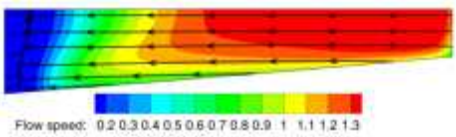
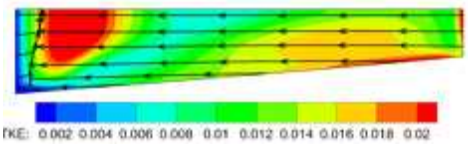
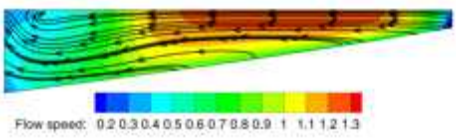
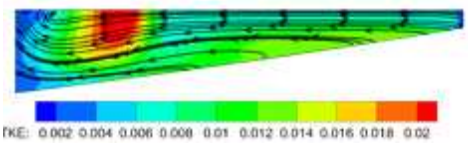
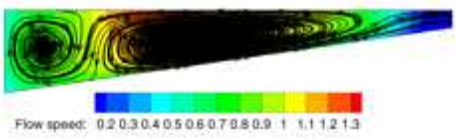
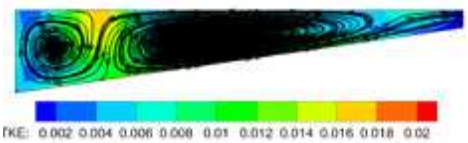
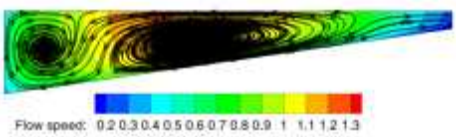
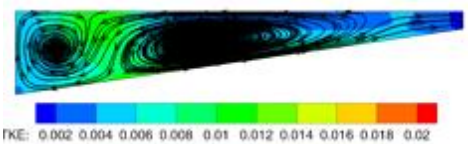
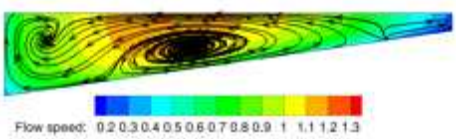
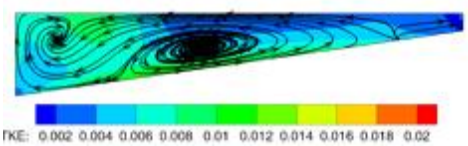


recirculation (X)

위치	case30 (R=25/ =50/α=0/l=2.5/h=0.5)	
	secondary flow	
		
A		
B		
C		
D		
F		
G		
H		
I		

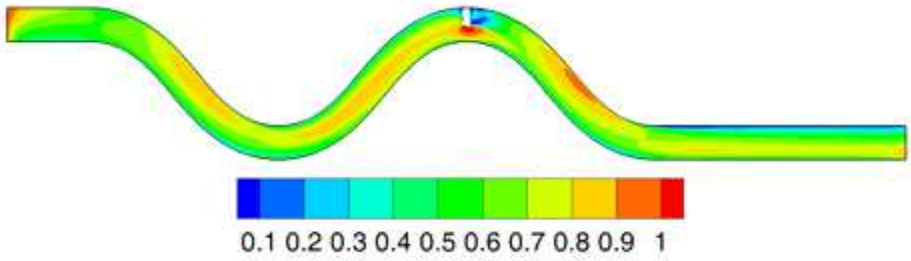
case32 (bottom/R=25/ =50/α=0/l=2.5/h=1)
Flow speed

Turbulent kinetic energy (TKE)

Recirculation
 Normalized recirculation length : 1.5997

case32 (top/R=25/ =50/α=0/l=2.5/h=1)
Flow speed

Turbulent kinetic energy (TKE)

Recirculation
 Normalized recirculation length : 1.4689

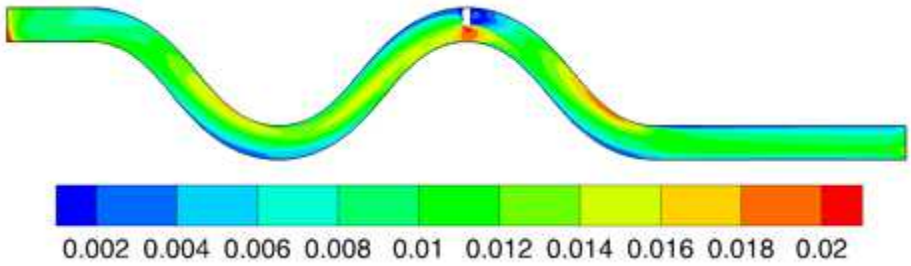
위치	case32 (R=25/ =50/α=0/l=2.5/h=1)	
	secondary flow	
		
A		
B		
C		
D		
F		
G		
H		
I		

case34 (bottom/R=25/ =50/α=0/l=5/h=0.5)

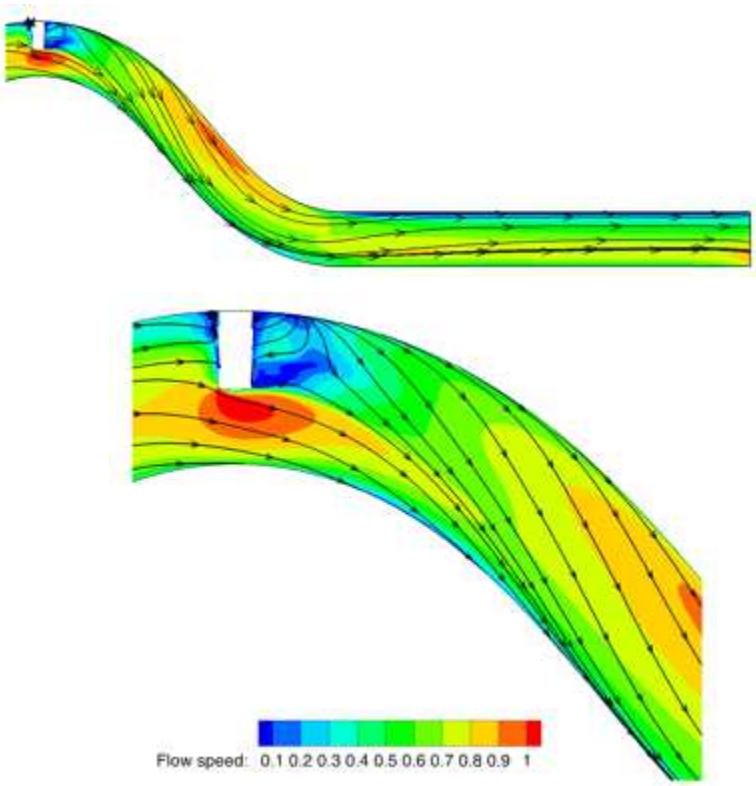
Flow speed



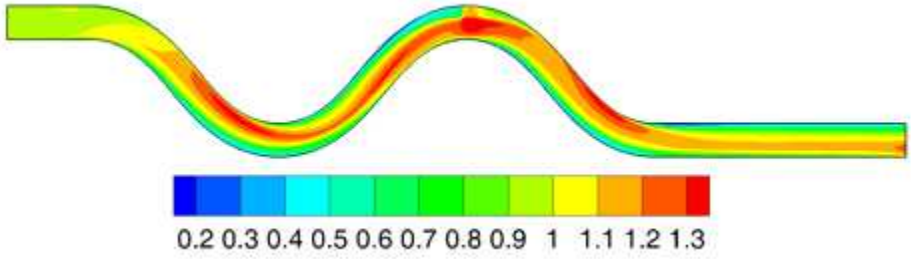
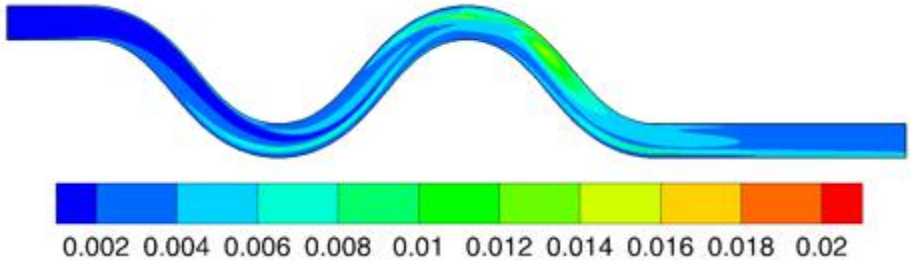
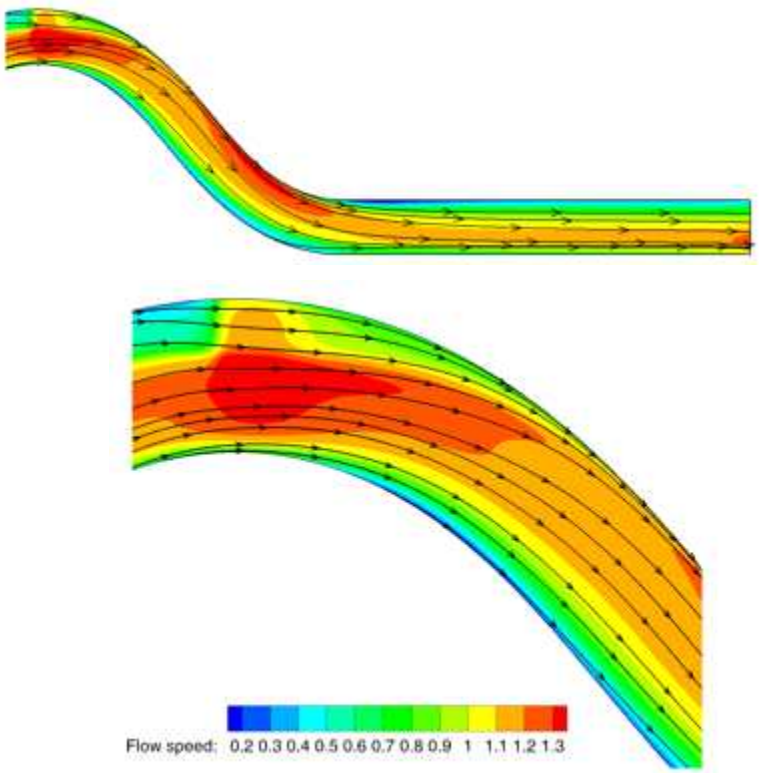
Turbulent kinetic energy (TKE)

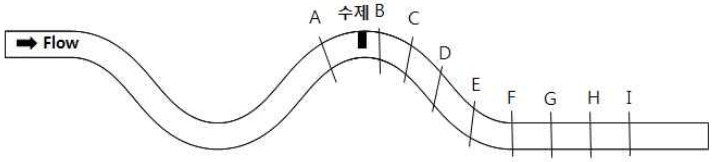
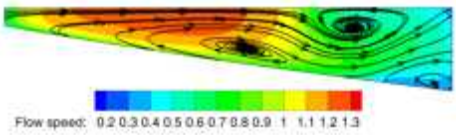
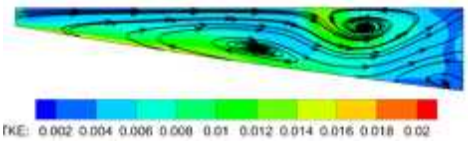
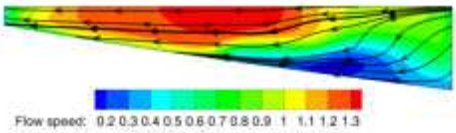
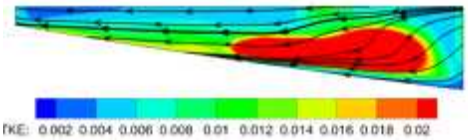
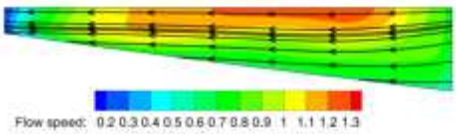
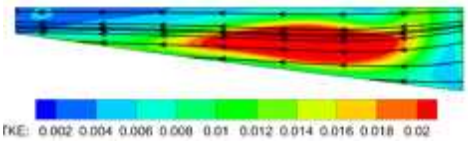
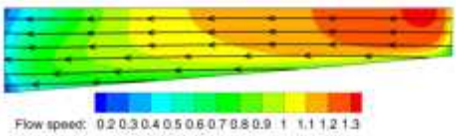
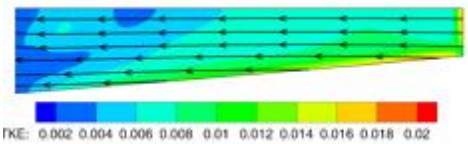
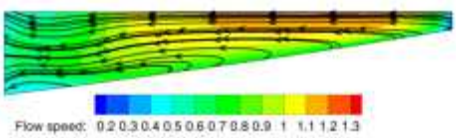
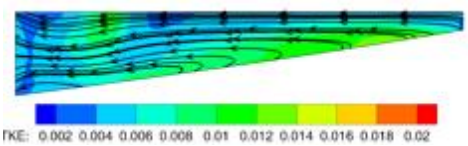
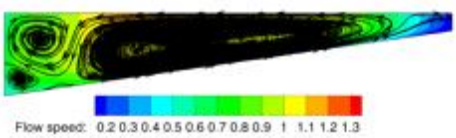
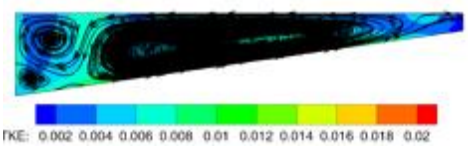
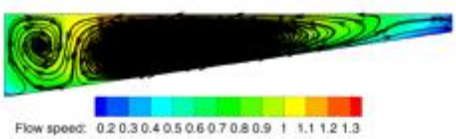
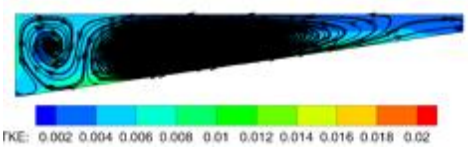
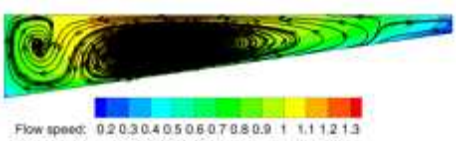
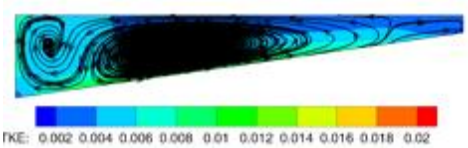


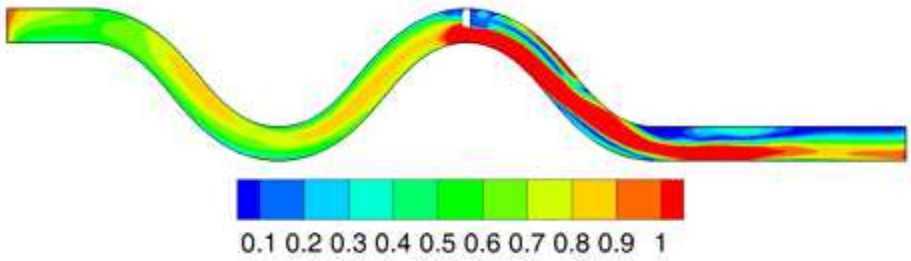
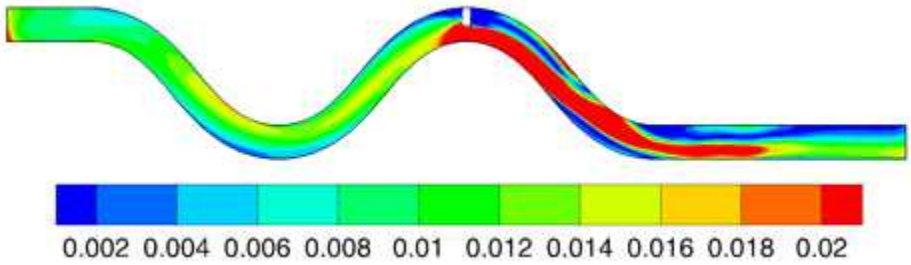
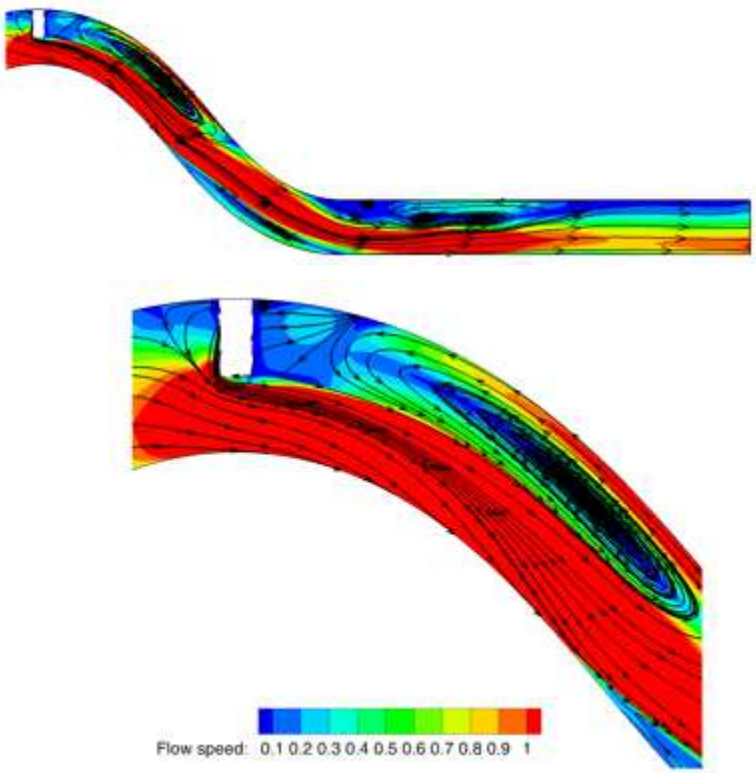
Recirculation

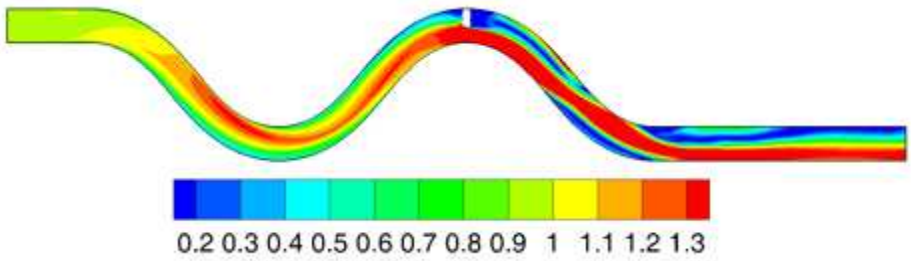
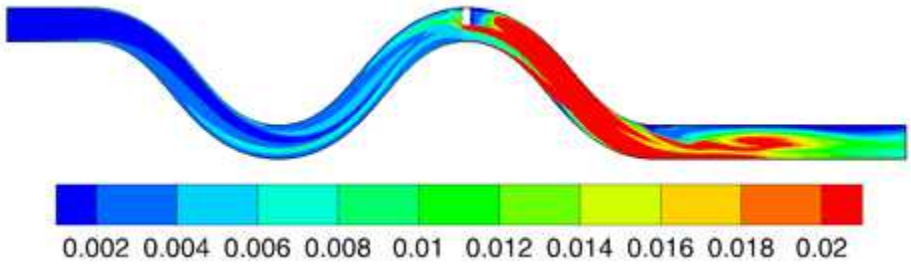
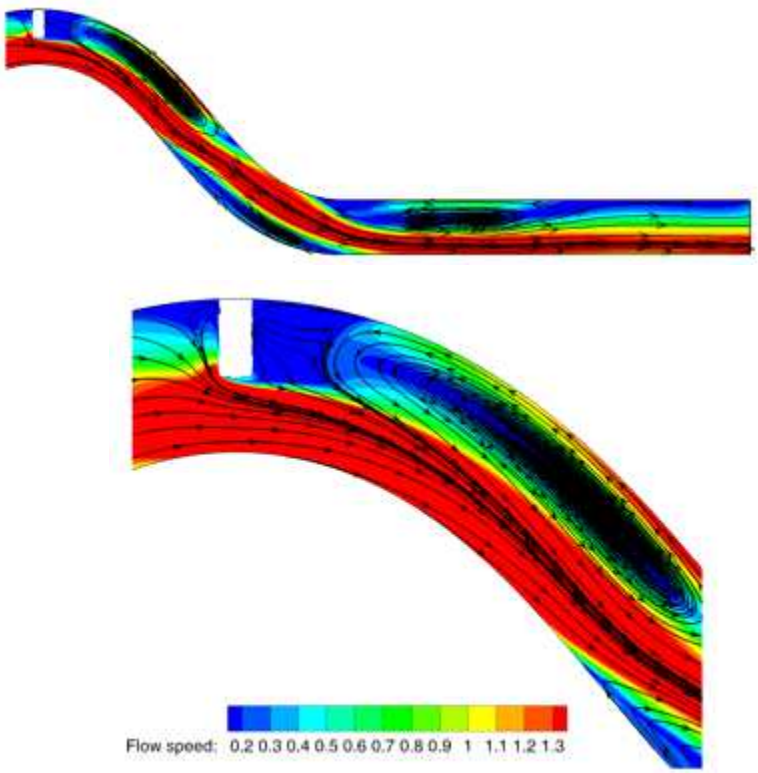


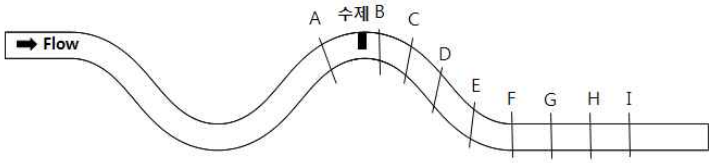
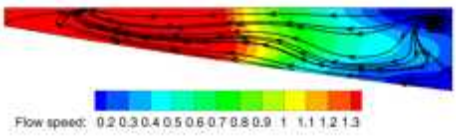
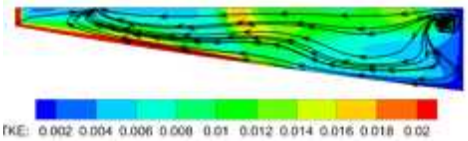
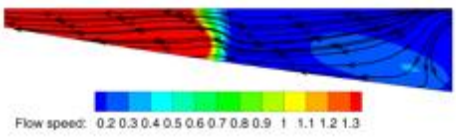
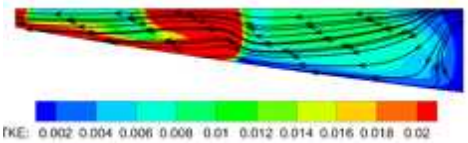
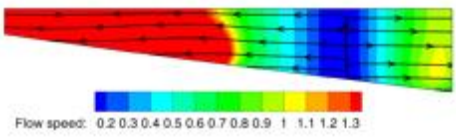
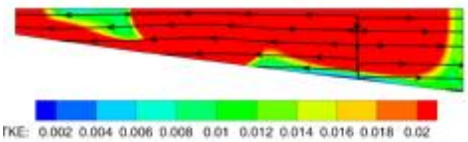
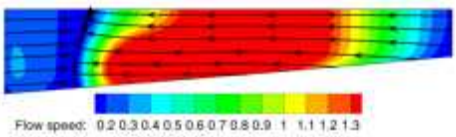
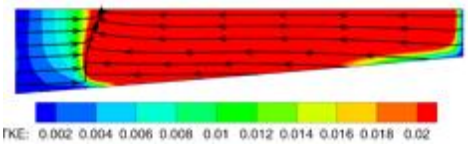
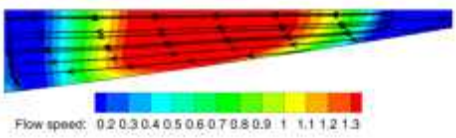
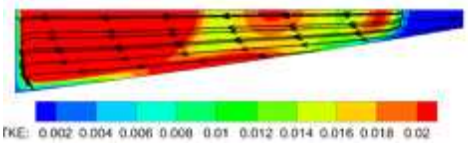
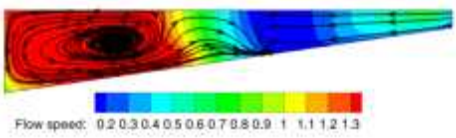
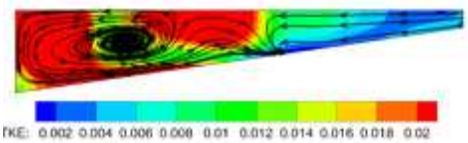
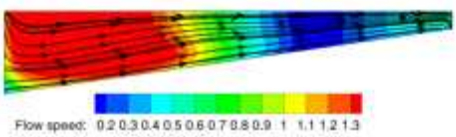
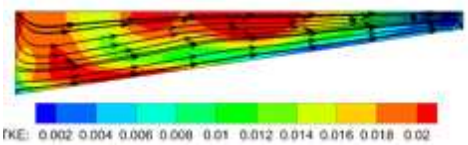
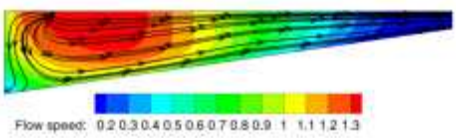
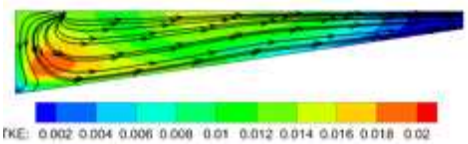
Normalized recirculation length : 0.4048

case34 (top/R=25/ =50/α=0/l=5/h=0.5)
Flow speed

Turbulent kinetic energy (TKE)

Recirculation
 recirculation (X)

위치	case34 (R=25/ =50/α=0/l=5/h=0.5)	
	secondary flow	
		
A		
B		
C		
D		
F		
G		
H		
I		

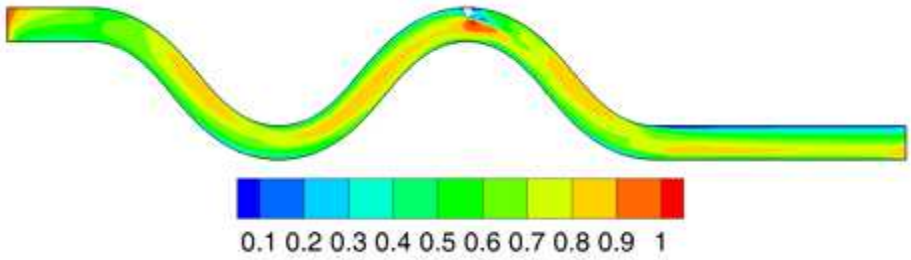
case36 (bottom/R=25/ =50/α=0/l=5/h=1)
Flow speed

Turbulent kinetic energy (TKE)

Recirculation
 Normalized recirculation length : 3.5173

case36 (top/R=25/ =50/α=0/l=5/h=1)
Flow speed

Turbulent kinetic energy (TKE)

Recirculation
 Normalized recirculation length : 3.4762

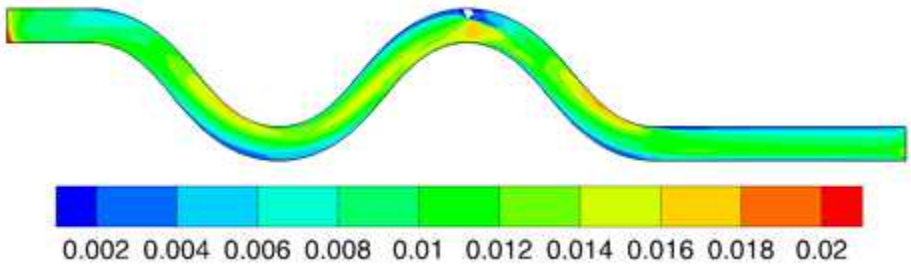
위치	case36 (R=25/ =50/α=0/l=5/h=1)	
	secondary flow	
		
A		
B		
C		
D		
F		
G		
H		
I		

case46 (bottom/R=25/ =50/α=+30/l=2.5/h=0.5)

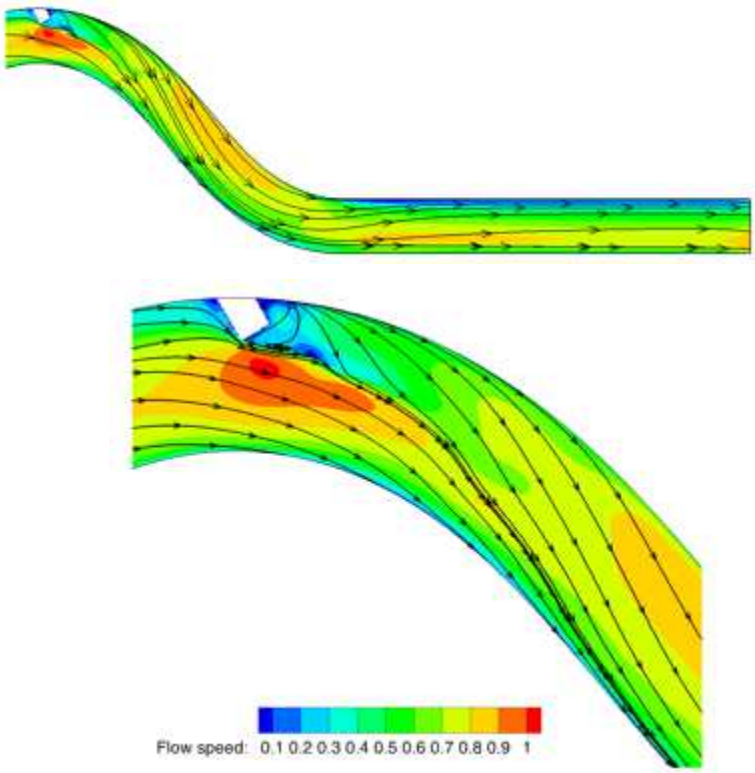
Flow speed



Turbulent kinetic energy (TKE)



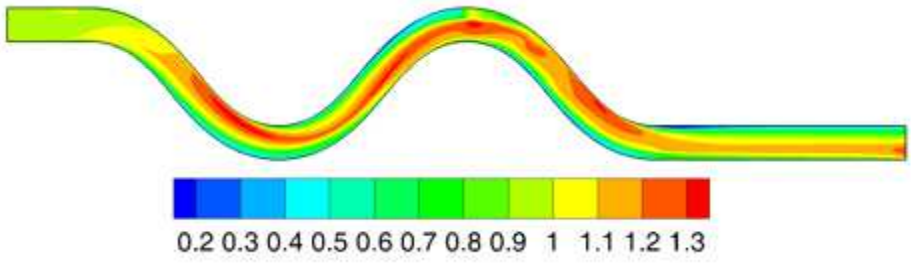
Recirculation



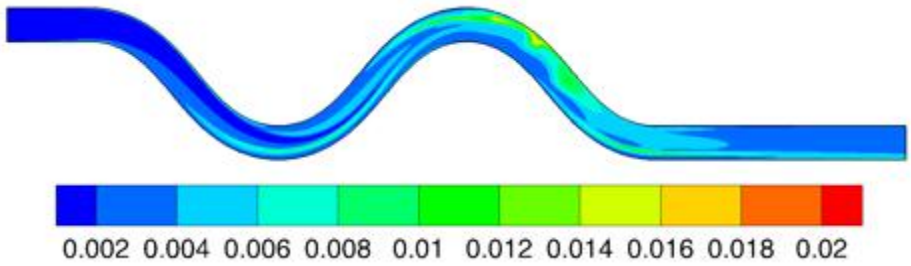
Normalized recirculation length : 0.3671

case46 (top/R=25/ =50/α=+30/l=2.5/h=0.5)

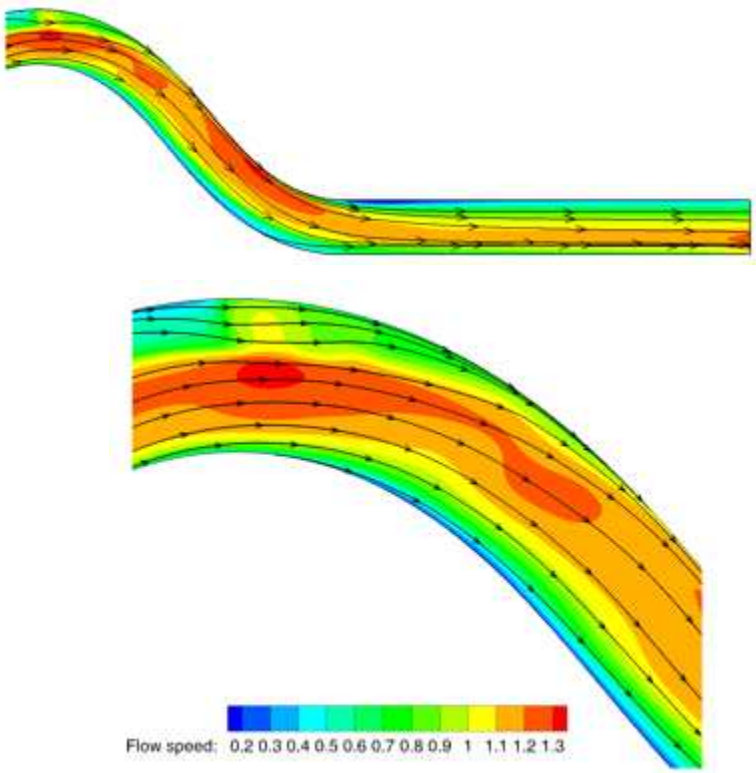
Flow speed



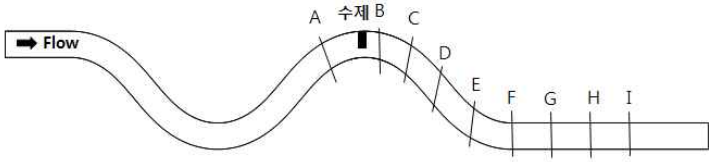
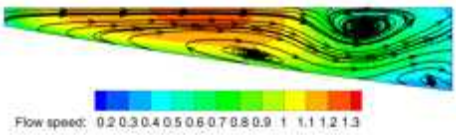
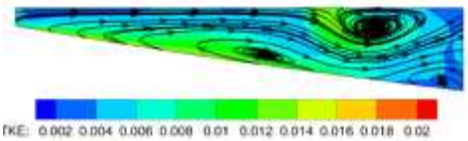
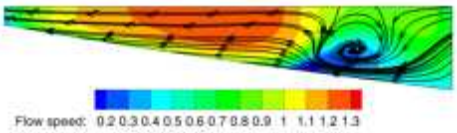
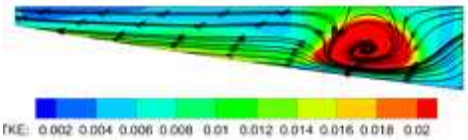
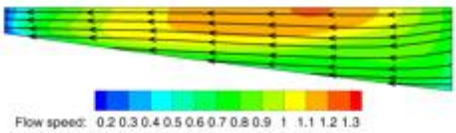
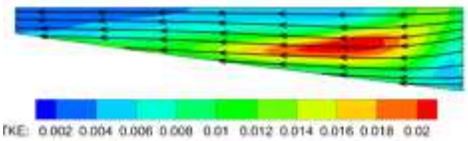
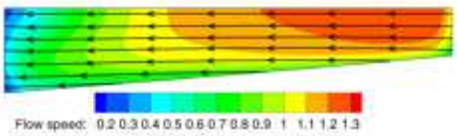
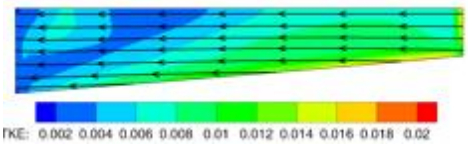
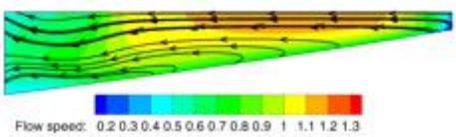
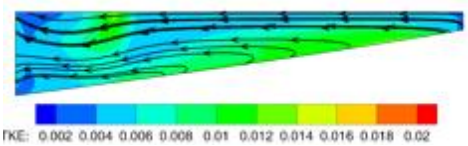
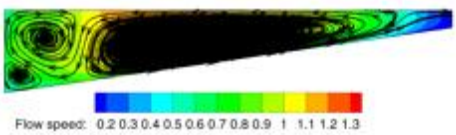
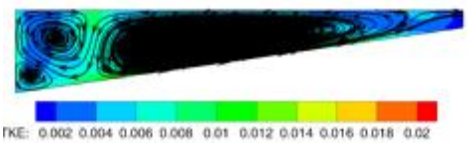
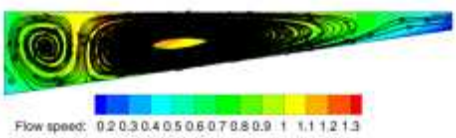
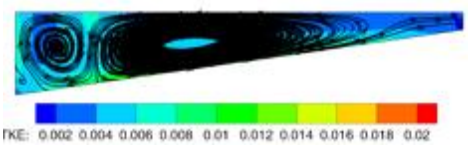
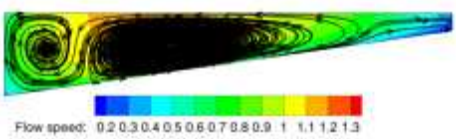
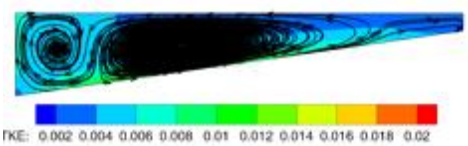
Turbulent kinetic energy (TKE)

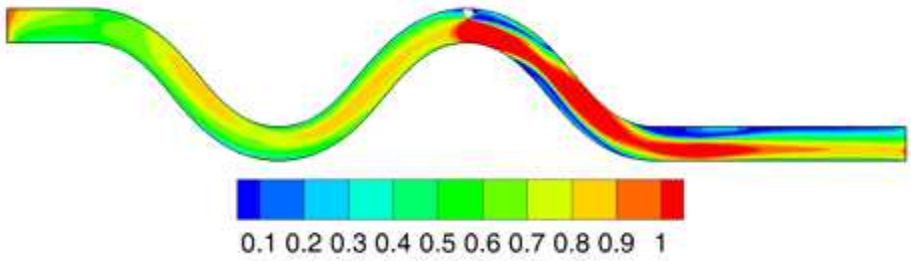
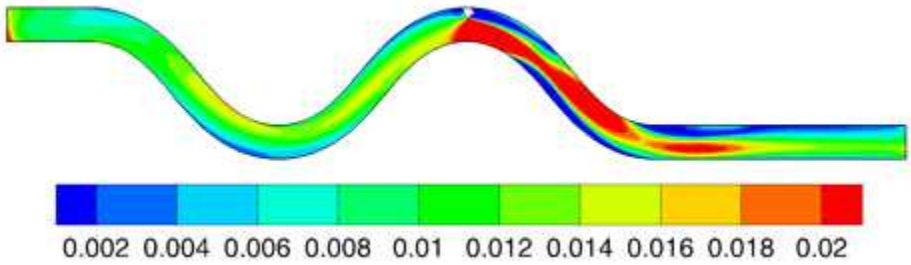
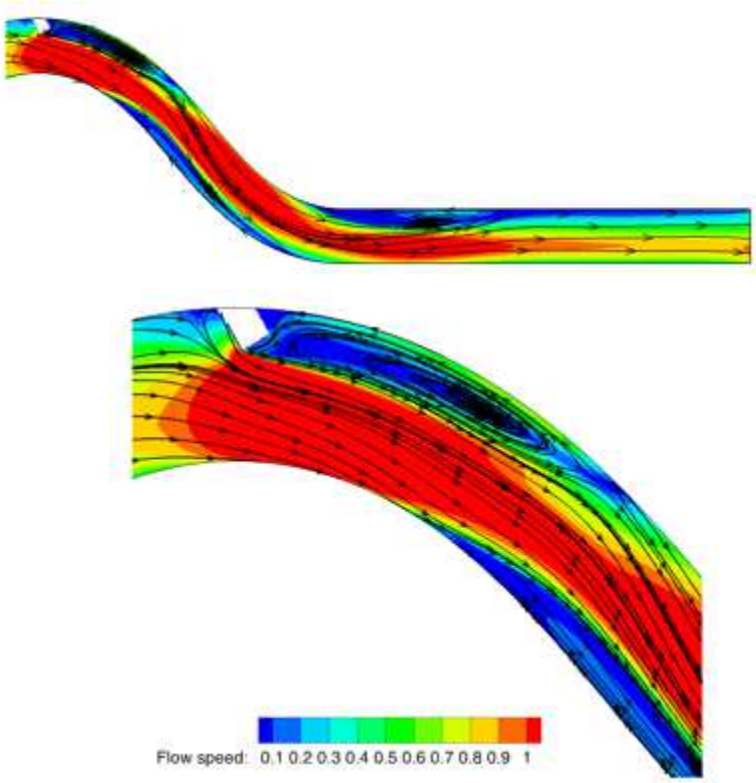


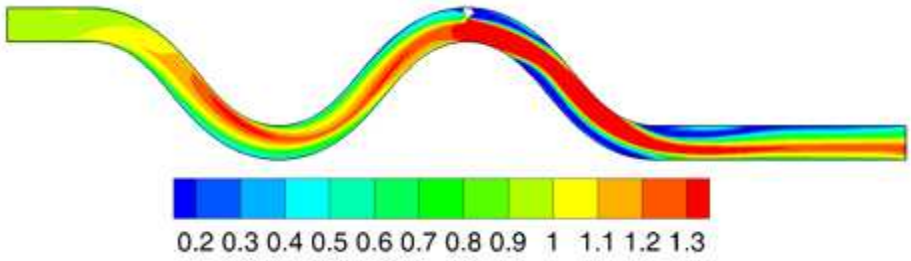
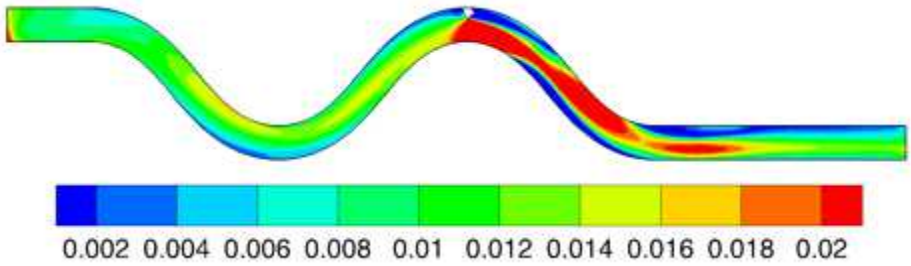
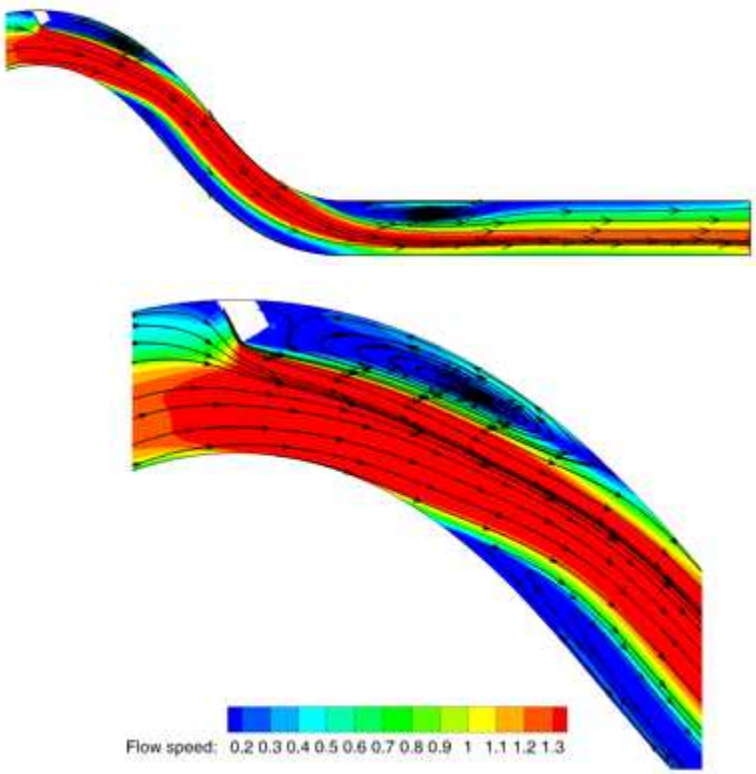
Recirculation

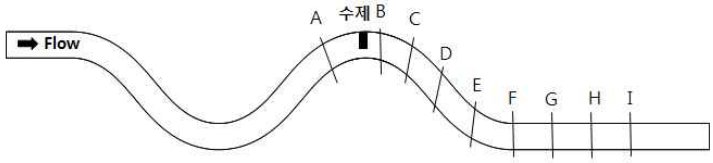
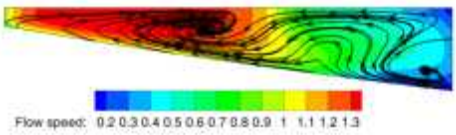
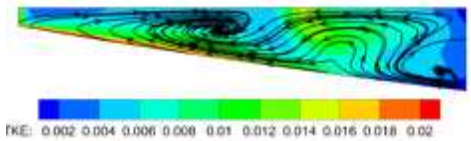
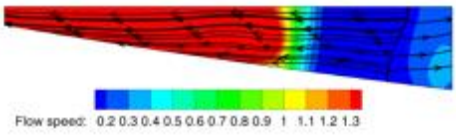
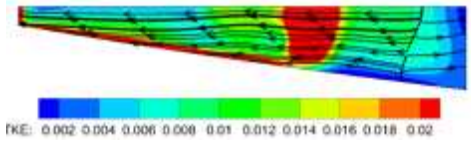
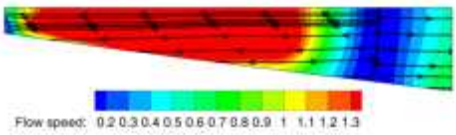
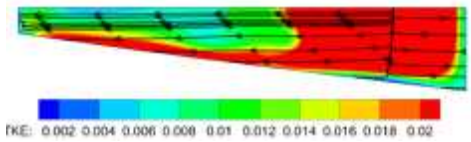
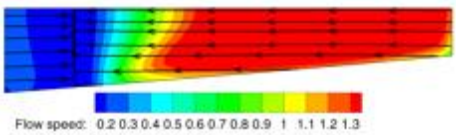
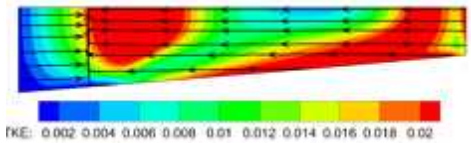
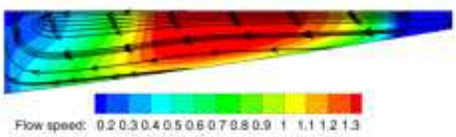
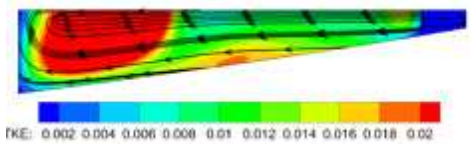
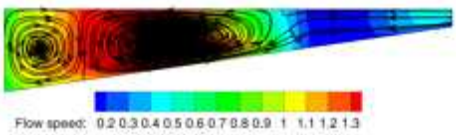
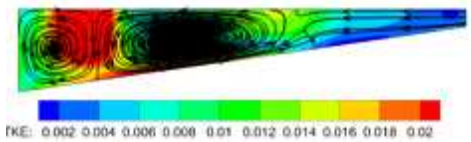
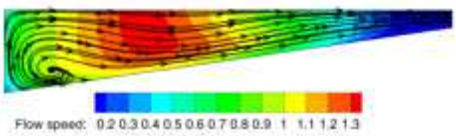
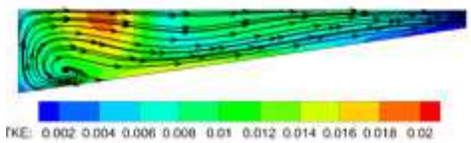
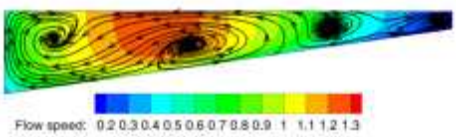
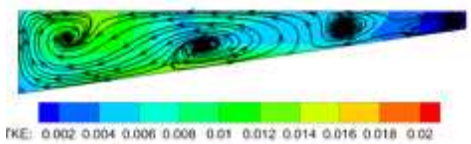


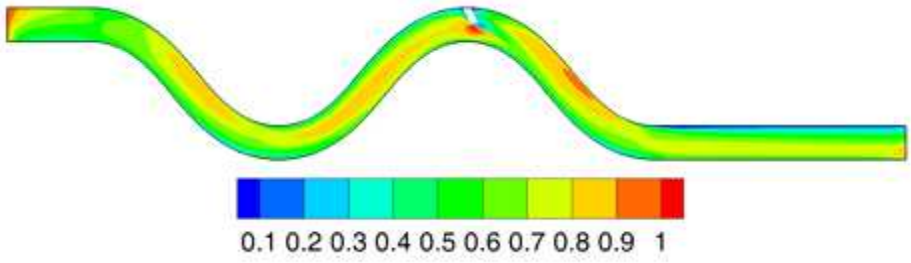
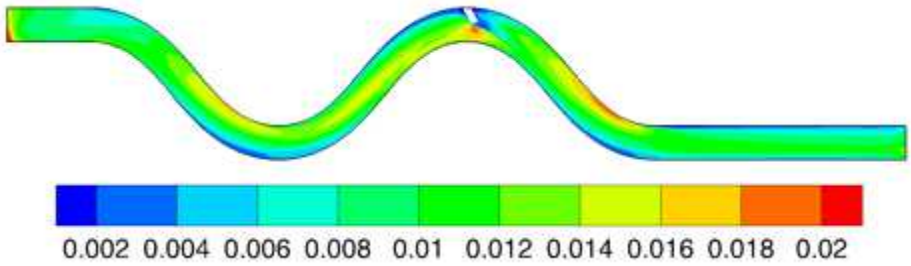
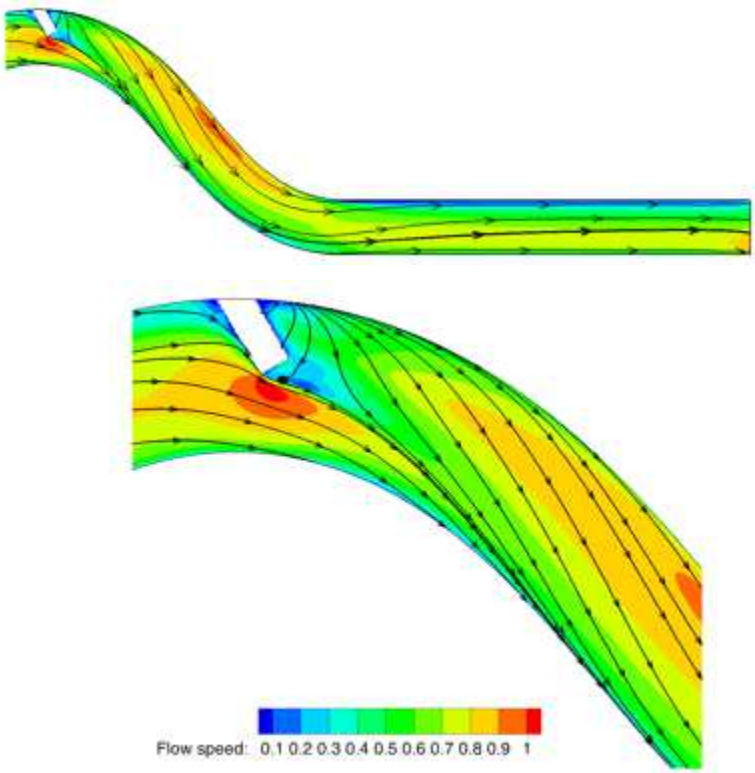
recirculation (X)

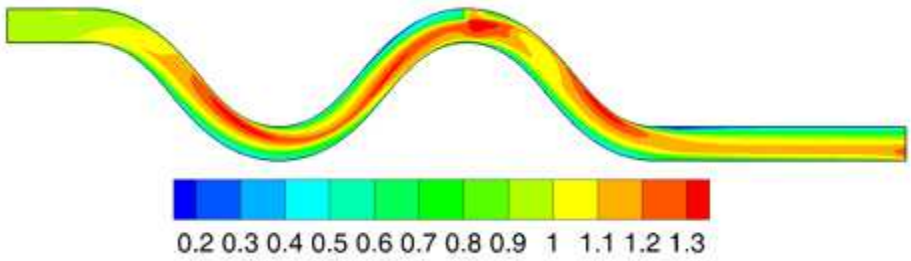
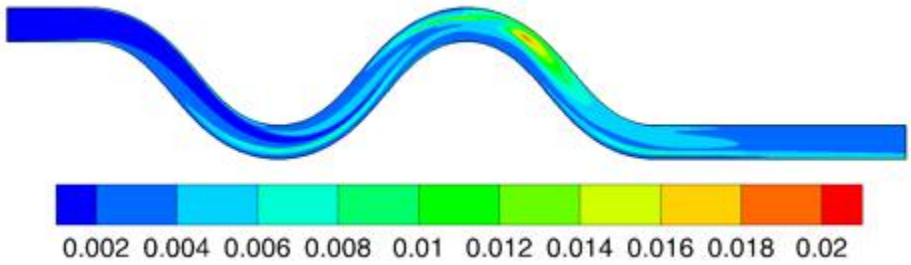
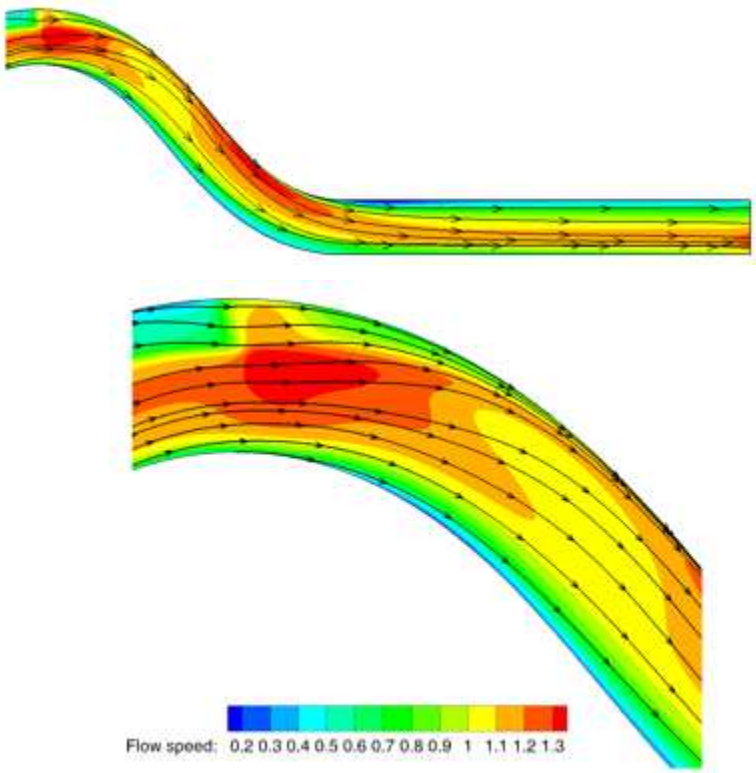
위치	case46 (R=25/ =50/α=+30/l=2.5/h=0.5)	
	secondary flow	
		
A		
B		
C		
D		
F		
G		
H		
I		

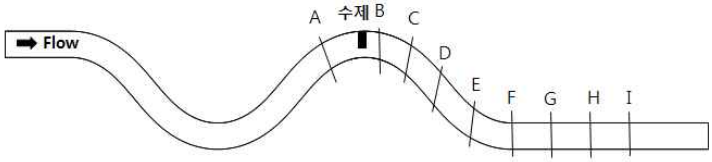
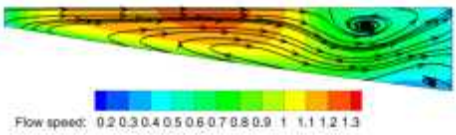
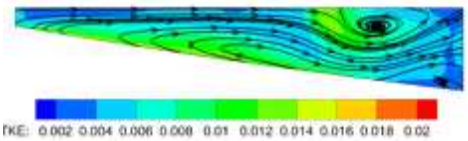
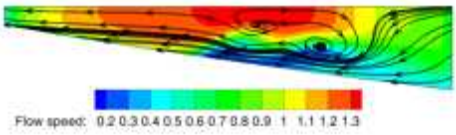
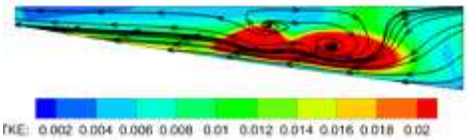
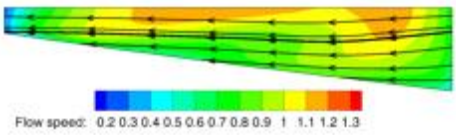
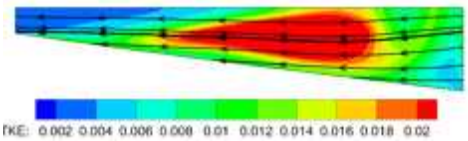
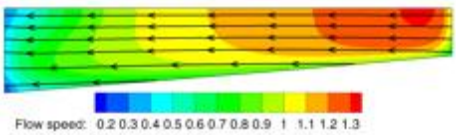
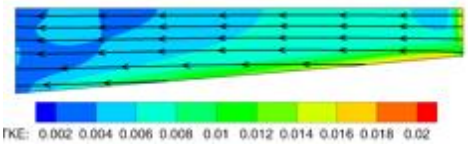
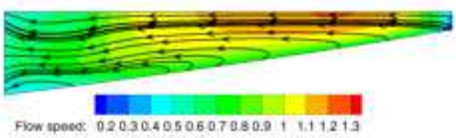
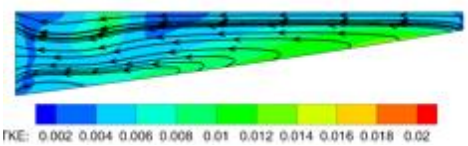
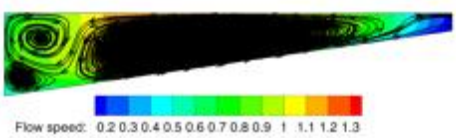
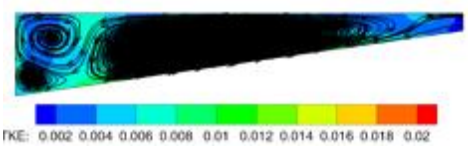
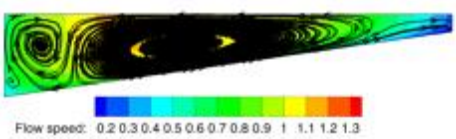
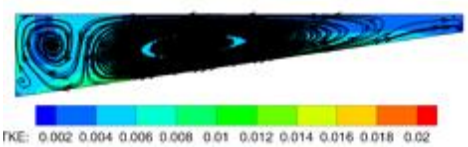
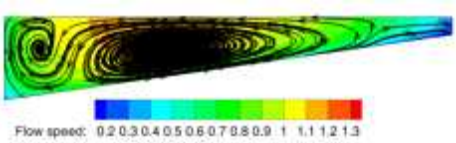
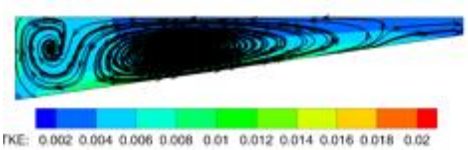
case48 (bottom/R=25/ =50/α=+30/l=2.5/h=1)
Flow speed

Turbulent kinetic energy (TKE)

Recirculation
 Normalized recirculation length : 2.3833

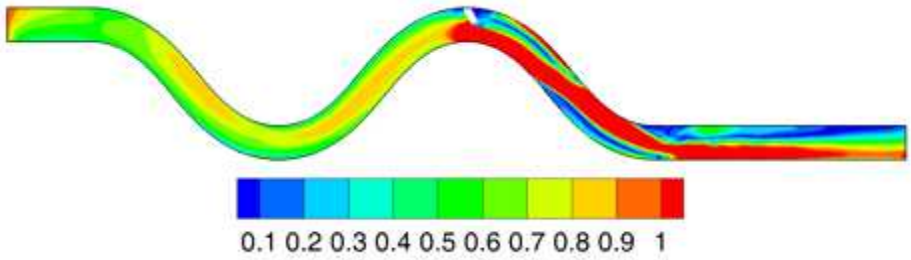
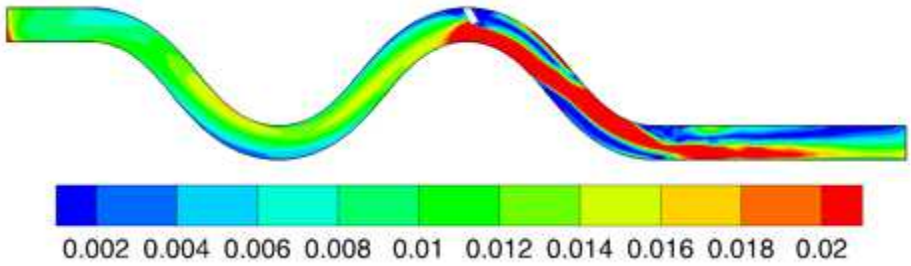
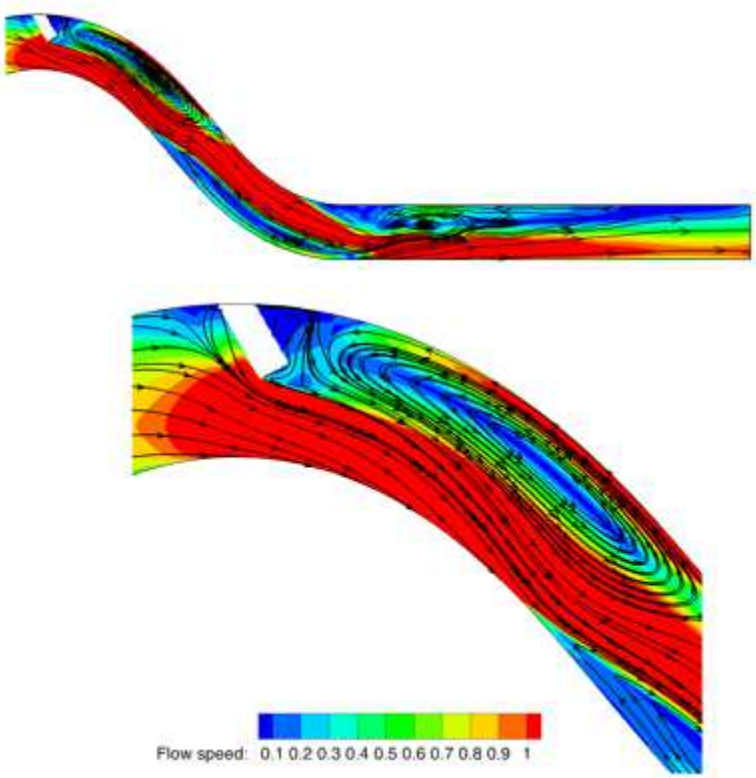
case48 (top/R=25/ =50/α=+30/l=2.5/h=1)
Flow speed

Turbulent kinetic energy (TKE)

Recirculation
 Normalized recirculation length : 2.2723

위치	case48 (R=25/ =50/α=+30/l=2.5/h=1)	
	secondary flow	
		
A		
B		
C		
D		
F		
G		
H		
I		

case50 (bottom/R=25/ =50/α=+30/l=5/h=0.5)
Flow speed

Turbulent kinetic energy (TKE)

Recirculation
 Normalized recirculation length : 0.3784

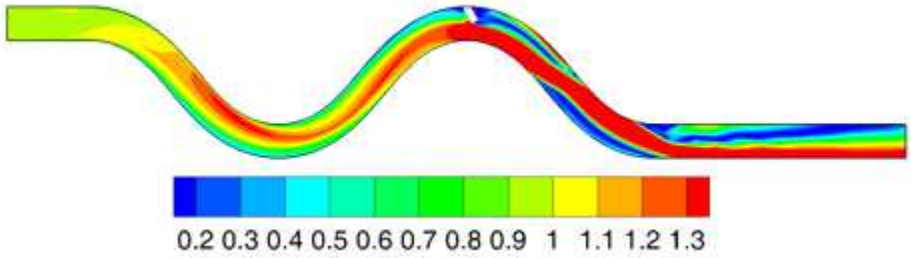
case50 (top/R=25/ =50/α=+30/l=5/h=0.5)
Flow speed

Turbulent kinetic energy (TKE)

Recirculation
 recirculation (X)

위치	case50 (R=25/ =50/α=+30/l=5/h=0.5)	
	secondary flow	
		
A		
B		
C		
D		
F		
G		
H		
I		

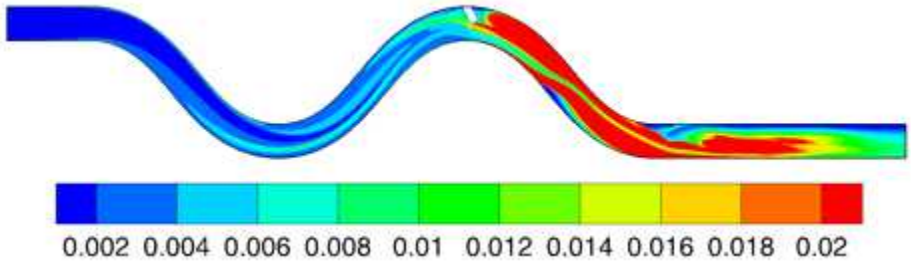
case52 (bottom/R=25/ =50/α=+30/l=5/h=1)
Flow speed

Turbulent kinetic energy (TKE)

Recirculation
 Normalized recirculation length : 3.2092

case52 (top/R=25/ =50/α=+30/l=5/h=1)

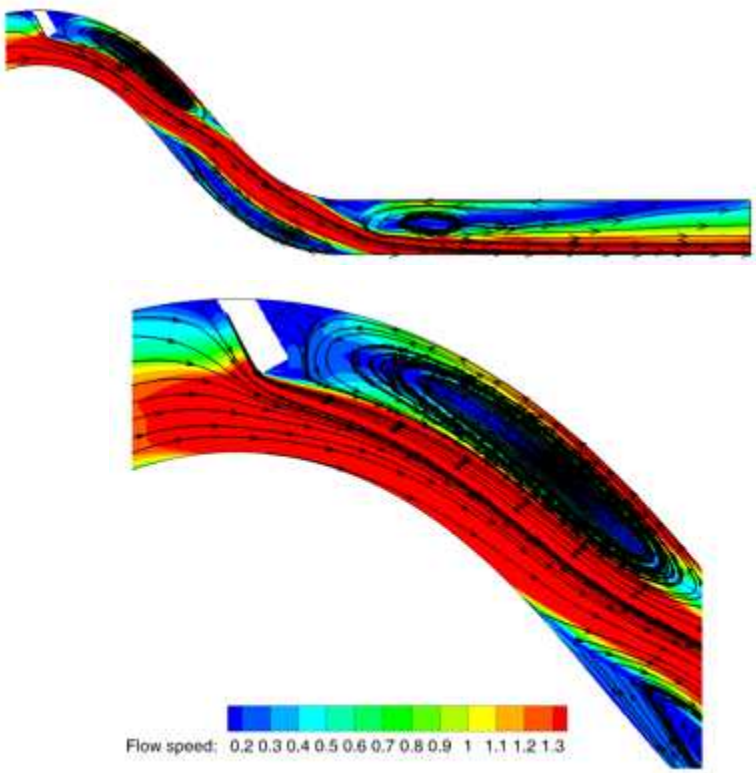
Flow speed



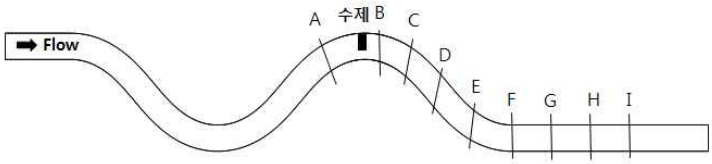
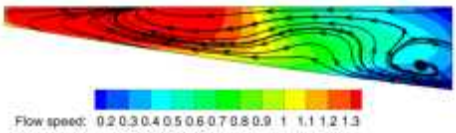
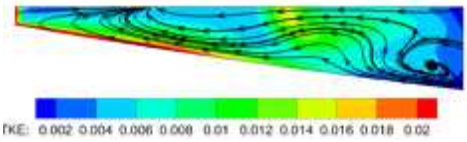
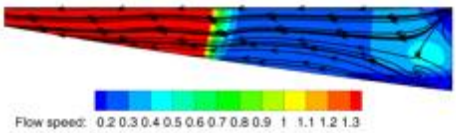
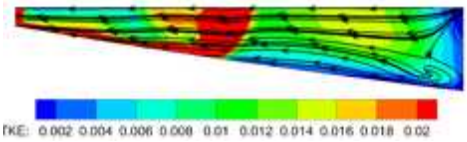
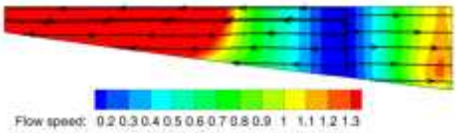
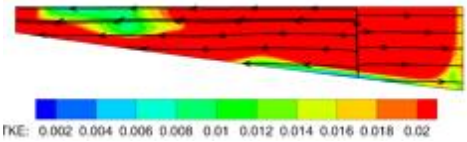
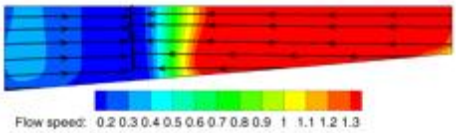
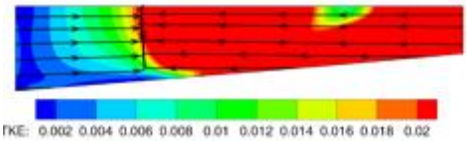
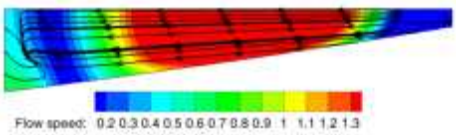
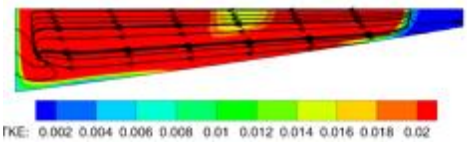
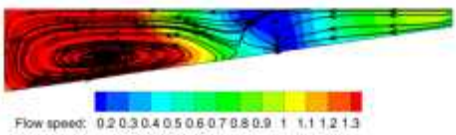
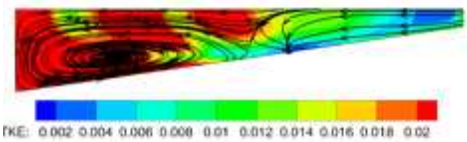
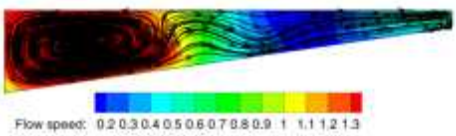
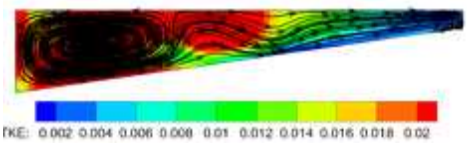
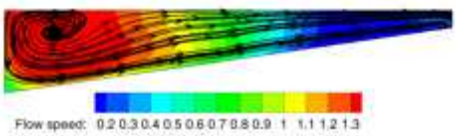
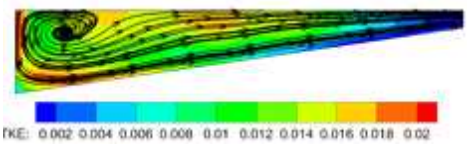
Turbulent kinetic energy (TKE)

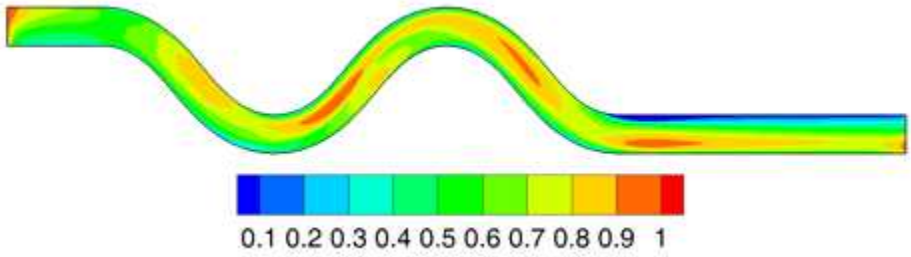
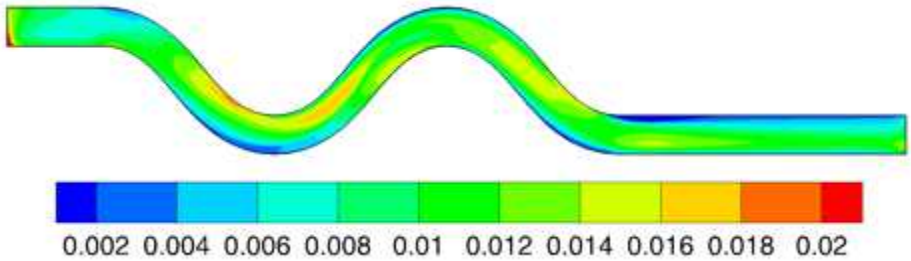
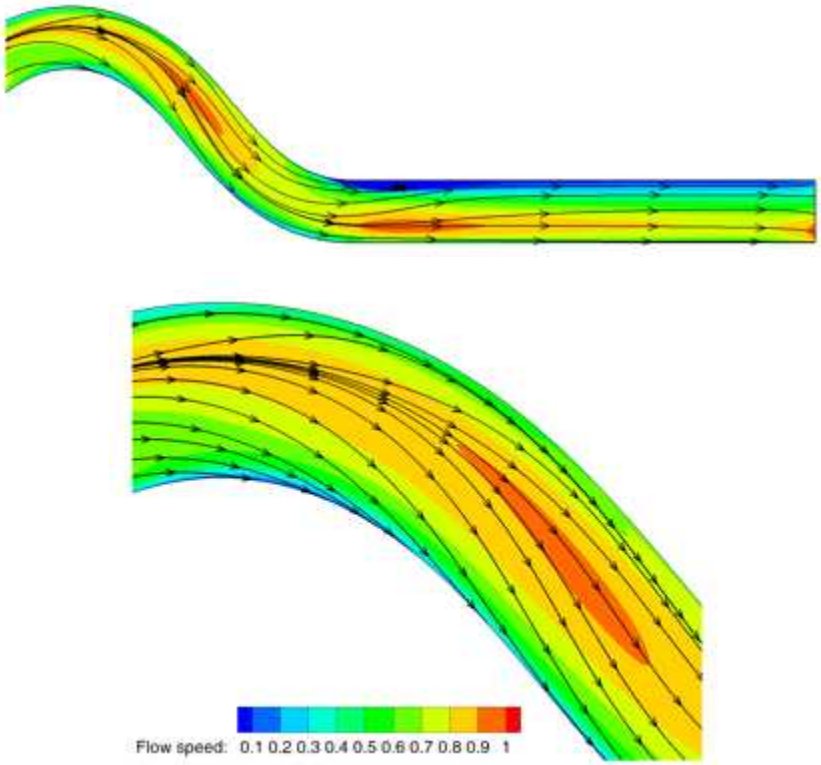


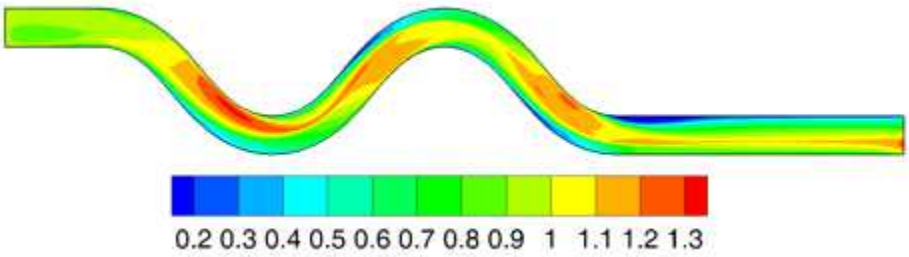
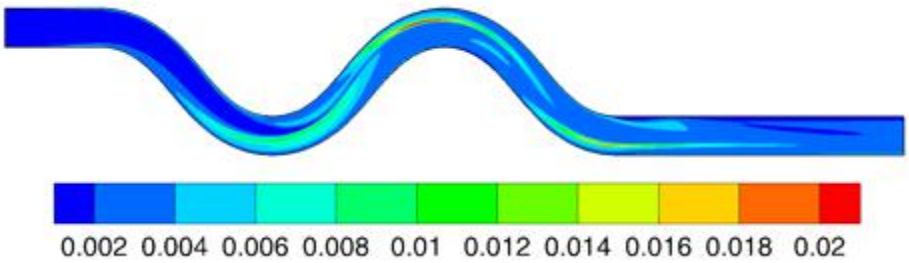
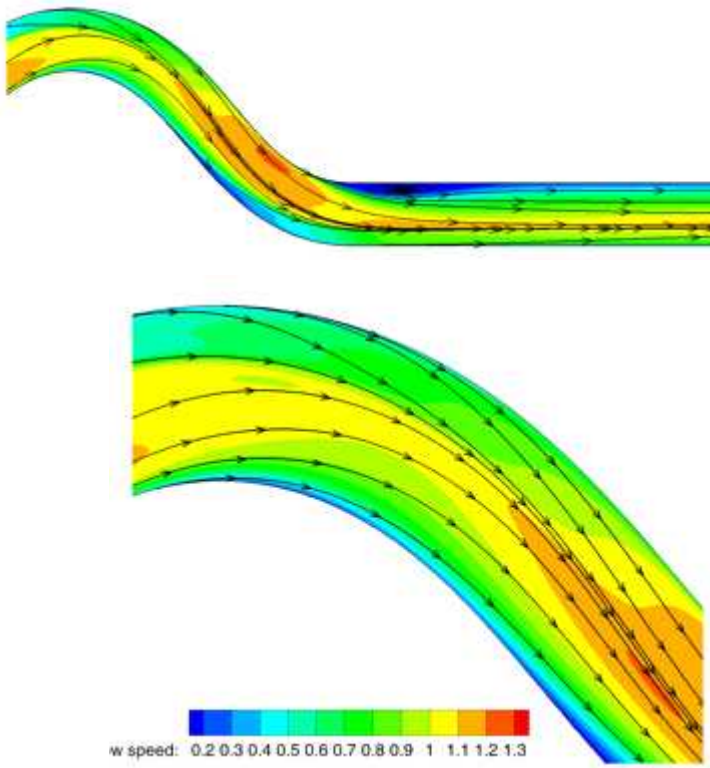
Recirculation

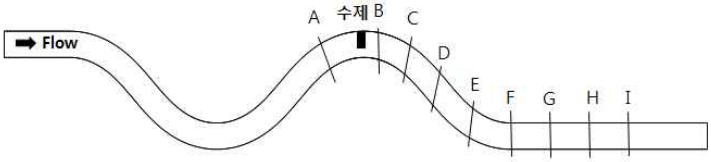
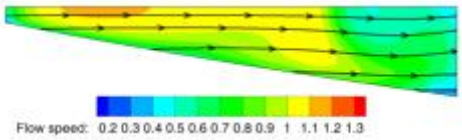
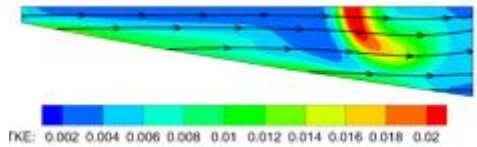
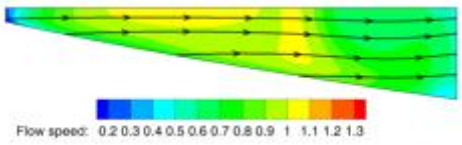
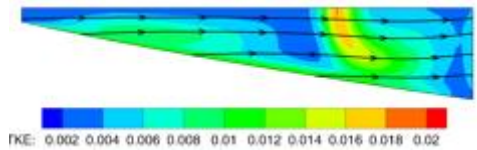
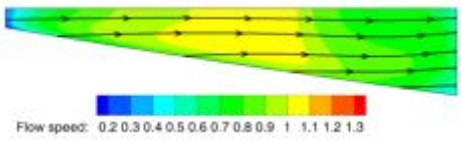
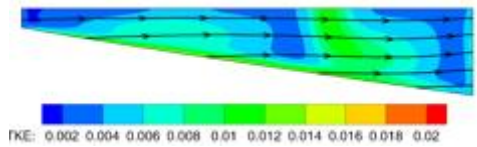
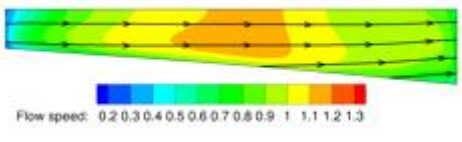
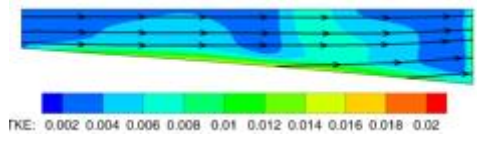
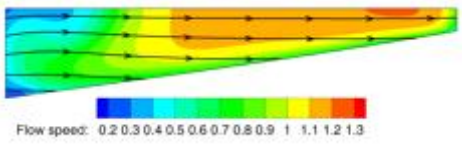
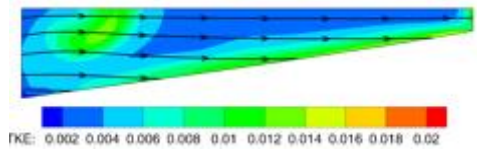
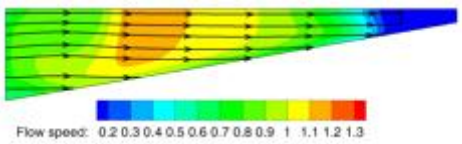
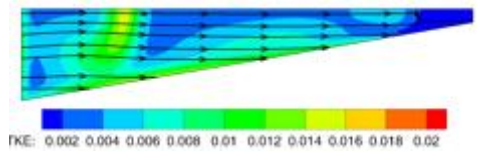
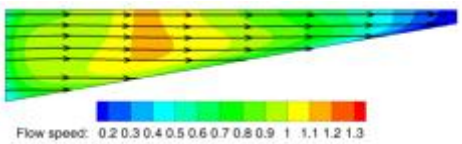
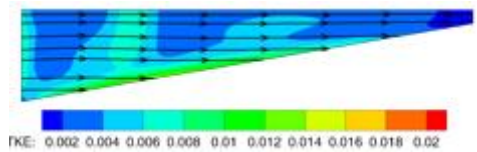
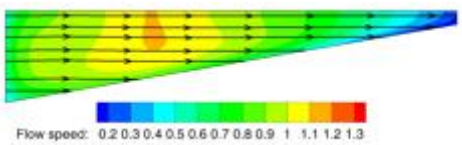
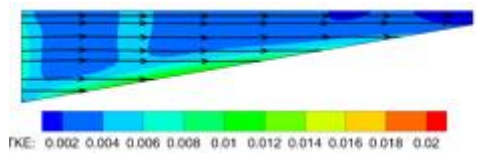


Normalized recirculation length : 3.1723

위치	case52 (R=25/ =50/α=+30/l=5/h=1)	
	secondary flow	
		
A		
B		
C		
D		
F		
G		
H		
I		

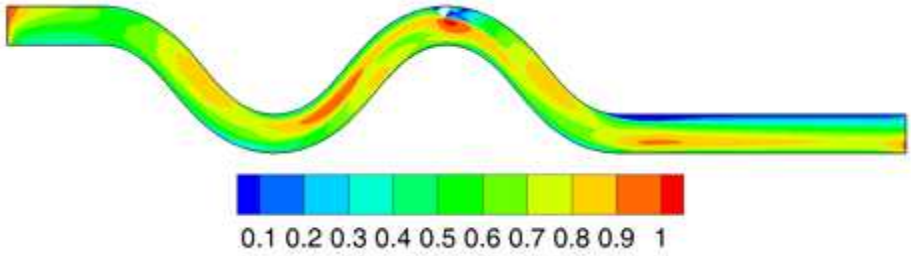
case4 (bottom/R=25/ =50/l=2.5/h=0.5)
Flow speed

Turbulent kinetic energy (TKE)

Recirculation
 recirculation (X)

case4 (top/R=20/ =50/l=2.5/h=0.5)
Flow speed

Turbulent kinetic energy (TKE)

Recirculation
 recirculation (X)

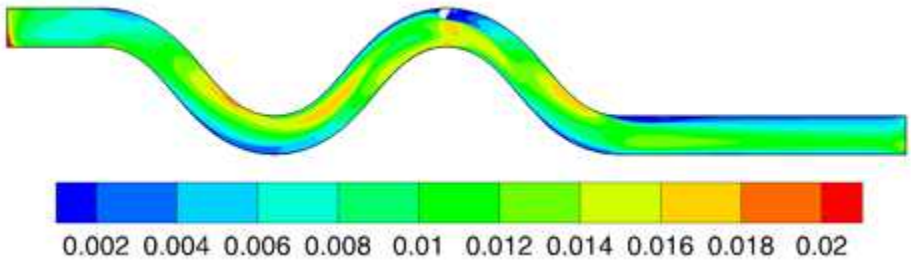
위치	case4 (R=20/ =50/l=2.5/h=0.5) secondary flow	
		
A		
B		
C		
D		
F		
G		
H		
I		

case6 (bottom/R=20/ =50/α=-30/l=2.5/h=0.5)

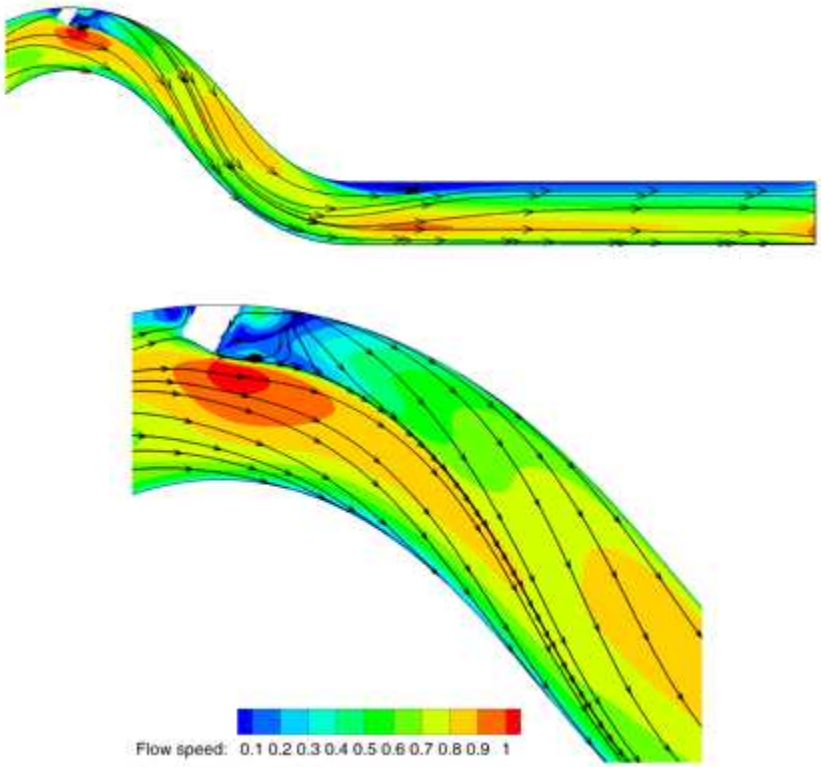
Flow speed



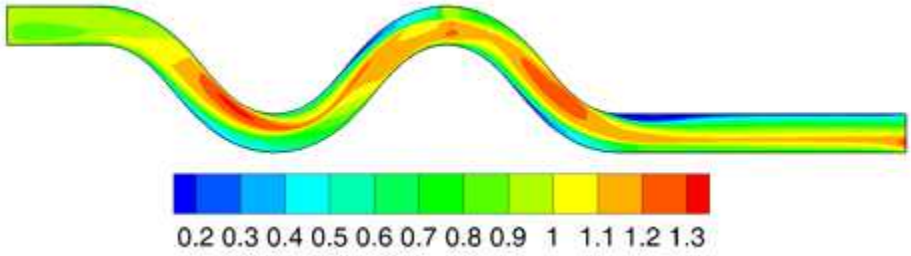
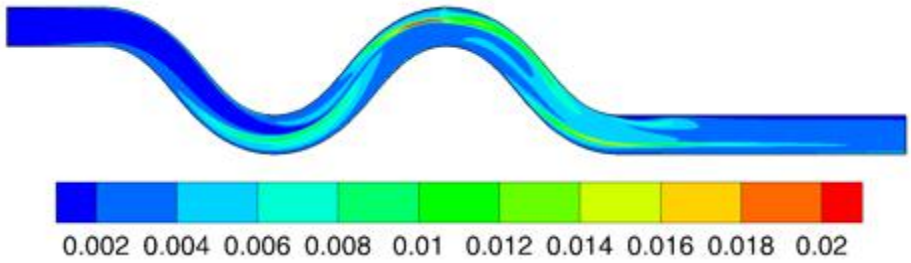
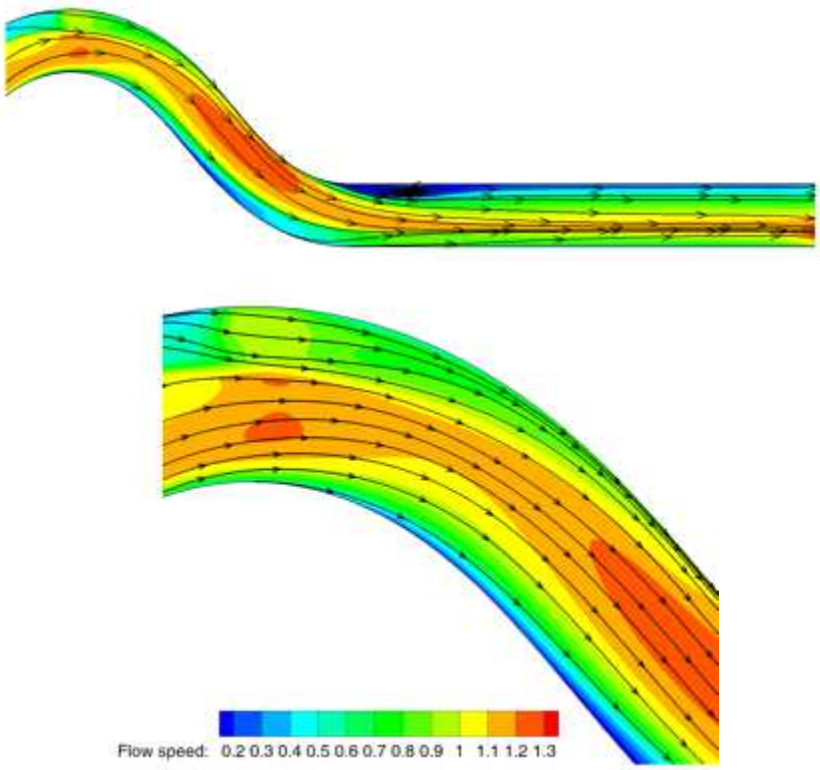
Turbulent kinetic energy (TKE)

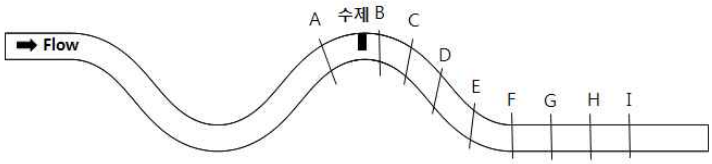
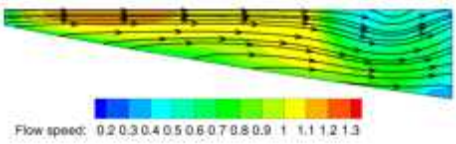
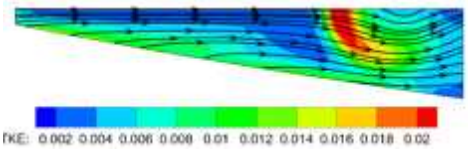
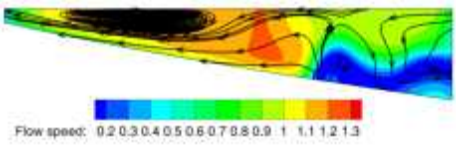
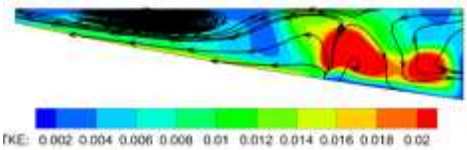
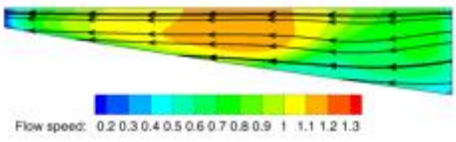
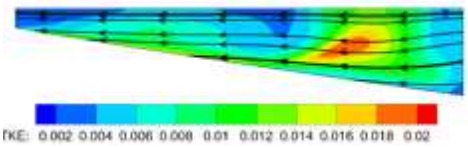
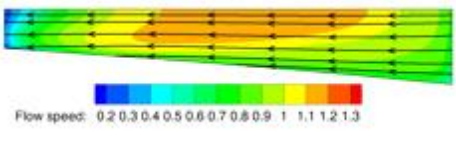
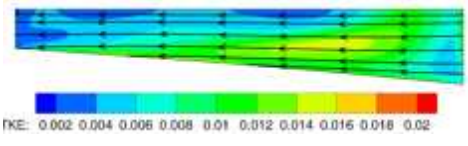
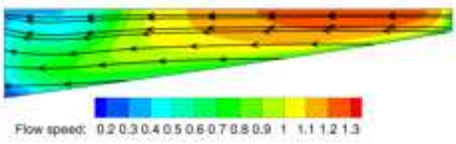
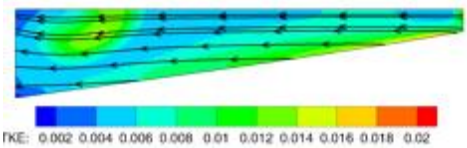
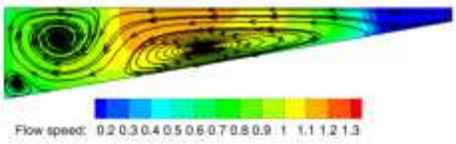
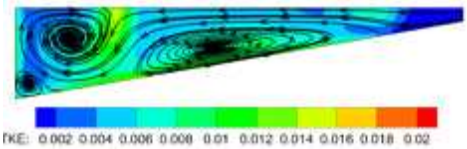
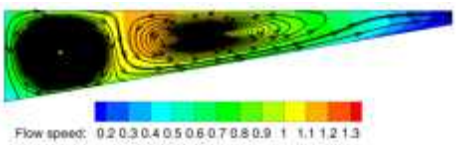
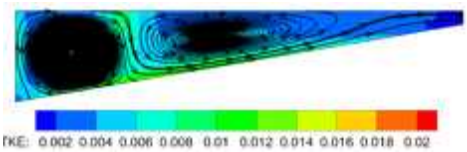
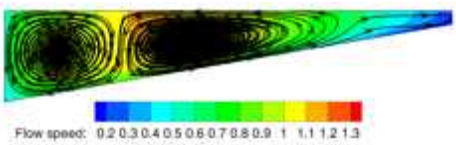
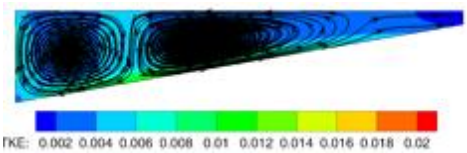


Recirculation



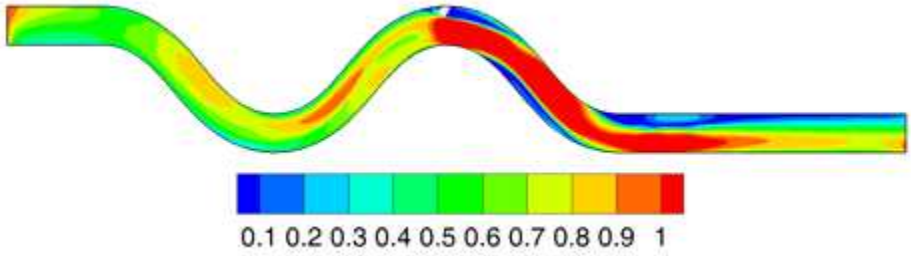
Normalized recirculation length : 0.3416

case6 (top/R=20/ =50/α=-30/l=2.5/h=0.5)
Flow speed

Turbulent kinetic energy (TKE)

Recirculation
 recirculation (X)

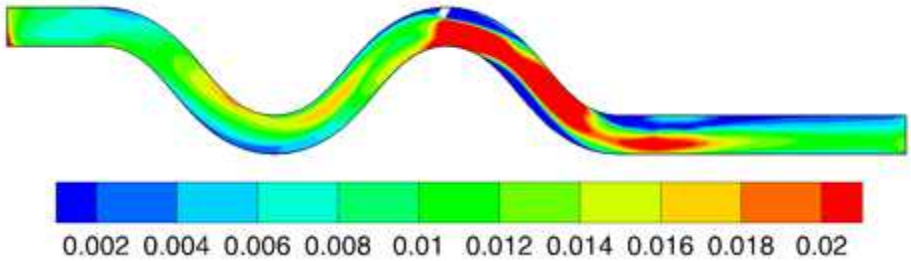
위치	case6 (R=20/ =50/α=-30/l=2.5/h=0.5)	
	secondary flow	
		
A		
B		
C		
D		
F		
G		
H		
I		

case8 (bottom/R=20/ =50/α=-30/l=2.5/h=1)

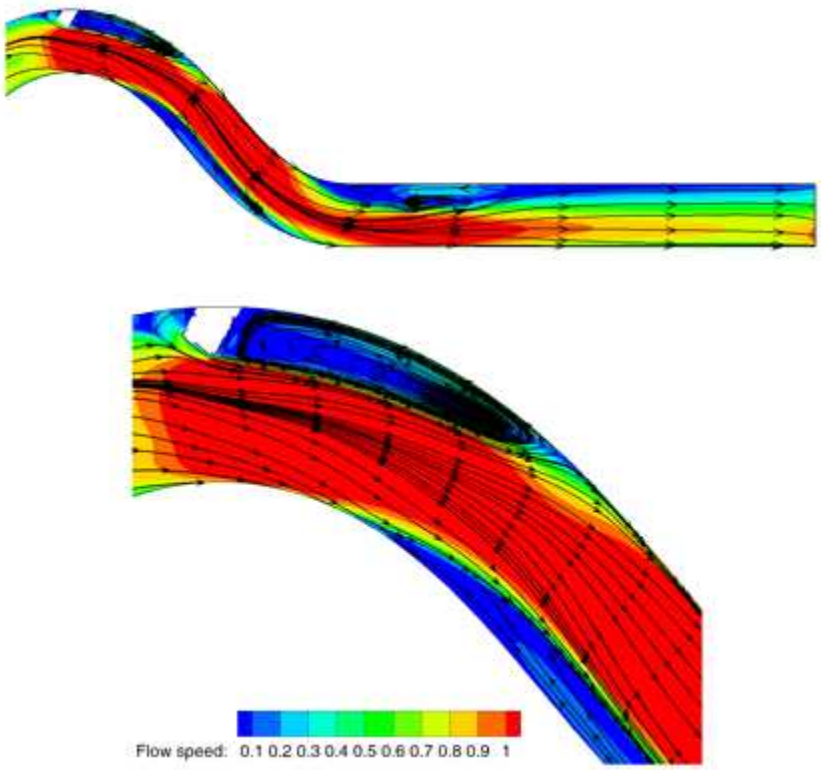
Flow speed



Turbulent kinetic energy (TKE)



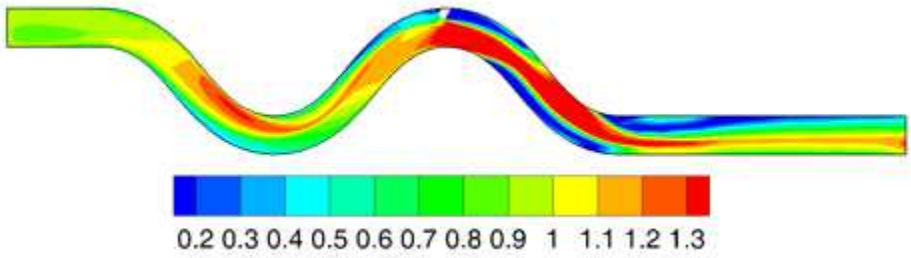
Recirculation



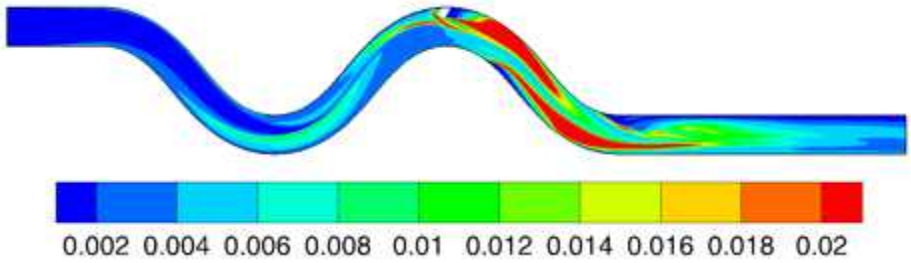
Normalized recirculation length : 1.8862

case8 (top/R=20/ =50/α=-30/l=2.5/h=1)

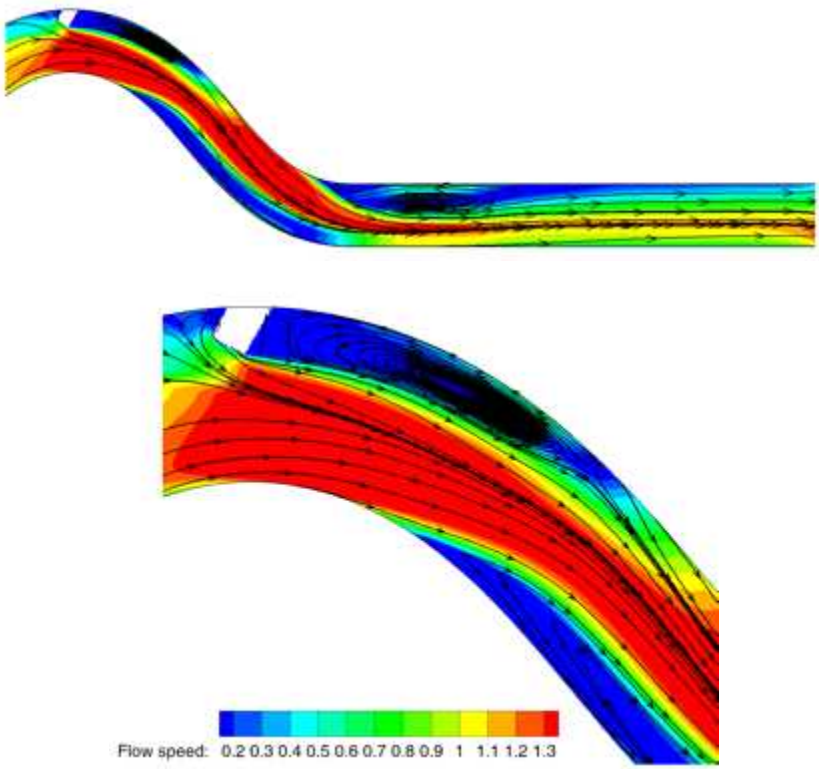
Flow speed



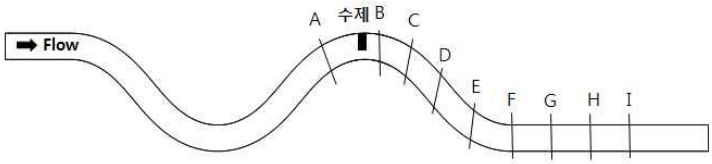
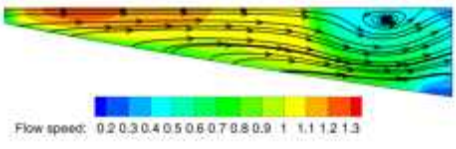
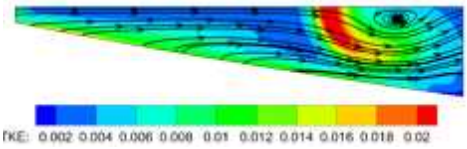
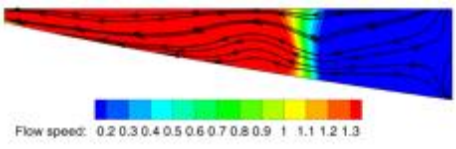
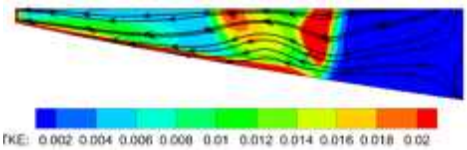
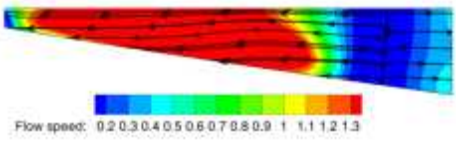
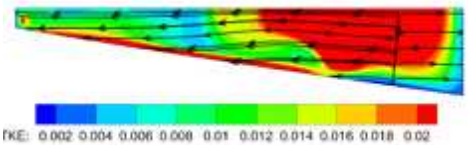
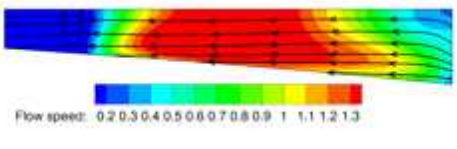
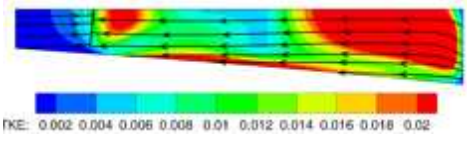
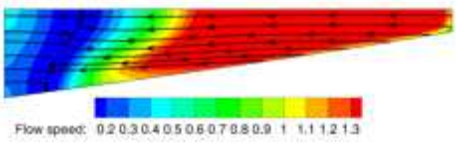
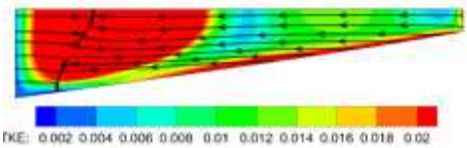
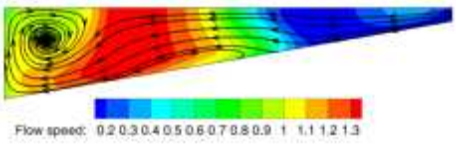
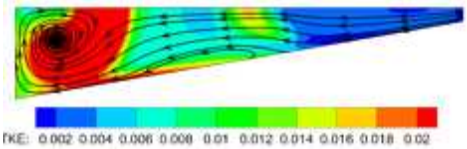
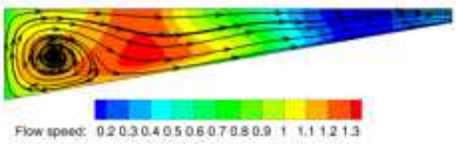
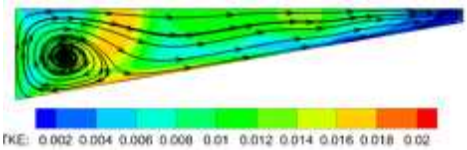
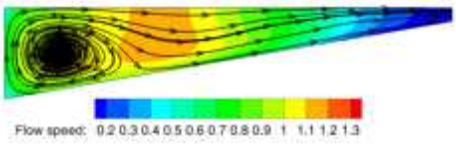
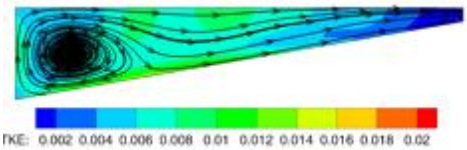
Turbulent kinetic energy (TKE)



Recirculation

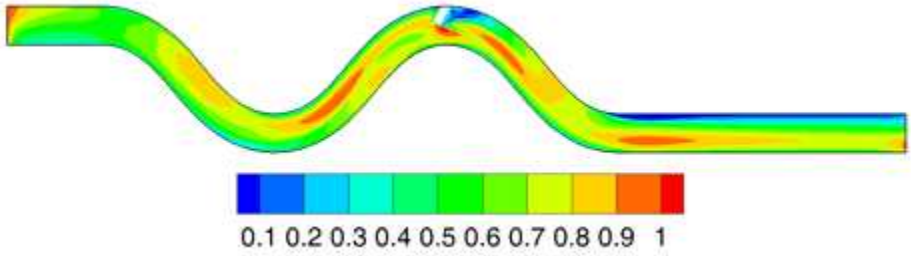


Normalized recirculation length : 1.8833

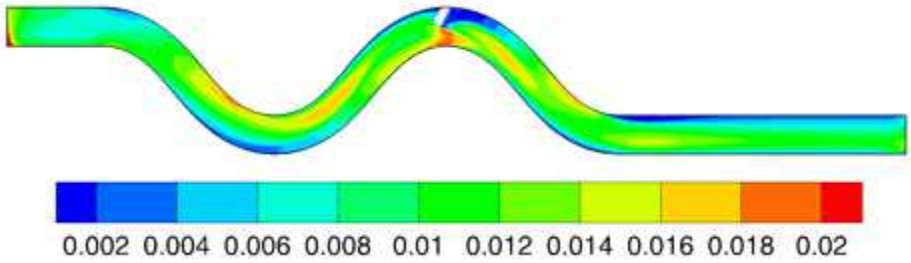
위치	case8 (R=20/ =50/α=-30/l=2.5/h=1)	
	secondary flow	
		
A		
B		
C		
D		
F		
G		
H		
I		

case10 (bottom/R=20/ =50/α=-30/l=5/h=0.5)

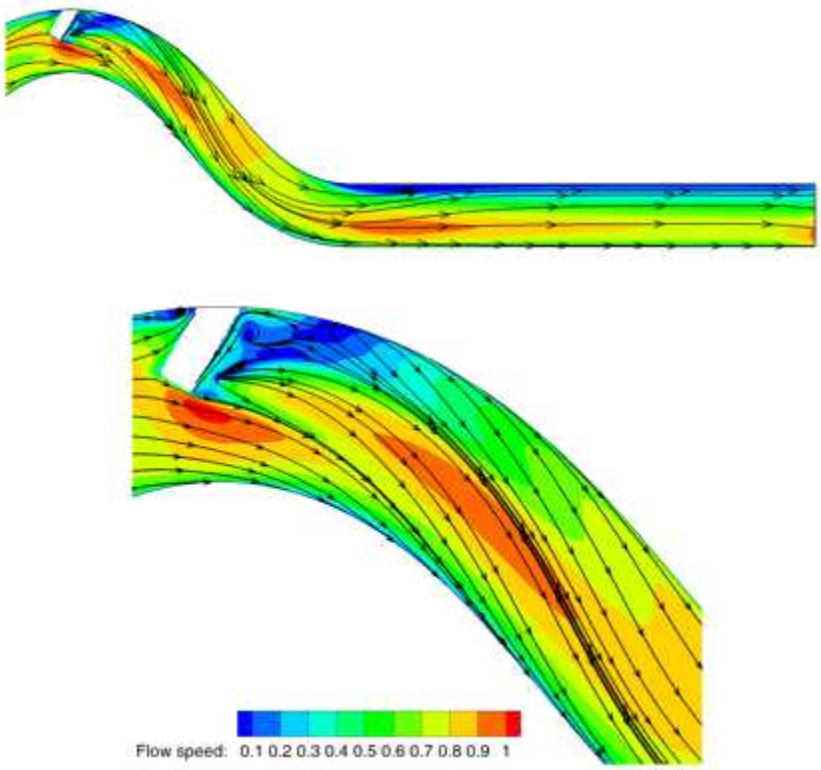
Flow speed



Turbulent kinetic energy (TKE)



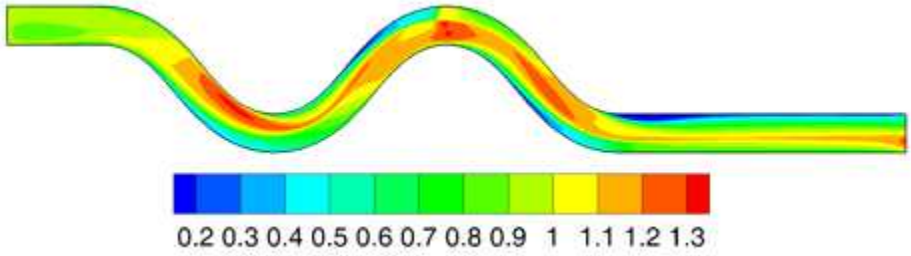
Recirculation



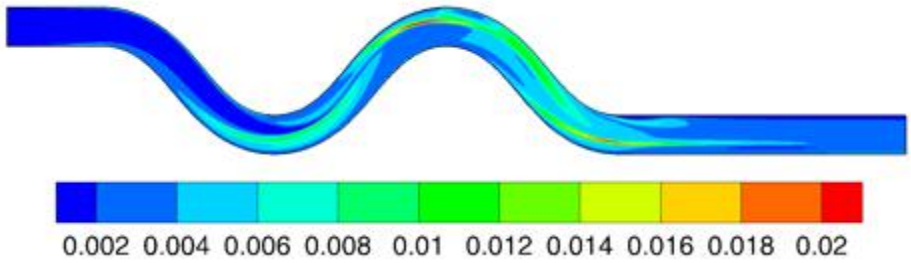
Normalized recirculation length : 0.5357

case10 (top/R=20/ =50/α=-30/l=5/h=0.5)

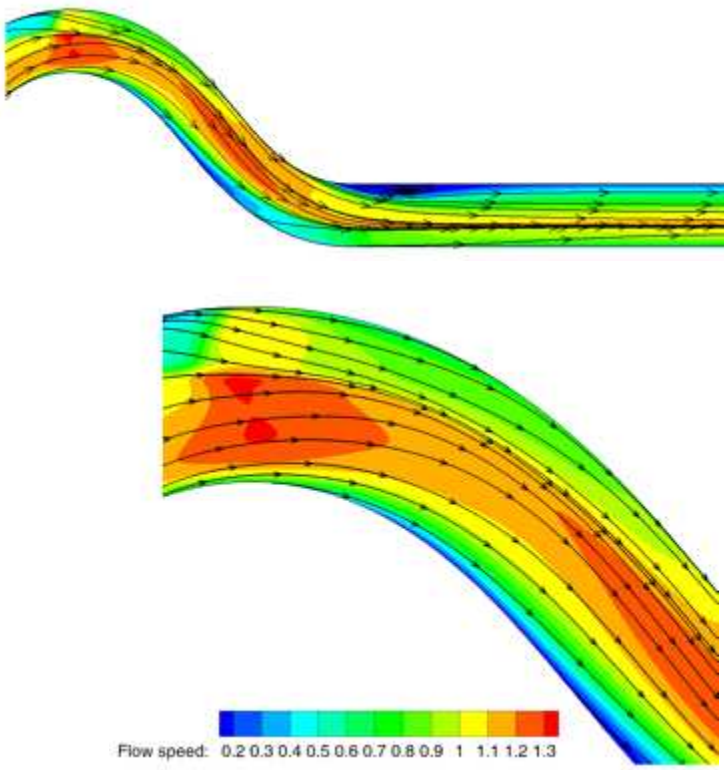
Flow speed



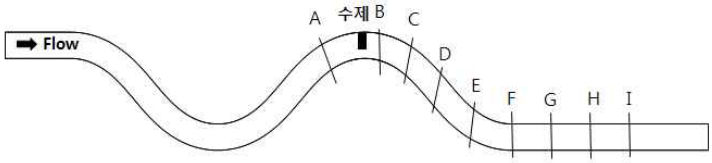
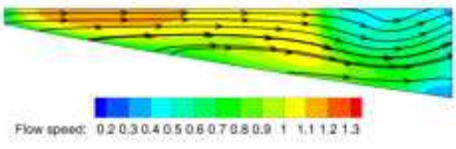
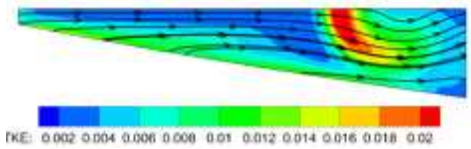
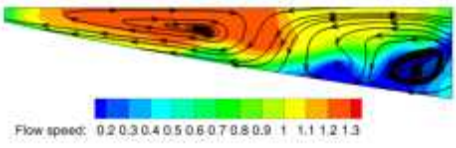
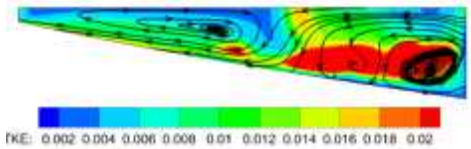
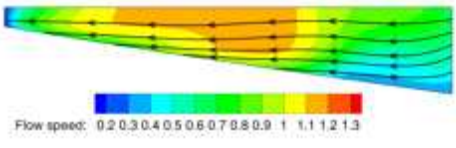
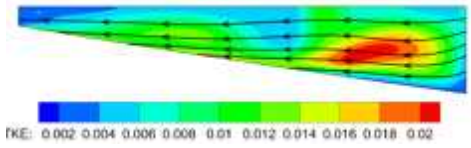
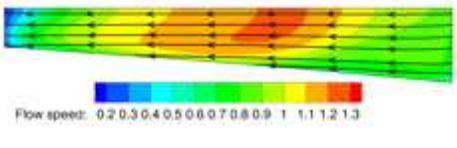
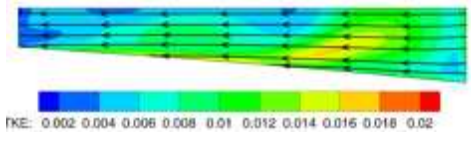
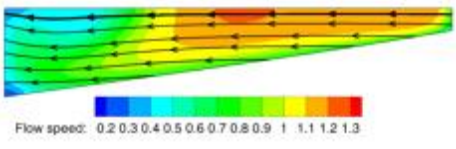
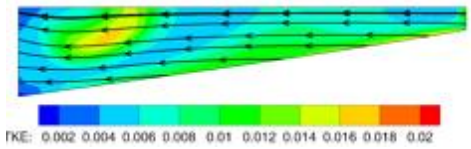
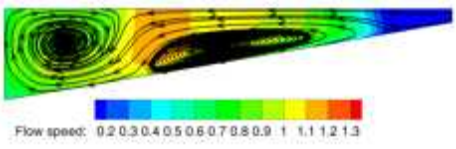
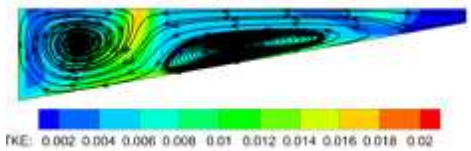
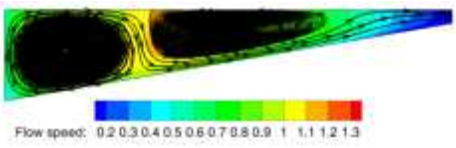
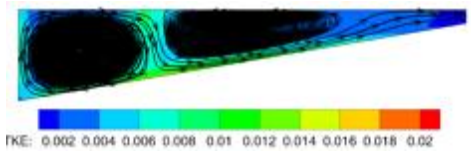
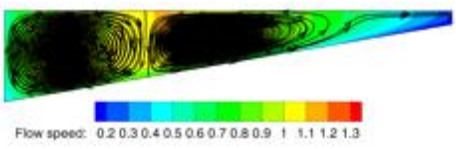
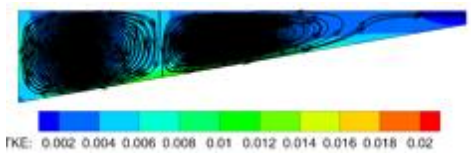
Turbulent kinetic energy (TKE)



Recirculation

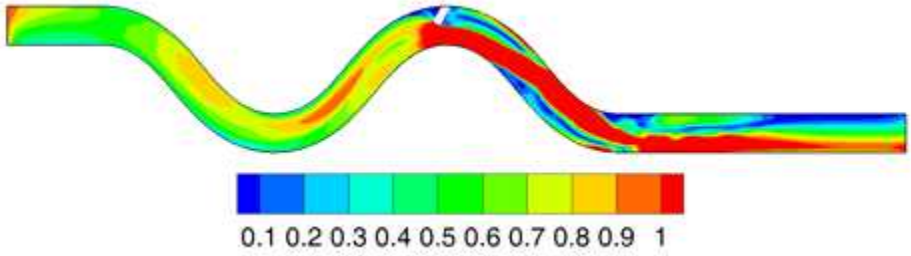


recirculation (X)

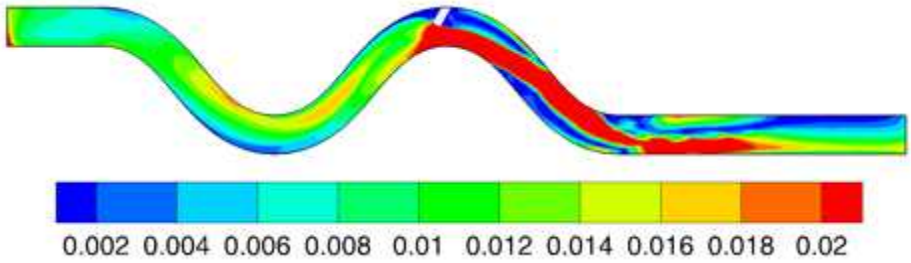
위치	case10 (R=20/ =50/α=-30/l=5/h=0.5)	
	secondary flow	
		
A		
B		
C		
D		
F		
G		
H		
I		

case12 (bottom/R=20/ =50/α=-30/l=5/h=1)

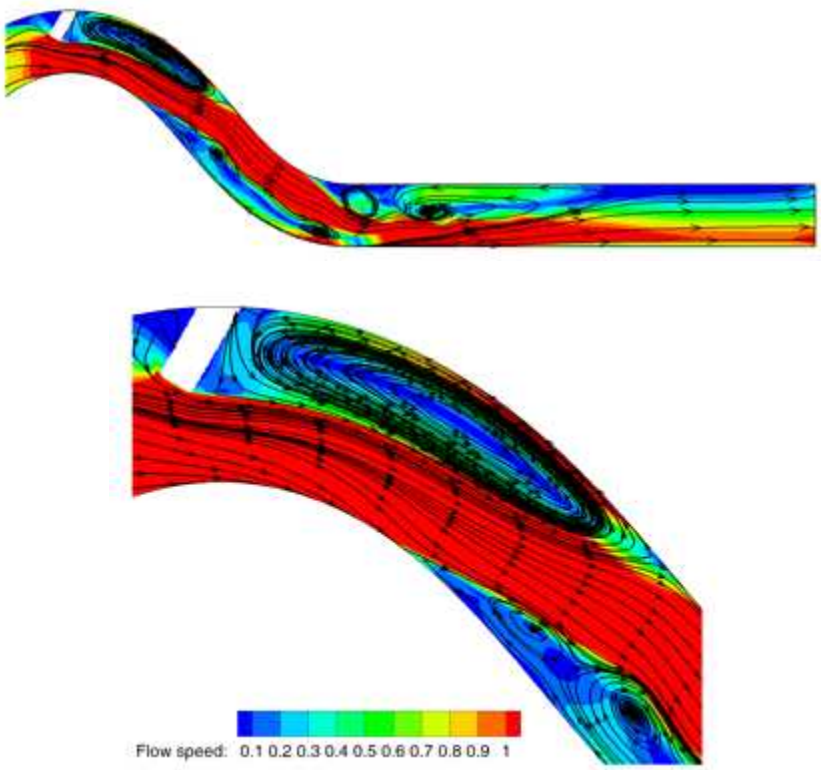
Flow speed



Turbulent kinetic energy (TKE)



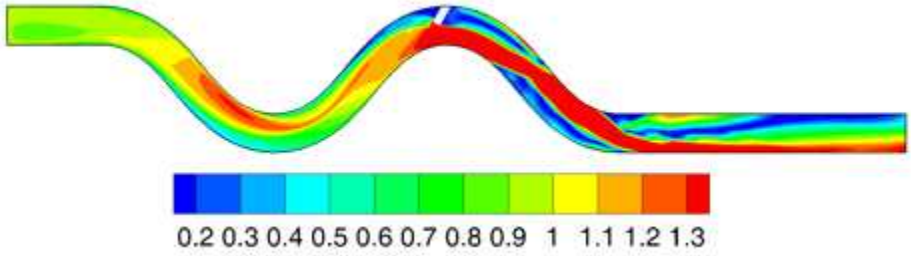
Recirculation



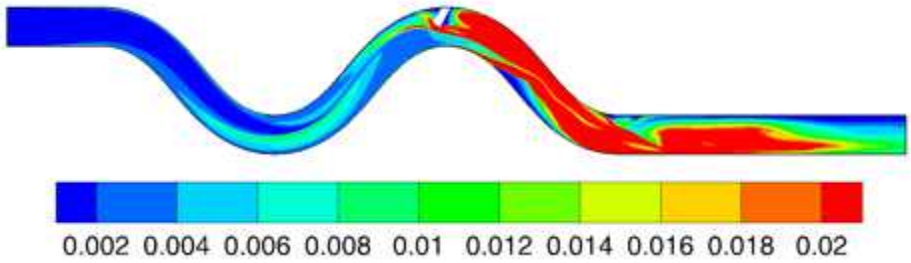
Normalized recirculation length : 2.3911

case12 (top/R=20/ =50/α=-30/l=5/h=1)

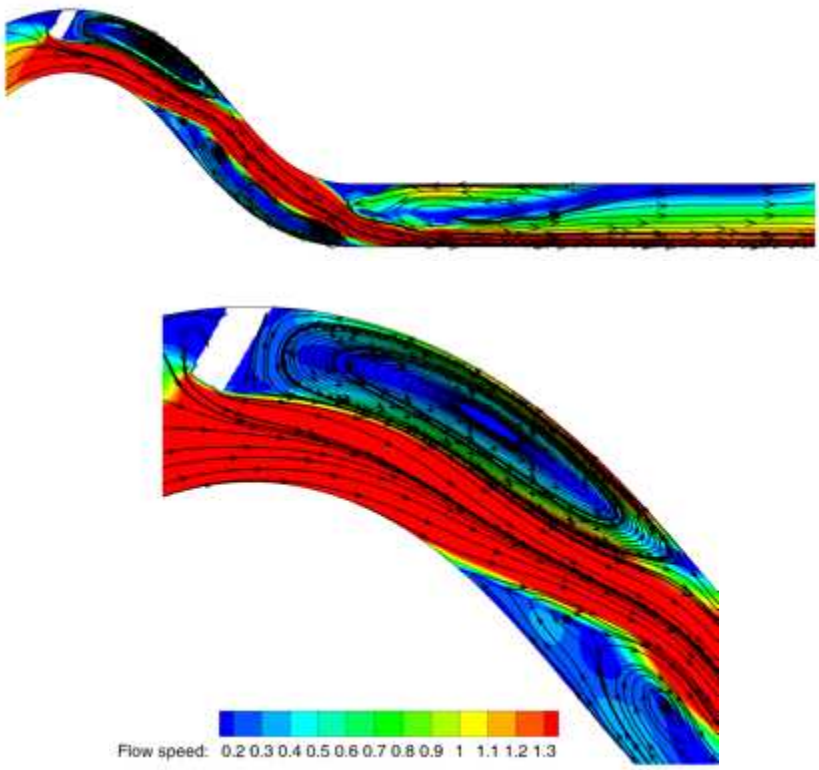
Flow speed



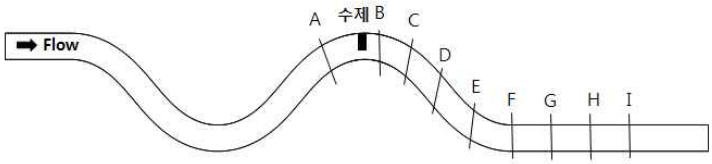
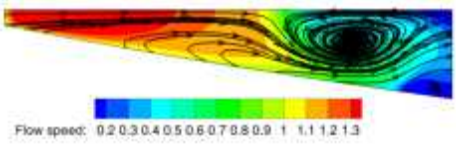
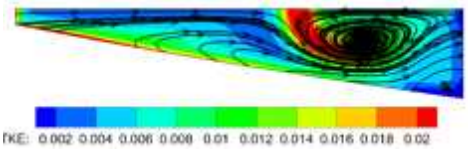
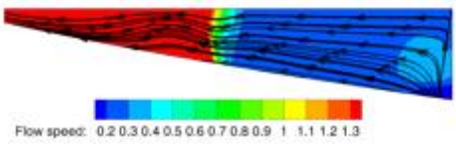
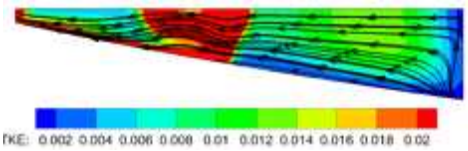
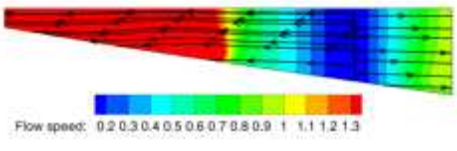
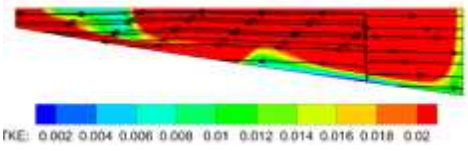
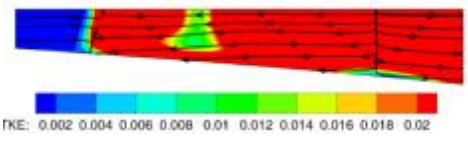
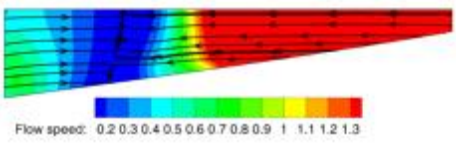
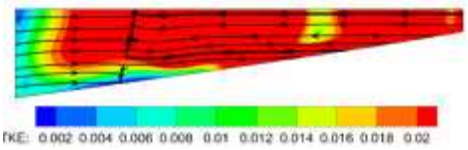
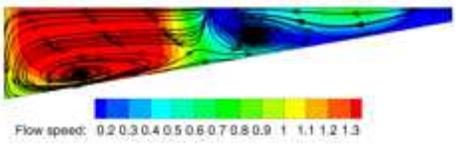
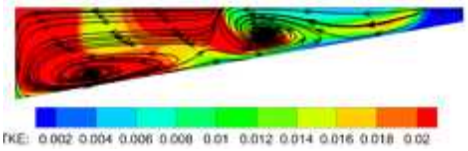
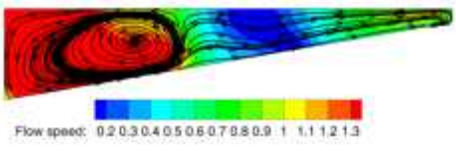
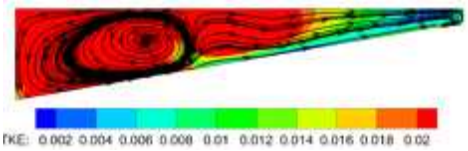
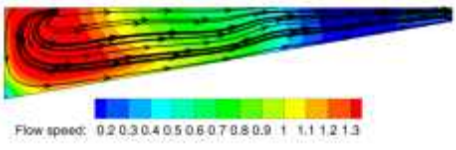
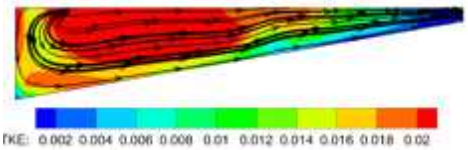
Turbulent kinetic energy (TKE)



Recirculation

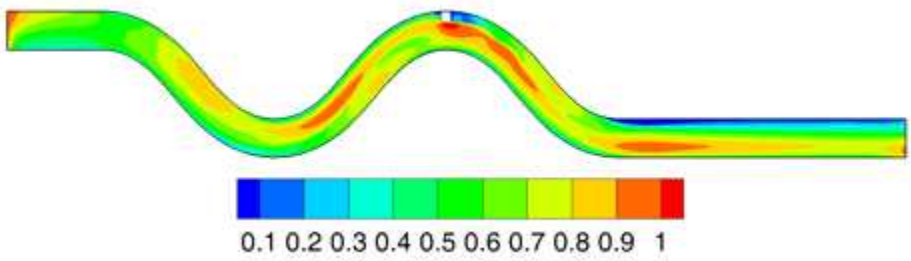


Normalized recirculation length : 2.4090

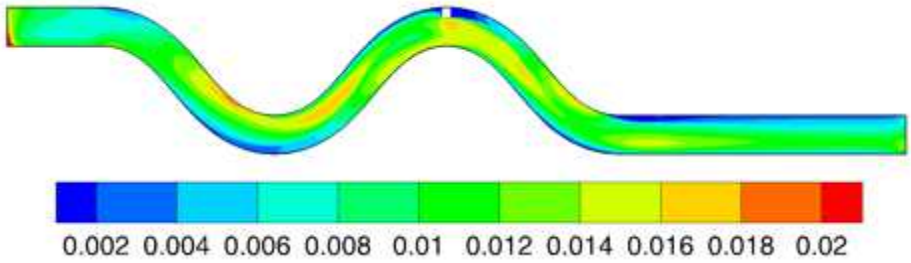
위치	case12 (R=20/ =50/α=-30/l=5/h=1)	
	secondary flow	
		
A		
B		
C		
D		
F		
G		
H		
I		

case22 (bottom/R=20/ =50/α=0/l=2.5/h=0.5)

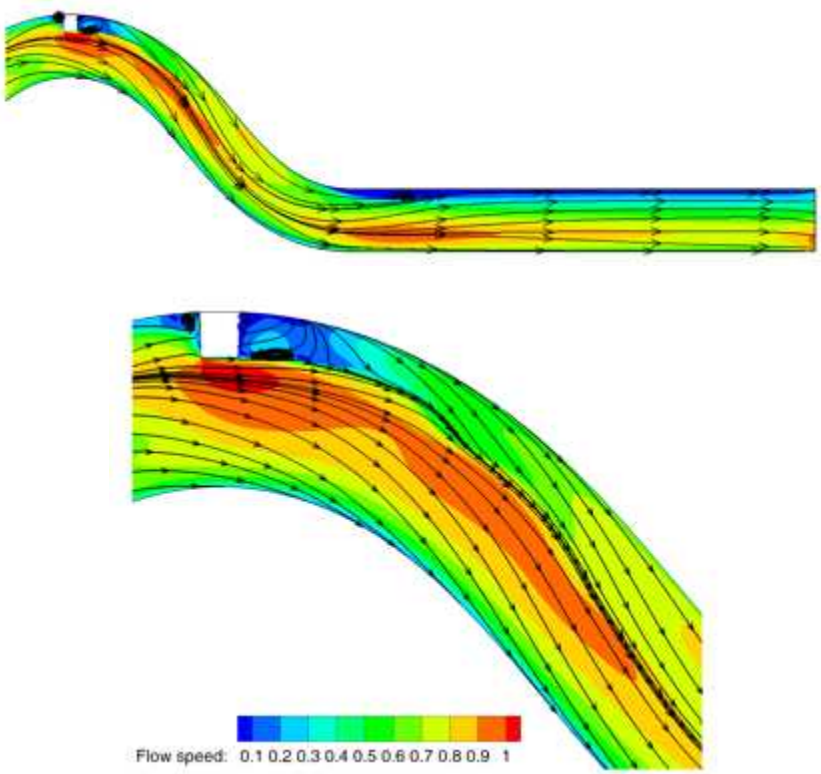
Flow speed



Turbulent kinetic energy (TKE)



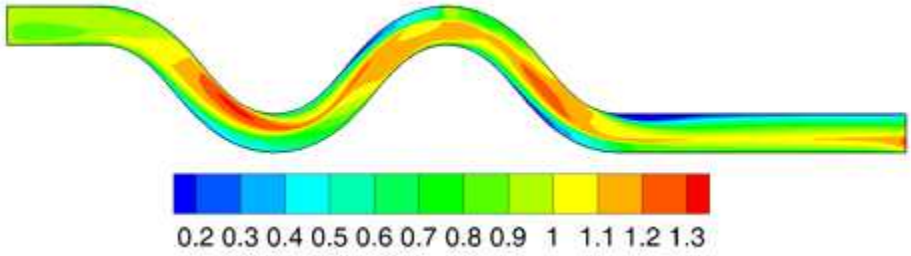
Recirculation



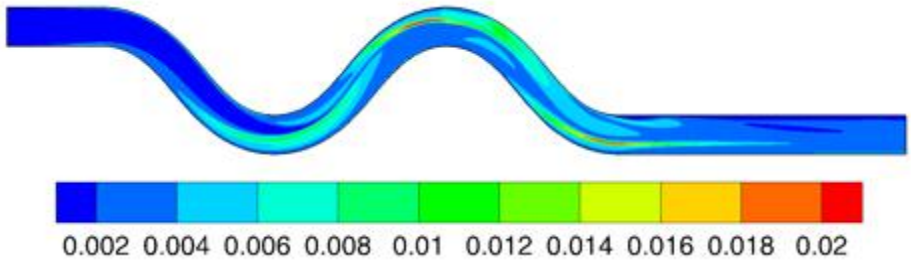
Normalized recirculation length : 0.3935

case22 (top/R=20/ =50/α=0/l=2.5/h=0.5)

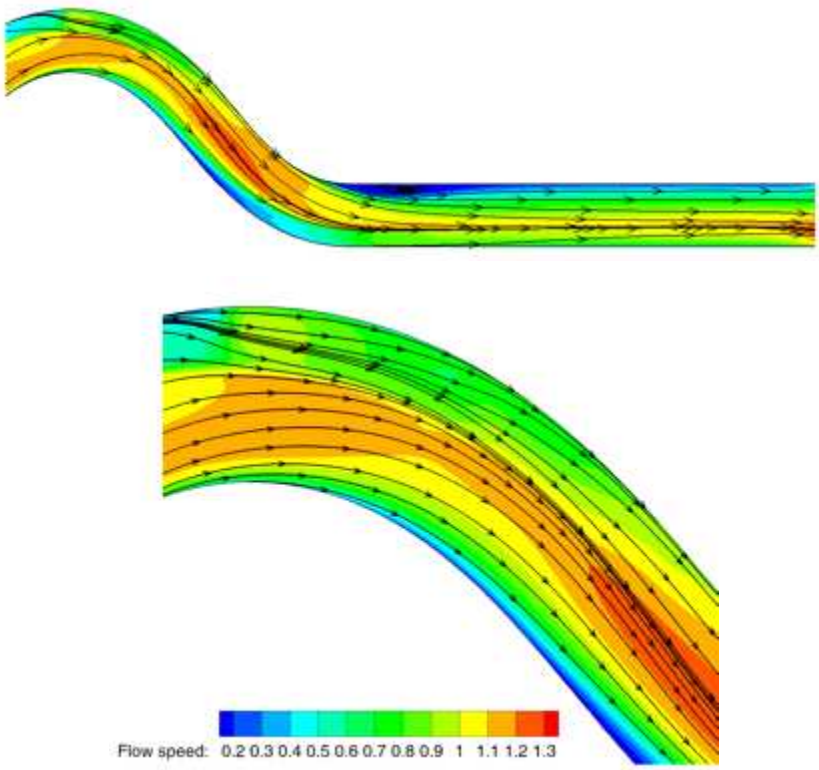
Flow speed



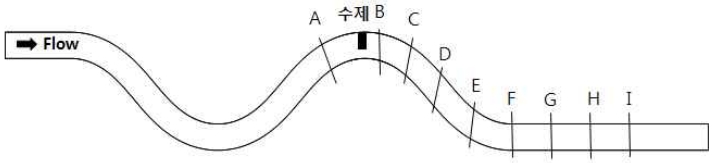
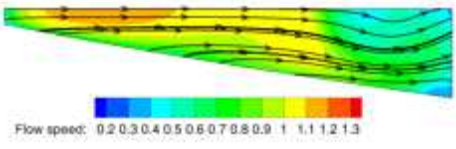
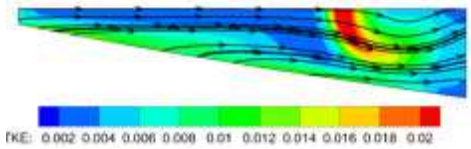
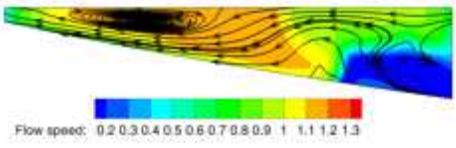
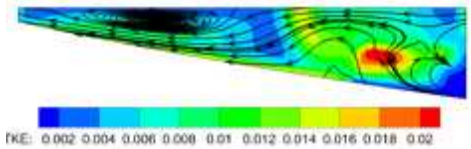
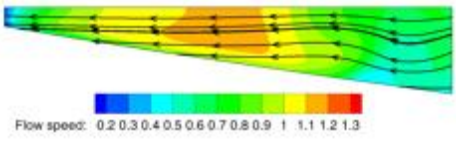
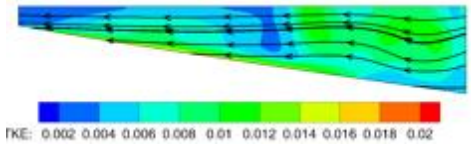
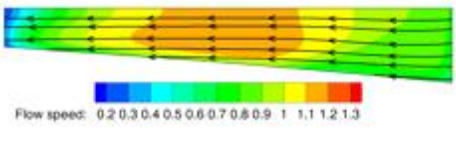
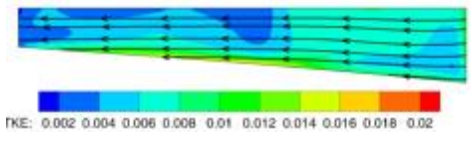
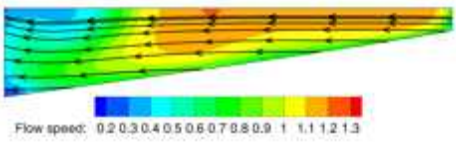
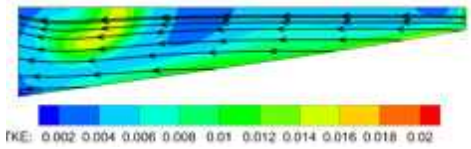
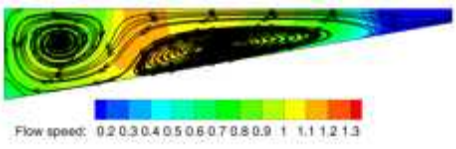
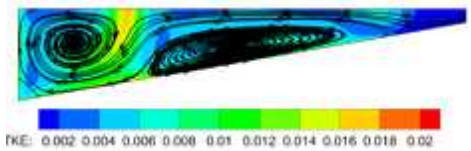
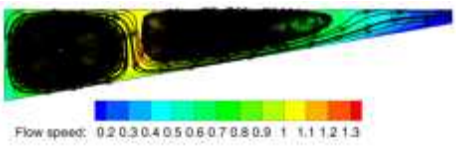
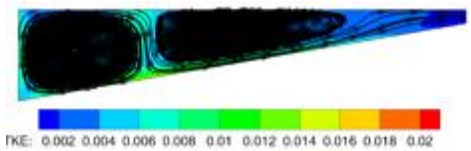
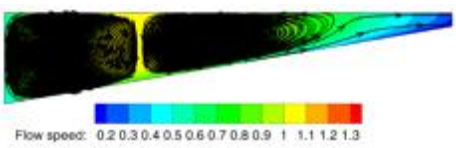
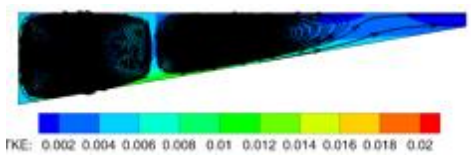
Turbulent kinetic energy (TKE)



Recirculation

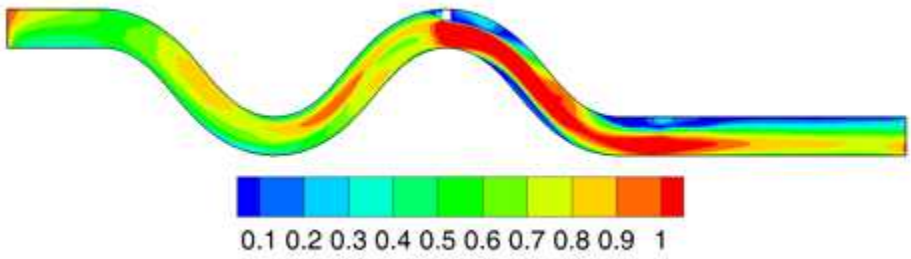


recirculation (X)

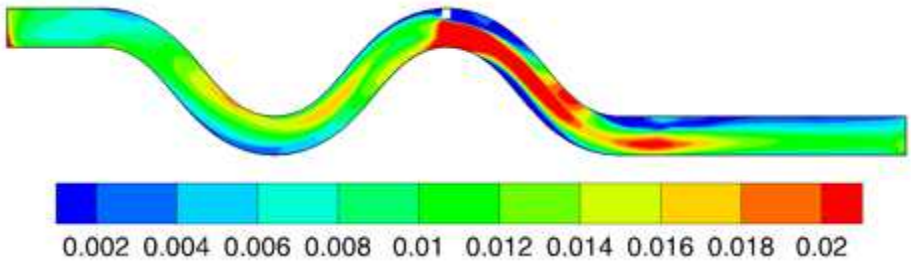
위치	case22 (R=20/ =50/α=0/l=2.5/h=0.5)	
	secondary flow	
		
A		
B		
C		
D		
F		
G		
H		
I		

case24 (bottom/R=20/ =50/α=0/l=2.5/h=1)

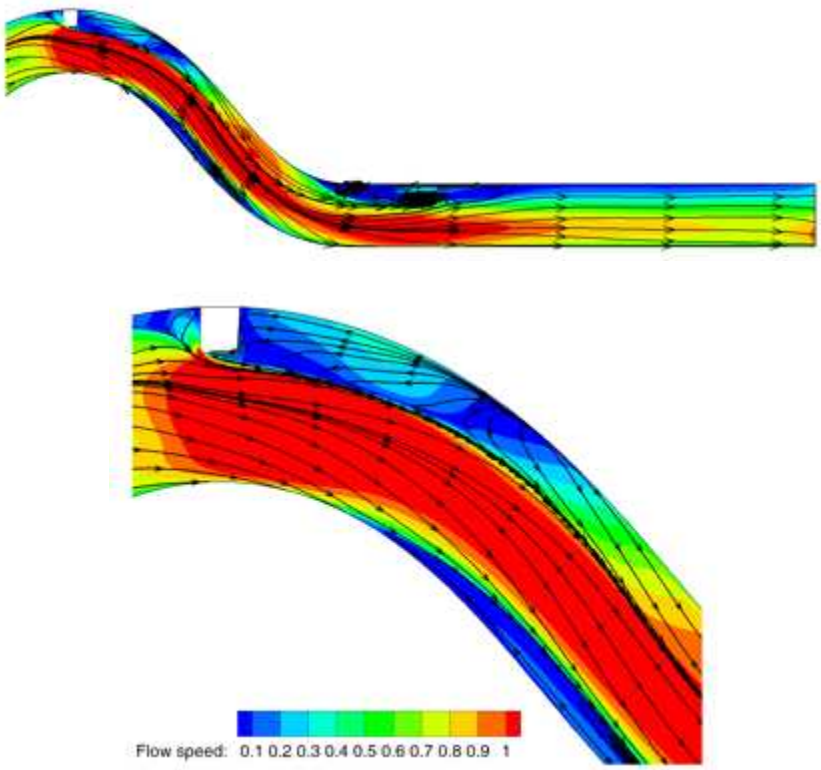
Flow speed



Turbulent kinetic energy (TKE)



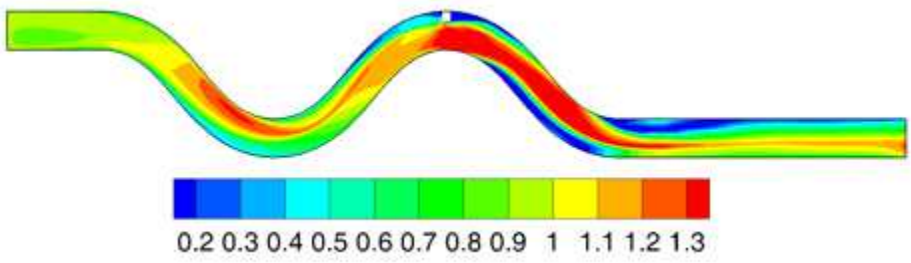
Recirculation



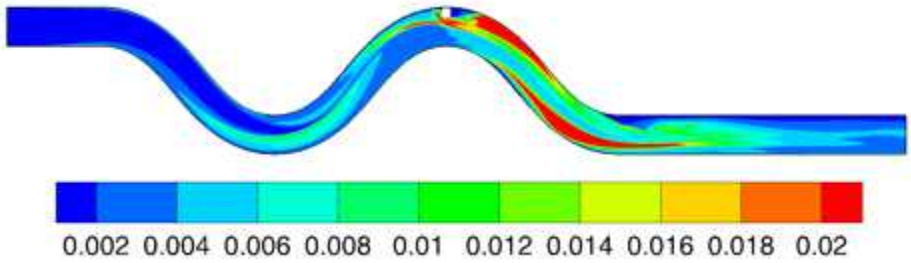
Normalized recirculation length : 1.6927

case24 (top/R=20/ =50/α=0/l=2.5/h=1)

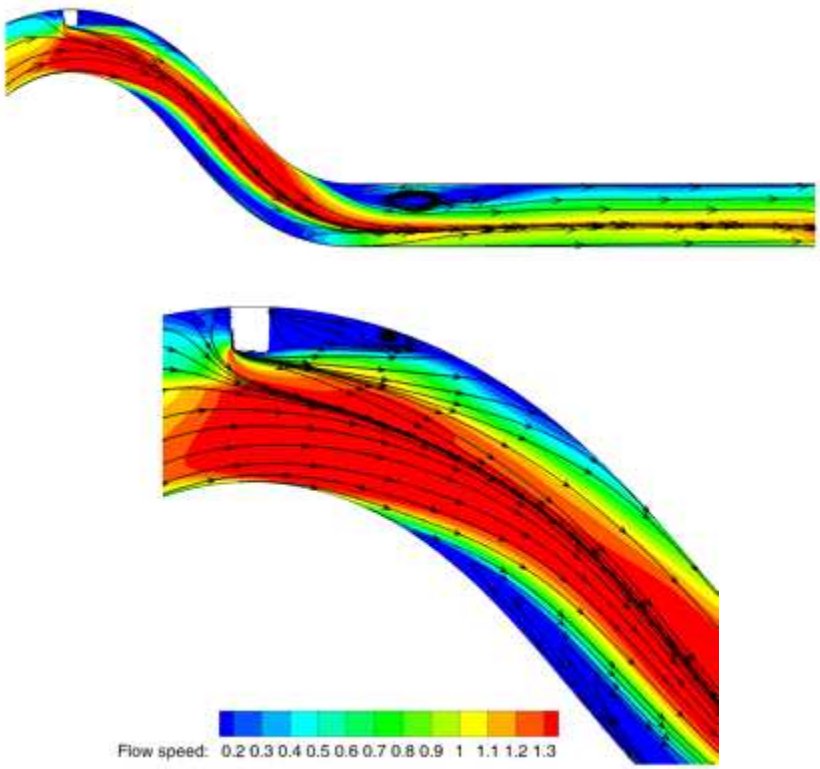
Flow speed



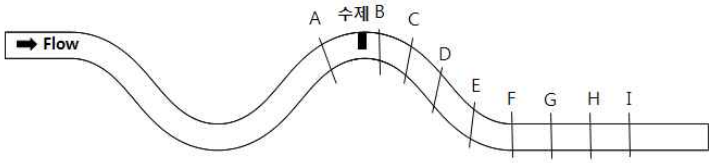
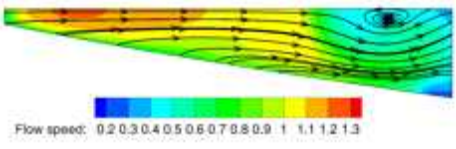
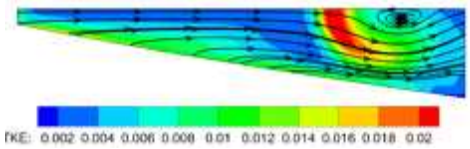
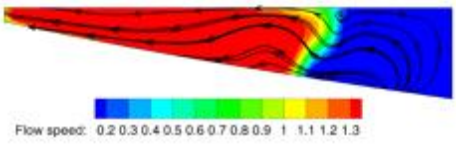
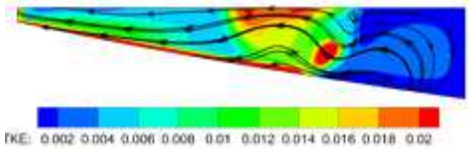
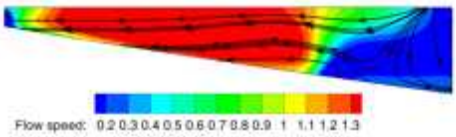
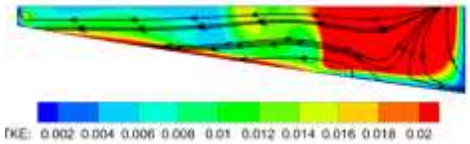
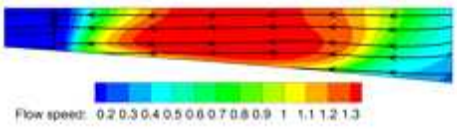
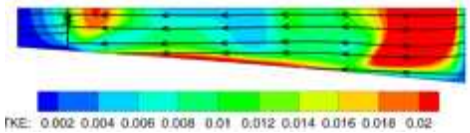
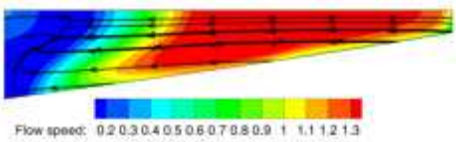
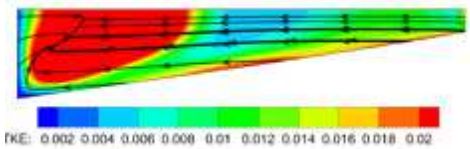
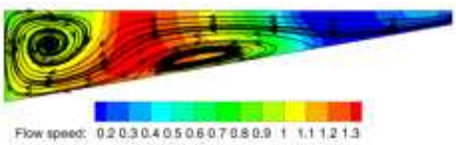
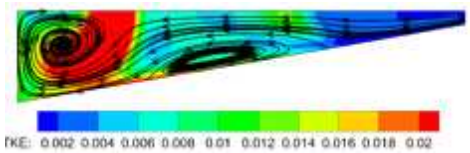
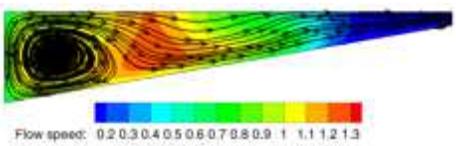
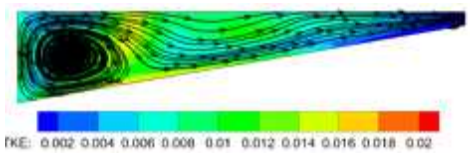
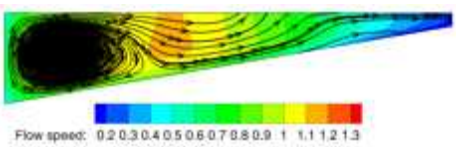
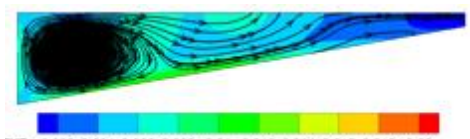
Turbulent kinetic energy (TKE)



Recirculation

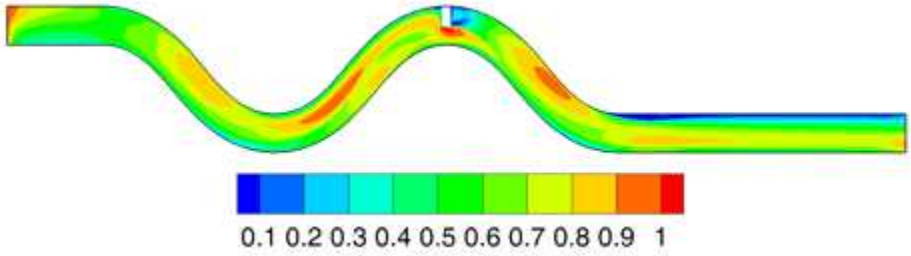


Normalized recirculation length : 0.8728

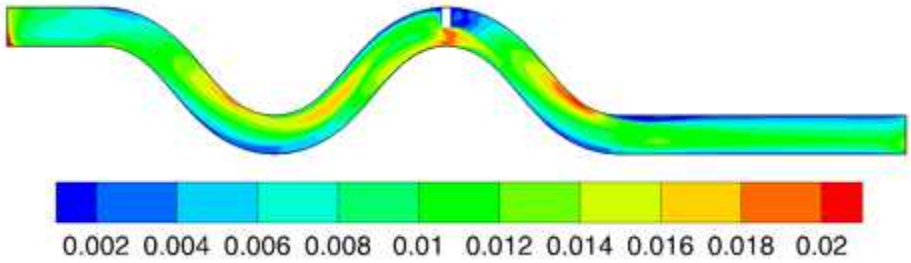
위치	case24 (R=20/ =50/α=0/l=2.5/h=1)	
	secondary flow	
		
A		
B		
C		
D		
F		
G		
H		
I		

case26 (bottom/R=20/ =50/α=0/l=5/h=0.5)

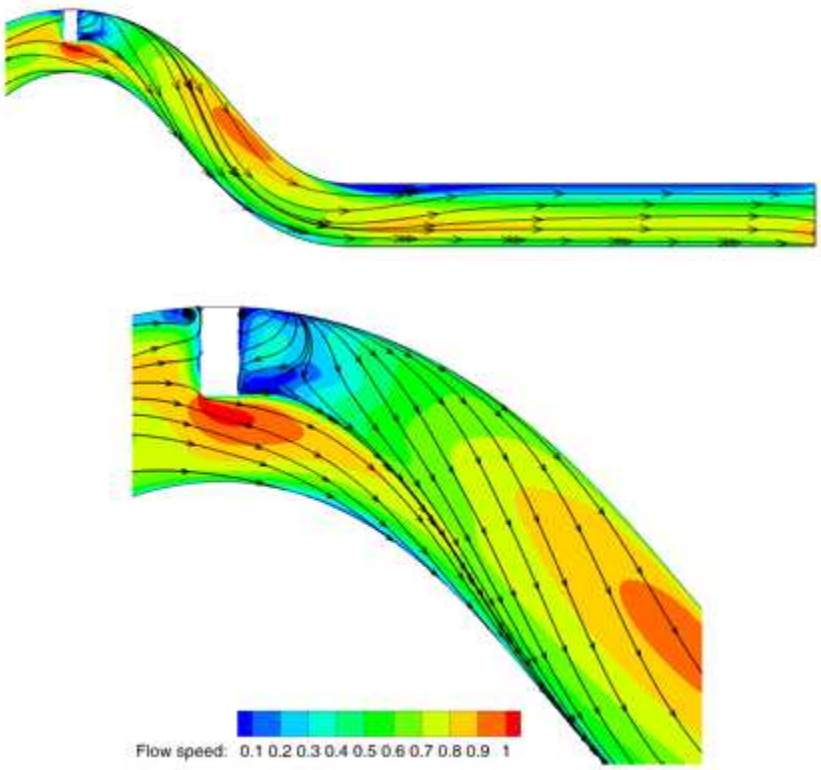
Flow speed



Turbulent kinetic energy (TKE)



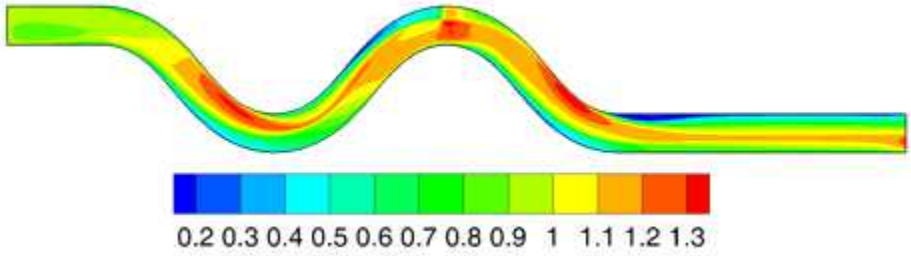
Recirculation



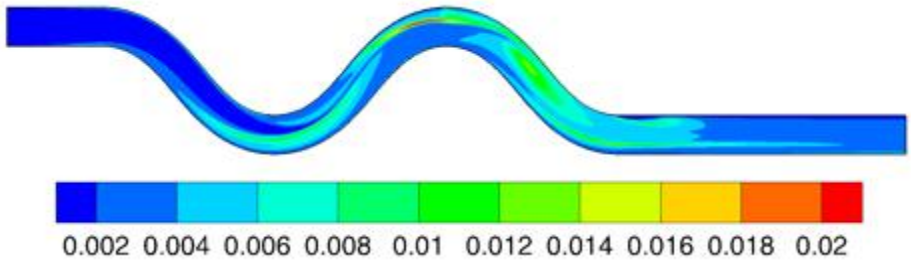
Normalized recirculation length : 0.3876

case26 (top/R=20/ =50/α=0/l=5/h=0.5)

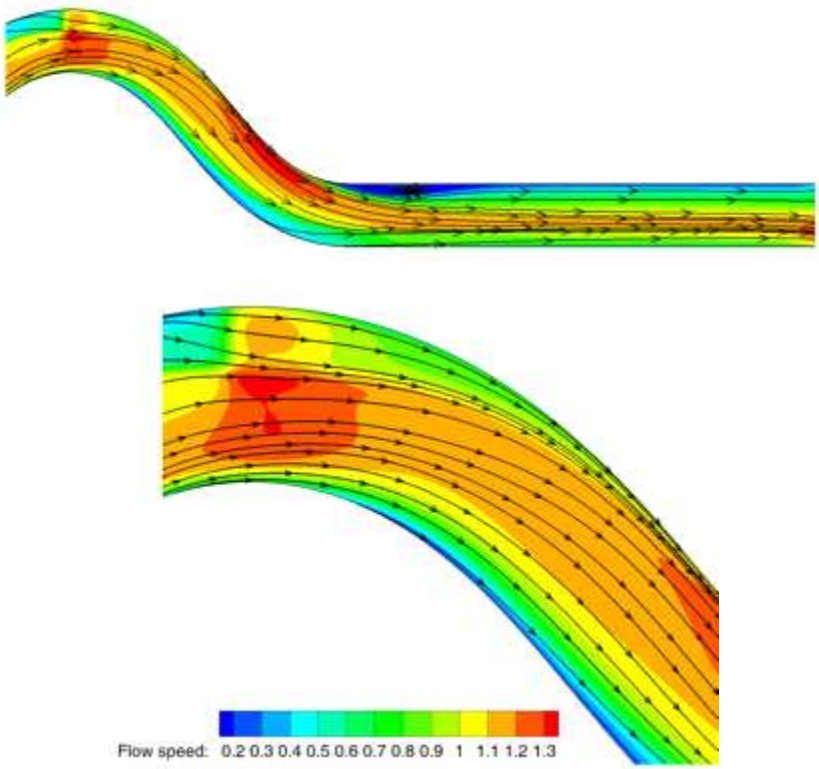
Flow speed



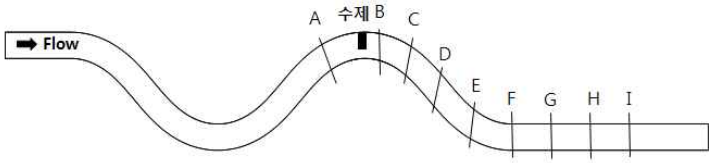
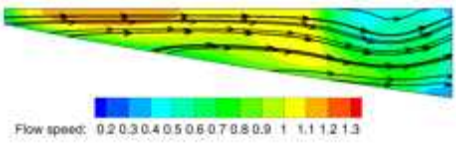
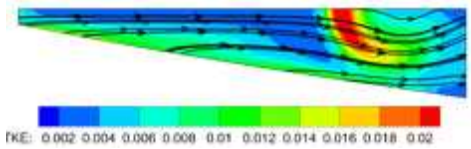
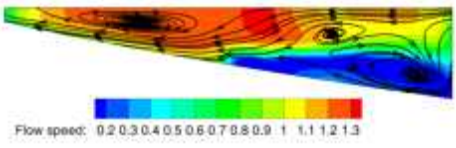
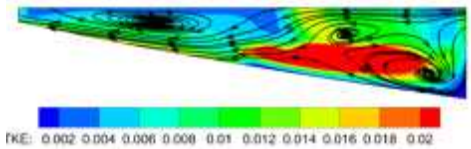
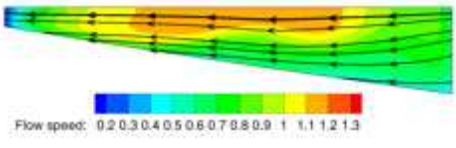
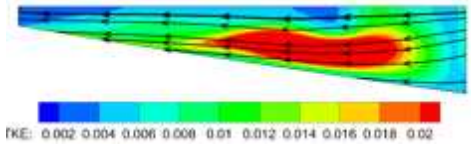
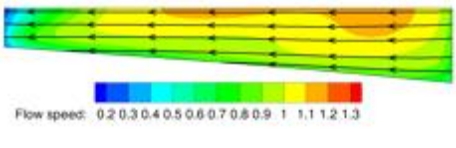
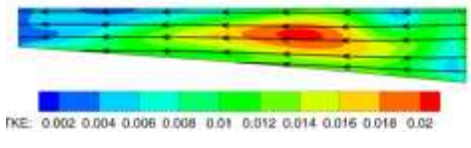
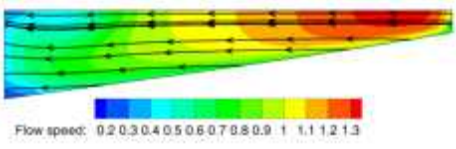
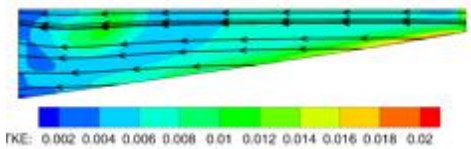
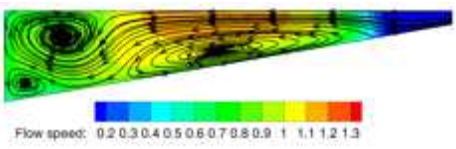
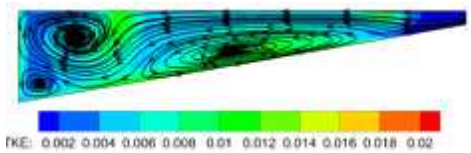
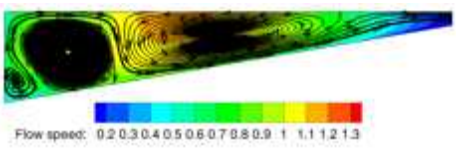
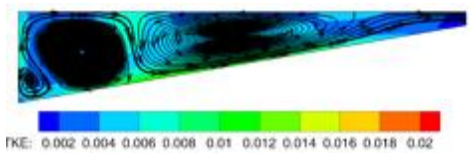
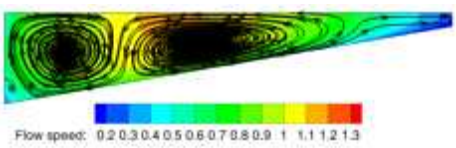
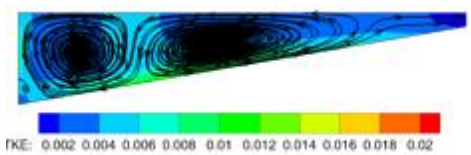
Turbulent kinetic energy (TKE)

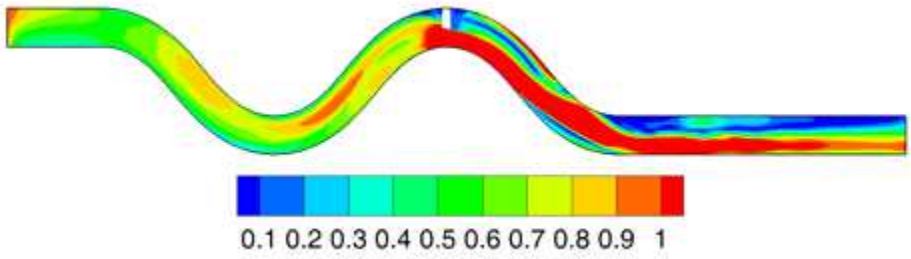
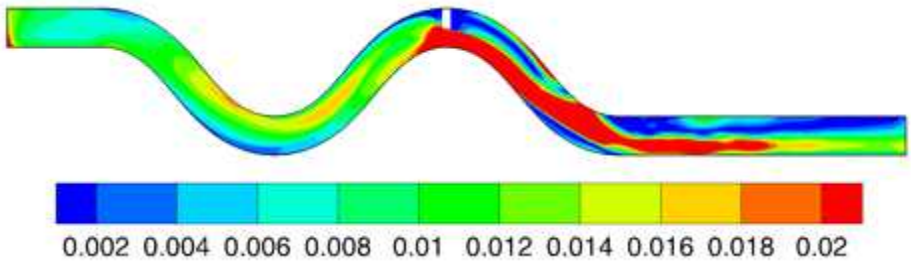
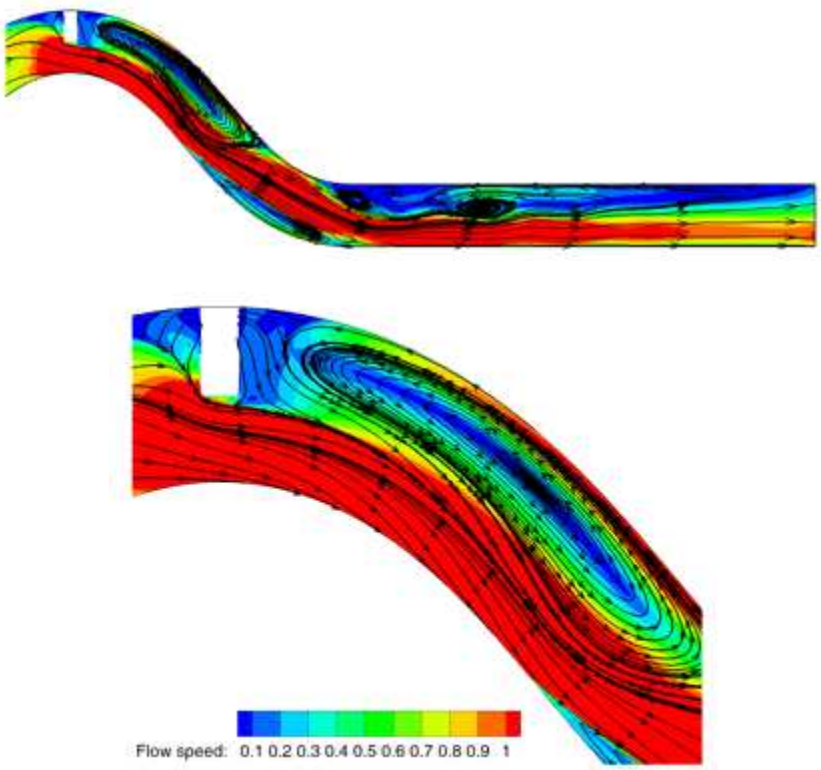


Recirculation



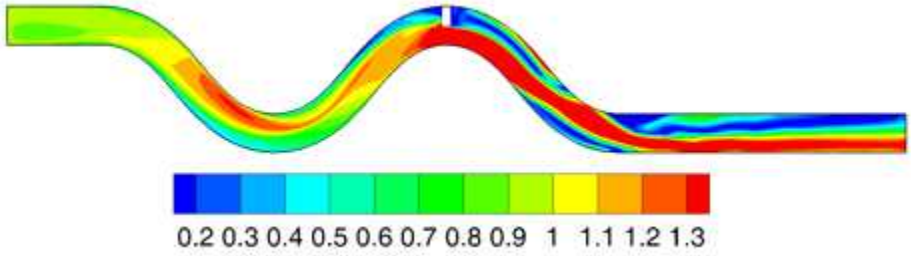
recirculation (X)

위치	case26 (R=20/ =50/α=0/l=5/h=0.5)	
	secondary flow	
		
A		
B		
C		
D		
F		
G		
H		
I		

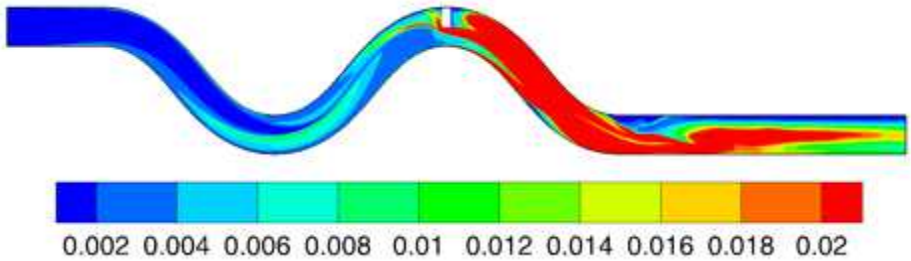
case28 (bottom/R=20/ =50/α=0/l=5/h=1)
Flow speed

Turbulent kinetic energy (TKE)

Recirculation
 Normalized recirculation length : 3.0044

case28 (top/R=20/ =50/α=0/l=5/h=1)

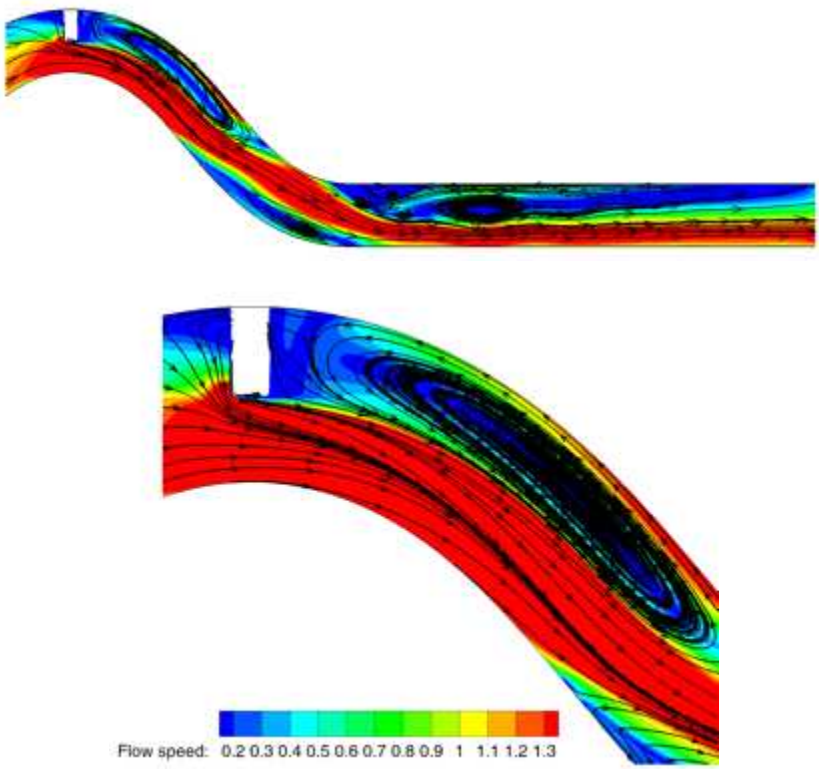
Flow speed



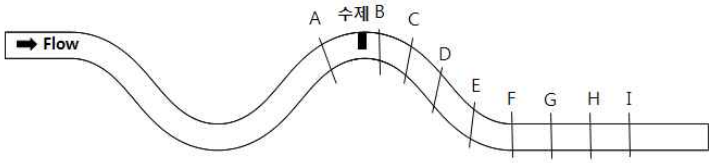
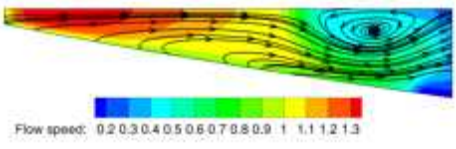
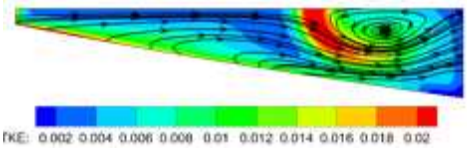
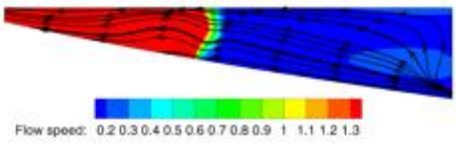
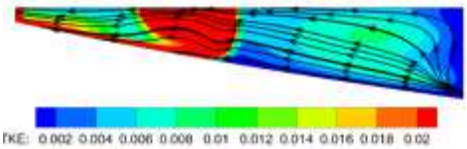
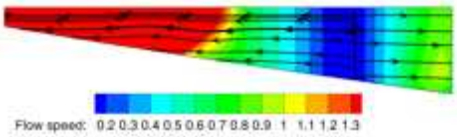
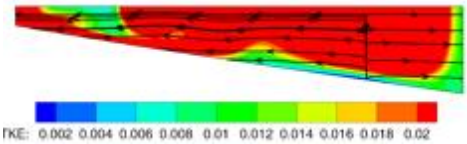
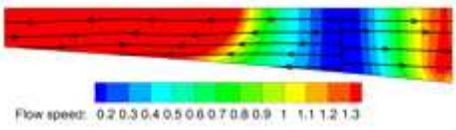
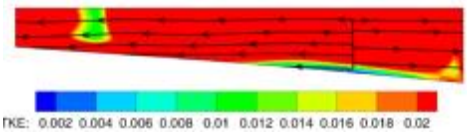
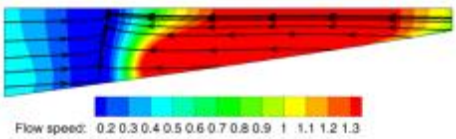
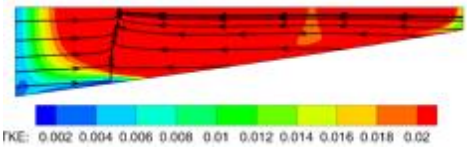
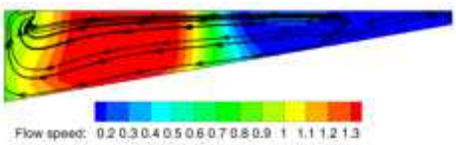
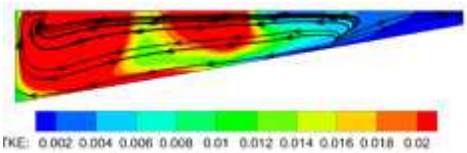
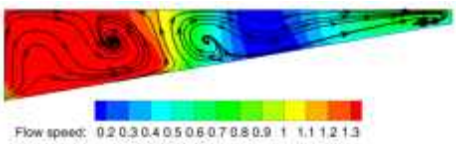
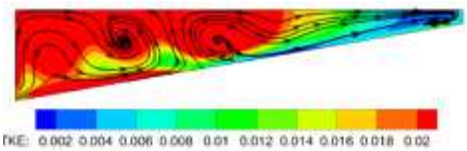
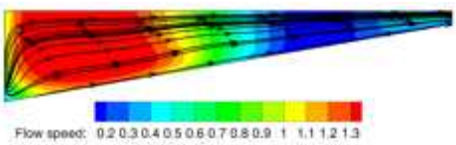
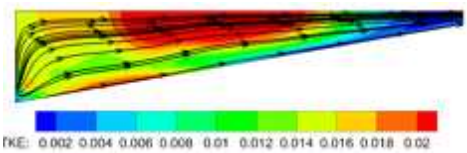
Turbulent kinetic energy (TKE)



Recirculation

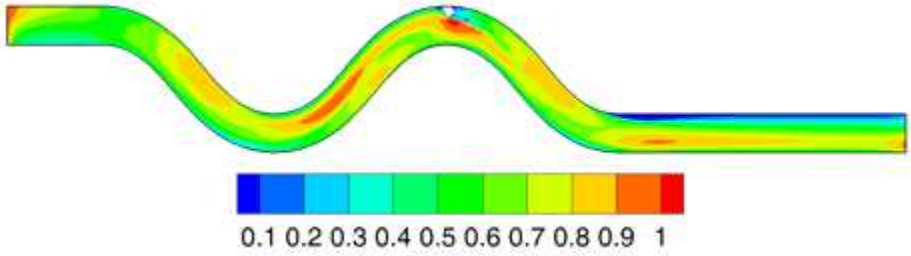


Normalized recirculation length : 2.9873

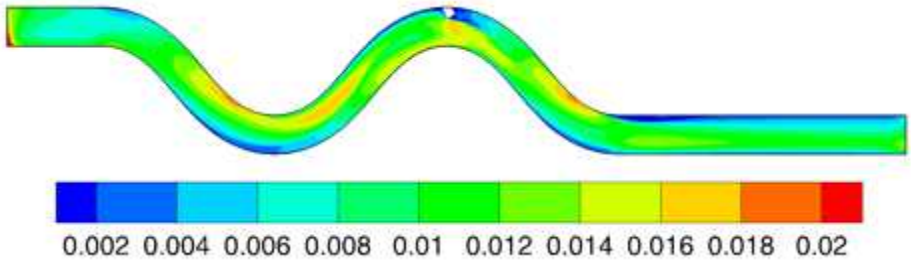
위치	case28 (R=20/ =50/α=0/l=5/h=1)	
	secondary flow	
		
A		
B		
C		
D		
F		
G		
H		
I		

case38 (bottom/R=20/ =50/α=+30/l=2.5/h=0.5)

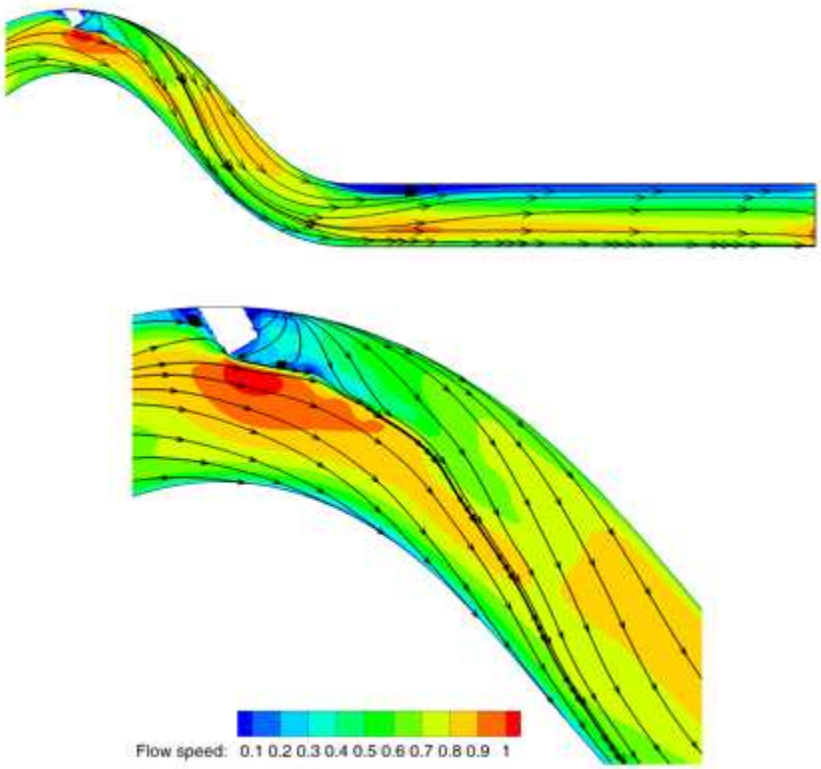
Flow speed



Turbulent kinetic energy (TKE)



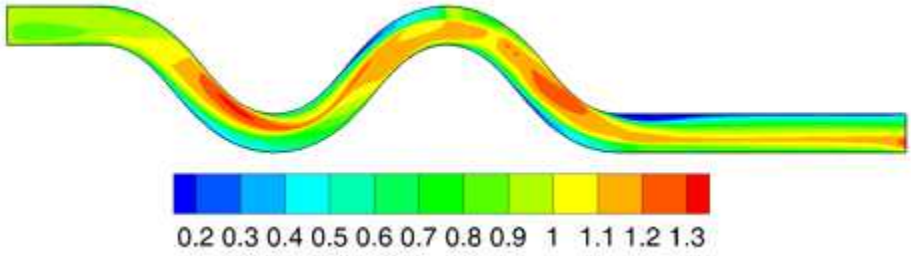
Recirculation



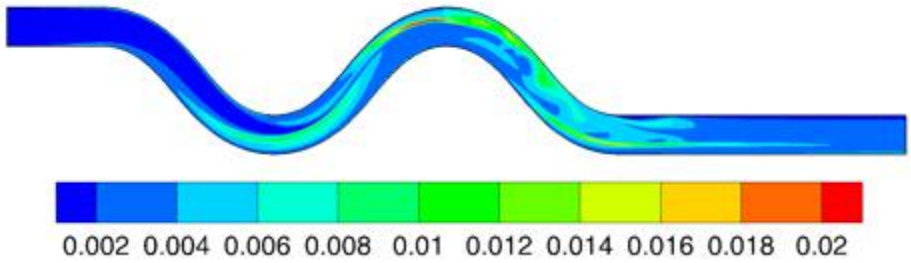
Normalized recirculation length : 0.3912

case38 (top/R=20/ =50/α=+30/l=2.5/h=0.5)

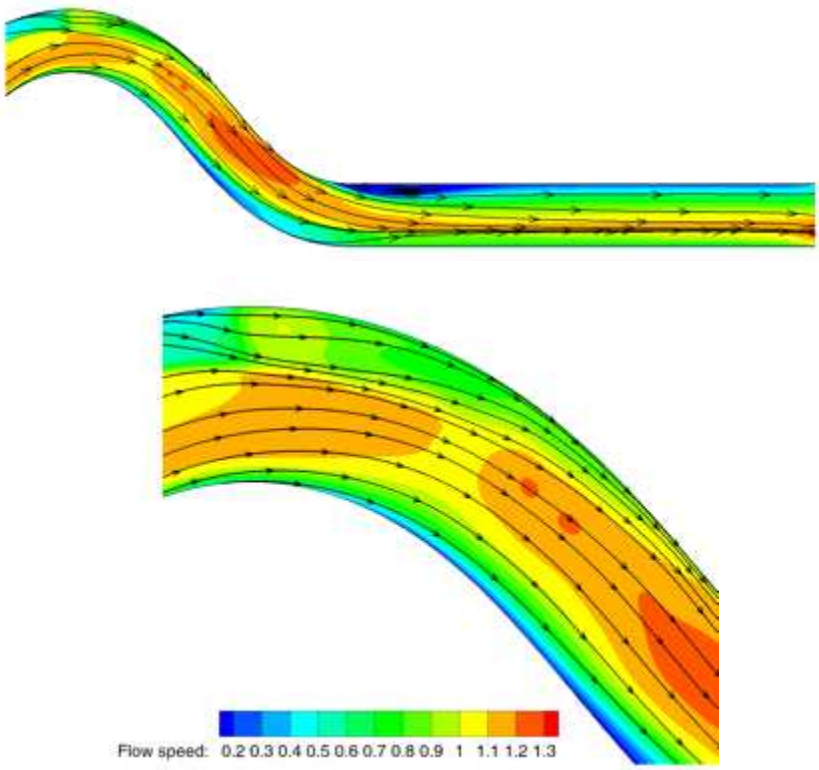
Flow speed



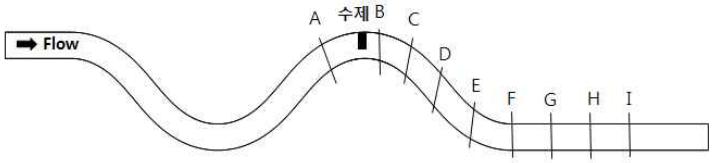
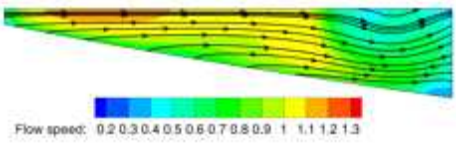
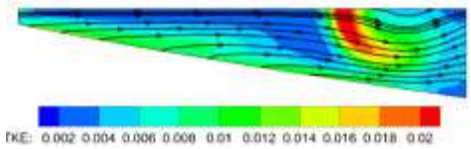
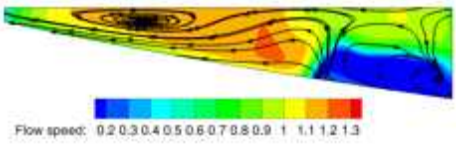
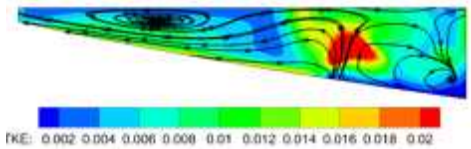
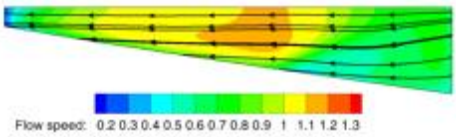
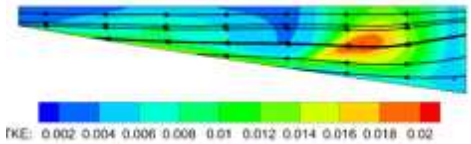
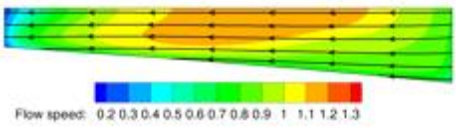
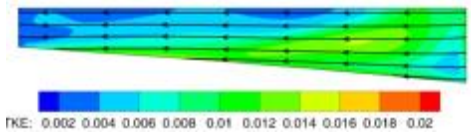
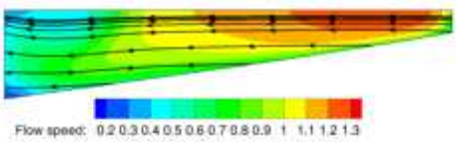
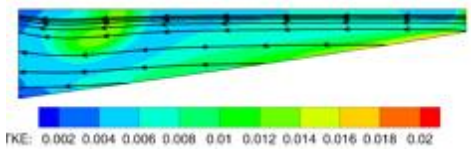
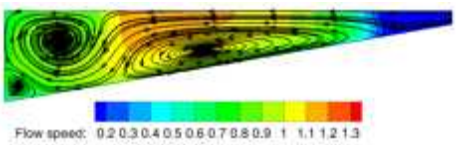
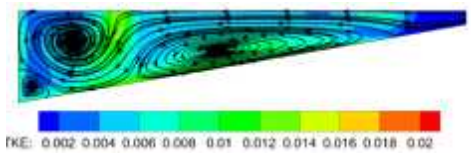
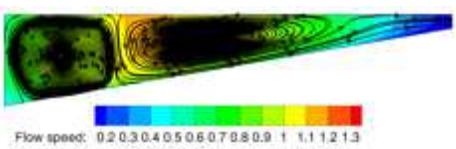
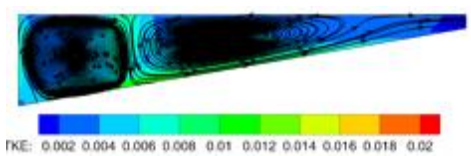
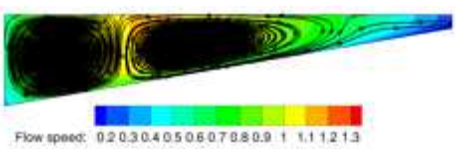
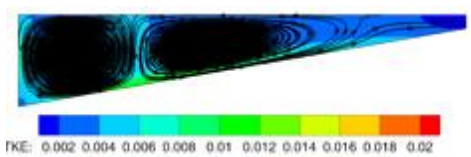
Turbulent kinetic energy (TKE)



Recirculation

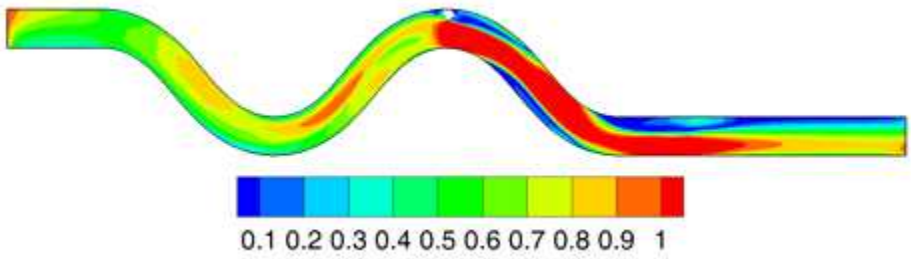


recirculation (X)

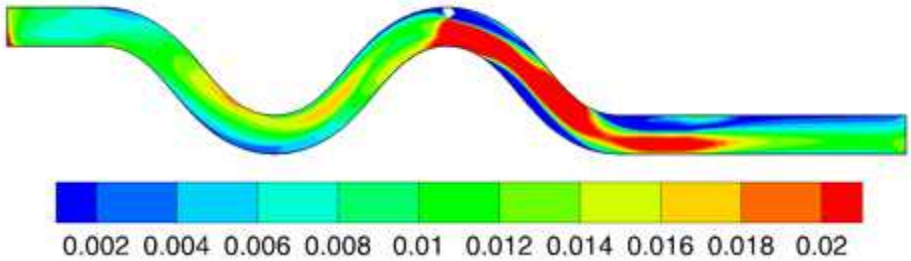
위치	case38 (R=20/ =50/α=+30/l=2.5/h=0.5)	
	secondary flow	
		
A		
B		
C		
D		
F		
G		
H		
I		

case40 (bottom/R=20/ =50/α=+30/l=2.5/h=1)

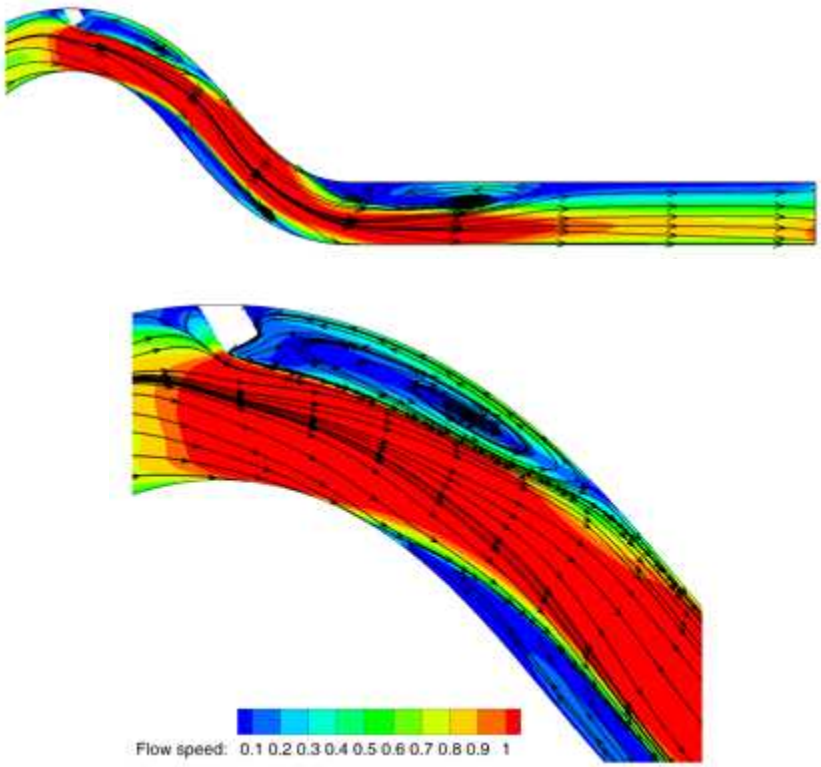
Flow speed



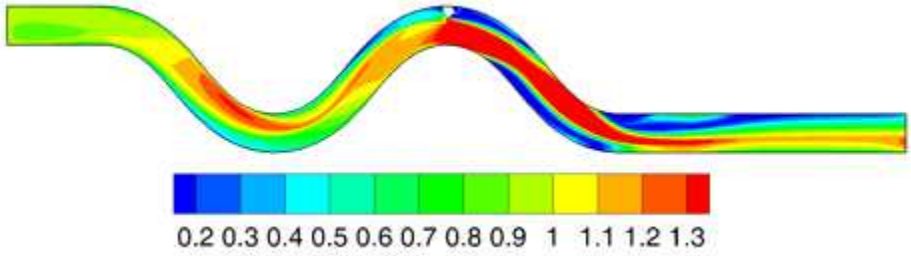
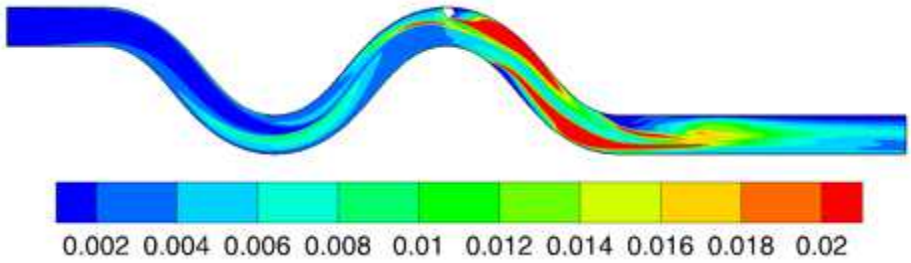
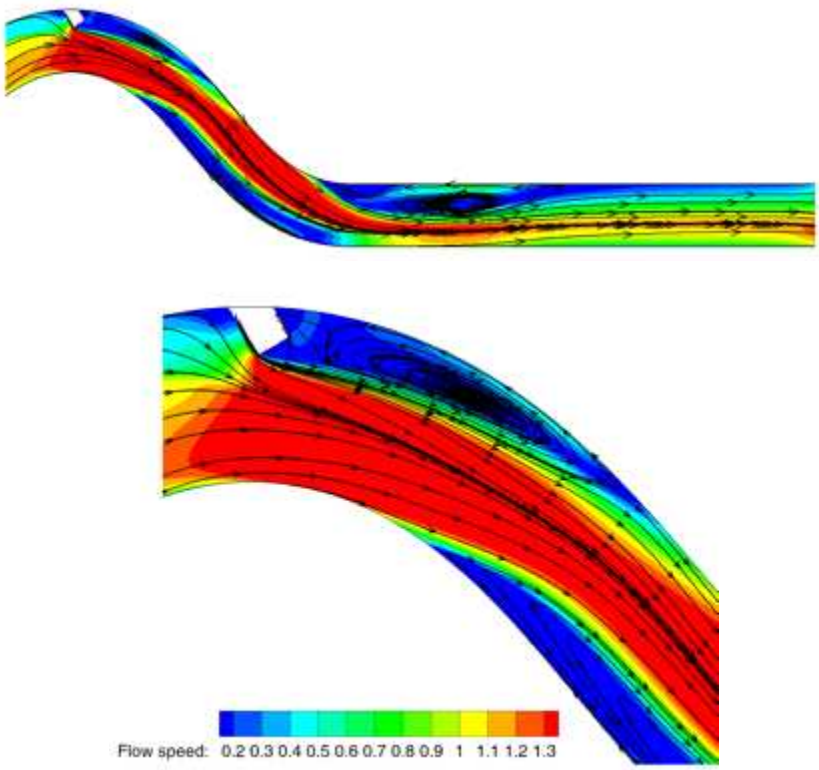
Turbulent kinetic energy (TKE)

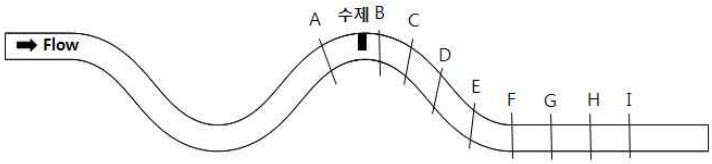
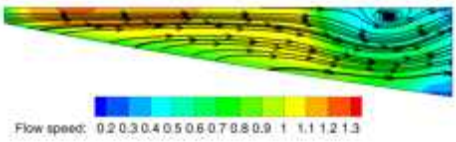
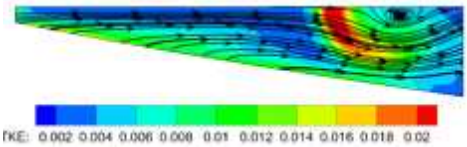
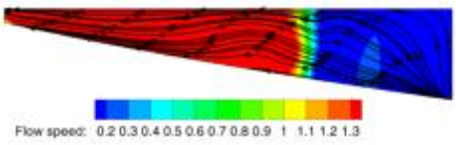
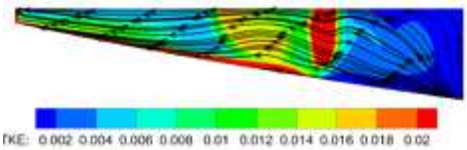
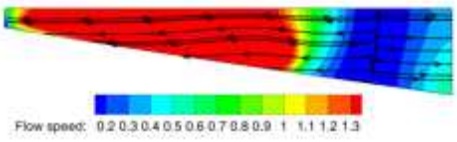
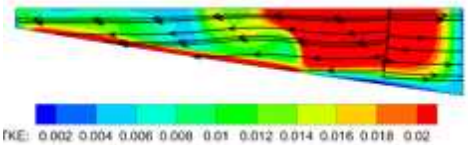
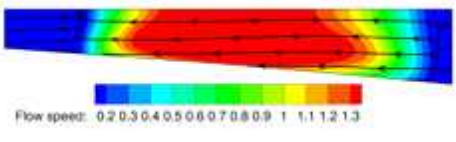
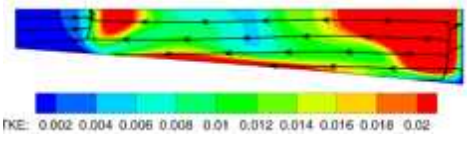
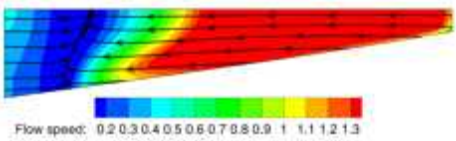
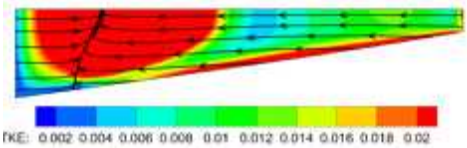
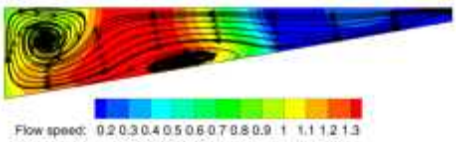
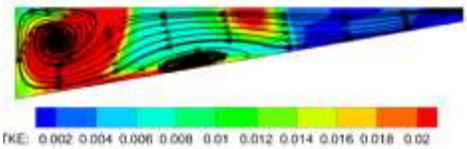
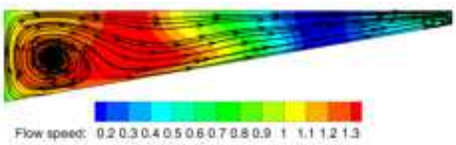
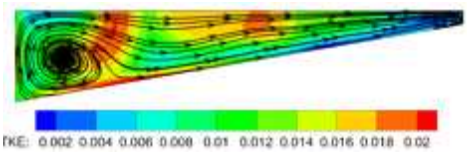
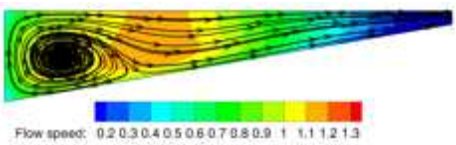
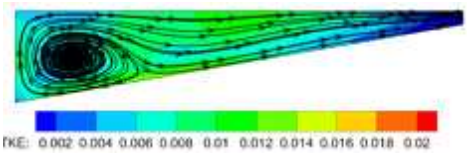


Recirculation



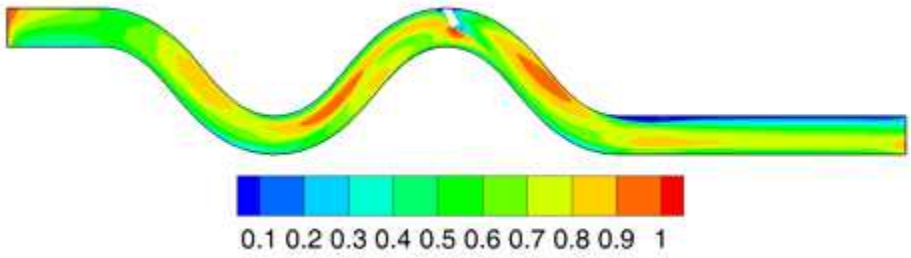
Normalized recirculation length : 2.0681

case40 (top/R=20/ =50/α=+30/l=2.5/h=1)
Flow speed

Turbulent kinetic energy (TKE)

Recirculation
 Normalized recirculation length : 2.0183

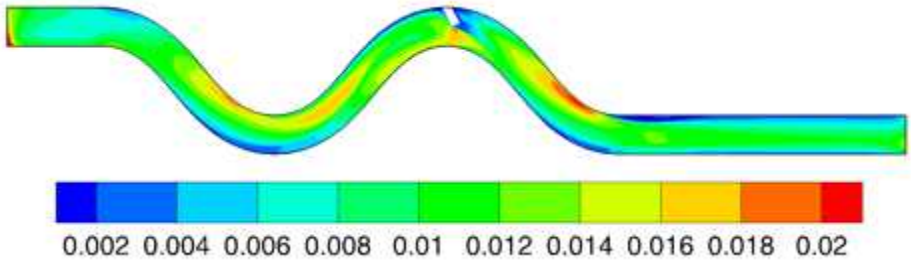
위치	case40 (R=20/ =50/α=+30/l=2.5/h=1)	
	secondary flow	
		
A		
B		
C		
D		
F		
G		
H		
I		

case42 (bottom/R=20/ =50/α=+30/l=5/h=0.5)

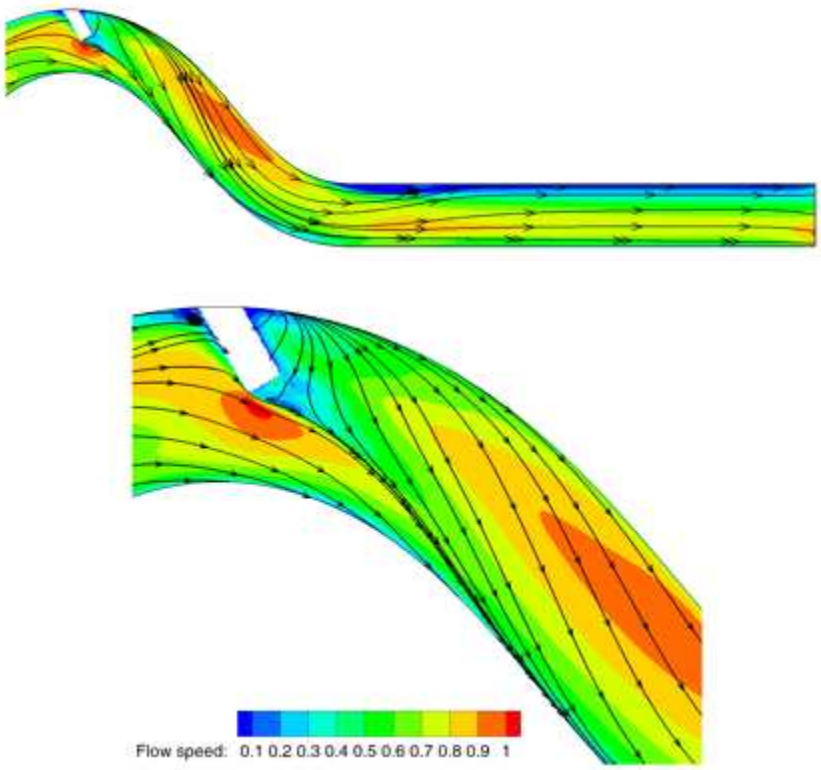
Flow speed



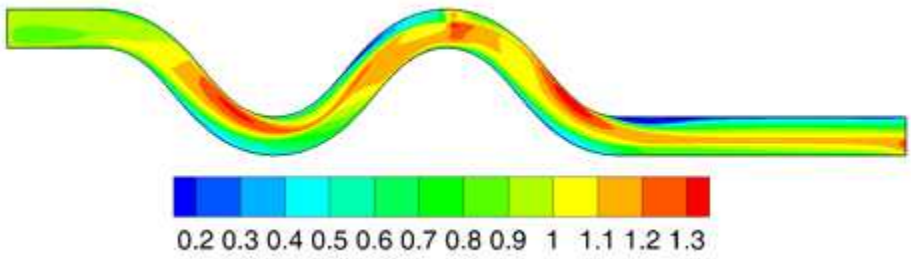
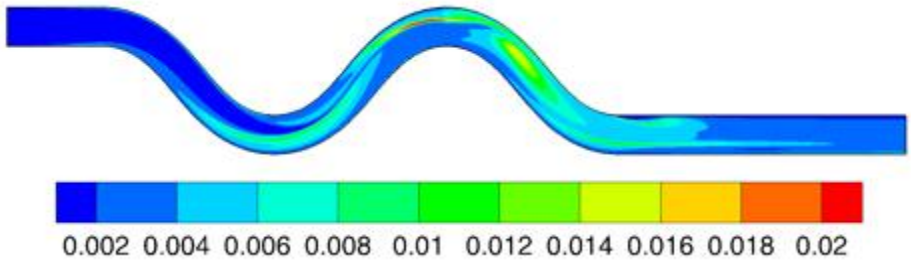
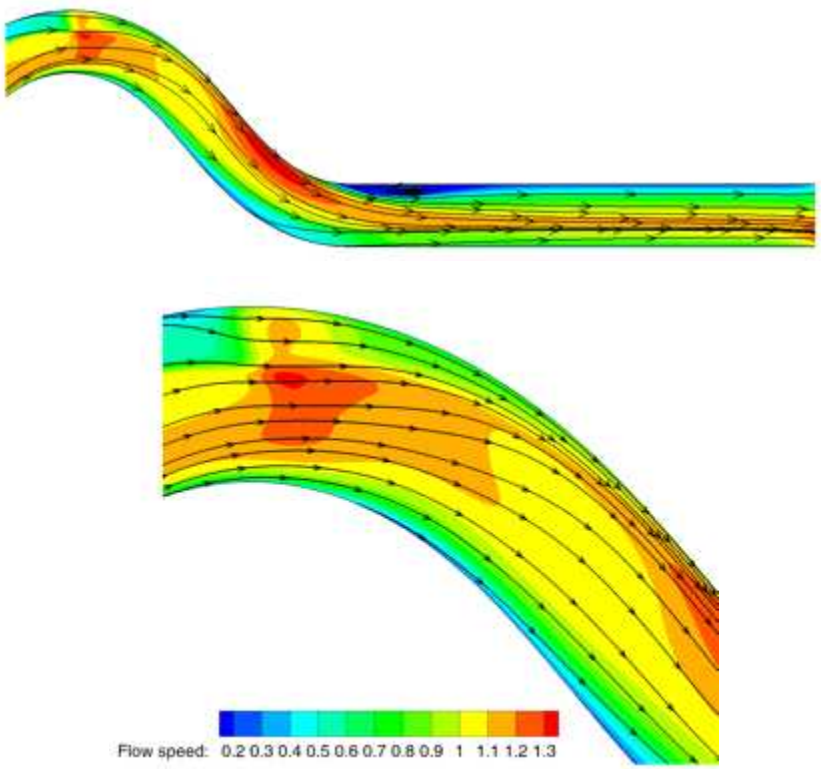
Turbulent kinetic energy (TKE)

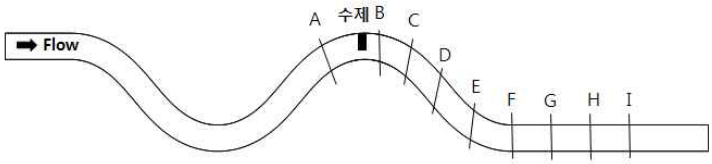
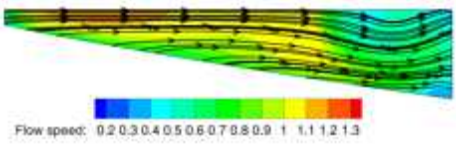
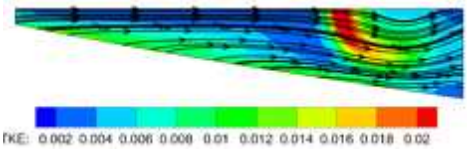
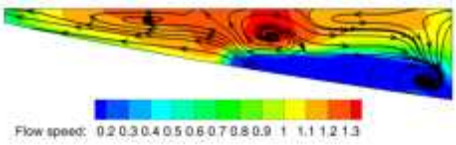
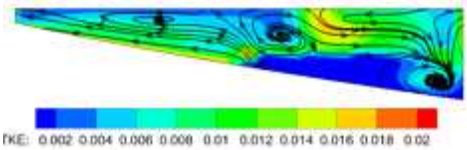
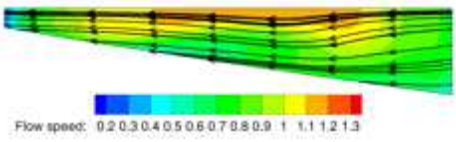
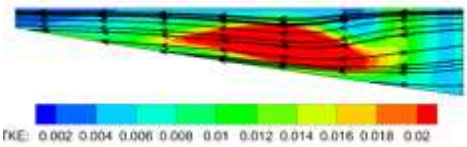
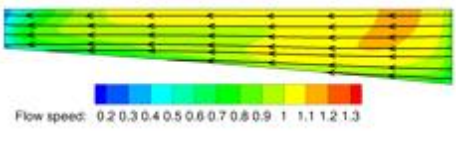
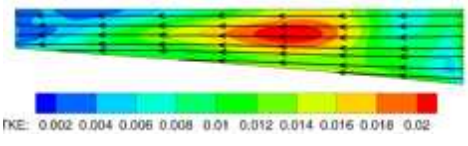
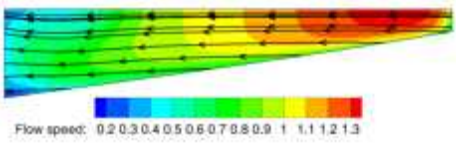
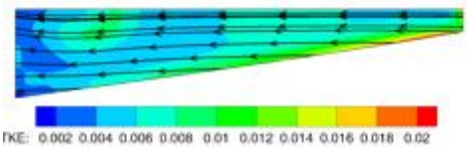
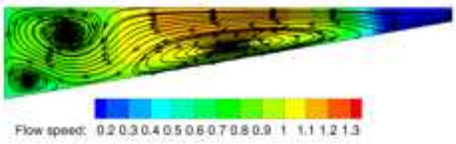
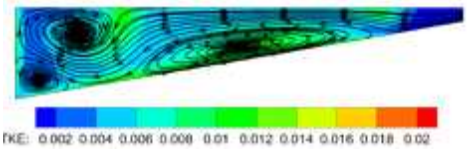
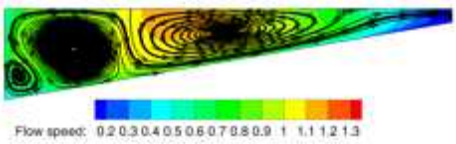
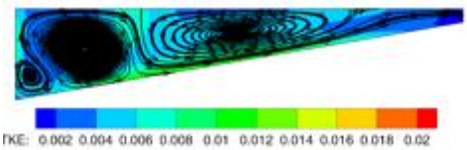
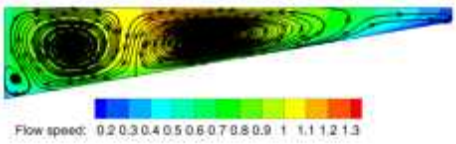
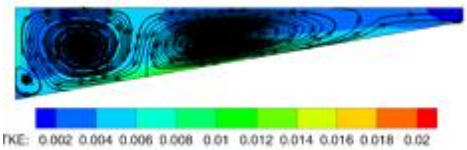


Recirculation



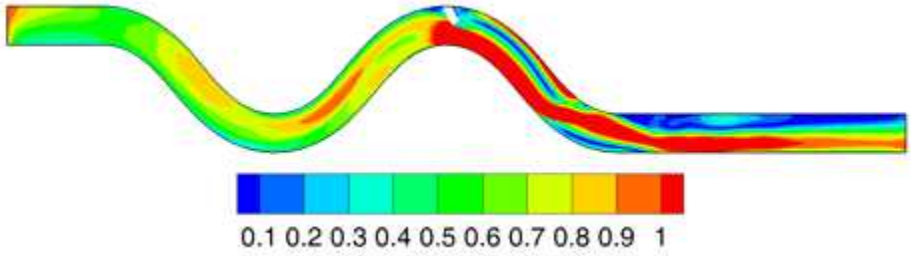
Normalized recirculation length : 0.3652

case42 (top/R=20/ =50/α=+30/l=5/h=0.5)
Flow speed

Turbulent kinetic energy (TKE)

Recirculation
 recirculation (X)

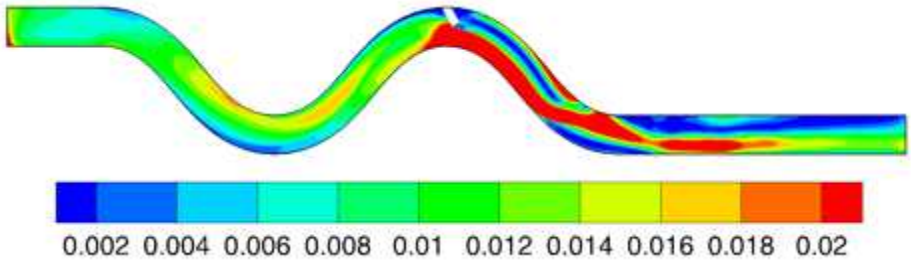
위치	case42 (R=20/ =50/α=+30/l=5/h=0.5)	
	secondary flow	
		
A		
B		
C		
D		
F		
G		
H		
I		

case44 (bottom/R=20/ =50/α=+30/l=5/h=1)

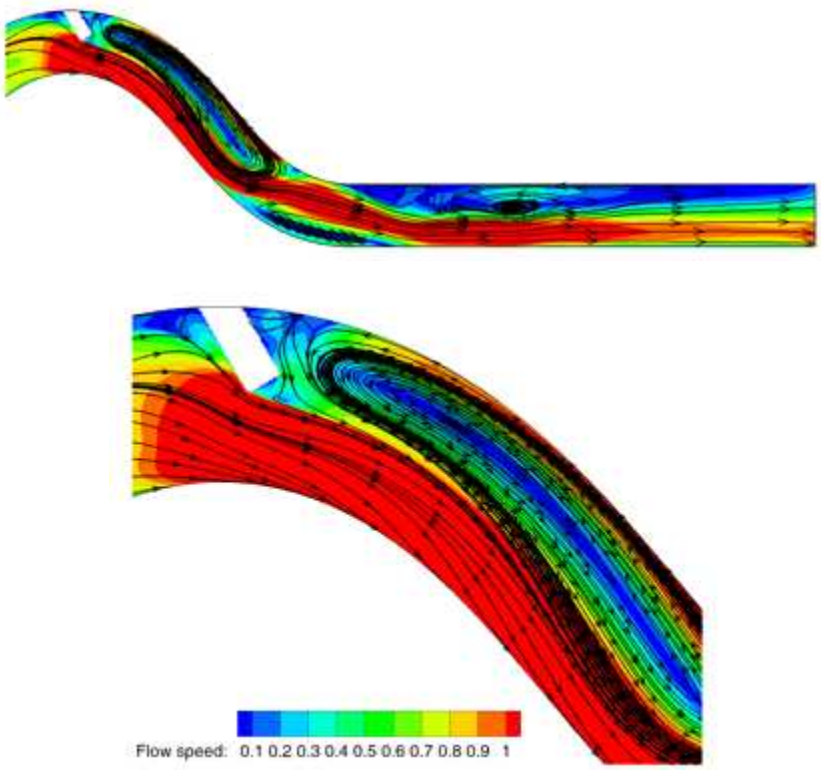
Flow speed



Turbulent kinetic energy (TKE)



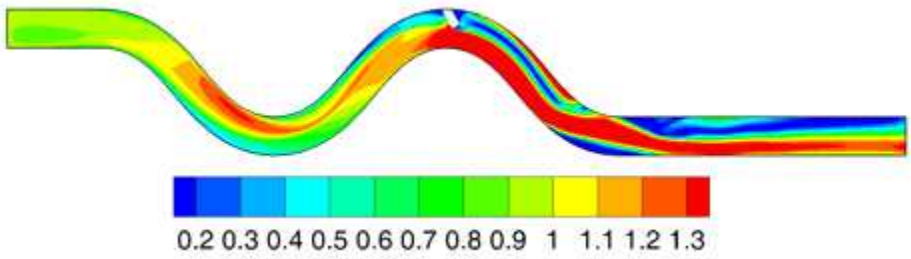
Recirculation



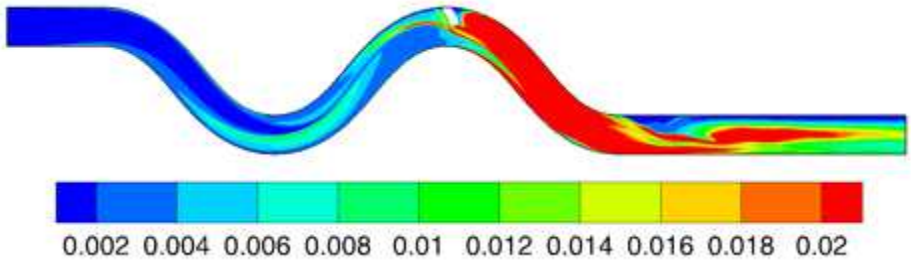
Normalized recirculation length : 3.5137

case44 (top/R=20/ =50/α=+30/l=5/h=1)

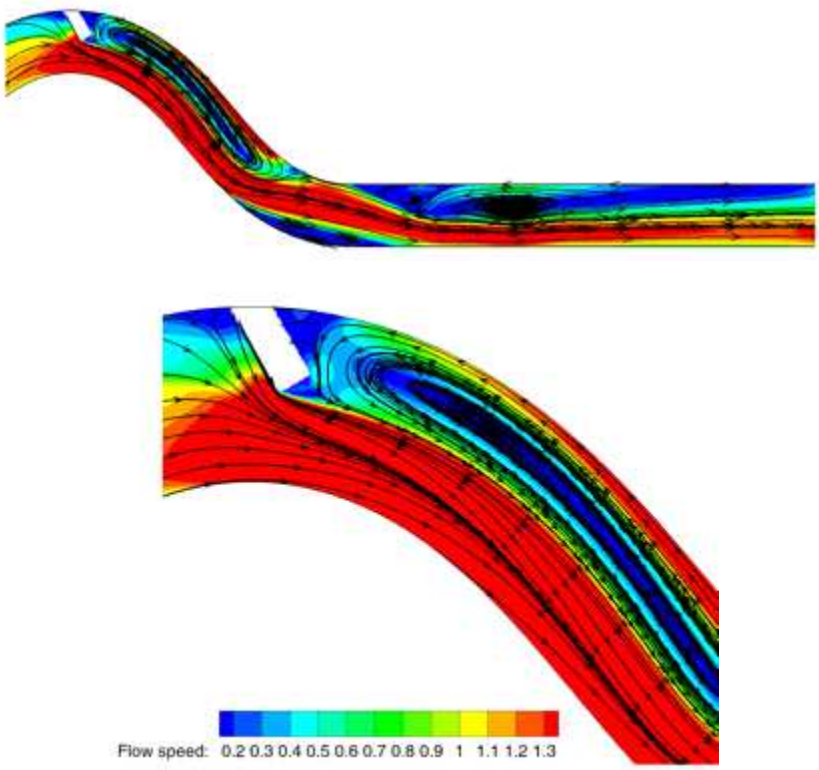
Flow speed



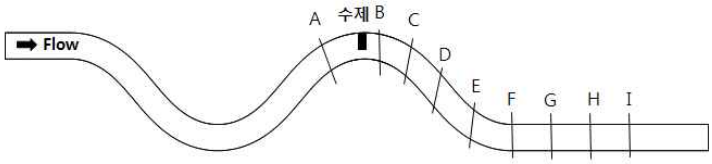
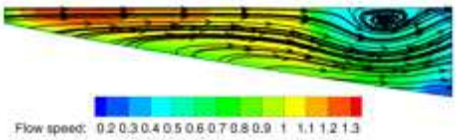
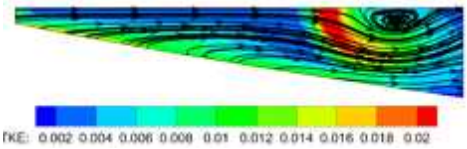
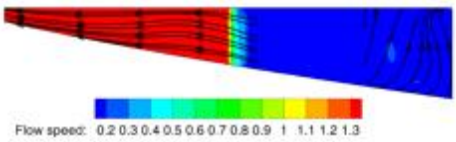
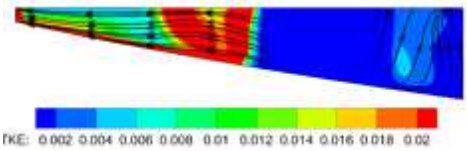
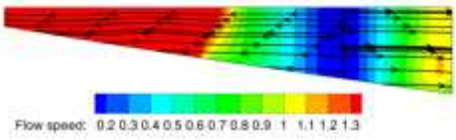
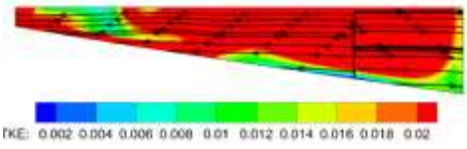
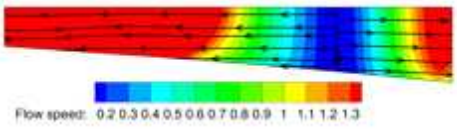
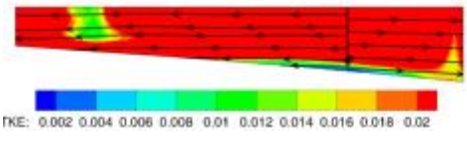
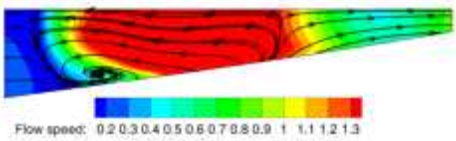
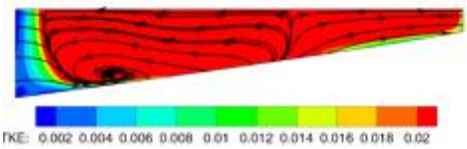
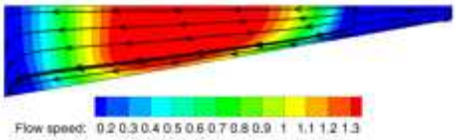
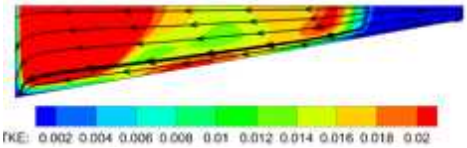
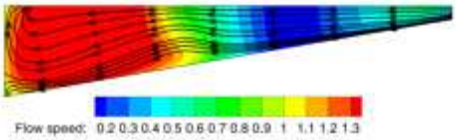
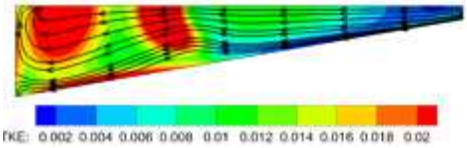
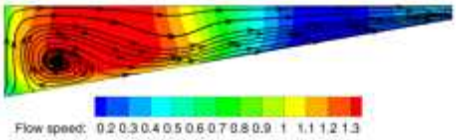
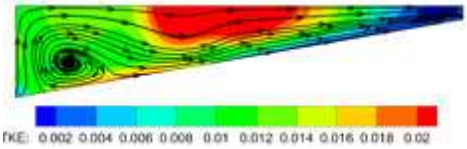
Turbulent kinetic energy (TKE)



Recirculation



Normalized recirculation length : 3.4936

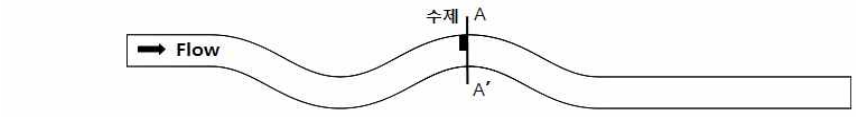
위치	case44 (R=20/ =50/α=+30/l=5/h=1)	
	secondary flow	
		
A		
B		
C		
D		
F		
G		
H		
I		

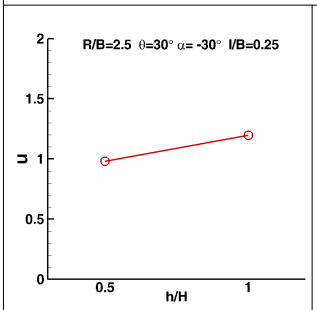
2) 수치해석 결과분석

(1) 무차원 단면 평균 유속 (u)

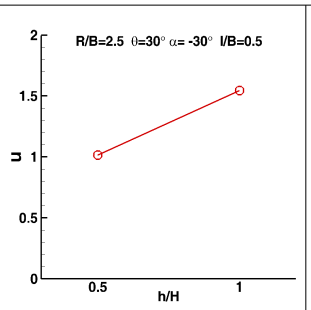
<그림 1-1> AA′ 단면 평균 유속 (u)

(l : 수제 길이, B : 하천 폭, R : 하천 반지름
: 하천 각도, α : 수제 각도. h : 수제 높이, H : 수심)

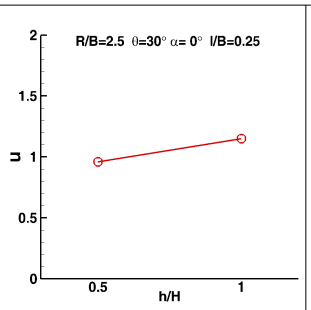




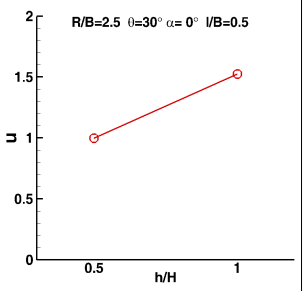
①



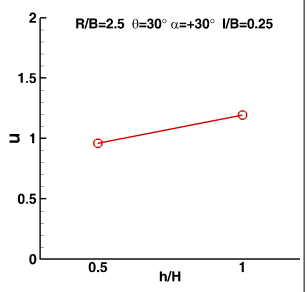
②



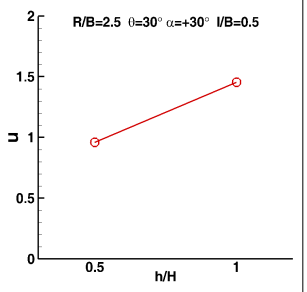
③



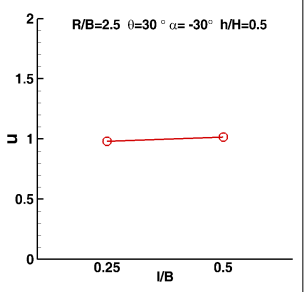
④



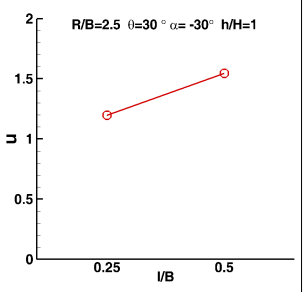
⑤



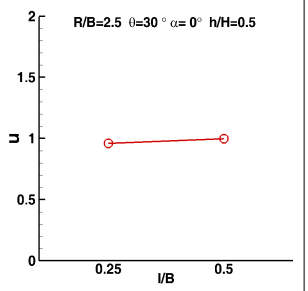
⑥



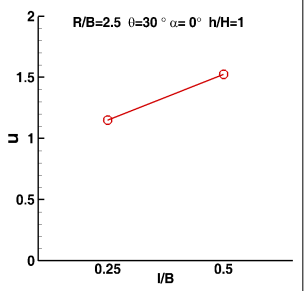
⑦



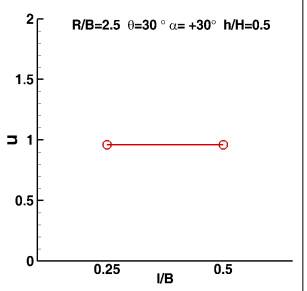
⑧



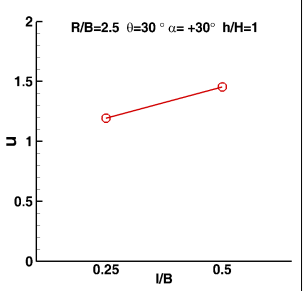
⑨



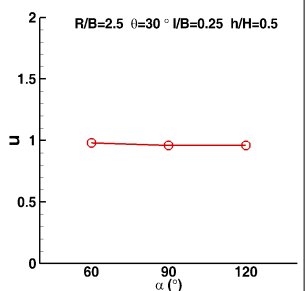
⑩



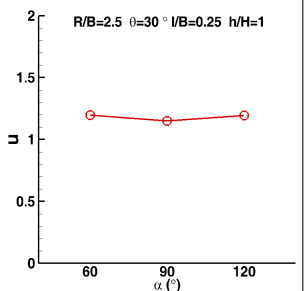
⑪



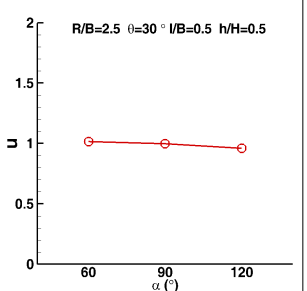
⑫



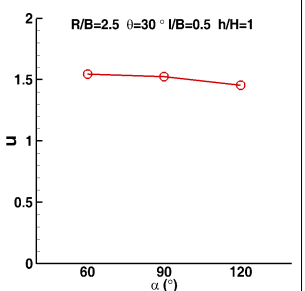
⑬



⑭



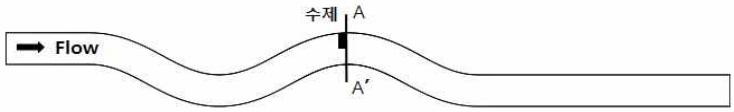
⑮

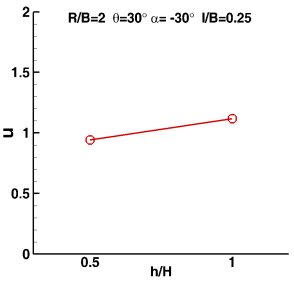


⑯

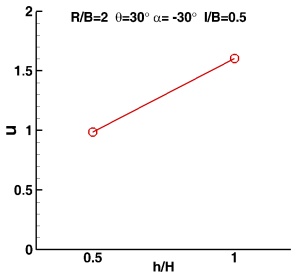
<그림 1-2> AA′ 단면 평균 유속 (u)

(l : 수제 길이, B : 하천 폭, R : 하천 반지름
: 하천 각도, α : 수제 각도. h : 수제 높이, H : 수심)

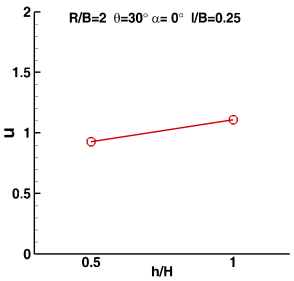




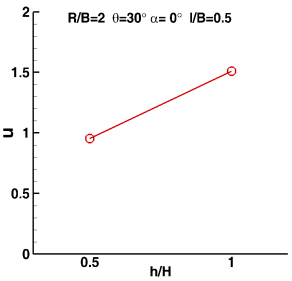
①



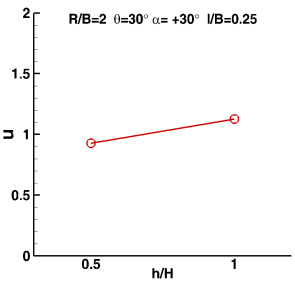
②



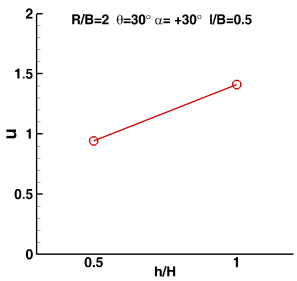
③



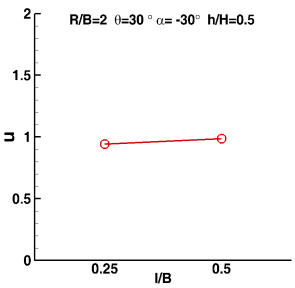
④



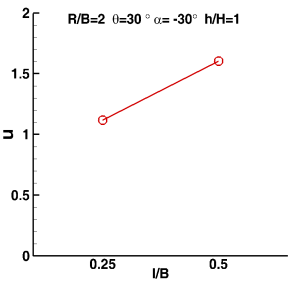
⑤



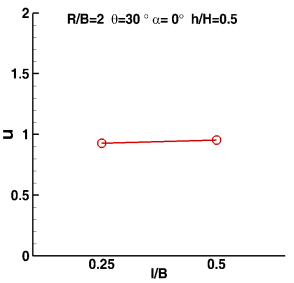
⑥



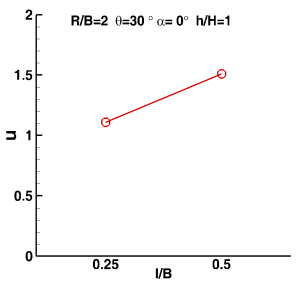
⑦



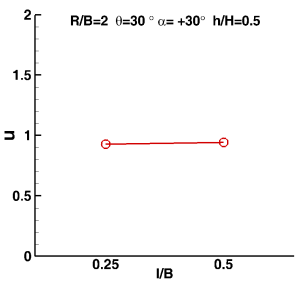
⑧



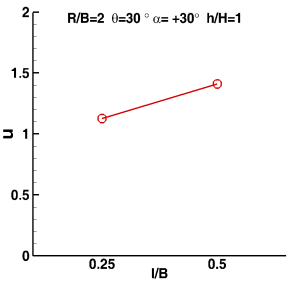
⑨



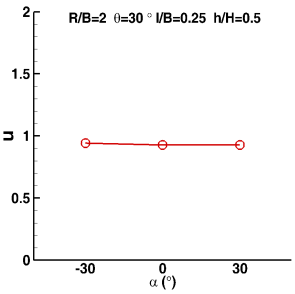
⑩



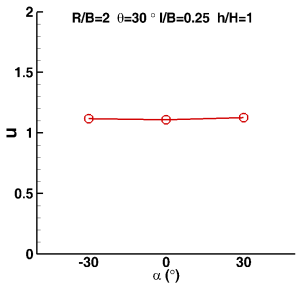
⑪



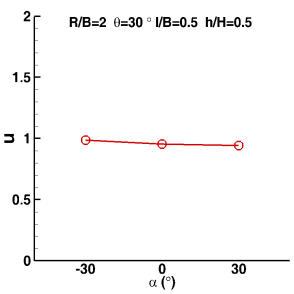
⑫



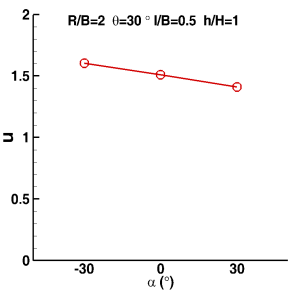
⑬



⑭



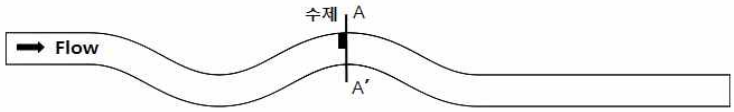
⑮

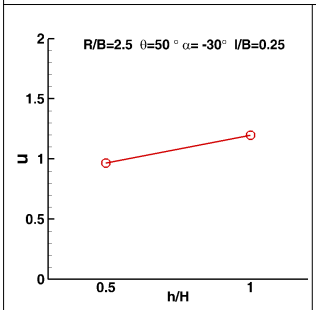


⑯

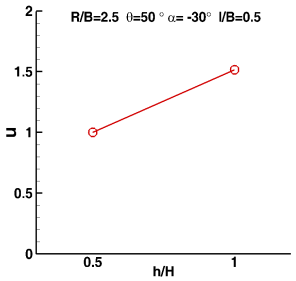
<그림 1-3> AA′ 단면 평균 유속 (u)

(l : 수제 길이, B : 하천 폭, R : 하천 반지름
: 하천 각도, α : 수제 각도. h : 수제 높이, H : 수심)

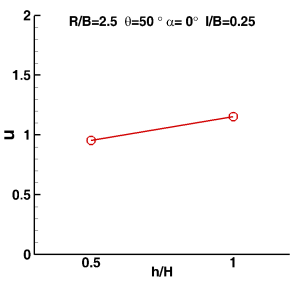




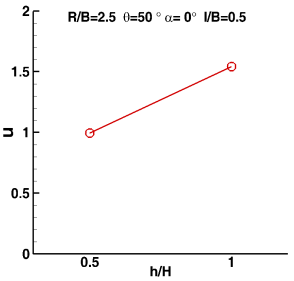
①



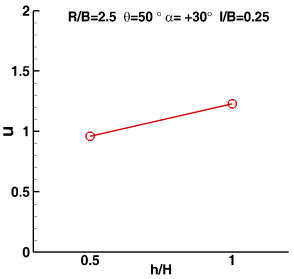
②



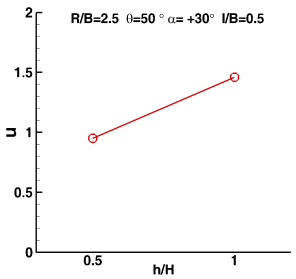
③



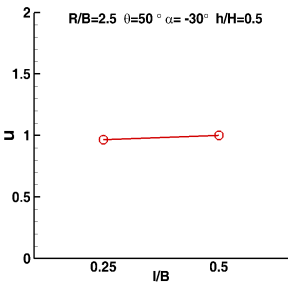
④



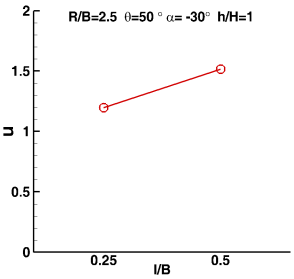
⑤



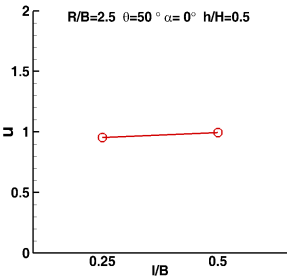
⑥



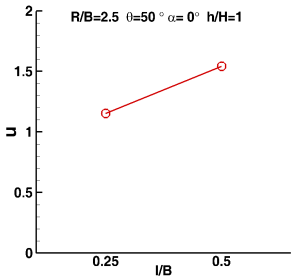
⑦



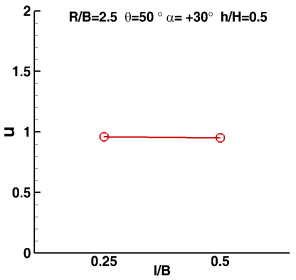
⑧



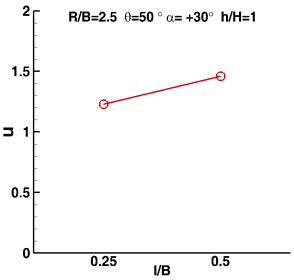
⑨



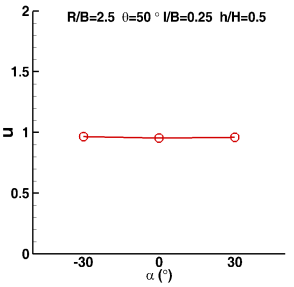
⑩



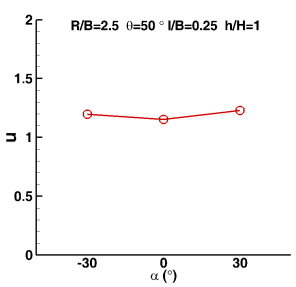
⑪



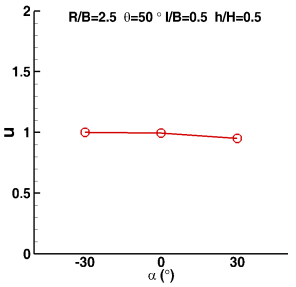
⑫



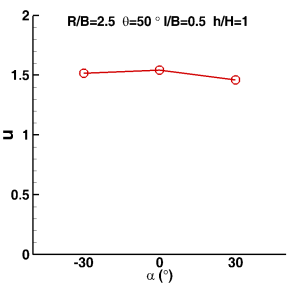
⑬



⑭



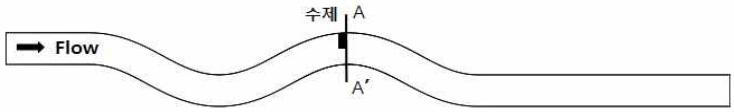
⑮

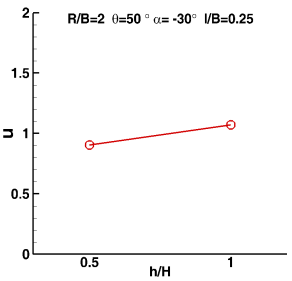


⑯

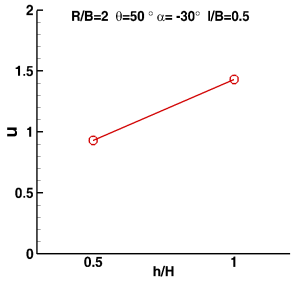
<그림 1-4> AA′ 단면 평균 유속 (u)

(l : 수제 길이, B : 하천 폭, R : 하천 반지름
: 하천 각도, α : 수제 각도. h : 수제 높이, H : 수심)

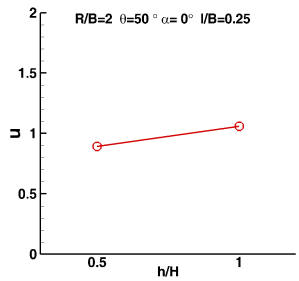




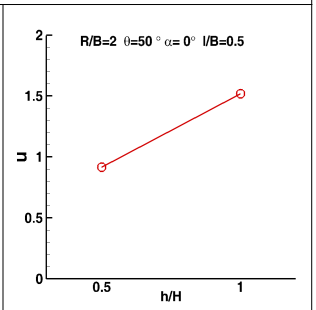
①



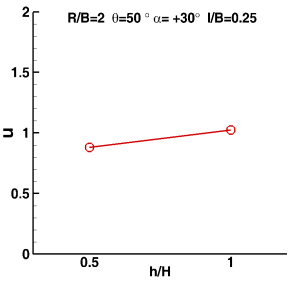
②



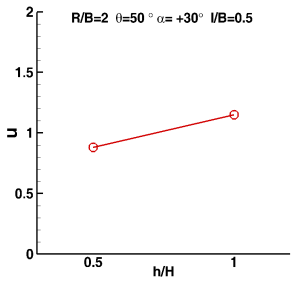
③



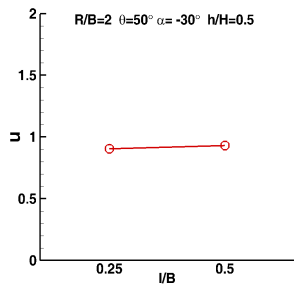
④



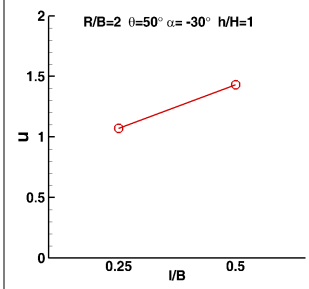
⑤



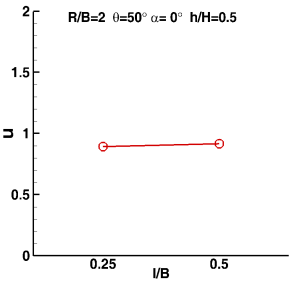
⑥



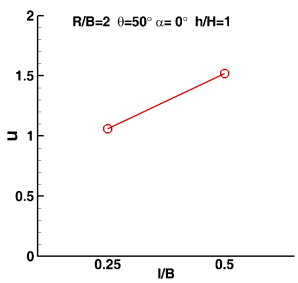
⑦



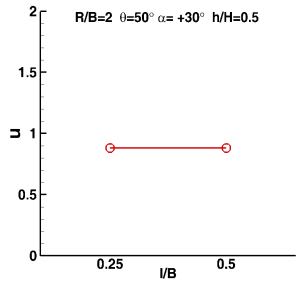
⑧



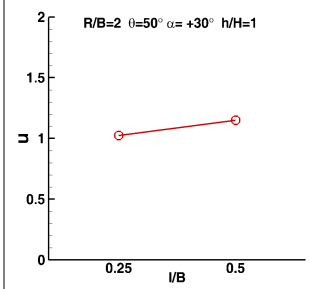
⑨



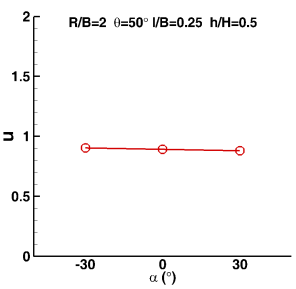
⑩



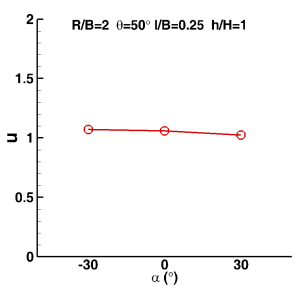
⑪



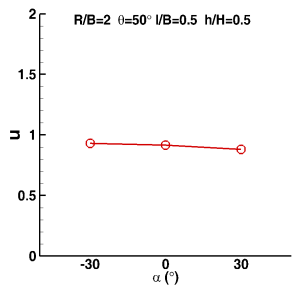
⑫



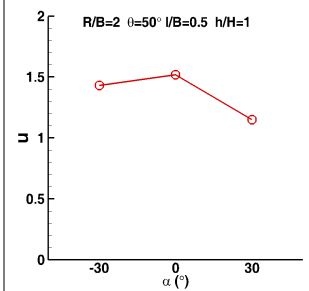
⑬



⑭



⑮



⑯

○ 그림 <1-1~4> 모든 경우에서, ①~⑥의 경우 l/B=0.25에서 l/B=0.5로 증가할 때, 무차원 유속이 증가하는 것을 통해, 같은 조건에서 수제 길이가 길어질 때 수제와 가장 근접한 단면(A-A′)의 유속이 증가한다는 것을 알 수 있다.

○ 그림 <1-1~4> 모든 경우에서, ⑦~⑫의 경우 h/H=0.5에서 h/H=1로 증가할 때, 무차원 유속이 증가하는 것을 통해, 같은 조건에서 수제의 높이가 증가할 때 수제와 가장 근접한 단면(A-A′)의 유속이 증가한다는 것을 알 수 있다.

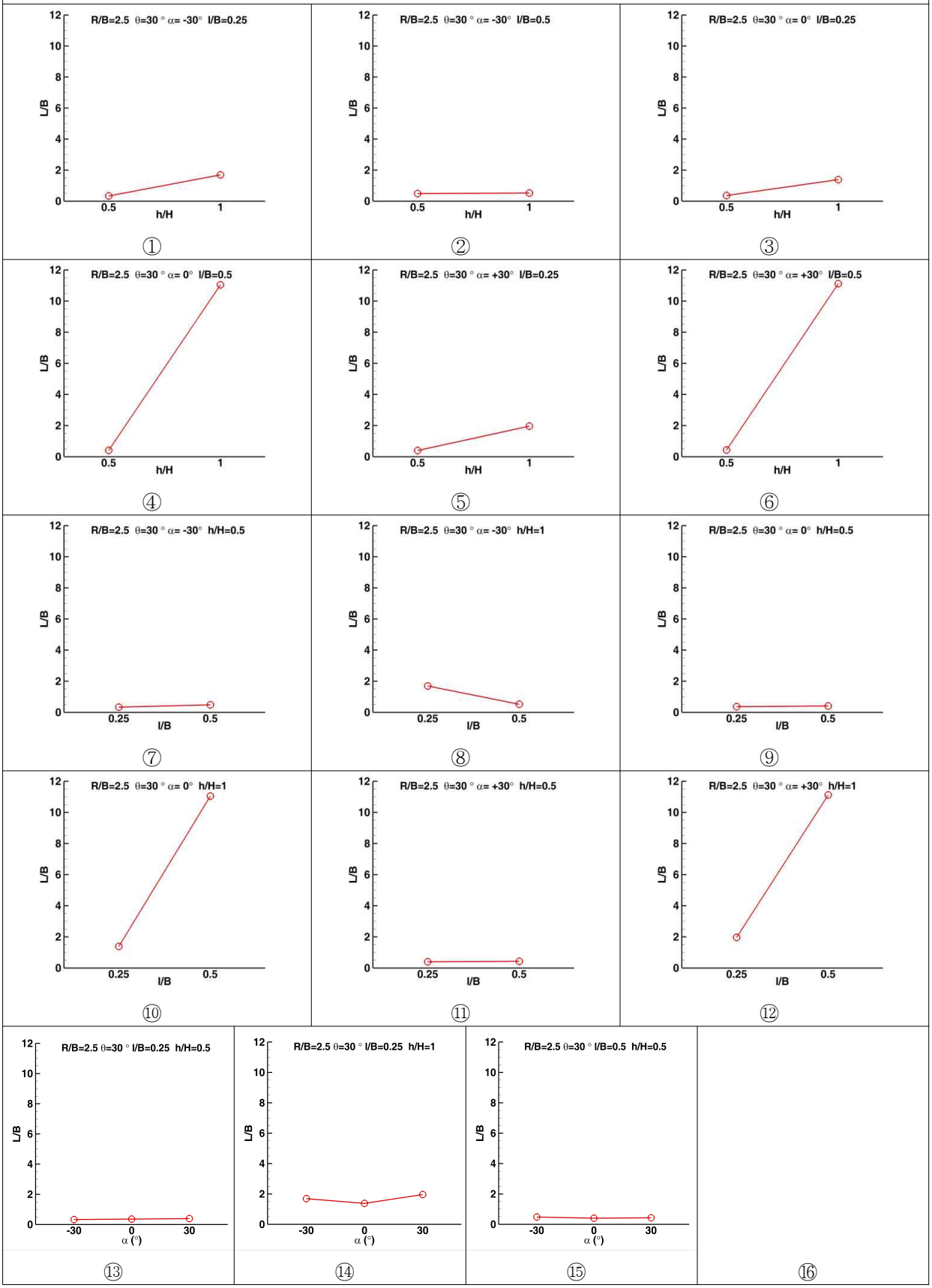
○ 바로 위의 경우를 그림 <1-1~4>의 ⑬~⑯의 경우에서도 확인할 수 있다. 같은 조건일 때, h/H=0.5일 때보다 h/H=1일 때의 그래프에서 UU 값이 더 위쪽에 있는 것을 통해 같은 조건에서 수제의 높이가 증가할 때 수제와 가장 근접한 단면(A-A′)의 유속이 증가한다는 것을 알 수 있다.

○ 그림 <1-1,2>에서는 l/B=0.5, h/H=1이고 =-30°일 때 무차원 유속의 크기가 가장 컸고, 그림 <1-3,4>에서는 l/B=0.5, h/H=1이고 θ= 0°일 때 무차원 유속의 크기가 가장 크다는 것을 알 수 있다.

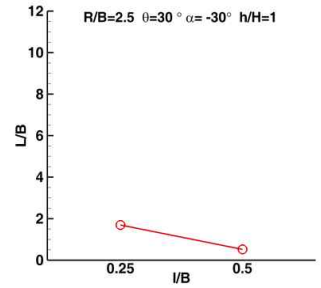
(2) 무차원 재순환영역 길이

<그림 2-1-1> 하상에서의 무차원 재순환영역 길이 (L/B)

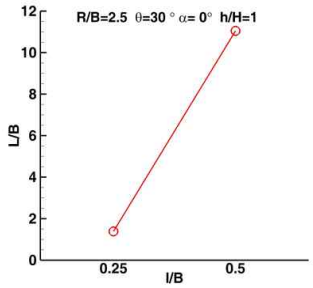
(L : 재순환영역 길이, l : 수제 길이, B : 하천 폭, R : 하천 반지름
: 하천 각도, α : 수제 각도. h : 수제 높이, H : 수심)



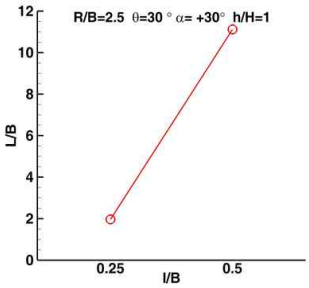
<그림 2-1-2> 수면에서의 무차원 재순환영역 길이 (L/B)
(단, 수면에서 h/H=0.5인 경우는 재순환영역이 존재하지 않는다.)



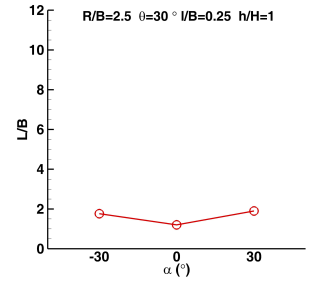
①



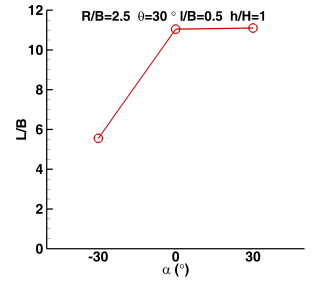
②



③



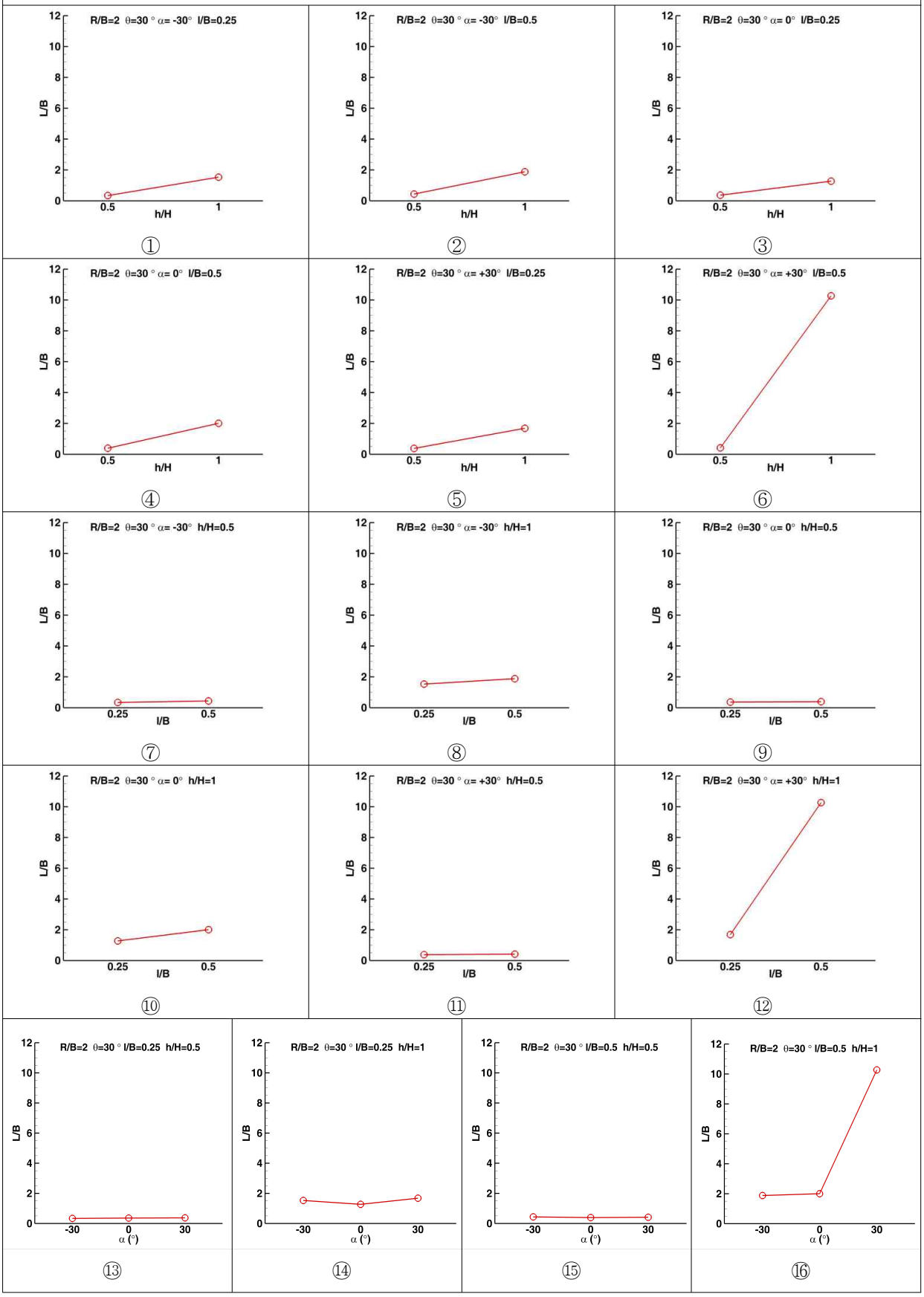
④



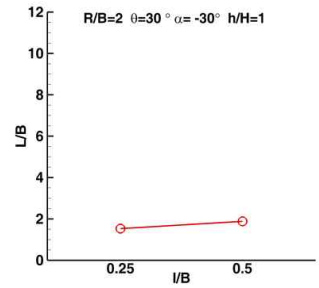
⑤

<그림 2-2-1> 하상에서의 무차원 재순환영역 길이 (L/B)

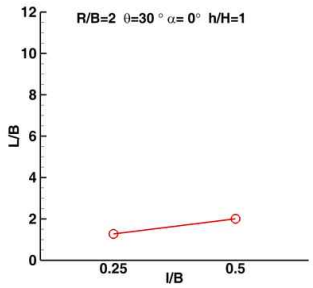
(L : 재순환영역 길이, l : 수제 길이, B : 하천 폭, R : 하천 반지름
: 하천 각도, α : 수제 각도. h : 수제 높이, H : 수심)



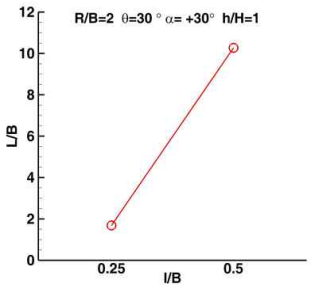
<그림 2-2-2> 수면에서의 무차원 재순환영역 길이 (L/B)
(단, 수면에서 h/H=0.5인 경우는 재순환영역이 존재하지 않는다.)



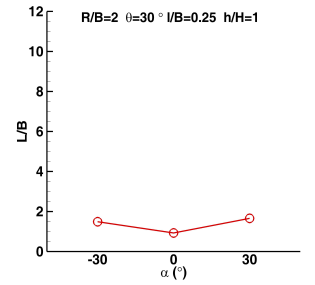
①



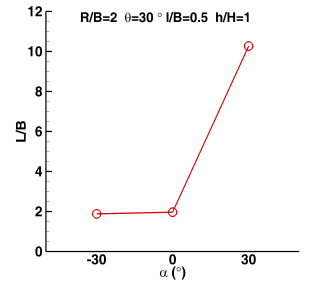
②



③



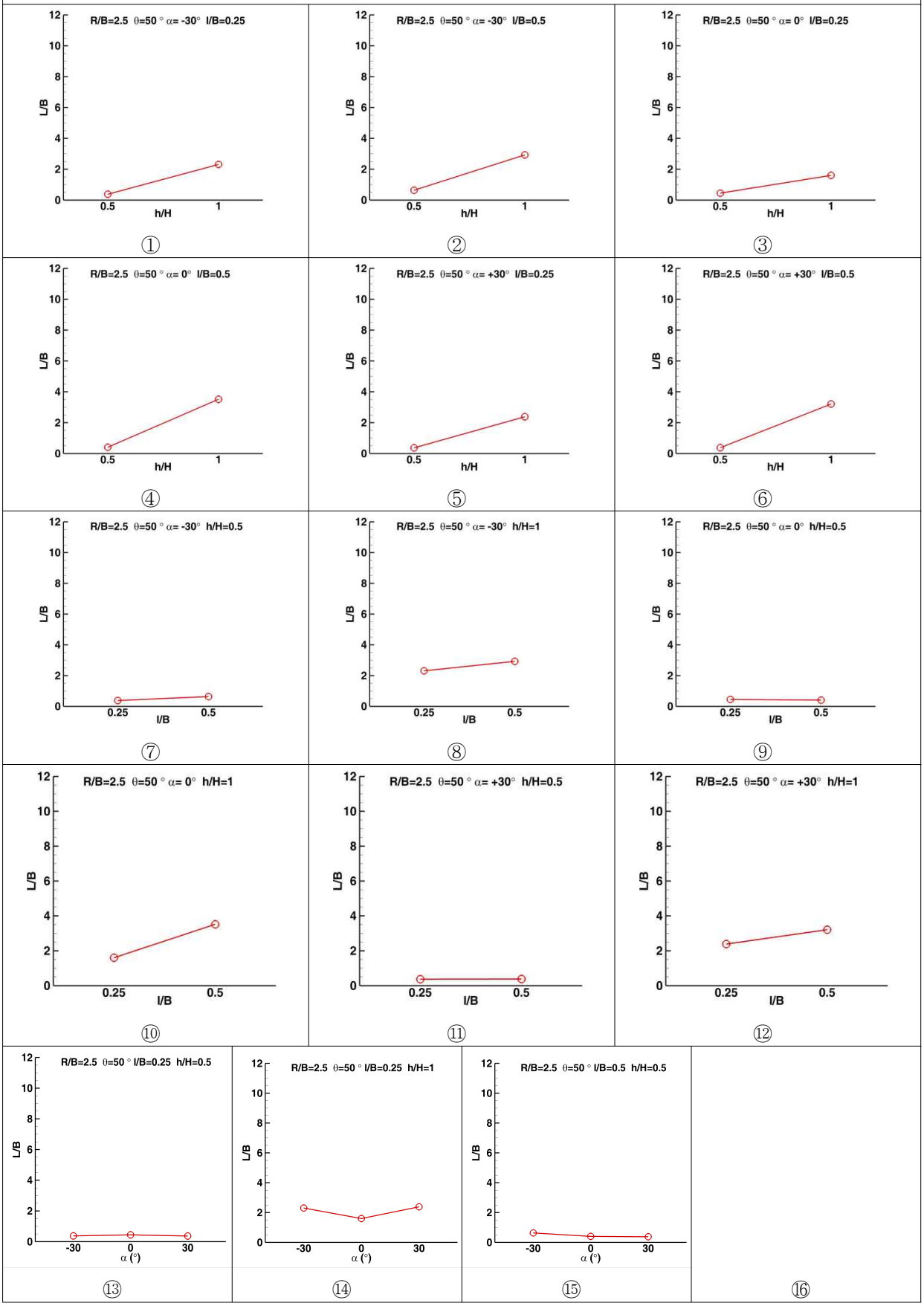
④



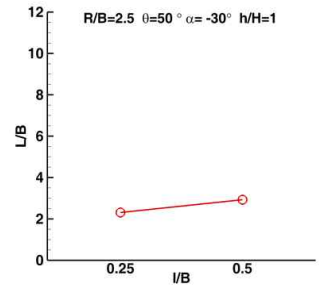
⑤

<그림 2-3-1> 하상에서의 무차원 재순환영역 길이 (L/B)

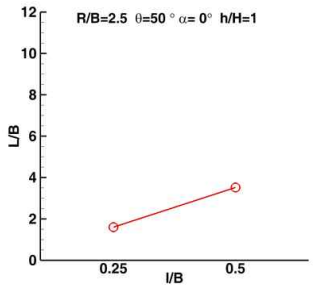
(L : 재순환영역 길이, l : 수제 길이, B : 하천 폭, R : 하천 반지름
: 하천 각도, α : 수제 각도. h : 수제 높이, H : 수심)



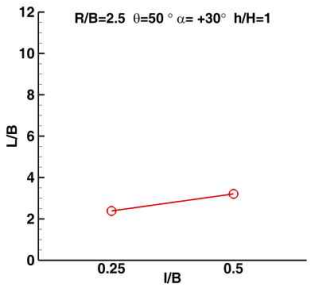
<그림 2-3-2> 수면에서의 무차원 재순환영역 길이 (L/B)
(단, 수면에서 h/H=0.5인 경우는 재순환영역이 존재하지 않는다.)



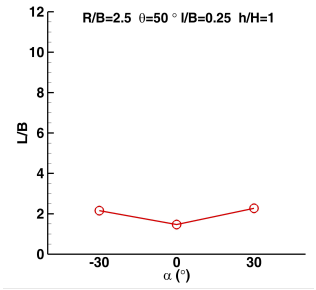
①



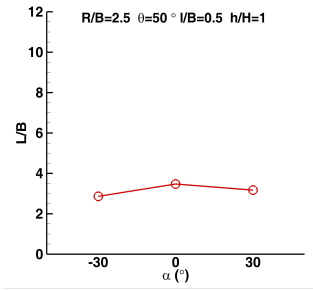
②



③



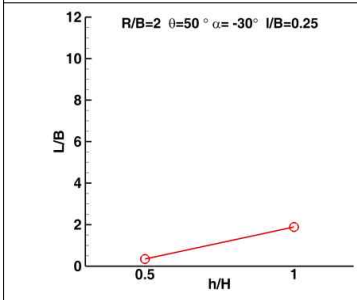
④



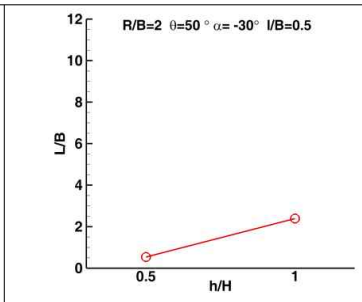
⑤

<그림 2-4-1> 하상에서의 무차원 재순환영역 길이 (L/B)

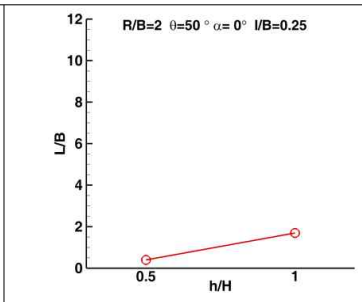
(L : 재순환영역 길이, l : 수제 길이, B : 하천 폭, R : 하천 반지름
: 하천 각도, α : 수제 각도. h : 수제 높이, H : 하천 수심)



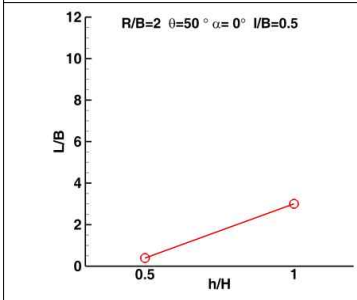
①



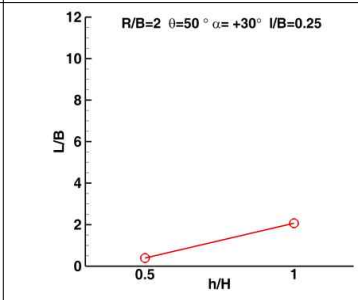
②



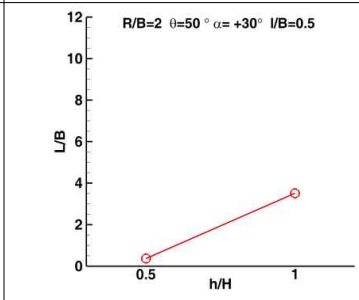
③



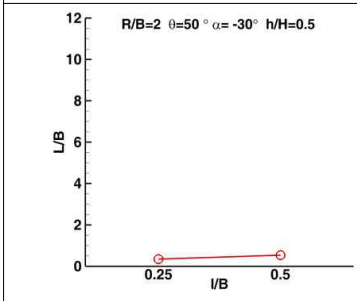
④



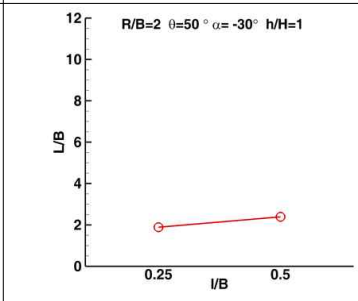
⑤



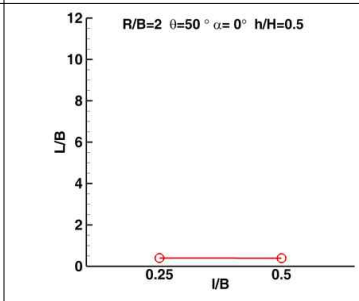
⑥



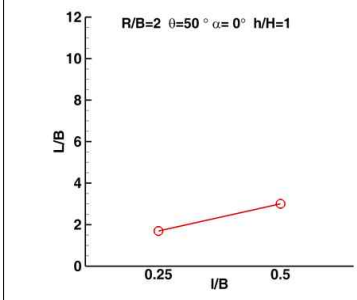
⑦



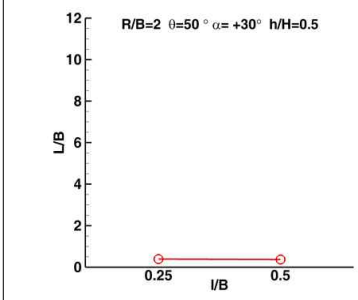
⑧



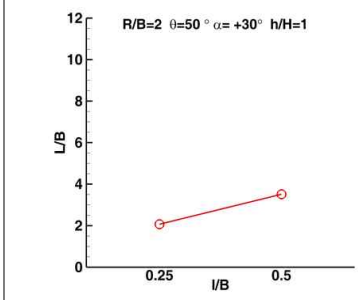
⑨



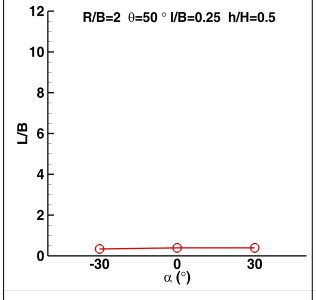
⑩



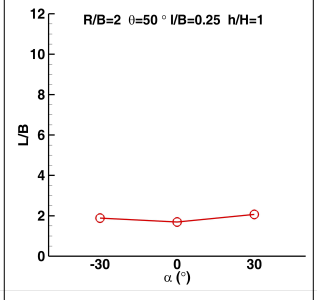
⑪



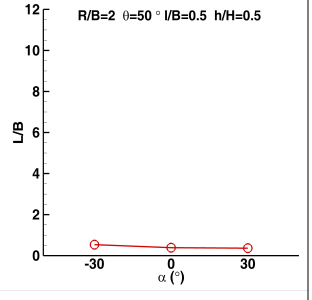
⑫



⑬



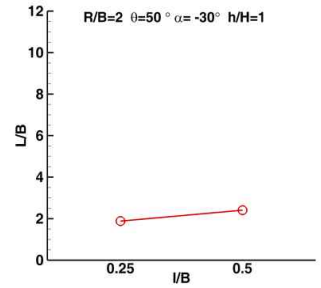
⑭



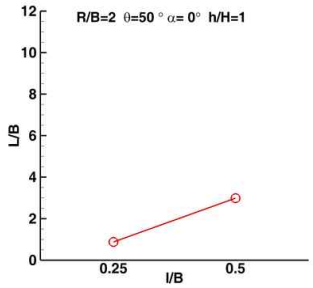
⑮

⑯

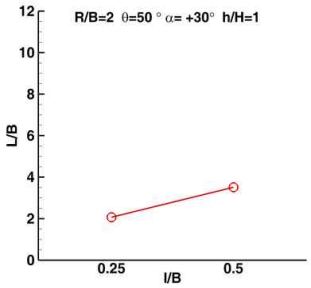
<그림 2-4-2> 수면에서의 무차원 재순환영역 길이 (L/B)
(단, 수면에서 h/H=0.5인 경우는 재순환영역이 존재하지 않는다.)



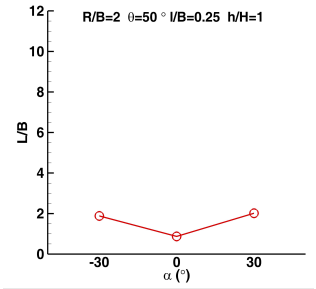
①



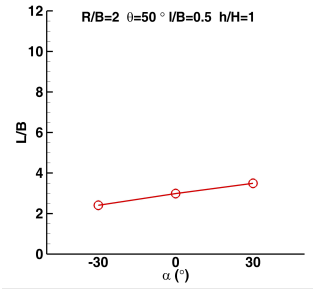
②



③



④



⑤

○ <그림 2-1-1>, <그림 2-2-1>, <그림 2-3-1>, <그림 2-4-1>에서 ①~⑥ 통해, h/H=0.5일 때는 무차원 재순환영역 길이(L/B)값이 0에 가까운 값을 나타내는 것으로 보아 무차원 재순환영역 길이는 수제가 반 정도 잠겼을 때 수제의 길이와, 각도와 상관없이 아주 작다는 것을 알 수 있다.

○ <그림 2-1-1>에서 ③~⑥, ⑨~⑫, ⑯을 통해 수제 각도가 0°, +30°로 기울었을 때는 수제의 길이가 길어질 때, 수제의 높이가 높아질 때, 바닥에서의 무차원 재순환영역의 길이가 크게 증가한 다는 것을 알 수 있다. 특히 ⑯을 통해 수제 각도가 0°, +30°로 기울었을 때 바닥에서의 무차원 재순환영역의 길이가 최댓값이라는 것을 알 수 있다. 또한 <그림2-1-2> ②, ③, ⑤을 통해 수면에서도 수제 각도가 0°, +30°로 기울었을 때 무차원 재순환영역의 길이가 최댓값이라는 것을 알 수 있다.

○ <그림 2-1-1>, <그림 2-2-1>, <그림 2-3-1>, <그림 2-4-1> 인 경우는 ⑦, ⑨, ⑪, ⑬, ⑮을 통해 수제가 반 정도 잠겼을 때(h/H=0.5)는 수제의 길이와, 수제의 각도에 상관없이 무차원 재순환영역 길이의 변화가 거의 없다는 것을 알 수 있다.

○ <그림 2-2-1>에서는 ⑤~⑥, ⑪~⑫, ⑯을 통해 수제 각도가 +30°로 기울었을 때는 수제의 길이가 길어질 때, 수제의 높이가 높아질 때, 바닥에서의 무차원 재순환영역의 길이가 크게 증가 한다는 것을 알 수 있다. 특히 ⑯을 통해 수제 각도가 +30°로 기울었을 때 바닥에서의 무차원 재순환영역의 길이가 최댓값이라는 것을 알 수 있다. 또한 <그림2-2-2> ③, ⑤을 통해 수면에서도 수제 각도가 +30°로 기울었을 때 재순환영역의 길이가 최댓값이라는 것을 알 수 있다.

○ <그림 2-3-1>, <그림 2-4-1> 에서는 ⑭을 통해 l/B=0.25, h/H=0.5일 때 수제 각도가 0°로 기울었을 때 바닥에서의 무차원 재순환영역 길이가 최솟값이라는 것을 알 수 있다.

○ <그림 2-3-1> 에서는 l/B=0.5, h/H=1, 수제 각도가 0°로 기울었을 때 바닥에서의 무차원 재순환영역의 길이가 최댓값이라는 것을 알 수 있다. 또한 <그림 2-3-2> ⑤을 통해 수면에서도 l/B=0.5, h/H=1, 수제 각도가 0°로 기울었을 때 무차원 재순환영역의 길이가 최댓값이라는 것을 알 수 있다.

○ <그림 2-4-1> 에서는 l/B=0.5, h/H=1, 수제 각도가 +30°로 기울었을 때 바닥에서의 무차원 재순환영역의 길이가 최댓값이라는 것을 알 수 있다. 또한 <그림 2-4-2> ⑤을 통해 수면에서 도 l/B=0.5, h/H=1, 수제 각도가 +30°로 기울었을 때 무차원 재순환영역의 길이가 최댓값이라는 것을 알 수 있다.

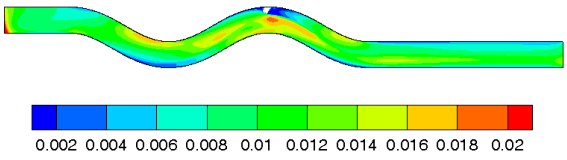
○ <그림 2-3-1>, <그림 2-4-1>의 경우는 전반적으로 ①~⑥을 통해, 수제 높이가 높아질 때 바닥에서의 무차원 재순환영역의 길이가 증가한다는 것을 알 수 있다.

○ <그림 2-3-2>, <그림 2-4-2>의 경우는 전반적으로 ①~③을 통해, 수제 길이가 길어질 때 수면에서의 무차원 재순환영역의 길이가 증가한다는 것을 알 수 있다.

(3) 무차원 난류운동에너지 (TKE)

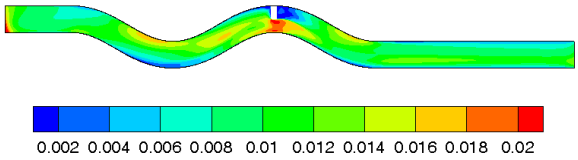
<그림 3-1-1> 하상에서의 무차원 난류운동에너지 (TKE)

case13 R/B=2.5 θ=30° α= -30° l/B=0.25 h/H=0.5



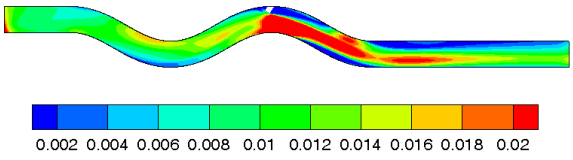
①

case33 R/B=2.5 θ=30° α= 0° l/B=0.5 h/H=0.5



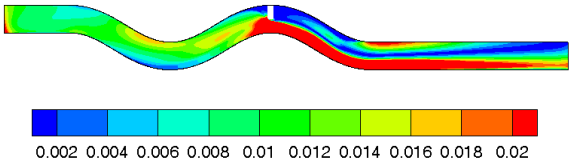
⑦

case15 R/B=2.5 θ=30° α= -30° l/B=0.25 h/H=1



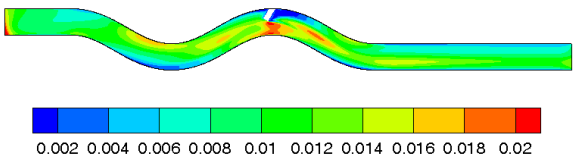
②

case35 R/B=2.5 θ=30° α= 0° l/B=0.5 h/H=1



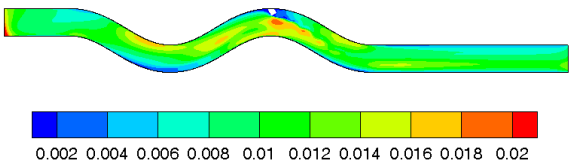
⑧

case17 R/B=2.5 θ=30° α= -30° l/B=0.5 h/H=0.5



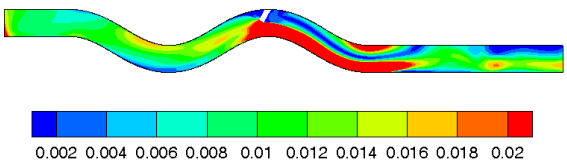
③

case45 R/B=2.5 θ=30° α= +30° l/B=0.25 h/H=0.5



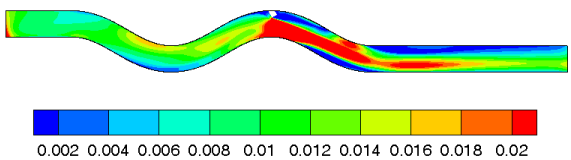
⑨

case19 R/B=2.5 θ=30° α= -30° l/B=0.5 h/H=1



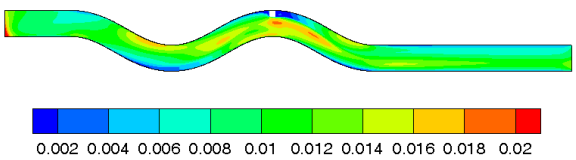
④

case47 R/B=2.5 θ=30° α= +30° l/B=0.25 h/H=1



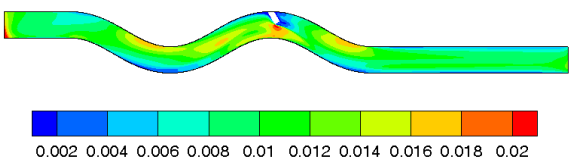
⑩

case29 R/B=2.5 θ=30° α= 0° l/B=0.25 h/H=0.5



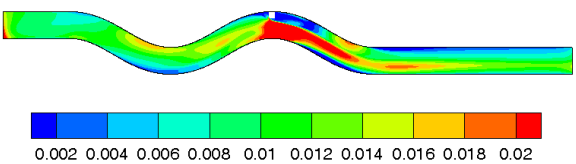
⑤

case49 R/B=2.5 θ=30° α= +30° l/B=0.5 h/H=0.5



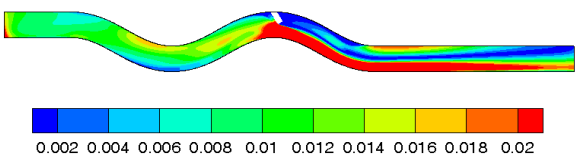
⑪

case31 R/B=2.5 θ=30° α= 0° l/B=0.25 h/H=1



⑥

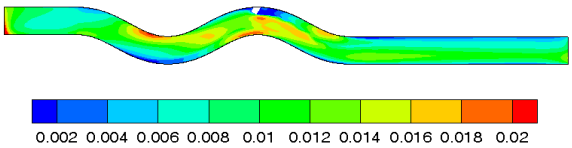
case51 R/B=2.5 θ=30° α= +30° l/B=0.5 h/H=1



⑫

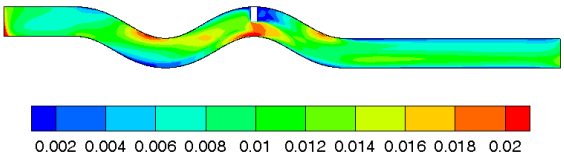
<그림 3-1-2> 하상에서의 무차원 난류운동에너지 (TKE)

case5 R/B=2 θ=30° α= -30° l/B=0.25 h/H=0.5



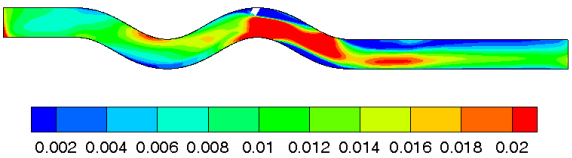
①

case25 R/B=2 θ=30° α= 0° l/B=0.5 h/H=0.5



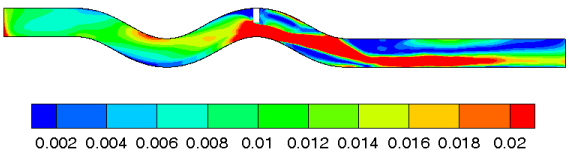
⑦

case7 R/B=2 θ=30° α= -30° l/B=0.25 h/H=1



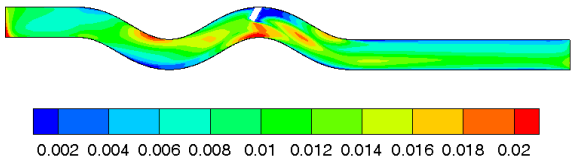
②

case27 R/B=2 θ=30° α= 0° l/B=0.5 h/H=1



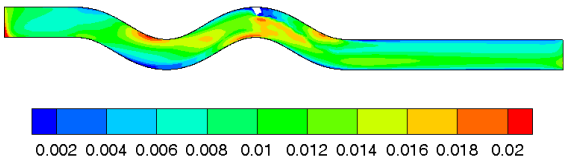
⑧

case9 R/B=2 θ=30° α= -30° l/B=0.5 h/H=0.5



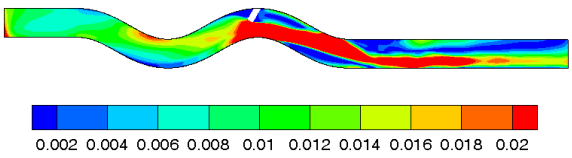
③

case37 R/B=2 θ=30° α= +30° l/B=0.25 h/H=0.5



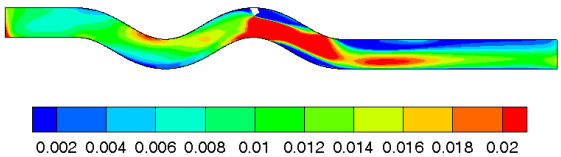
⑨

case11 R/B=2 θ=30° α= -30° l/B=0.5 h/H=1



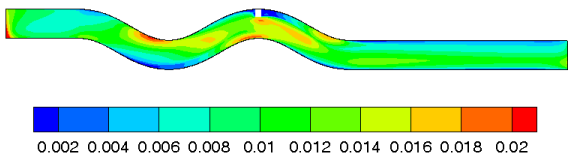
④

case39 R/B=2 θ=30° α= +30° l/B=0.25 h/H=1



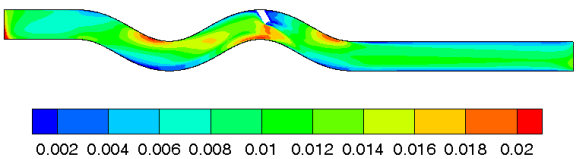
⑩

case21 R/B=2 θ=30° α= 0° l/B=0.25 h/H=0.5



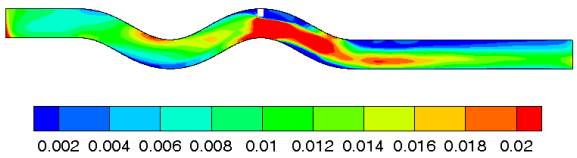
⑤

case41 R/B=2 θ=30° α= +30° l/B=0.5 h/H=0.5



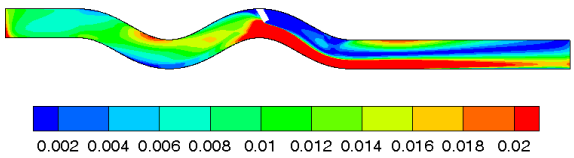
⑪

case23 R/B=2 θ=30° α= 0° l/B=0.25 h/H=1



⑥

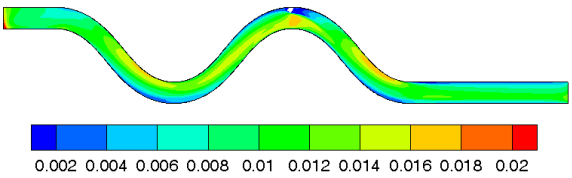
case43 R/B=2 θ=30° α= +30° l/B=0.5 h/H=1



⑫

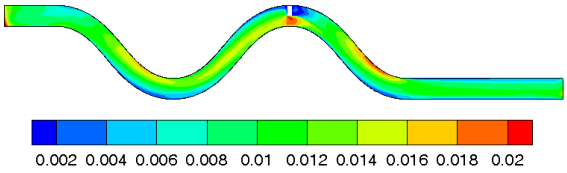
<그림 3-1-3> 하상에서의 무차원 난류운동에너지 (TKE)

case14 R/B=2.5 θ=50° α= -30° l/B=0.25 h/H=0.5



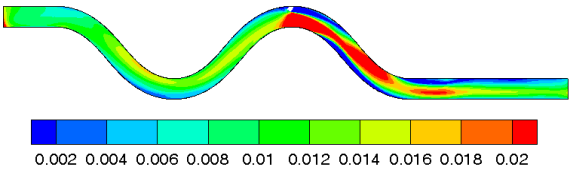
①

case34 R/B=2.5 θ=50° α= 0° l/B=0.5 h/H=0.5



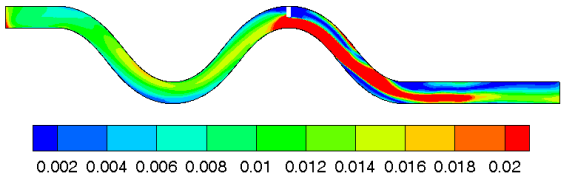
⑦

case16 R/B=2.5 θ=50° α= -30° l/B=0.25 h/H=1



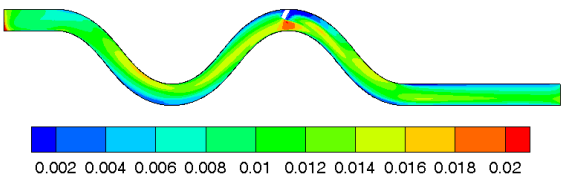
②

case36 R/B=2.5 θ=50° α= 0° l/B=0.5 h/H=1



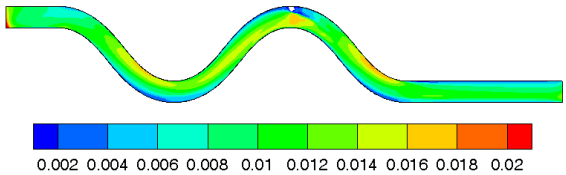
⑧

case18 R/B=2.5 θ=50° α= -30° l/B=0.5 h/H=0.5



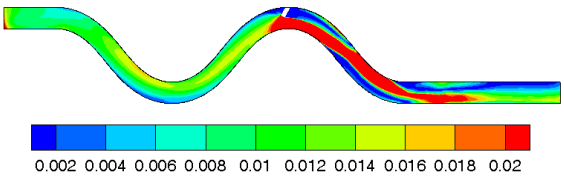
③

case46 R/B=2.5 θ=50° α= +30° l/B=0.25 h/H=0.5



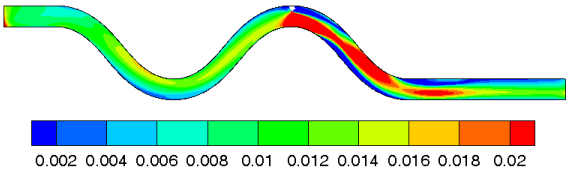
⑨

case20 R/B=2.5 θ=50° α= -30° l/B=0.5 h/H=1



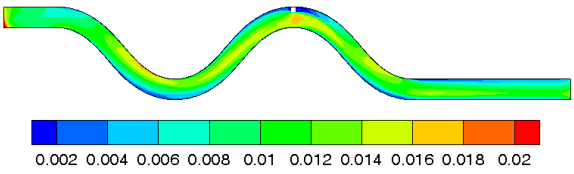
④

case48 R/B=2.5 θ=50° α= +30° l/B=0.25 h/H=1



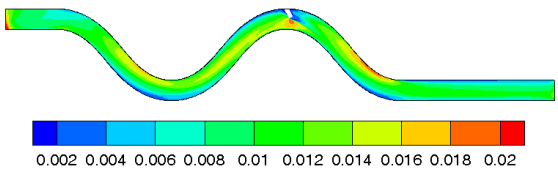
⑩

case30 R/B=2.5 θ=50° α= 0° l/B=0.25 h/H=0.5



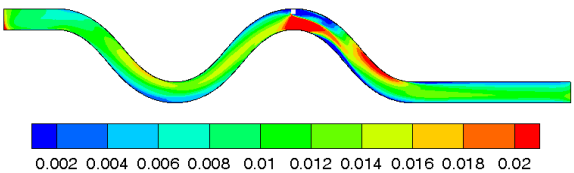
⑤

case50 R/B=2.5 θ=50° α= +30° l/B=0.5 h/H=0.5



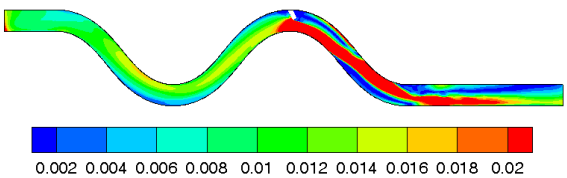
⑪

case32 R/B=2.5 θ=50° α= 0° l/B=0.25 h/H=1



⑥

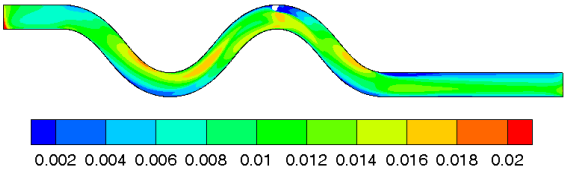
case52 R/B=2.5 θ=50° α= +30° l/B=0.5 h/H=1



⑫

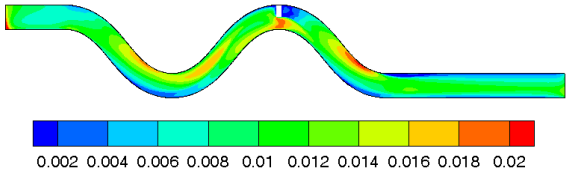
<그림 3-1-4> 하상에서의 무차원 난류운동에너지 (TKE)

case6 R/B=2 θ=50° α= -30° l/B=0.25 h/H=0.5



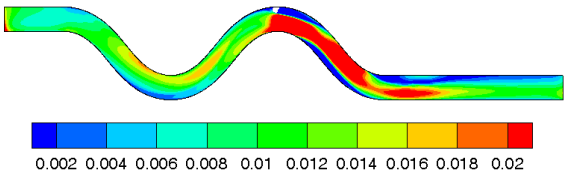
①

case26 R/B=2 θ=50° α= 0° l/B=0.5 h/H=0.5



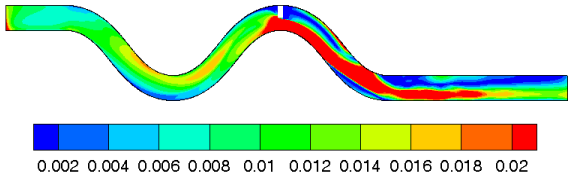
⑦

case8 R/B=2 θ=50° α= -30° l/B=0.25 h/H=1



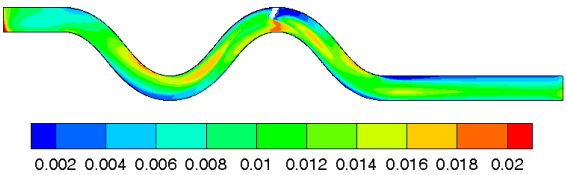
②

case28 R/B=2 θ=50° α= 0° l/B=0.5 h/H=1



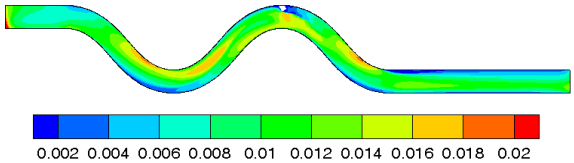
⑧

case10 R/B=2 θ=50° α= -30° l/B=0.5 h/H=0.5



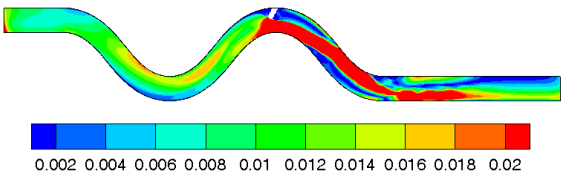
③

case38 R/B=2 θ=50° α= +30° l/B=0.25 h/H=0.5



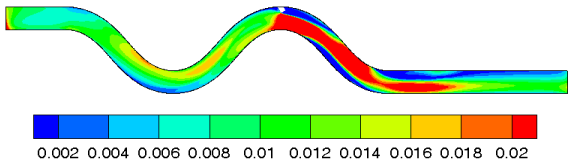
⑨

case12 R/B=2 θ=50° α= -30° l/B=0.5 h/H=1



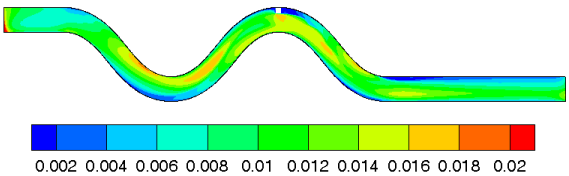
④

case40 R/B=2 θ=50° α= +30° l/B=0.25 h/H=1



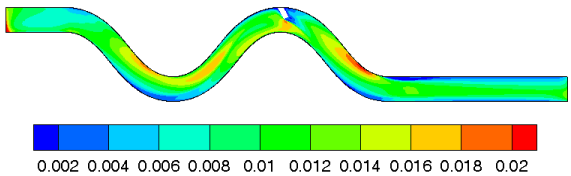
⑩

case22 R/B=2 θ=50° α= 0° l/B=0.25 h/H=0.5



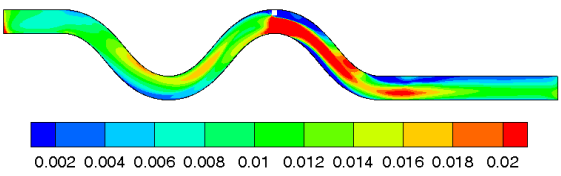
⑤

case42 R/B=2 θ=50° α= +30° l/B=0.5 h/H=0.5



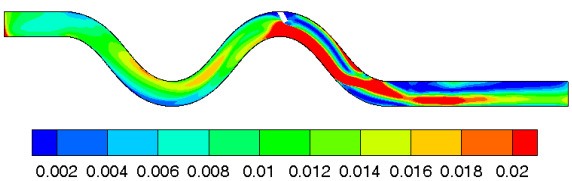
⑪

case24 R/B=2 θ=50° α= 0° l/B=0.25 h/H=1



⑥

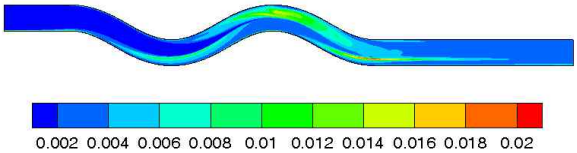
case44 R/B=2 θ=50° α= +30° l/B=0.5 h/H=1



⑫

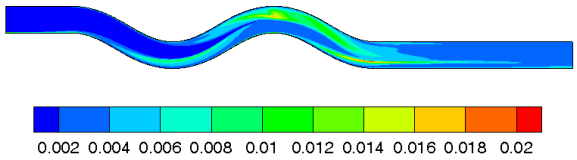
<그림 3-2-1> 수면에서의 무차원 난류운동에너지 (TKE)

case13 R/B=2.5 θ=30° α= -30° l/B=0.25 h/H=0.5



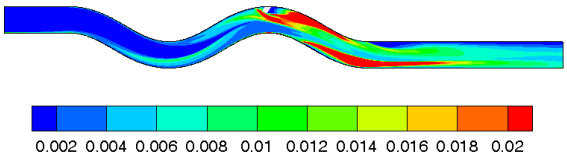
①

case33 R/B=2.5 θ=30° α= 0° l/B=0.5 h/H=0.5



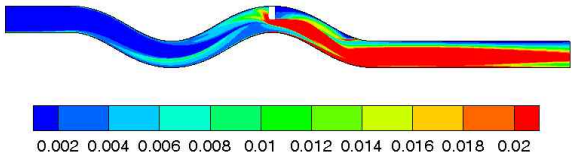
⑦

case15 R/B=2.5 θ=30° α= -30° l/B=0.25 h/H=1



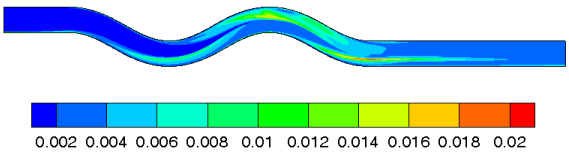
②

case35 R/B=2.5 θ=30° α= 0° l/B=0.5 h/H=1



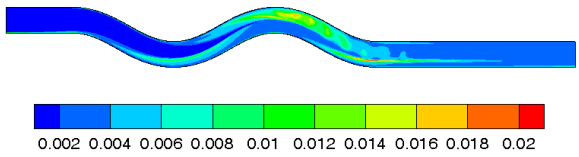
⑧

case17 R/B=2.5 θ=30° α= -30° l/B=0.5 h/H=0.5



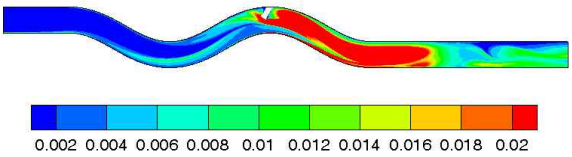
③

case45 R/B=2.5 θ=30° α= +30° l/B=0.25 h/H=0.5



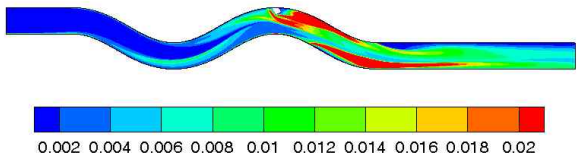
⑨

case19 R/B=2.5 θ=30° α= -30° l/B=0.5 h/H=1



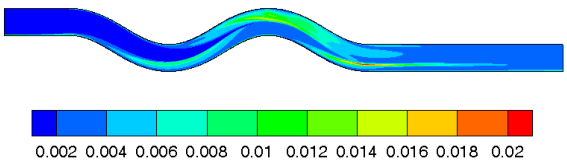
④

case47 R/B=2.5 θ=30° α= +30° l/B=0.25 h/H=1



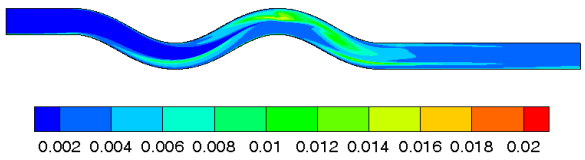
⑩

case29 R/B=2.5 θ=30° α= 0° l/B=0.25 h/H=0.5



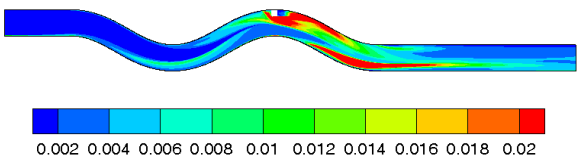
⑤

case49 R/B=2.5 θ=30° α= +30° l/B=0.5 h/H=0.5



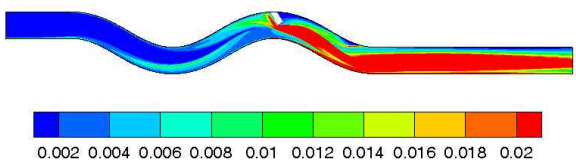
⑪

case31 R/B=2.5 θ=30° α= 0° l/B=0.25 h/H=1



⑥

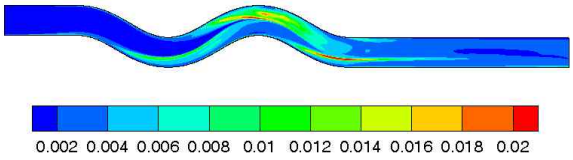
case51 R/B=2.5 θ=30° α= +30° l/B=0.5 h/H=1



⑫

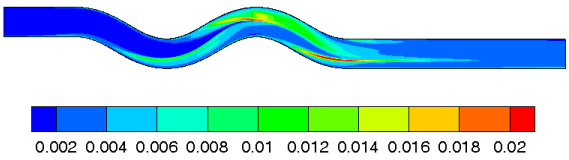
<그림 3-2-2> 수면에서의 무차원 난류운동에너지 (TKE)

case5 R/B=2 θ=30° α= -30° l/B=0.25 h/H=0.5



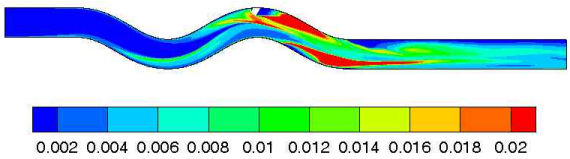
①

case25 R/B=2 θ=30° α= 0° l/B=0.5 h/H=0.5



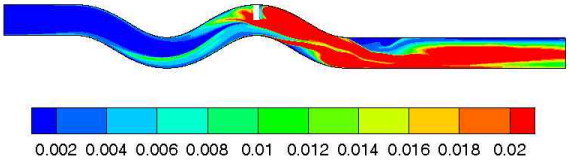
⑦

case7 R/B=2 θ=30° α= -30° l/B=0.25 h/H=1



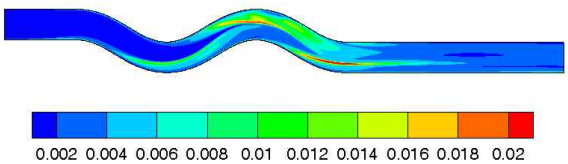
②

case27 R/B=2 θ=30° α= 0° l/B=0.5 h/H=1



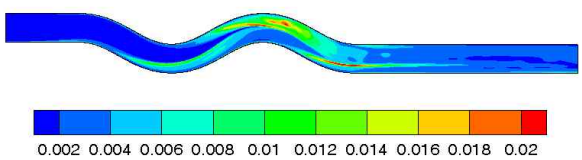
⑧

case9 R/B=2 θ=30° α= -30° l/B=0.5 h/H=0.5



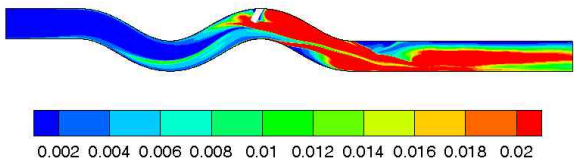
③

case37 R/B=2 θ=30° α= +30° l/B=0.25 h/H=0.5



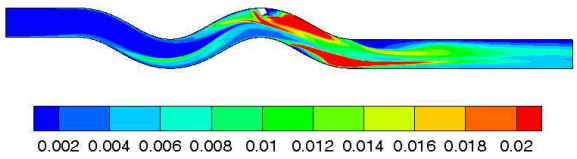
⑨

case11 R/B=2 θ=30° α= -30° l/B=0.5 h/H=1



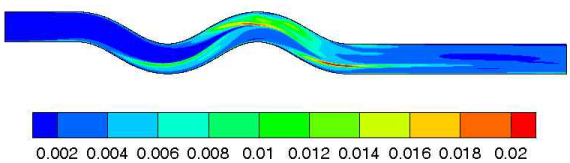
④

case39 R/B=2 θ=30° α= +30° l/B=0.25 h/H=1



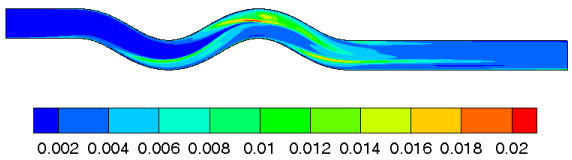
⑩

case21 R/B=2 θ=30° α= 0° l/B=0.25 h/H=0.5



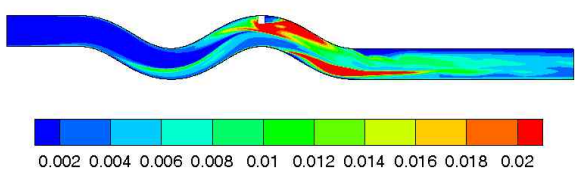
⑤

case41 R/B=2 θ=30° α= +30° l/B=0.5 h/H=0.5



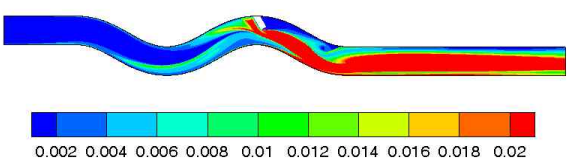
⑪

case23 R/B=2 θ=30° α= 0° l/B=0.25 h/H=1



⑥

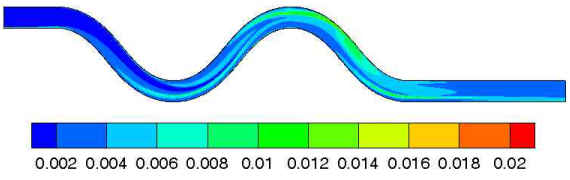
case43 R/B=2 θ=30° α= +30° l/B=0.5 h/H=1



⑫

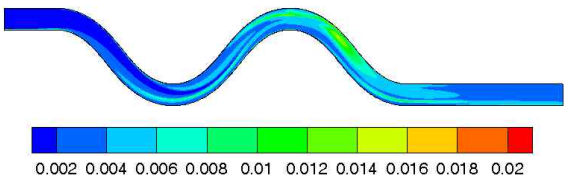
<그림 3-2-3> 수면에서의 무차원 난류운동에너지 (TKE)

case14 R/B=2.5 θ=50° α= -30° l/B=0.25 h/H=0.5



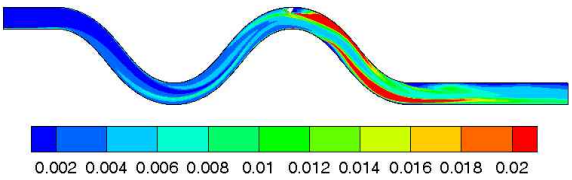
①

case34 R/B=2.5 θ=50° α= 0° l/B=0.5 h/H=0.5



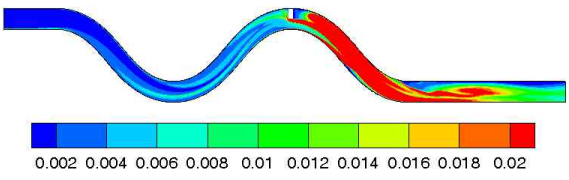
⑦

case16 R/B=2.5 θ=50° α= -30° l/B=0.25 h/H=1



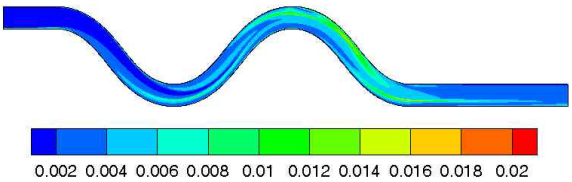
②

case36 R/B=2.5 θ=50° α= 0° l/B=0.5 h/H=1



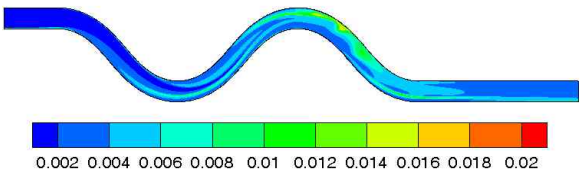
⑧

case18 R/B=2.5 θ=50° α= -30° l/B=0.5 h/H=0.5



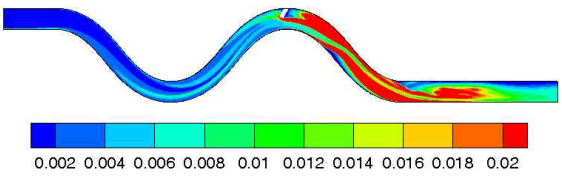
③

case46 R/B=2.5 θ=50° α= +30° l/B=0.25 h/H=0.5



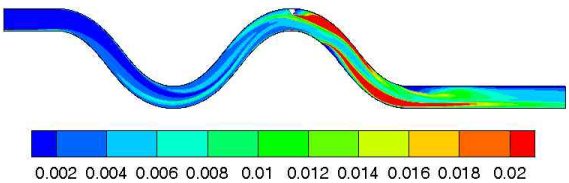
⑨

case20 R/B=2.5 θ=50° α= -30° l/B=0.5 h/H=1



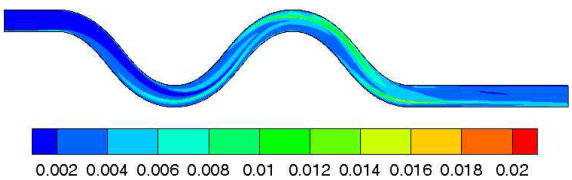
④

case48 R/B=2.5 θ=50° α= +30° l/B=0.25 h/H=1



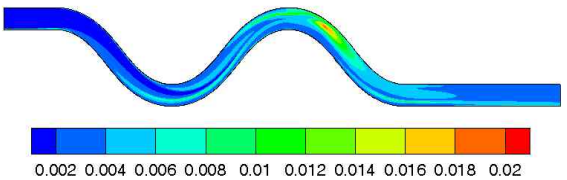
⑩

case30 R/B=2.5 θ=50° α= 0° l/B=0.25 h/H=0.5



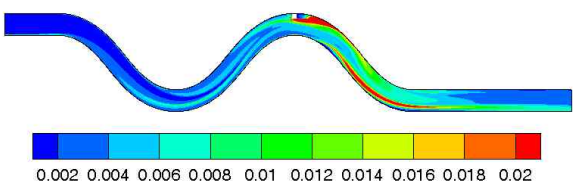
⑤

case50 R/B=2.5 θ=50° α= +30° l/B=0.5 h/H=0.5



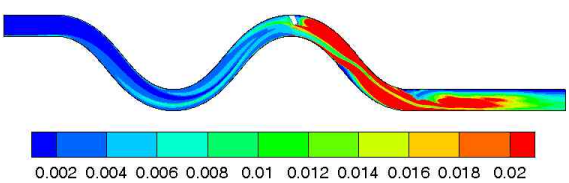
⑪

case32 R/B=2.5 θ=50° α= 0° l/B=0.25 h/H=1



⑥

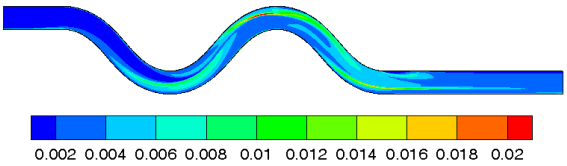
case52 R/B=2.5 θ=50° α= +30° l/B=0.5 h/H=1



⑫

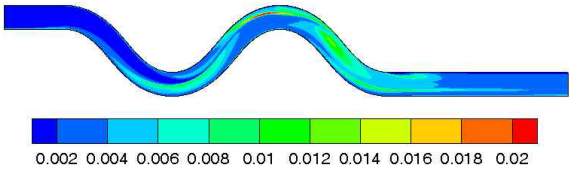
<그림 3-2-4> 수면에서의 무차원 난류운동에너지 (TKE)

case6 R/B=2 θ=50° α= -30° l/B=0.25 h/H=0.5



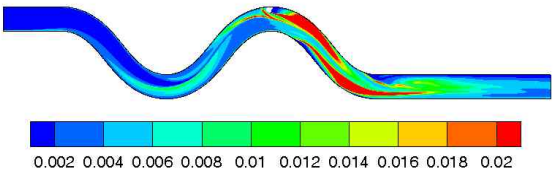
①

case26 R/B=2 θ=50° α= 0° l/B=0.5 h/H=0.5



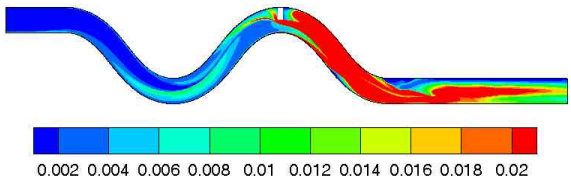
⑦

case8 R/B=2 θ=50° α= -30° l/B=0.25 h/H=1



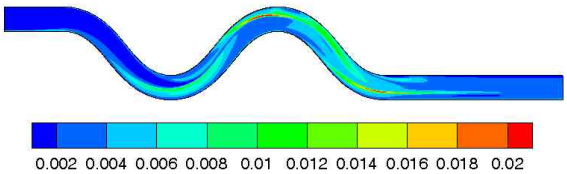
②

case28 R/B=2 θ=50° α= 0° l/B=0.5 h/H=1



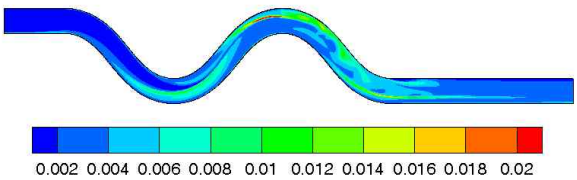
⑧

case10 R/B=2 θ=50° α= -30° l/B=0.5 h/H=0.5



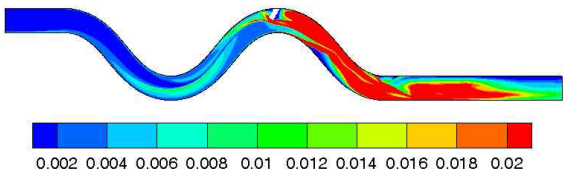
③

case38 R/B=2 θ=50° α= +30° l/B=0.25 h/H=0.5



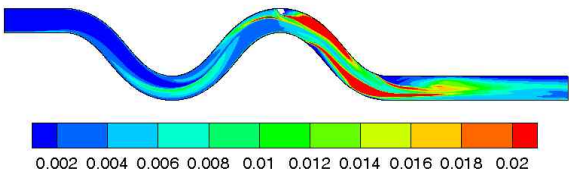
⑨

case12 R/B=2 θ=50° α= -30° l/B=0.5 h/H=1



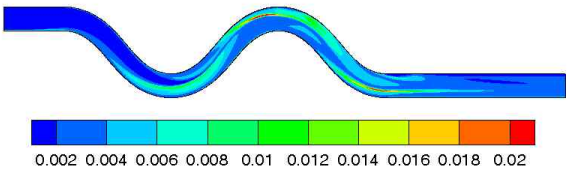
④

case40 R/B=2 θ=50° α= +30° l/B=0.25 h/H=1



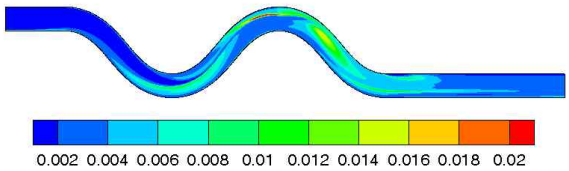
⑩

case22 R/B=2 θ=50° α= 0° l/B=0.25 h/H=0.5



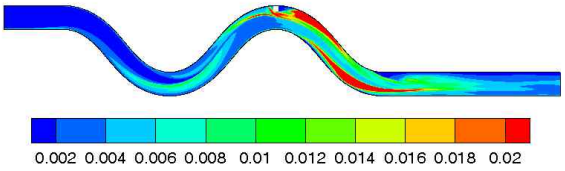
⑤

case42 R/B=2 θ=50° α= +30° l/B=0.5 h/H=0.5



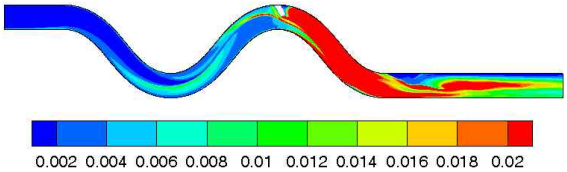
⑪

case24 R/B=2 θ=50° α= 0° l/B=0.25 h/H=1



⑥

case44 R/B=2 θ=50° α= +30° l/B=0.5 h/H=1



⑫

○ <그림 3-1-1~4>의 ①~⑥를 통해, h/H=0.5인 경우에는 수제의 기울어진 각도에 상관없이 l/B=0.25에서 l/B=0.5로 증가할 때, 수제 끝부분에서의 난류에너지가 증가하는 것을 알 수 있다.

○ <그림 3-1-1~4>의 ⑨를 통해, l/B=0.25, h/H=1, 수제가 0°로 기울었을 때, 난류운동에너지 값이 최소라는 것을 알 수 있다.

○ <그림 3-1-1~4>의 ⑫을 통해, l/B=0.5, h/H=1, 수제가 =+30°일 때, 난류운동에너지가 0.02 이상인 값이 가장 길게 존재한다는 것과 동시에, 난류운동에너지가 0.002 이하인 값이 가장 길게 존재한다는 것을 알 수 있다.

○ <그림 3-1-1~4>의 ⑦~⑫을 통해 l/B=0.25에서 l/B=0.5로 증가할 때, 수제 근방 하류부에서의 난류운동에너지 값이 작은 곳의 범위가 커진다는 것을 볼 수 있다.

○ <그림 3-2-1~4>의 ①~⑥을 통해, l/B=0.5, α(°)에 상관없이 h/H=0.5일 때는 모든 경우에서의 난류운동에너지 값이 매우 작다는 것을 알 수 있다.

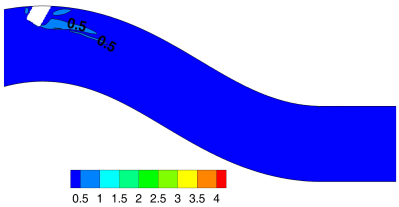
○ <그림 3-2-1~4>의 ⑦~⑫을 통해 l/B=0.25에서 l/B=0.5로 증가할 때, 수제 근방 하류부에서의 난류운동에너지 값이 0.2보다 큰 값을 나타내는 곳의 범위가 커진다는 것을 볼 수 있다.

○ <그림 3-2-3~4>의 ⑧, ⑩, ⑫을 통해 l/B=0.5, h/H=1일 때 α(°) 값에 상관없이 수제 하류부 난류운동에너지의 값이 0.02 이상이고 그 경향이 비슷하다는 것을 알 수 있다.

(3) 무차원 하상전단응력

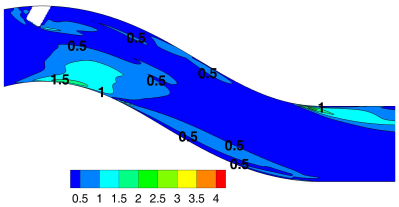
<그림 4-1> 무차원 하상전단응력

case13 R/B=2.5 θ=30 ° α= -30° l/B=0.25 h/H=0.5



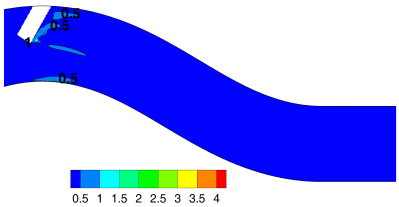
①

case15 R/B=2.5 θ=30 ° α= -30° l/B=0.25 h/H=1



⑦

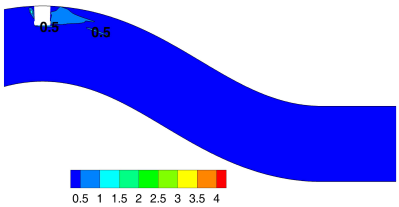
case17 R/B=2.5 θ=30 ° α= -30° l/B=0.5 h/H=0.5



②

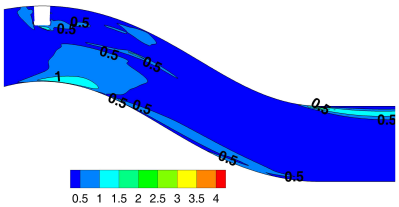
⑧

case29 R/B=2.5 θ=30 ° α= 0° l/B=0.25 h/H=0.5



③

case31 R/B=2.5 θ=30 ° α= 0° l/B=0.25 h/H=1



⑨

④

⑩

⑤

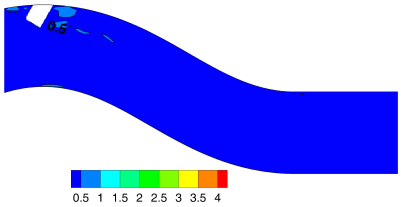
⑪

⑥

⑫

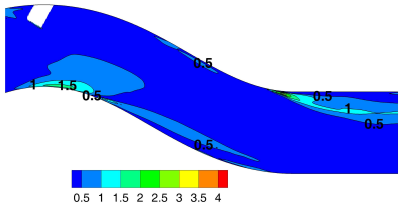
<그림 4-2> 무차원 하상전단응력

case5 R/B=2 θ=30° α= -30° l/B=0.25 h/H=0.5



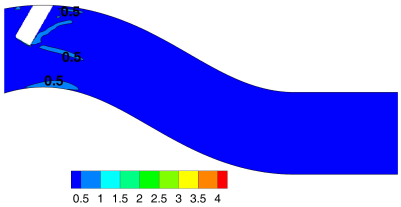
①

case7 R/B=2 θ=30° α= -30° l/B=0.25 h/H=1



⑦

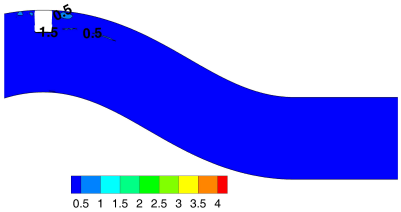
case9 R/B=2 θ=30° α= -30° l/B=0.5 h/H=0.5



②

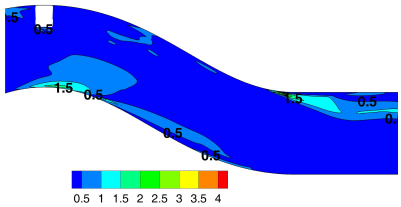
⑧

case21 R/B=2 θ=30° α= 0° l/B=0.25 h/H=0.5



③

case23 R/B=2 θ=30° α= 0° l/B=0.25 h/H=1



⑨

④

⑩

⑤

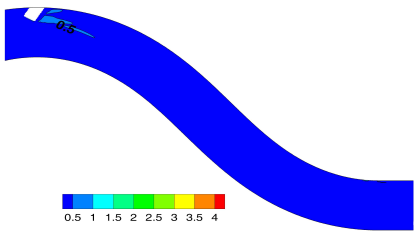
⑪

⑥

⑫

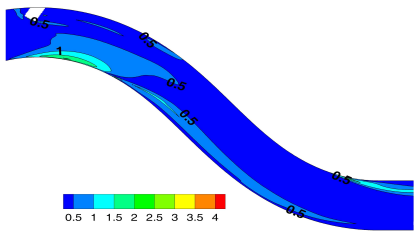
<그림 4-3> 무차원 하상전단응력

case14 R/B=2.5 θ=50 ° α=60° l/B=0.25 h/H=0.5



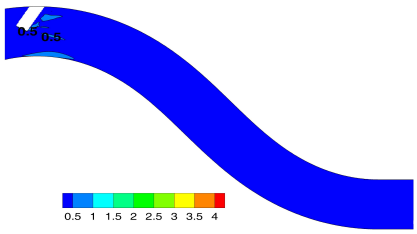
①

case16 R/B=2.5 θ=50 ° α= -30° l/B=0.25 h/H=1



⑦

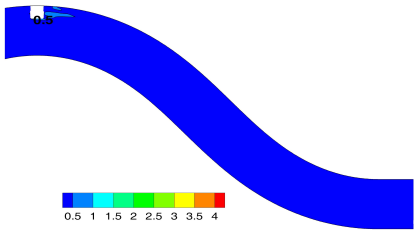
case18 R/B=2.5 θ=50 ° α= -30° l/B=0.5 h/H=0.5



②

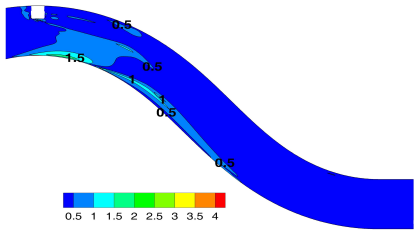
⑧

case30 R/B=2.5 θ=50 ° α= 0° l/B=0.25 h/H=0.5



③

case32 R/B=2.5 θ=50 ° α= 0° l/B=0.25 h/H=1



⑨

④

⑩

⑤

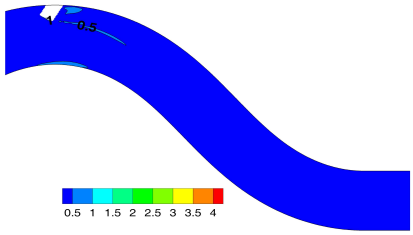
⑪

⑥

⑫

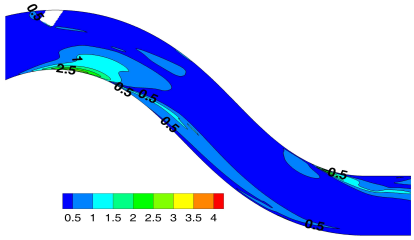
<그림 4-4> 무차원 하상전단응력

case6 R/B=2 θ=50 ° α= -30° l/B=0.25 h/H=0.5



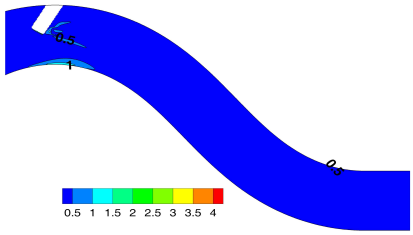
①

case8 R/B=2 θ=50 ° α= -30° l/B=0.25 h/H=1



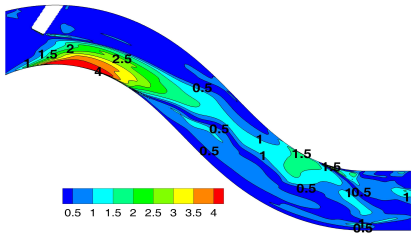
⑦

case10 R/B=2 θ=50 ° α= -30° l/B=0.5 h/H=0.5



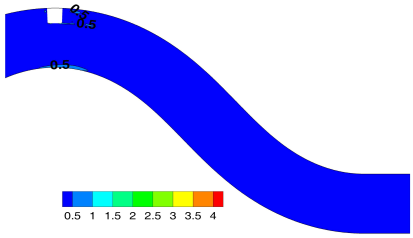
②

case12 R/B=2 θ=50 ° α= -30° l/B=0.5 h/H=1



⑧

case22 R/B=2 θ=50 ° α= 0° l/B=0.25 h/H=0.5



③

⑨

④

⑩

⑤

⑪

⑥

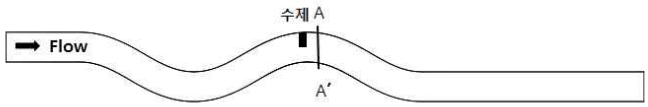
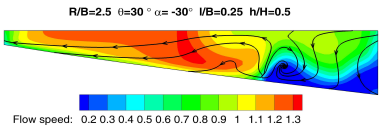
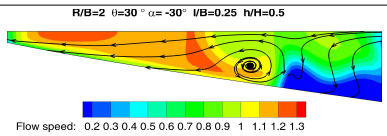
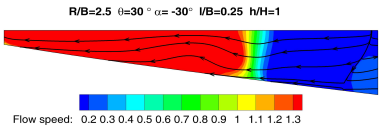
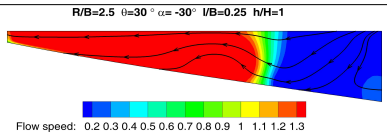
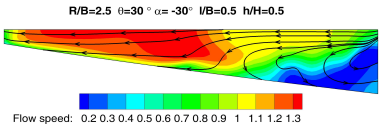
⑫

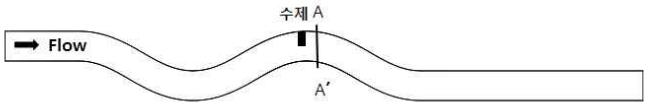
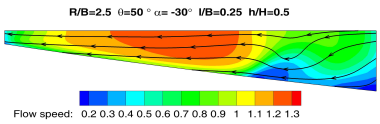
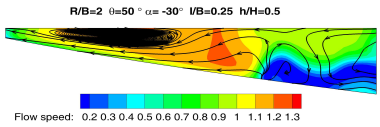
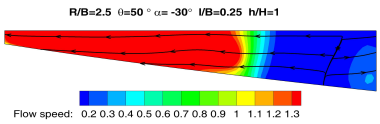
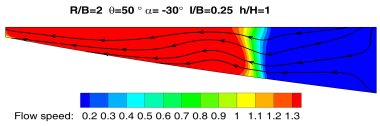
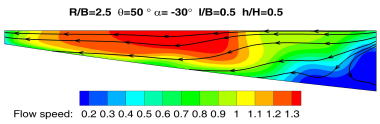
○ <그림 4-1~4> ①~⑥을 통해 l/B=0.5, h/H=0.5인 경우 (°)값에 상관없이 무차원 하상전단응력 값이 매우 작은 것을 알 수 있다.

○ <그림 4-1~4> ⑦~⑫을 통해 h/H=1인 경우 모든 α(°)에 대해서, l/B=0.25에서 l/B=0.5로 증가할 때, 하상전단응력 값이 증가하는 것을 알 수 있다.

○ <그림 4-1~4> ⑧, ⑩, ⑫을 통해 l/B=0.5, h/H=1인 경우 α(°)와 상관없이 수제 tip 부분에서 하상전단응력 값이 최대이고 그 값은 4이상을 나타내는 경향이 비슷한 것을 볼 수 있다.

(5) 이차류 (secondary flow)

<table>
<tr><td></td><td colspan="3"><그림 5-1> AA‘ 단면 이차류(secondary flow)</td></tr>
<tr><td></td><td colspan="3"> 
</td></tr>
<tr><td>case13</td><td> 
</td><td>case5</td><td> 
</td></tr>
<tr><td>case15</td><td> 
</td><td>case7</td><td> 
</td></tr>
<tr><td>case17</td><td> 
</td><td>case9</td><td></td></tr>
<tr><td>case19</td><td></td><td>case11</td><td></td></tr>
<tr><td>case29</td><td></td><td>case21</td><td></td></tr>
<tr><td>case31</td><td></td><td>case23</td><td></td></tr>
<tr><td>case33</td><td></td><td>case25</td><td></td></tr>
<tr><td>case35</td><td></td><td>case27</td><td></td></tr>
<tr><td>case45</td><td></td><td>case37</td><td></td></tr>
<tr><td>case47</td><td></td><td>case39</td><td></td></tr>
<tr><td>case49</td><td></td><td>case41</td><td></td></tr>
<tr><td>case51</td><td></td><td>case43</td><td></td></tr>
</table>

	<그림 5-2> AA‘ 단면 이차류(secondary flow)		
			
case14		case6	
case16		case8	
case18		case10	
case20		case12	
case30		case22	
case32		case24	
case34		case26	
case36		case28	
case46		case38	
case48		case40	
case50		case42	
case52		case44	

○ R/B=2.5보다 R/B=2의 경우 이차류 현상이 더 활발히 일어난다.
○ h/H=0.5보다 h/H=1인 경우 좌우 흐름 분리 현상이 뚜렷하다.
○ (°)는 이차류의 변화에 큰 영향을 끼치지 않는다.

제4장. 목표 달성도 및 관련 분야 기여도

1. 목표 달성도

번호	세 부 연 구 목 표	달 성 내 용	달성도(%)
1	설계인자 설정 (4가지)	설계인자 설정(4가지)	100
2	수리모형실험 (2건)	수리모형실험 (2건)	100
3	수치모형실험 시나리오 구축(40건)	수치모형실험 시나리오 구축(52건)	130
4	수치모의 수행(40건)	수치모의 수행(52건)	130
5	주요설계인자와 유동장 간의 상관관계식 또는 도표(5건)	주요설계인자와 유동장 간의 상관관계식 또는 도표(5건)	100
6	특허 출원(1건)	특허 출원(1건)	100
7	특허 등록(1건)	특허 등록(0건)	0
8	국외 학술전문지 게재(3건)	국외 학술전문지 게재(6건)	200
9	국내 학술전문지 게재(3건)	국내 학술전문지 게재(3건)	100

2. 관련 분야 기여도

- 수제설치는 하천의 형태, 수문현상, 수리특성 등 국지적인 요인을 적용한 국내 상황에 맞는 설계가 필수적이나, 현재 국내에는 수제설치에 대한 설계지침이 충분치 않고, 수제 설치 사례가 적어 수제 설치에 따른 변화양상을 관찰하기도 힘든 실정임
- 수제 관련 연구과제 조사 결과 지금까지의 연구는 직선하도에 대한 수리실험이 대부분이며 만곡하천에 적용 가능한 연구는 거의 전무했으며 만곡도에 따른 하천지형 별 맞춤 수제 설계 관련 인자 연구는 국내·외 전무함
- 지금까지 수제 연구와 관련하여 수치해석을 실시한 연구에서는 대부분 1, 2차원적인 해석을 수행하였으며, 3차원 모형을 사용하더라도 난류에너지 및 자유수면 해석까지 도달하지 못했으며, 수천만-수억개의 격자망을 이용한 고정밀 3차원 LES모형을 사용하여 만곡하천 내 수제 주위의 흐름을 해석한 사례도 존재하지 않음
- 본 연구에서는 수리모형실험과 더불어 고정밀 병렬 3차원 LES 수치해석 기법을 만곡하천 내의 수제 주위 흐름 해석에 적용하여 난류흐름과 관련된 물리현상을 규명하였으며 수제 설계인자들을 설정하였고 궁극적으로 인자들의 특성을 분석하여 설계 주요인자를 규명하였음
- 이와 같이 본 연구에서는 국내·외 최초로 수충부 및 제방 보호를 위한 과학적인 수제 설계기법을 위해 인자요소를 정립하여 향후 수제연구에 있어 설계기술 가이드라인을 비롯한 선진적 원천기술을 제공할 수 있다고 사료됨

제5장. 연구개발성과의 활용계획

- 국내 최초로 슈퍼컴퓨팅 기술을 활용하여 수공구조물 설계기준에 주요한 인자에 관한 연구를 통하여 새로운 연구 패러다임을 제시함
- 수제 주위의 3차원 정밀 유속장 정보를 제공함으로서 실무 수공기술자의 3차원 흐름특성에 관한 이해를 증진시킬수 있음
- 본 연구를 통해 얻게 될 결과는 수제설계시 주요한 인자들 및 그 범위임. 이러한 연구결과는 향후 수제설계 가이드라인의 초석이 될 수 있으며, 다음과 같은 기술·환경적 측면에 응용될 것으로 기대됨
- 하도가 지나치게 넓고 난류가 발생되고 있어서 유로를 고정할 필요가 있는 곳에는 긴 수제가 필요하지만 너무 길면 유지가 곤란하여 주의가 필요한데, 본 연구를 활용하면 적절한 길이를 산정하여 설치할 수 있음
- 수충부의 보호를 목적으로 설치하는 곳에 규격보다 크고 긴 수제를 설치하면 새로운 수류를 발생시키므로 주의가 필요한데, 본 연구를 활용하여 적절한 규격을 산출할 수 있음
- 하천구조물에서의 유사제어와 관련된 문제는 환경적으로 매우 중요한 문제인데 본 연구를 활용하면 하천의 만곡도에 따라 유사 효과가 좋은 수제설계 각도, 수심, 길이를 기준으로 삼을 수 있음
- 현재의 수제 설계기준은 그 내용이 모호하고 구체성이 떨어지므로 실제 설계 시 활용이 어려움. 본 연구는 만곡하천에 맞추어서 개발된 설계 기준이지만 향후 설계 사례가 늘게 되면 공식을 보완하고 유지관리에 관한 기준으로도 활용가치가 높음
- 본 연구에서 취득할 수제의 3차원 수리 특성에 관한 정보는 향후 생물, 화학적 수질 변화 및 어류서식처 변화 등에 관한 생태적 연구에도 유용하게 사용될 수 있음
- 연구개발 결과는 국토해양부를 비롯한 하천관리 등의 물관리를 수행하는 국가기관을 통해 자연하천 보호 및 하천정비, 복원사업과 관련하여 수충부 수공구조물의 설계에 주도적 혹은 보조적으로 활용하는 것은 물론이고, 유지관리 및 정책수립에도 활용 가능함

제6장. 연구 과정에서 수집한 해외 과학기술 정보

■ 스위스 취리히주 'Sihl강': 석재를 이용한 수제공법

- 홍수피해가 큰 Sihl강의 주변시설물을 보호하기 위하여 석재를 이용, 여러 개의 수제를 설치하여 견고한 호안을 조성
- 조성결과, 수제의 배후는 완류부가 되어 하안이 보호되고, 물고기의 피난처 및 식생의 근거지로 이용됨. 또한 수제를 이용하여 주위 자연경관과 조화를 이루게 됨



그림<9> 철길 변의 수제로 보호받고 있는 Sihl강

■ 미국 미시시피주 'Hotophia Creek'

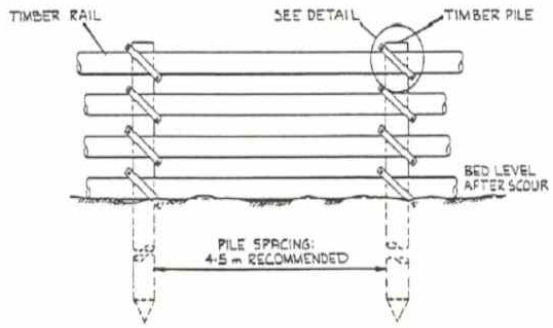
- 하천 경사를 바꾸거나 만곡도를 늘리는 대형 토목사업을 지양하기 위해 기존의 수제를 활용, 연장하여 여울과 소를 조성함. 흐름 방향과 반대 방향으로 교대로 경사지게 설치하는 하천복원설계
- 수제의 연장에 의한 맞은 편 강턱의 불안정을 막기 위해 강턱 밑에 사석 호안을 시공함
- 조성결과, 물고기의 종의 수가 늘었고 평균크기도 증하였으며 하도 내 식생은 유사의 퇴적을 유발하여 다른 식생의 자연 활착을 도와줌



그림<10> Hotophia강 복원사업 전후

■ 호주 빅토이라주

호주 빅토리아 주에서는 '수로 안정화를 위한 가이드라인'을 발간하여 수제설치를 위한 구체적인 현장조사 방법 및 각 인자별 가이드라인을 제시하고 있으며 특이한 점은 아래와 같이 부유물의 충격에너지를 고려한 수제안정성에 관한 값도 구체적으로 제시하고 있다. 그러나 가이드라인이 공식적인 규칙으로 설계자에게 제시되는 것이 아니라 실제현장의 구체적인 사전조사와 설계자의 감각을 바탕으로 수제를 설계하는 것을 더욱 중요시하고 있다.



충격 에너지 (KJ)	Timber Pile 지름(mm)	Timer Rail 지름(mm)
2.5	300	150
8.5	350	250
20.0	475	400

*부유물 충격에너지= $0.5mv^2$
m= 부유물의 질량,
V=충격순간의 부유물질의 속도

그림<11> Timber Pile & Timer Rail 지름 선정(목제 말뚝 수제인 경우)

■ 네덜란드

네델란드는 1980년대부터 치수목적의 수제가 Waal강을 비롯한 다수 하천에 설치되었으며 주운과 수상교통 등 이수목적의 하천 정비사업에도 수제공이 적용되고 있다. 특히 네덜란드 델프트 기술대학(TU Delft)에서 '하천 수제의 형태동역학'을 발간하여 수제에 관한 전반적인 이론들을 정리하고 있다.



그림<12> Waal강에 설치된 수제

제7장. 연구개발성과의 보안등급

가. 보안등급의 분류

보안	일반
	O

나. 결정사유

창의도전 연구 공고 및 2차 평가접수 안내서 참조

제8장. 국가과학기술종합정보시스템에 등록한 연구시설·장비 현황

해당사항 없음

제9장. 연구개발과제 수행에 따른 연구실 등의 안전 조치 이행 실적

<table>
<tr><td rowspan="3">교육내용</td><td rowspan="3">신규
연구활동종사자
현장교육</td><td colspan="2">교육시간</td><td colspan="4">2시간</td></tr>
<tr><td rowspan="2">교육
대상</td><td>입학생</td><td>3 명</td><td rowspan="2">교육
이수</td><td>입학생</td><td>3 명</td></tr>
<tr><td>복학생</td><td>0 명</td><td>복학생</td><td>0 명</td></tr>
<tr><td>교육강사
(안전책임자)</td><td>강석구 교수</td><td colspan="2">교육일시/장소</td><td colspan="4">2016.03.28. / 재성토목관
수리학 및 해안공학 실험실</td></tr>
</table>

제10장. 연구개발과제의 대표적 연구 실적

번호	구분 (논문/ 특허/ 기타)	논문명/특허명/ 기타	소속 기관명	역할	논문 게재지/ 특허 등록 국가	영향력 지수	논문 게재일 /특허 등록일	사사 여부 (단독 사사 또는 중복 사사)	특기 사항 (SCI 여부/인용 횟수 등)
1	논문	Numerical Study of Flow Dynamics Around a Stream Restoration Structure in a Meandering Channel	한양대학교		Journal of Hydraulic Research	1.762	2015.03.04		SCI/2회 인용
2	논문	Large-Eddy Simulation of Three-Dimensional Turbulent Free Surface Flow Past a Complex Stream Restoration Structure	한양대학교		Journal of Hydraulic Engineering	1.621	2015.10.01		SCI/3회 인용
3	논문	Fully Three-Dimensional Reynold-Averaged Navier-Stokes Modeling for Solving Free Surface Flows Around Coastal Dainage Gates	한양대학교		Journal of Hydro-environment Research	1.971	2015.06.30		SCI/ 0회 인용
4	논문	만곡수로 내 수리구조물에 따른 난류흐름 특성변화 실험 연구	한양대학교		한국수자원학회 논문집		2015.02.01		
5	논문	수제 주위의 난류 특성 변화에 대한 실험 연구	한양대학교		한국수자원학회 논문집		2016.08.13.		

제11장. 기타 사항

- 본 과제에서는 자연형 만곡하천에 설치되는 수제의 여러 설계 인자 중 4개의 인자(하천만곡도, 수제높이, 수제길이, 수제각도)에 대한 흐름의 민감도를 수치해석으로 분석하였음. 하지만 수제 설계 기술 개발을 위한 기초자료로 본 과제의 결과를 이용하기 위해서는 더욱 다양한 조건을 고려하는 자료가 필요하다고 판단이 되어짐. 따라서 향후 설정 인자의 확대(수제 설치 위치, 수제군, 수제 간격, 하도형태 및 이동상 등)를 통해 연구의 완성도를 높일 계획임.
- 본 과제에서 수행된 수리실험의 경우 유량규모가 작은 편이기 때문에 제방보호 차원의 목적 달성을 위해 향후 후속연구로서 큰 유량 조건에 대한 연구도 진행할 계획

제12장. 참고 문헌

강준구, 여홍구, 노영신 (2006) “수제 설치간격에 따른 수제주변 흐름특성에 관한 실험 연구”, 대한토목학회, 26(3B), 271-278.

강준구, 김성중, 여홍구, 윤병모 (2009) “수제주변 하상변동에 관한 실험연구 I-굴절수제”, 2009 대한토목학회 정기학술대회 발표논문집, 2640-2643.

건설교통부 국립건설시험소 (1987) 하천만곡부 제방안정공법에 관한 조사실험보고서. 한국건설기술연구원.

국토교통과학기술진흥원 (2013) 2013 국토교통 기술수준조사 보고서

국토해양부 (2009) 하천설계기준·해설. 발간등록번호: 11-1611000-000792-01.

안선복, 박효길, 전도석, 지홍기, 이순탁 (2008) “만곡하도에서 수제주변의 2차원 흐름특성 해석”, 2008 대한토목학회 정기학술대회 발표논문집, 702-705.

여홍구, 강준구, 김성중 (2007) “열쇠형 수제의 흐름특성에 관한 실험연구”, 대한토목학회 정기학술대회 발표논문집, 2625-2628.

여홍구, 강준구, 김성중, 윤병모 (2008) “ㄱ형 수제의 흐름특성에 관한 실험연구”, 2008 대한토목학회 정기학술대회 발표논문집, 2920-2923.

Bhuiyan, F., R.D. Hey, and P.R. Wormleaton (2010) “Bank-attached vanes for bank erosion control and restoration of river meanders” *Journal of Hydraulic Engineering*, 136(9), 583-596.

Brevis, W., M. Garcia-Villalba, and Y. Nino (2014) “Experimental and large eddy simulation study of the flow developed by a sequence of lateral obstacles” *Environmental Fluid Mechanics*, DOI:10.1007/s10652-013-9328-x

Copeland, R.R. (1983) “Bank protection technigues using spur dikes”, Miscellaneous paper HL83-1, U. S. Army Engineer Waterways Experiment Station.

FHWA (1985) Design of Spur-type Streambank Stabilization Structures. U. S. DOT, FHWA, Rep. No. FHWA/RD 84/101, McLean, VA.

Kang, J., H. Yeo, S. Kim, and U. Ji (2011) “Permeability effects of single groin on flow characteristics”, *Journal of Hydraulic Research*, 49(6), 728-735.

Kang, S., A. F. Lightbody, C. Hill, and F. Sotiropoulos (2011) “High-resolution numerical simulation of turbulence in natural waterways”, *Advances in Water Resources*, 34, 98-113.

Kang, S. and F. Sotiropoulos (2011) “Flow phenomena and mechanisms in a field-scale experimental meandering channel with a pool-riffle sequence: Insights gained via numerical simulation”, *Journal of Geophysical Research-Earth Surface*, 116.

Kang, S. and F. Sotiropoulos (2012a) “Assessing the predictive capabilities of isotropic, eddy-viscosity Reynolds-averaged turbulence models in a natural-like meandering channel”, *Water Resource Research*, 48, W06505, doi:10.1029/2011WR011375.

Kang, S. and F. Sotiropoulos (2012b) “Numerical modeling of 3D turbulent free surface flow in natural waterways”, *Advances in Water Resources,* 40, 23-36, doi:10.1016/j.advwatres.2012.01.012.

Khosronejad, A., C. Hill, S. Kang and F. Sotiropoulos (2013) “Computational and experimental investigation of scour past laboratory models of stream restoration rock structures”, *Advances in Water Resources*, 54, 191-207, doi:10.1016/j.advwatres.2013.01.008.

McCoy, A., G. Constantinescu and L.J. Weber (2008) “Numerical investigation of flow hydrodynamics in a channel with a series of groynes”, *ASCE Journal of Hydraulic Engineering*, 134(2), 157-172.

Sukhodolov A. (2014) “Hydrodynamics of groyne fields in a straight river reach: insight from field experiments” *Journal of Hydraulic Research,* 52(1), 105-120.

Sukhodolov A., W.S.J. Uijttewaal, and C. Engelhardt (2002) “On the correspondence between morphological and hydrodynamical patterns of groyne fields”, *Earth Surface Processes and Landforms*, 27(3), 289-305.

Yeo, H.K., J.K. Kang, and S.J. Kim (2005) “An experimental study on tip velocity and downstream recirculation zone of single groynes of permeability change”, *KSCE Journal of Civil Engineering*, 9(1), 29-38.

Yossef, M.F.M. and H.J. de Vriend (2011) “Flow details near river groynes: experimental investigation” *Journal of Hydraulic Engineering*, 137(5), 504-516.

주 의

1. 이 최종보고서는 국토교통부에서 시행한 국토교통기술촉진연구사업의 연구보고서입니다.

2. 이 최종보고서 내용을 발표하는 때에는 반드시 국토교통부에서 시행한 사업의 연구개발성과임을 밝혀야 합니다.

3. 국가과학기술 기밀 유지에 필요한 내용은 대외적으로 발표 또는 공개하여서는 안 됩니다.