

다양한 마하수 영역의 유동 해석을 위한 압력-속도 연계 해석 알고리즘 개발

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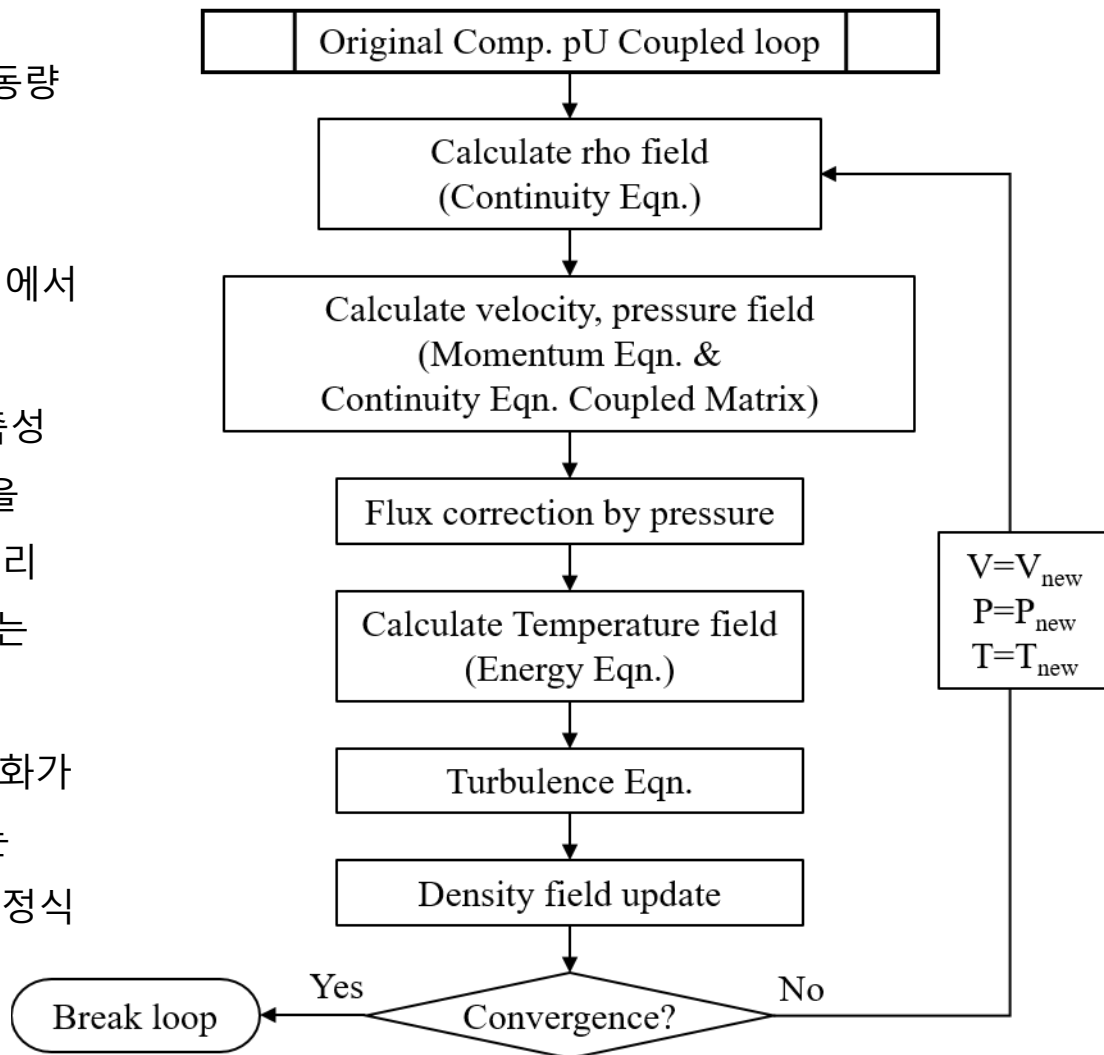
LVAFOAM

(Launch Vehicle Analysis OpenFOAM)

압력 속도 연계 해석

• pUCoupledFoam

- ✓ Pressure Based Coupled Solver 는 운동량 방정식의 ∇p 항의 압력값과 압력에 관한 식으로 변형된 연속방정식의 $\nabla \phi$ 항의 속도값을 현재의 반복 시점에서 계산되는 값들을 사용하는 방법
- ✓ 기존의 segregated solver에 비해 압축성 유동 영역에서 보다 강건하게 계산을 수행할 수 있는 장점이 있으나, 메모리 용량 및 한번의 반복 계산당 요구되는 계산 시간이 증가하는 단점이 존재
- ✓ 열에너지(엔탈피)에 의해 밀도의 변화가 급격하게 발생하는 유동의 경우에는 에너지 방정식을 해석한 후, 연속 방정식을 다시 해석해야 함

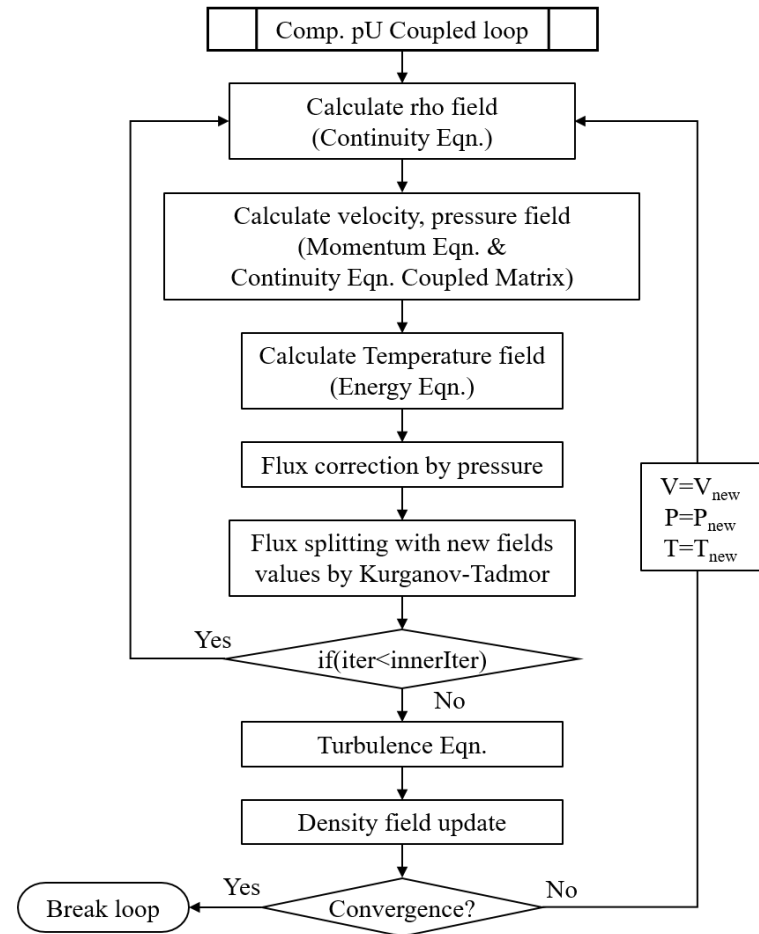
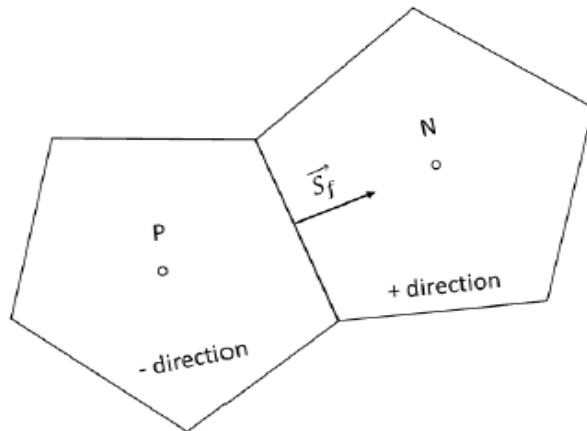


압력 속도 연계 해석

• 압력 기반 해석자에 flux splitting 기법 적용

- ✓ pressure based flux splitting central scheme 방법 적용
- ✓ 격자 면에서의 flux 계산에 적용
- ✓ Kurganov-Tadmor flux splitting scheme
- ✓ Low Mach number correction

$$\Psi_f \phi_f = \Psi_f^P (\alpha_f^P \phi_f^P + \alpha_f^P \alpha_f^{\min}) + \Psi_f^N (\alpha_f^N \phi_f^N - \alpha_f^P \alpha_f^{\min})$$



❖ M.Kraposhin(ISP RAS), S. Strizhak(HP) and A. Bovtrikova(ISP RAS), “Adaptation of Kurganov-Tadmor's numerical scheme for applying in combination with the PISO method in numerical simulation of flows in a wide range of Mach numbers”, Procedia Computer Science, Vol. 66, 2015, pp43-52

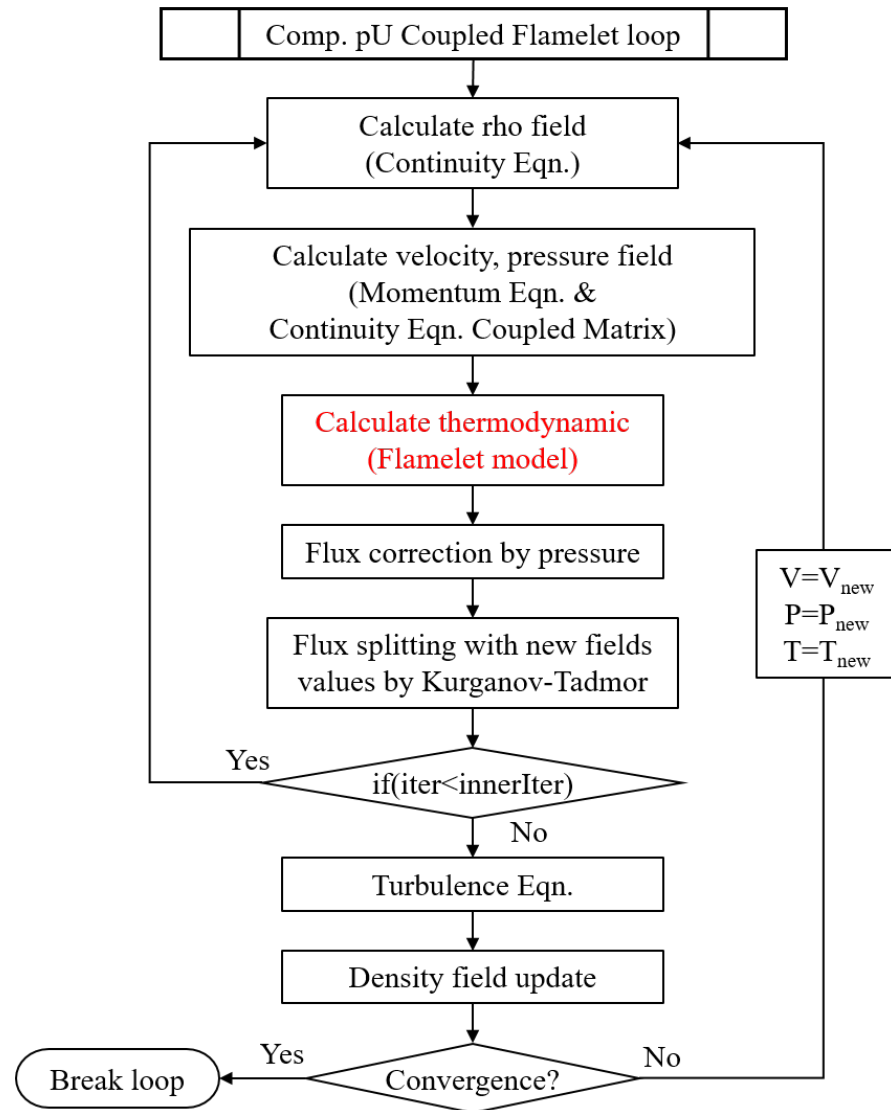
❖ 김태우, 길재홍, “압축성 유동 해석을 위한 압력 기반 해석자의 개선된 알고리즘 개발”, 한국전산유체공학회지, Vol.22, No.4, 2017



Flamelet 모델 결합

• Flamelet model 결합 내용

- ✓ 앞서 개발된 압력-속도 연계 해석자와 GIST의 연구에 의해 개발되어져 있는 Flamelet 모델을 결합
- ✓ 오른쪽과 같이 에너지 및 물성치 해석 부분을 기존 개발되어 있는 Flamelet 모델로 대체
- ✓ 기존 개발된 Flamelet 모델의 경우, 물성치 및 엔탈피 등을 PV와 같은 변수에 의한 table look-up 방식으로 계산하고 이를 기존의 유동 해석자와 결합하여 연소에 의한 유동 변화 효과를 고려



• 1D Sod problem



[초기]

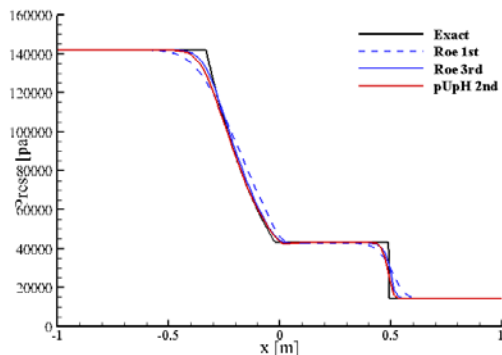


[종료]

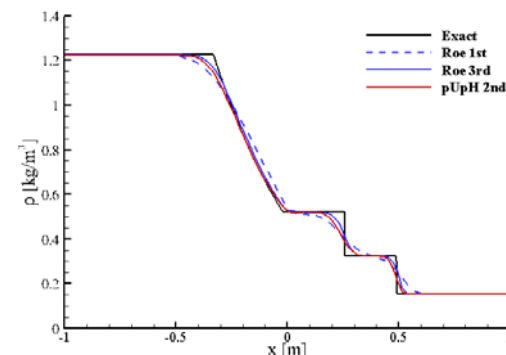
▪ Riemann Problem of Sod

- Standard shock tube problem
- Final time: 0.14, Mesh points: 100
- Boundary condition: Extrapolation

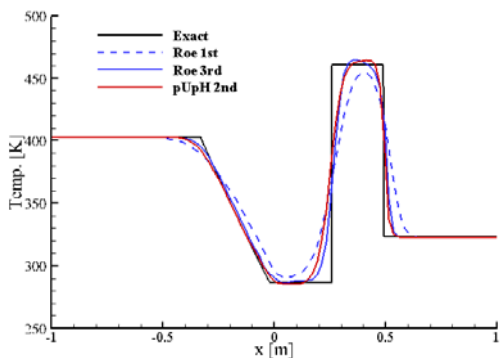
	Left $x \leq 0$	Right $x > 0$
ρ	1	0.125
u	0	0
p	1	0.1



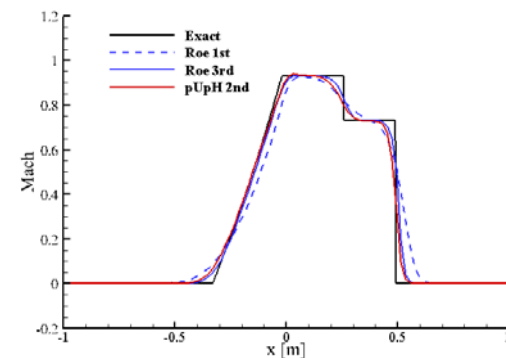
Pressure



Density



Temperature



Mach

• 1D Lax problem



[초기]

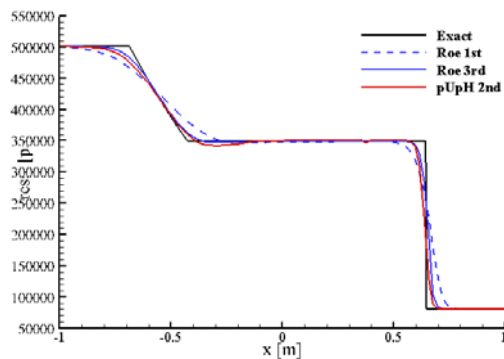


[종료]

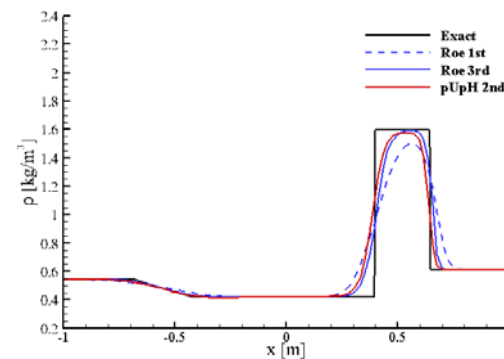
▪ Riemann Problem of Lax

- Shock tube problem with sever pressure difference
- Final time: 0.13, Mesh points: 100
- Boundary condition: Extrapolation

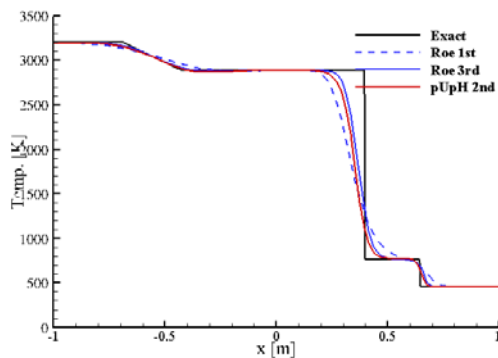
	Left $x \leq 0$	Right $x > 0$
ρ	0.445	0.5
u	0.698	0
p	3.528	0.571



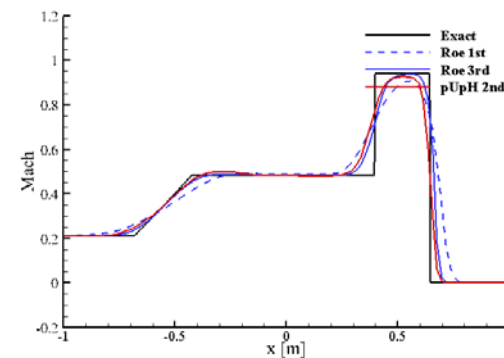
Pressure



Density



Temperature



Mach

• 1D Shu & Osher problem



[초기]

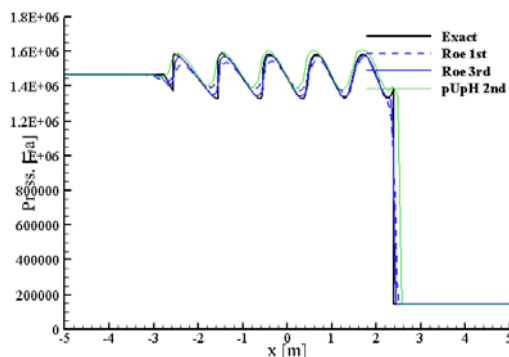


[종료]

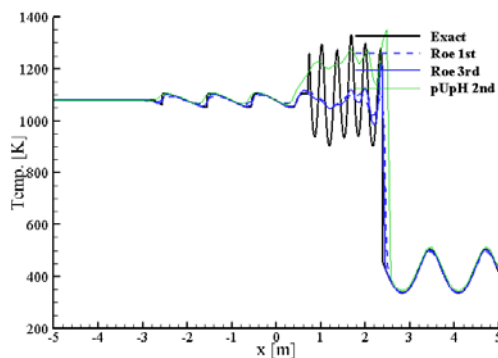
■ Shu-Osher's Problem

- Shock interacts with sinuous density field
- Final time: 0.18, Mesh points: 400
- Boundary condition: Extrapolation

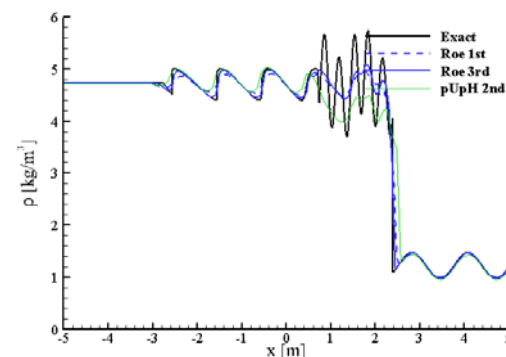
	Left $-5 \leq x < -4$	Right $-4 \leq x \leq 5$
ρ	3.85	$1+0.2\sin 5x$
u	2.63	0
p	10.3	1



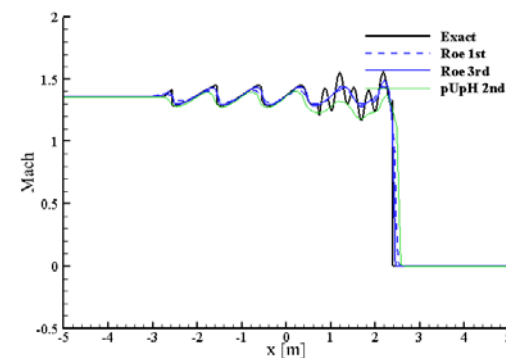
Pressure



Temperature



Density

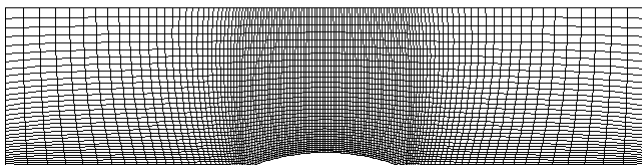


Mach

- 2D Euler 10% bump

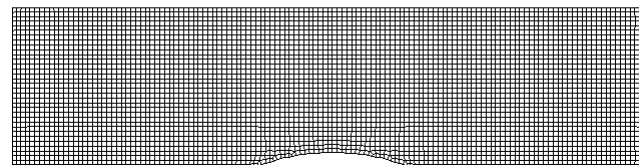
Precon./LM Roe FDS

Grid Size 121×35, Elliptic



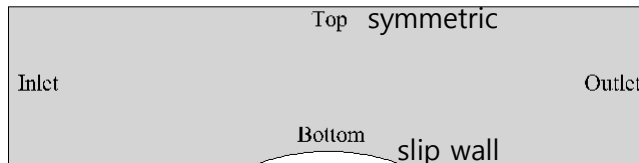
Present OpenFOAM

Grid Size 121×35, Salome, cfMesh



Boundary Name & Type

zerogradient



Subsonic: fixed value
Supersonic: zerogradient

Precon./LM Roe FDS

Solution Algorithm

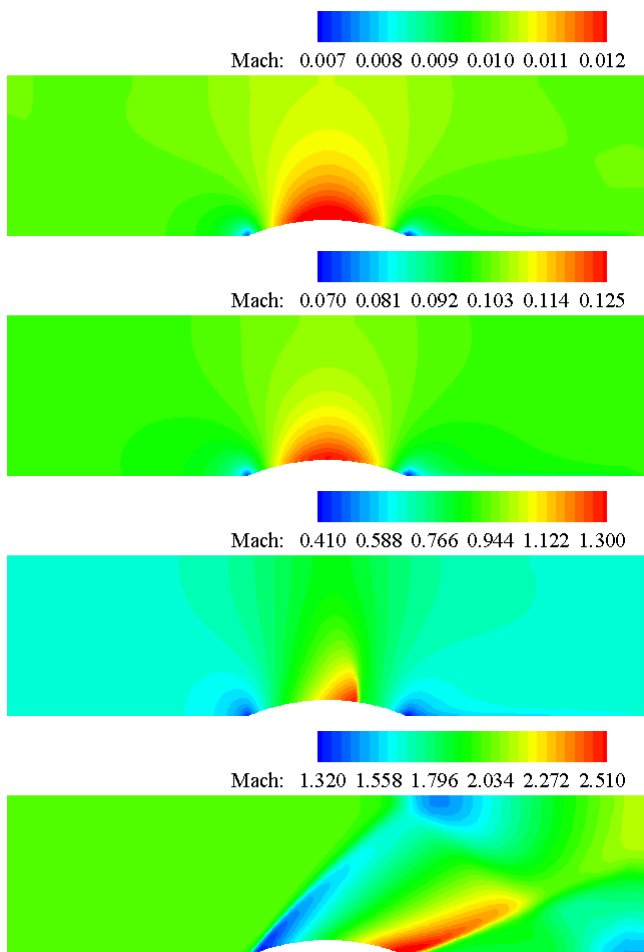
Present OpenFOAM

- Flux Scheme
 - Upwind type
 - Preconditioned Roe / LMRoe FDS
- Reconstruction Method
 - 2nd-order minmod limiter
- Integration Method
 - Fully Implicit LU-SGS

- Flux Scheme
 - 2nd-order Central difference type
 - Kurganov-Tadmor
- Reconstruction Method
 - minmod limiter
- Integration Method
 - Continuity: PCG
 - Moment. Energy: GMRES

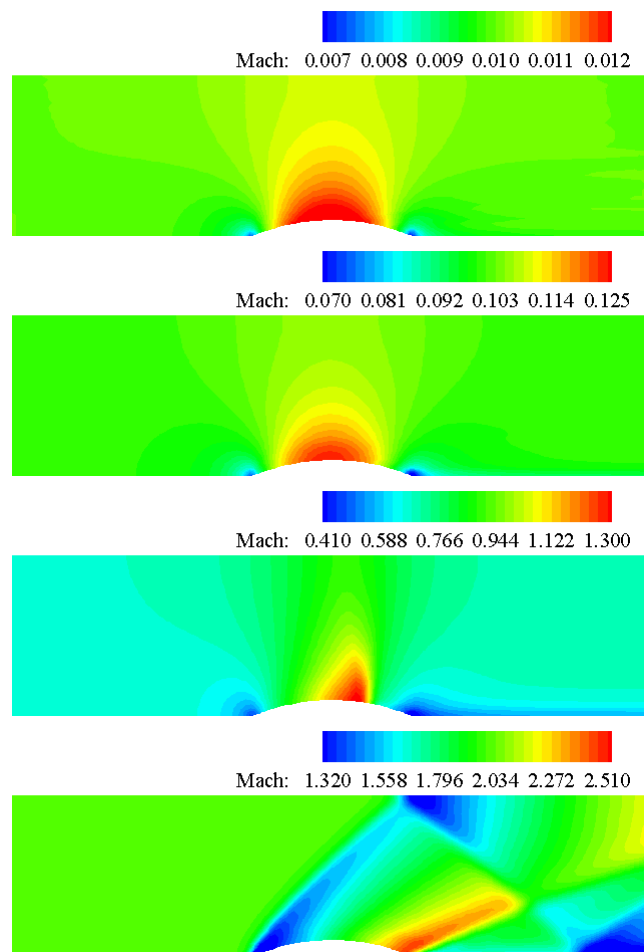
- 2D Euler 10% bump

Preconditioned Roe FDS



Present OpenFOAM

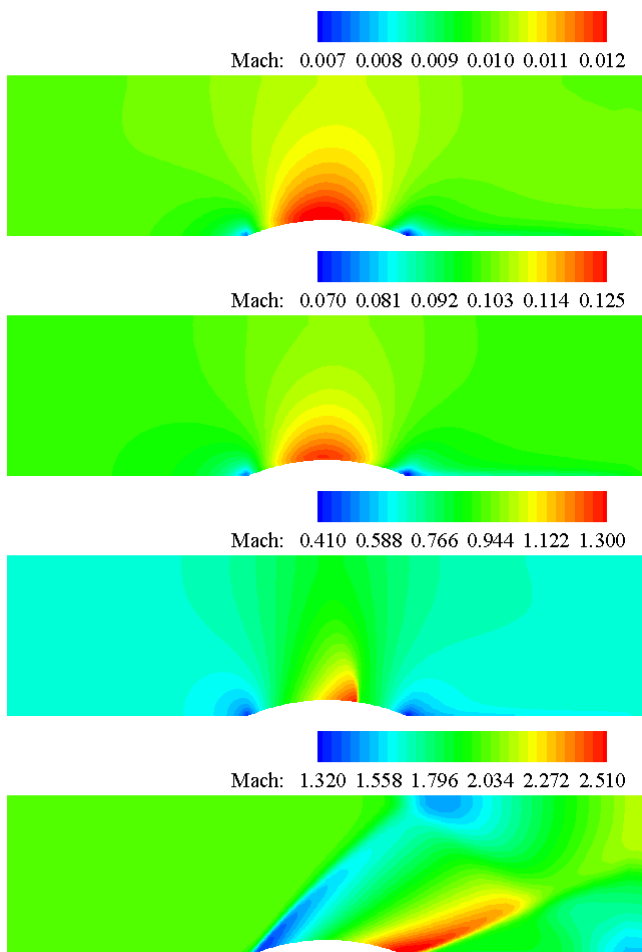
Mach=0.01



Mach=2.0

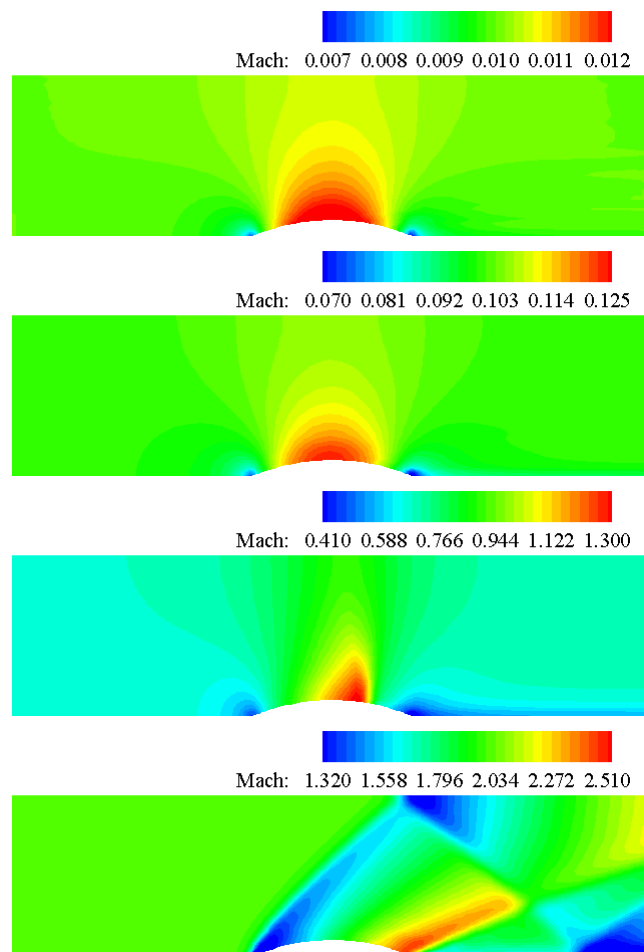
- 2D Euler 10% bump

LM Roe FDS



Present OpenFOAM

Mach=0.01

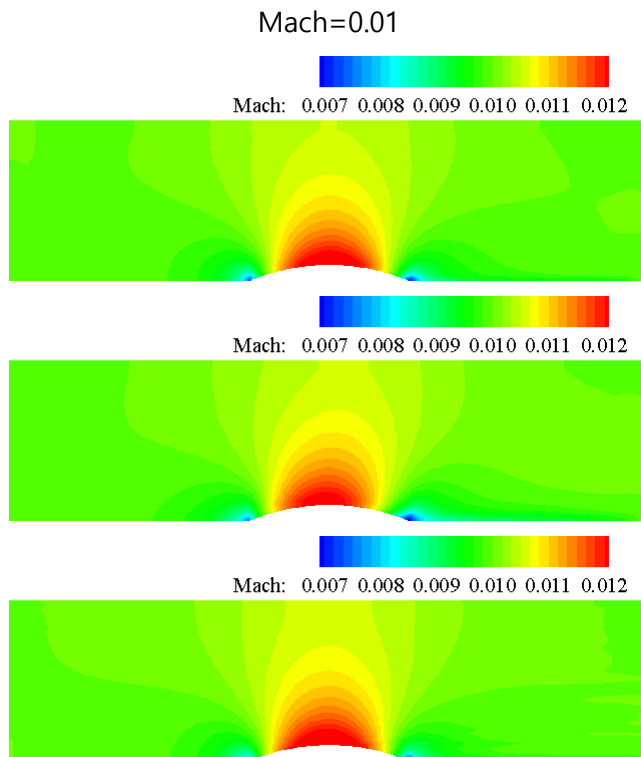


Mach=0.1

Mach=0.675

Mach=2.0

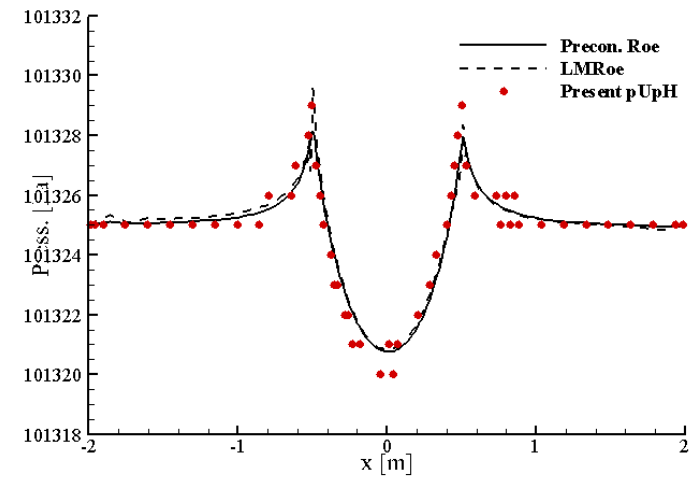
- 2D Euler 10% bump



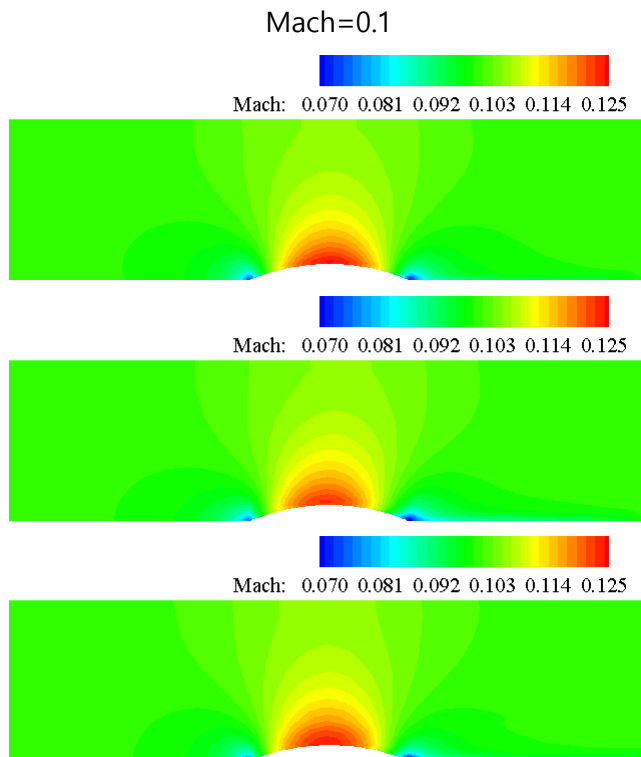
Precon. Roe

LMRoe

Present OpenFOAM



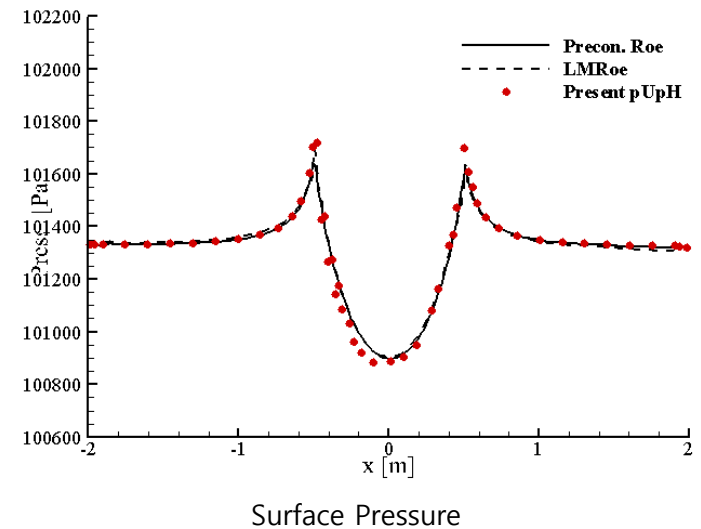
- 2D Euler 10% bump



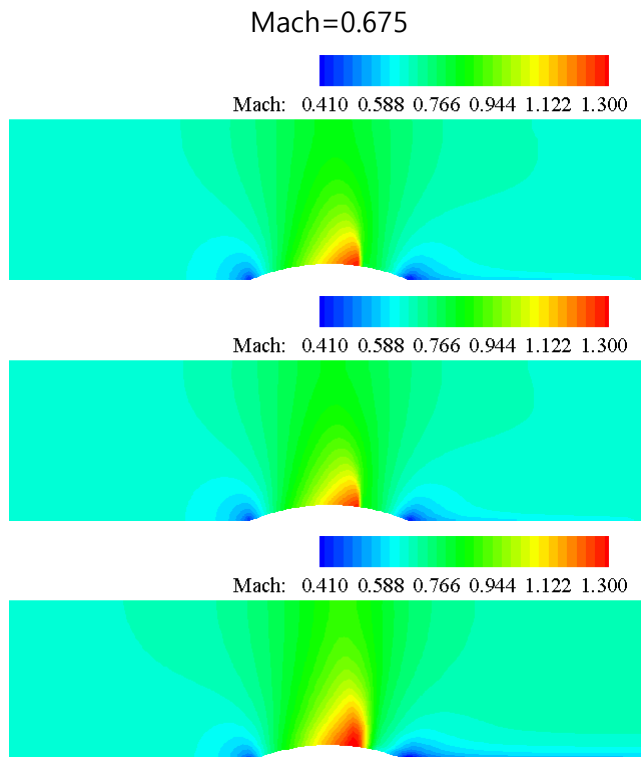
Precon. Roe

LMRoe

Present OpenFOAM



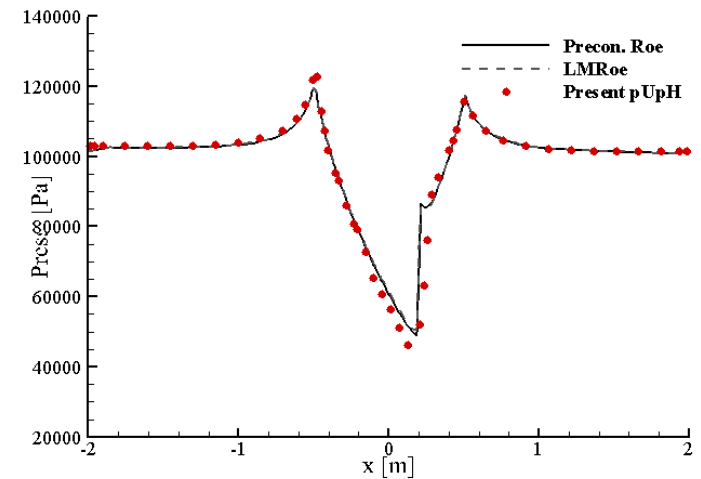
- 2D Euler 10% bump



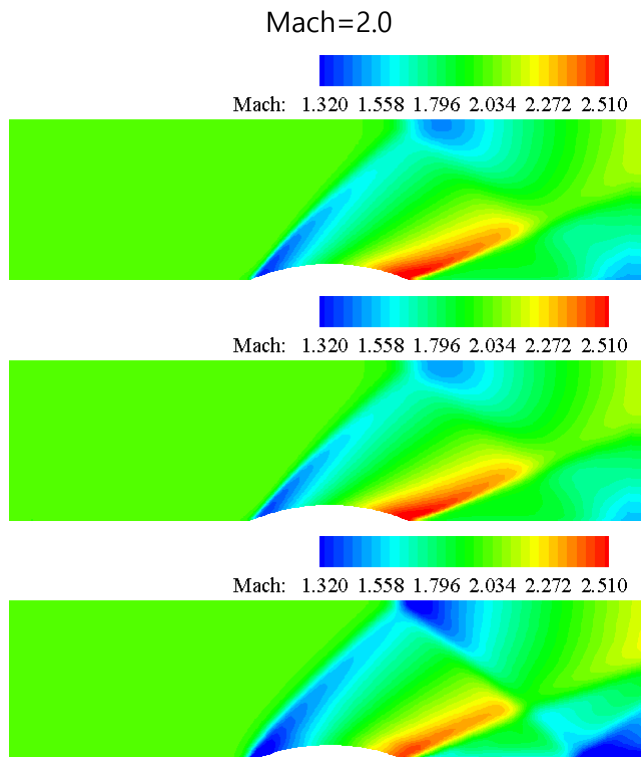
Precon. Roe

LMRoe

Present OpenFOAM



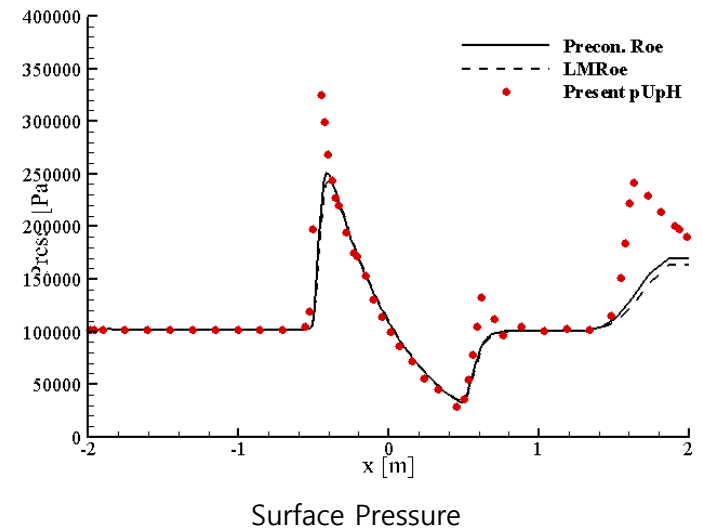
- 2D Euler 10% bump



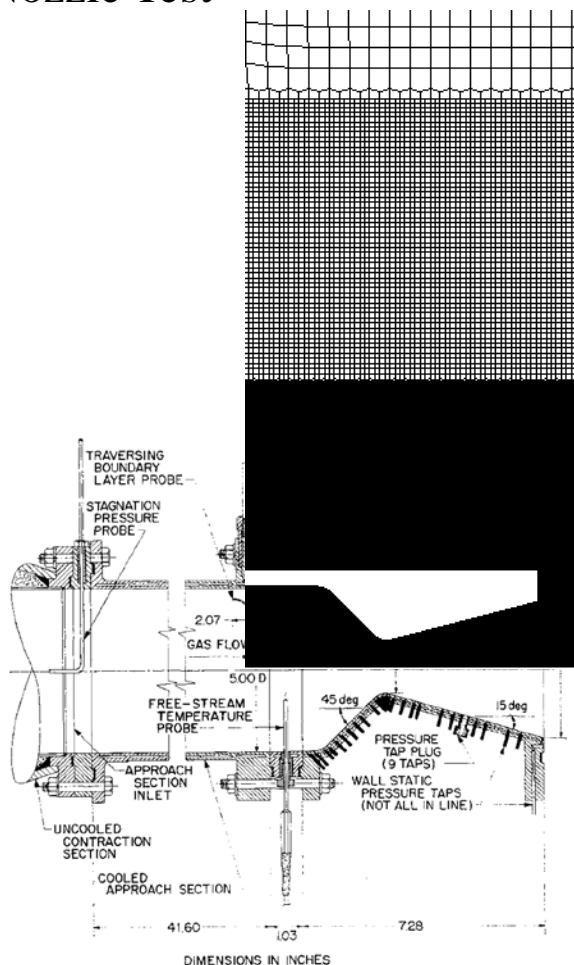
Precon. Roe

LMRoe

Present OpenFOAM



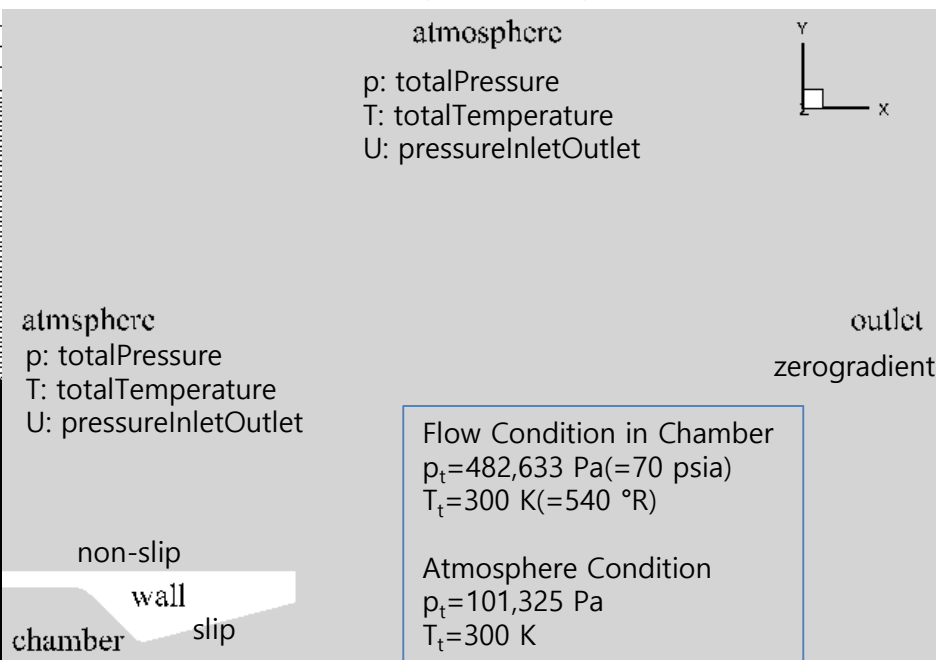
• JPL Nozzle Test



Experimental Configuration

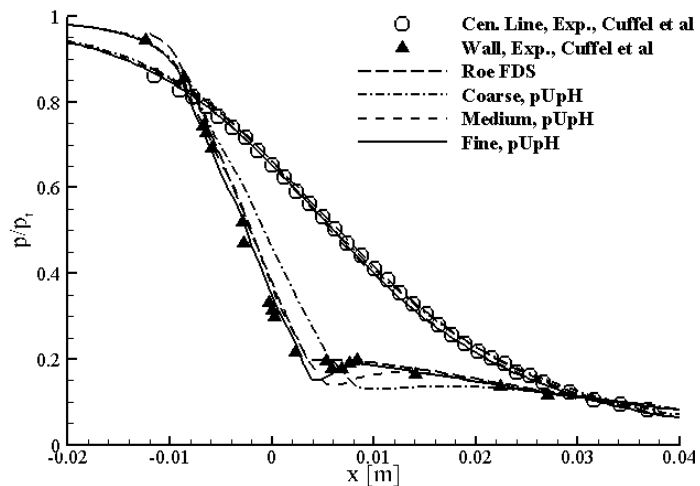
Cuffel et al, AIAA Journal, Vol.7, No. 7, pp. 1364-1366, 1969

Boundary Name & Type



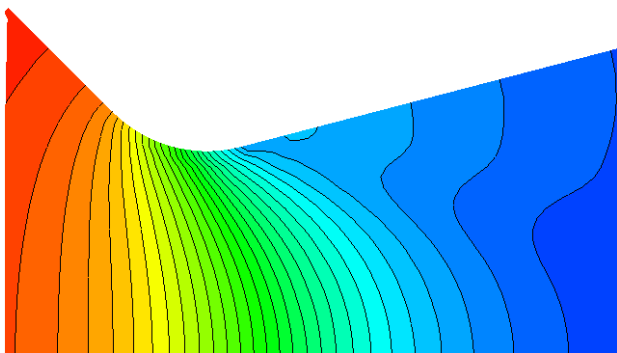


- Flux Scheme
 - 2nd-order Central difference type
 - Kurganov-Tadmor
- Reconstruction Method
 - minmod limiter
- Integration Method
 - Continuity: PCG
 - Moment. Energy: GMRES

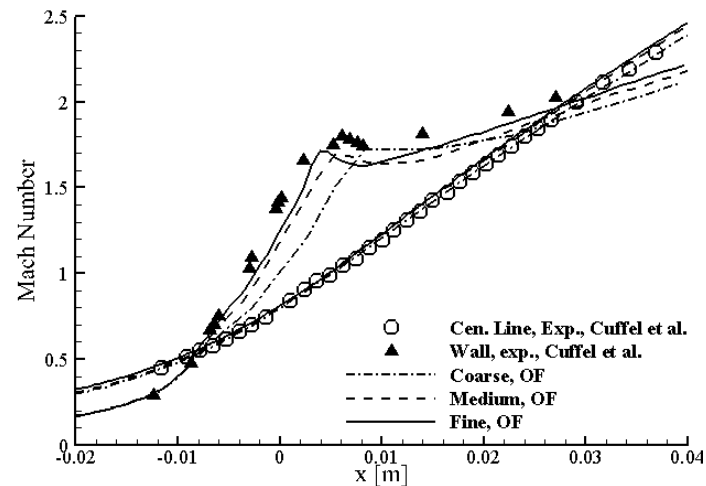
• JPL Nozzle Test





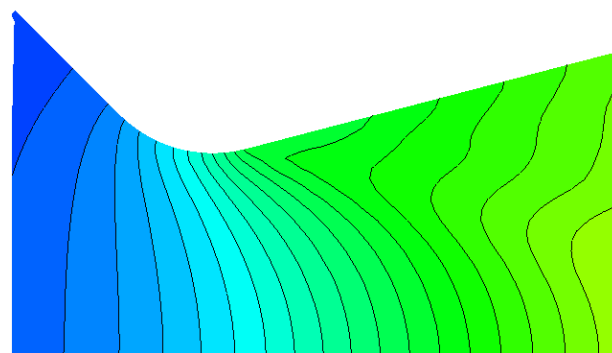
Pres. [MPa]: 0.01 0.10 0.20 0.29 0.39 0.48

Pressure Contour



Mach: 0.03 0.76 1.50 2.23 2.97 3.70

Mach Contour

• Flamelet Test [Piloted CH₄/air flame, SANDIA D]

- ✓ Partially premixed simple diffusion flame
 - ✓ Fuel : partially premixed CH₄(75%) and air(25%)
 - ✓ Oxidizer : air
- ✓ Stoichiometric mixture fraction : 0.351
- ✓ Reynolds number : 22400
- ✓ Fuel nozzle diameter : 7.2 mm
- ✓ Pilot nozzle diameter : 18.2 mm

✓ Pilot inlet condition

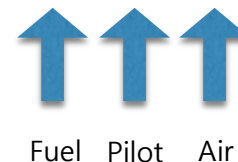
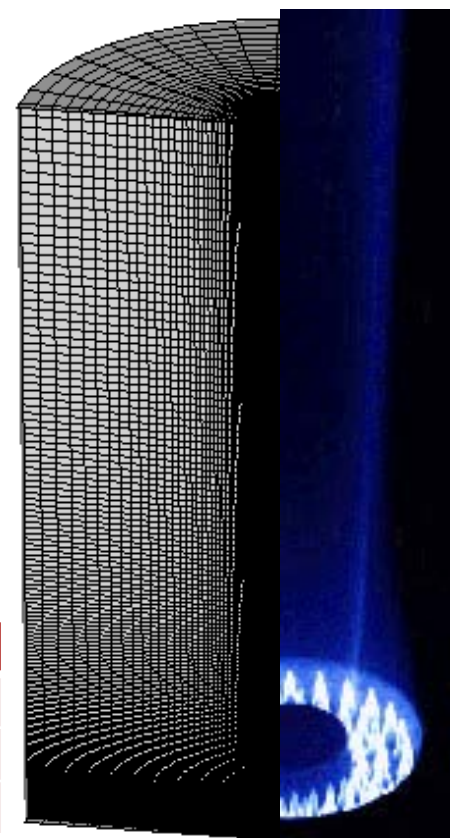
- ✓ mixture fraction : 0.271
- ✓ progress variable : 0.735
- ✓ Temperature : 1880 K

	Fuel	Pilot	Coflow
U [m/s]	49.6	11.4	0.9
T [K]	294	1880	291
Z	1	0.271	0

✓ Turbulence model : Smagorinsky LES

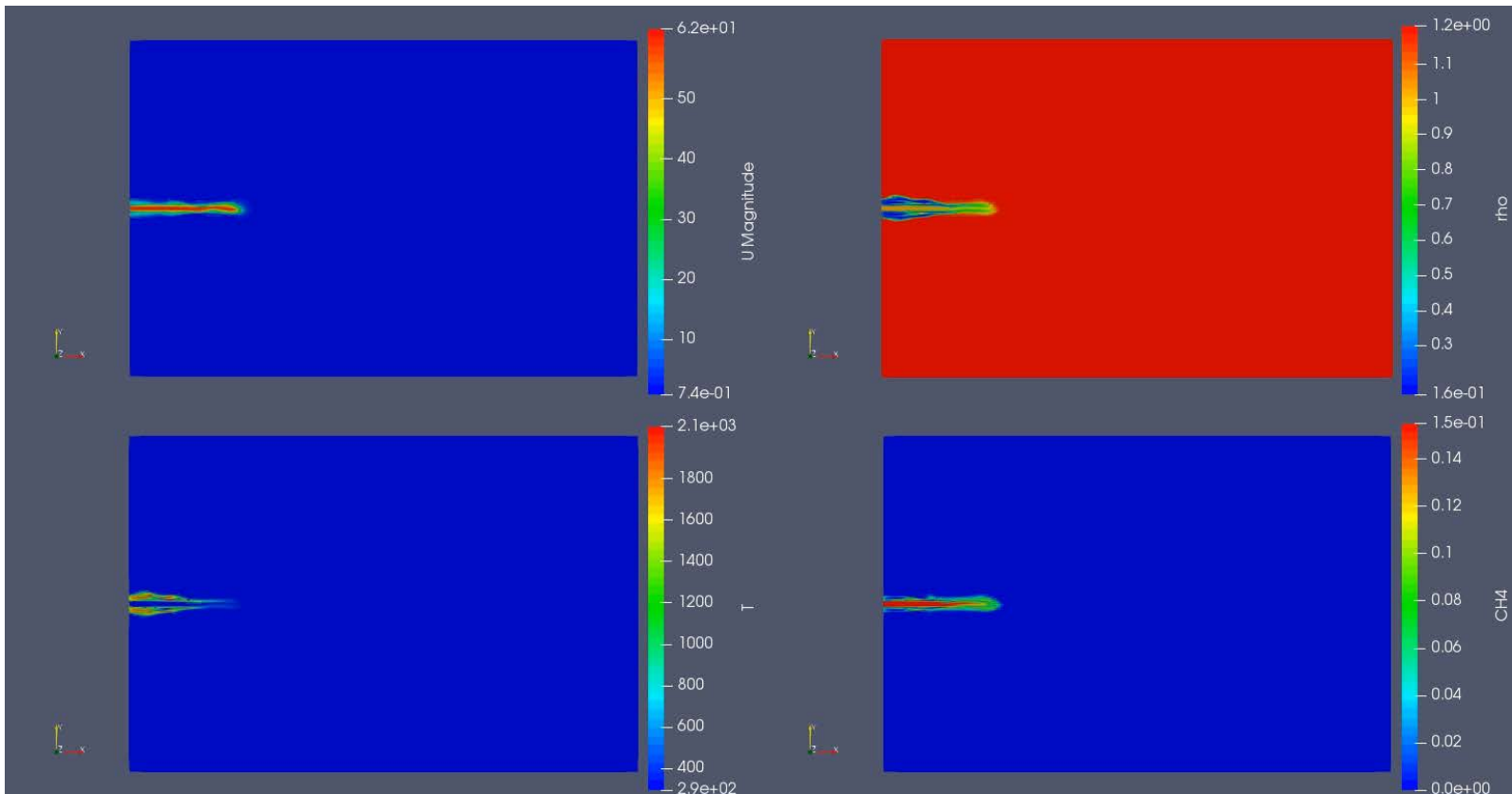
✓ Total cell : 459,000 cells

Barlow, R. S., Frank, J. H., A. N. Karpetis, and Chen, J.-Y., "Piloted Methane/Air Jet Flames: Scalar Structure and Transport Effects", Combust. Flame 143:433-449(2005)

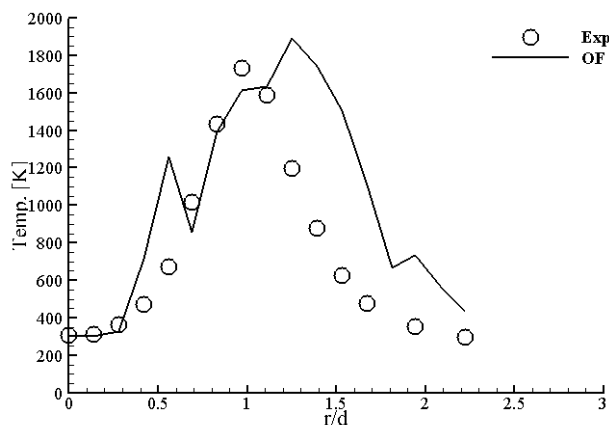


- Flamelet Test [Piloted CH₄/air flame, SANDIA D]

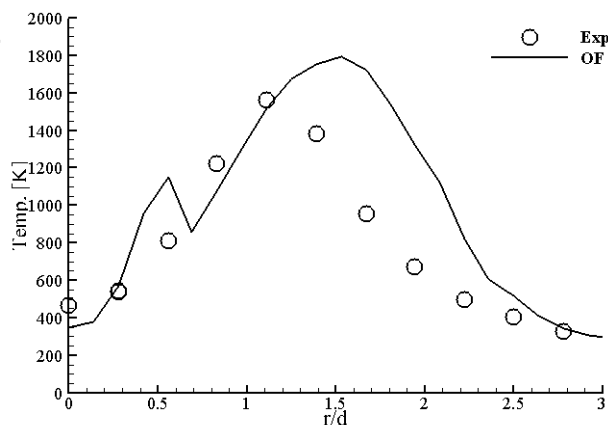
- ✓ 0.005초 간격으로 결과 출력
- ✓ 속도 및 온도, 밀도, CH₄의 결과 출력



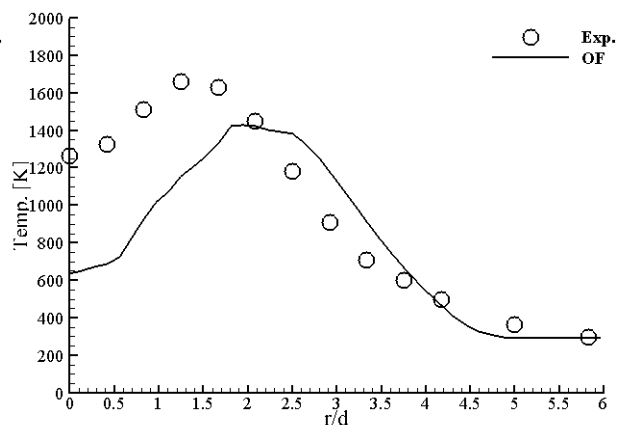
• Flamelet Test [Piloted CH₄/air flame, SANDIA D]



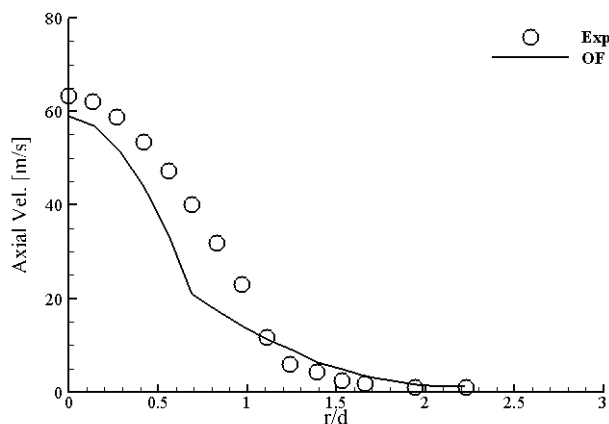
x/d=0.075, Temperature



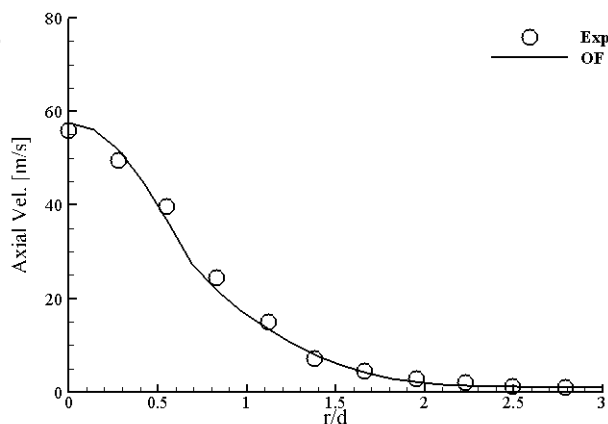
x/d=0.15, Temperature



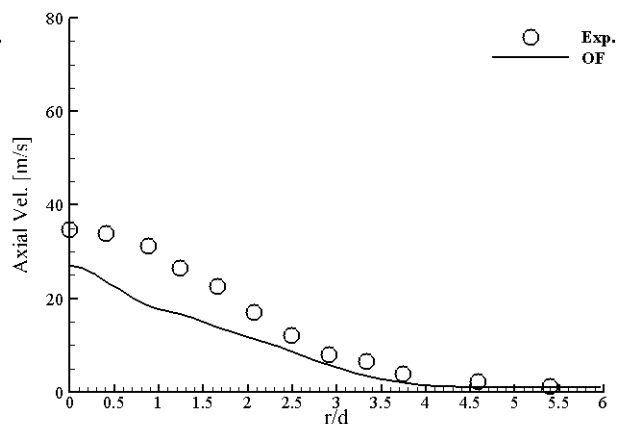
x/d=0.3, Temperature



x/d=0.075, Axial Velocity



x/d=0.15, Axial Velocity



x/d=0.3, Axial Velocity

결론 및 고찰

- 다양한 마하수 영역에서의 압력 변화가 큰 유동을 해석하기 위해 압력 기반의 압력-속도 연계 해석 알고리즘 개발
 - ✓ 기존의 segregated 방식이 아닌 coupled 방식의 속도 연계 알고리즘 개발
 - ✓ 충격파와 같은 불연속성 유동을 해석하기 위해 central scheme 기반의 flux splitting 기법 적용
 - ✓ 연소 현상을 해석하기 위한 table-lookup 기반의 flamelet 모델 적용
- 개발된 유동에 대한 다양한 유동 해석 적용
 - ✓ 대표적인 충격파 문제들에 대한 해석 적용 및 결과 비교를 통해 개발된 알고리즘을 적용한 압력 기반의 유동 해석자가 불연속적 유동 현상 해석에 서 적절한 결과를 도출
 - ✓ 다양한 마하수의 Bump 유동 해석을 통해 개발된 알고리즘이 저마하수 영역에서도 적절한 결과를 도출함을 확인
 - ✓ 연소 문제 해석을 통해 flamelet 모델이 적용한 해석 알고리즘이 연소 문제에 대해 적용 가능함을 확인
→ 추가적인 해석 및 결과 비교를 통해 해석자의 검증 수행 예정