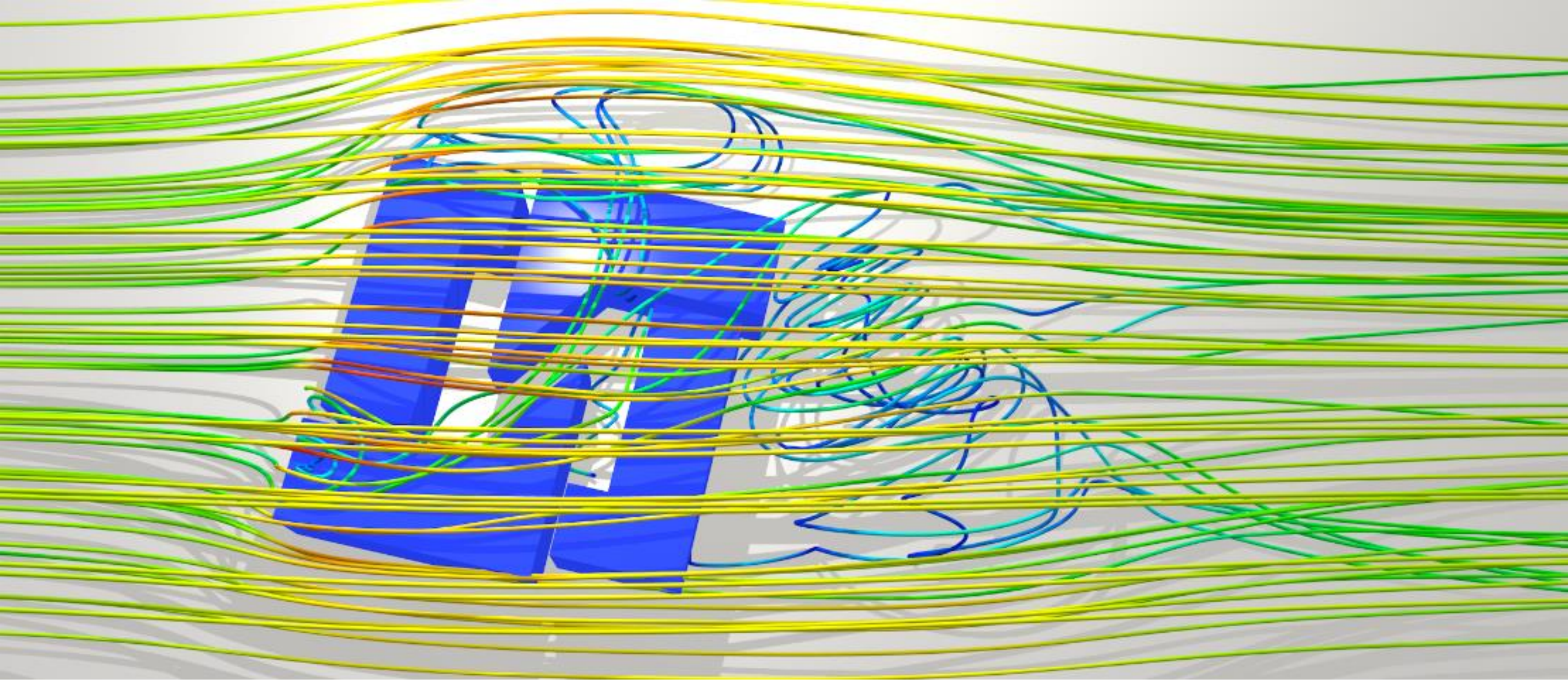
넥스트폼의 항공우주분야 개발 사례

2019. 09. 26

NEXTfoam
open source CFD consulting

목 차



열공력 솔버

1. 개발 사항

개발 사항

Pressure based

Incompressible

simpleNFoam
pimpleNFoam

Compressible

rhoSimpleFoam
rhoPimpleFoam
rhoCentralFoam

All speed range

Foundation
Extended

PCNFoam
pUCoupledCNFoam

Combustion

Flamelet

pUCoupledFCNFoam

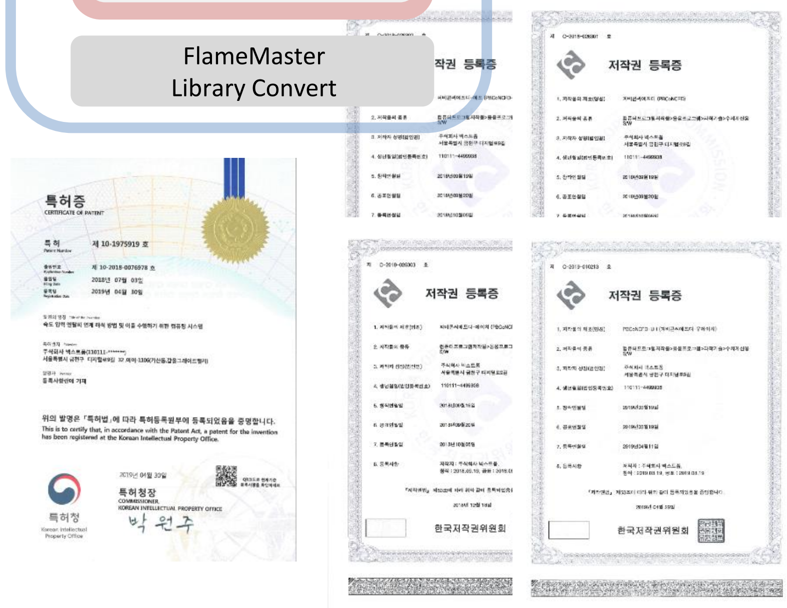
FlameMaster
Library Convert

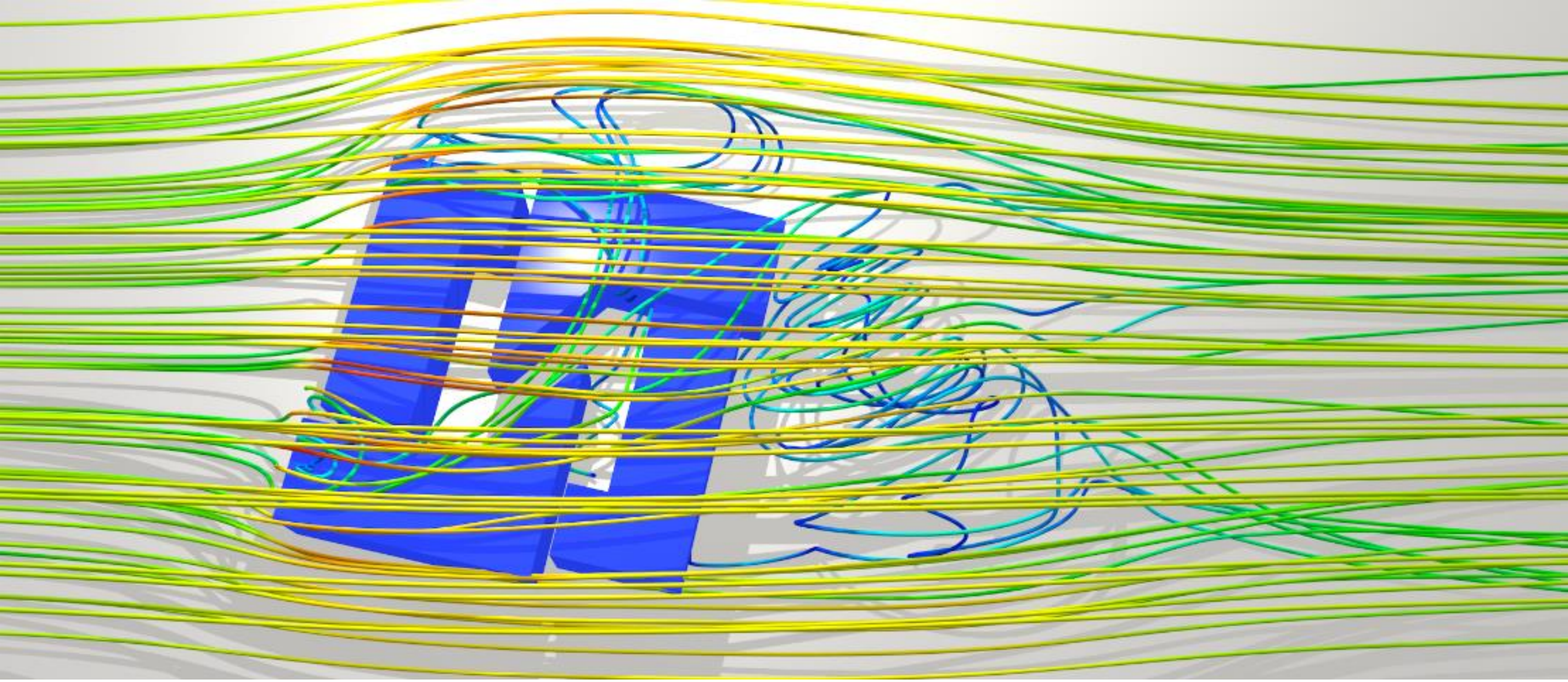
Density based

Implicit LU-SGS
RoeFDS

Compressible

TSLAeroFoam

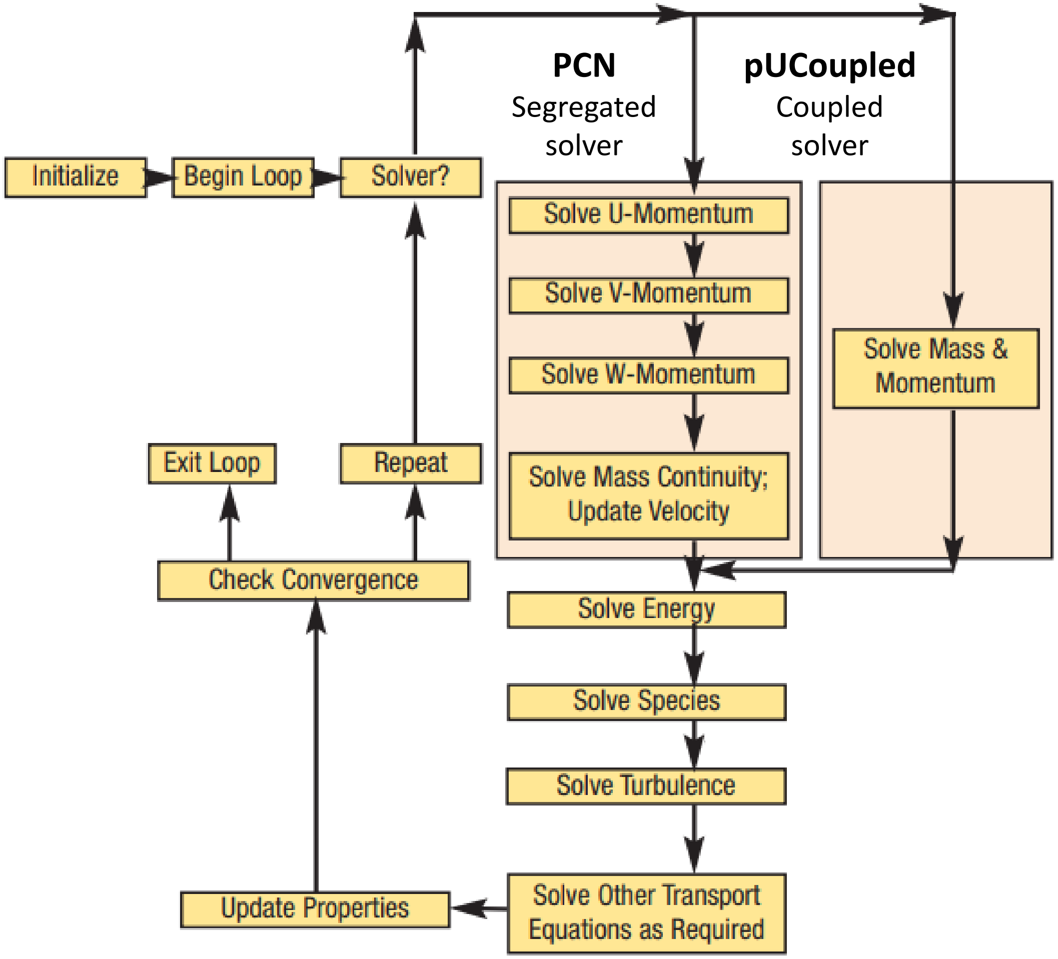




Pressure Based Compressible Solver

1. PCNFoam / pUCoupledCNFoam
2. Validation
3. Aerodynamic Performance
4. Practice Research

PCNFoam / pUCoupledCNFoam



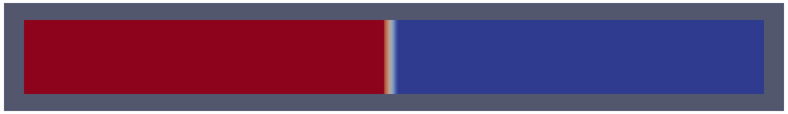
- pressure based flux splitting central scheme
  - 격자 면에서의 flux 계산에 적용

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

- Kurganov-Tadmor flux splitting scheme
  - Low Mach number correction
- Segregated 대비 압축성 영역 강건성
- 메모리 및 반복 시간 다소 손해

Validation

- 1D Lax problem

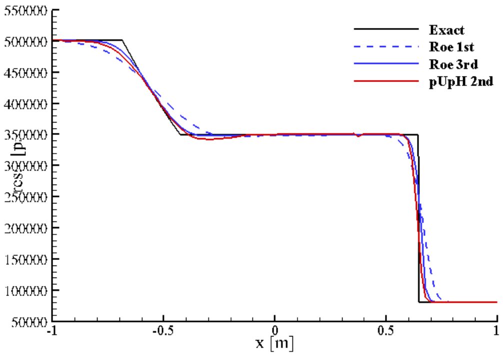


[초기]

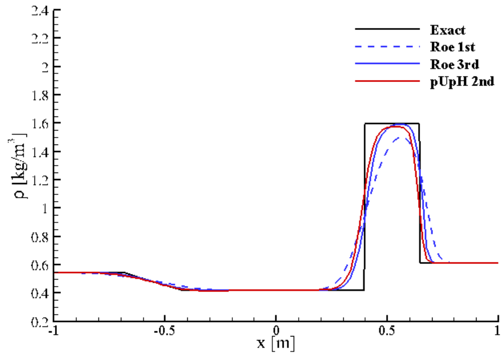
[종료]

- Riemann Problem of Lax
  - Shock tube problem with sever pressure
  - Finial time: 0.13, Mesh points: 100
  - Boundary condition: Extrapolation

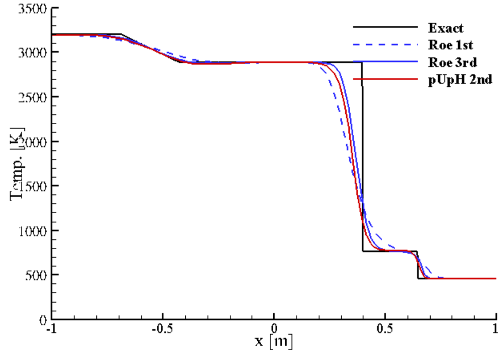
$$(\rho, u, p) = \begin{cases} (0.445, 0.698, 3.528) & \text{if } x \le 0 \\ (0.5, 0, 0.571) & \text{if } x > 0 \end{cases}$$



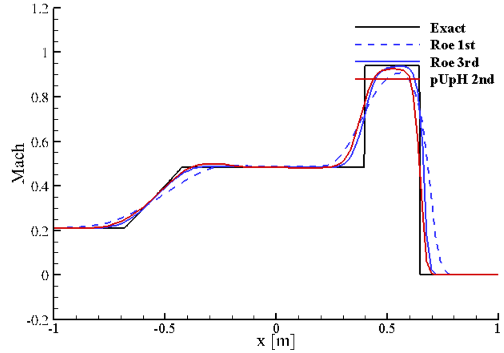
Pressure



Density



Temperature



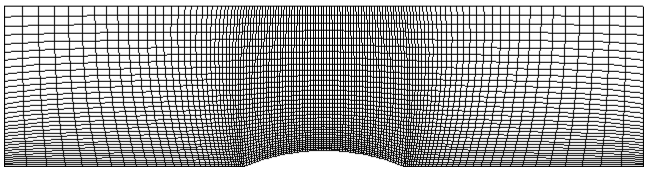
Mach

Validation

- 2D Euler 10% bump

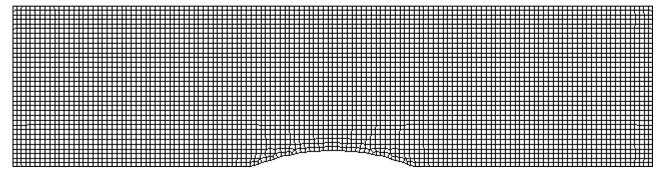
Precon./LM Roe FDS

Grid Size 121×35, Elliptic



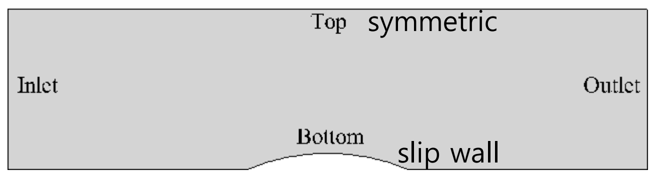
Present OpenFOAM

Grid Size 121×35, Salome, cfMesh



Boundary Name & Type

zerogradient



Subsonic: fixed value
Supersonic: zerogradient

Solution Algorithm

Precon./LM Roe FDS

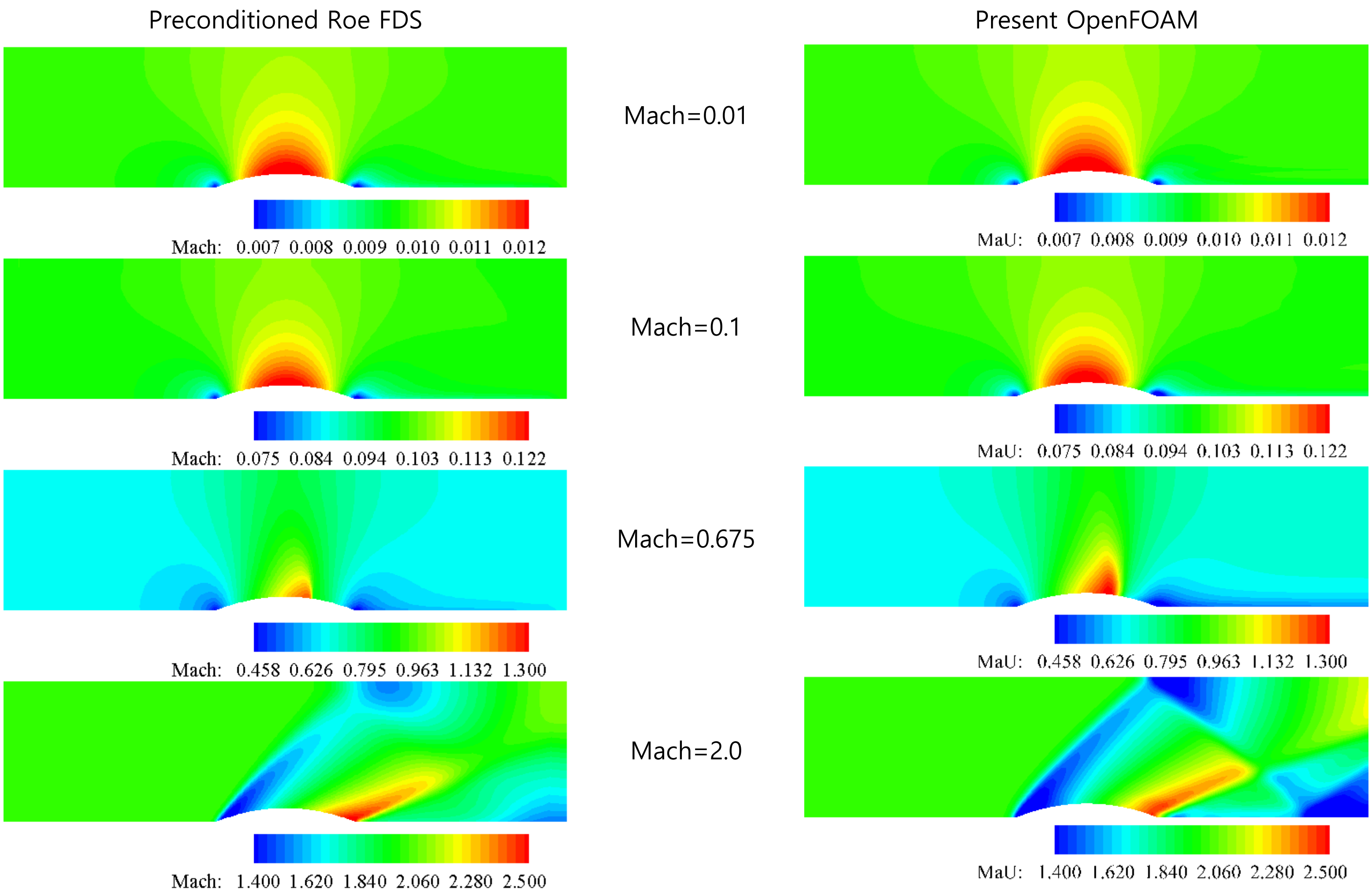
- Flux Scheme
  - Upwind type
  - Preconditioned Roe / LMRoe FDS
- Reconstruction Method
  - 2nd-order minmod limiter
- Integration Method
  - Fully Implicit LU-SGS

Present OpenFOAM

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

Validation

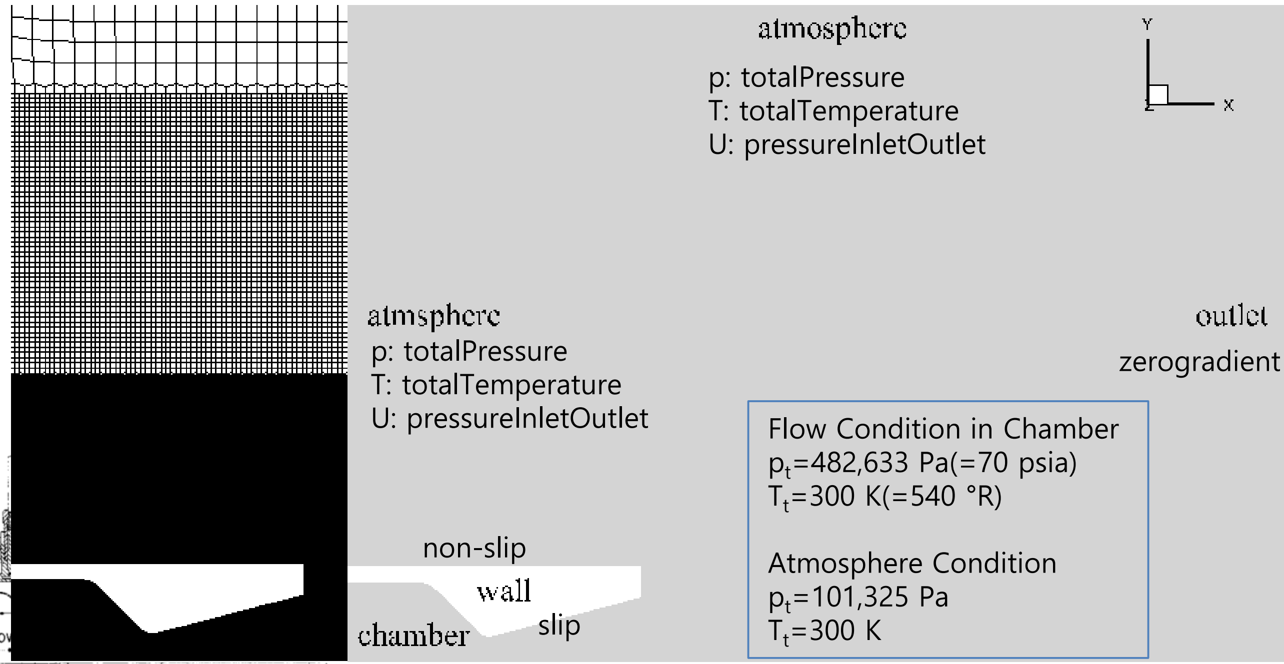
- 2D Euler 10% bump

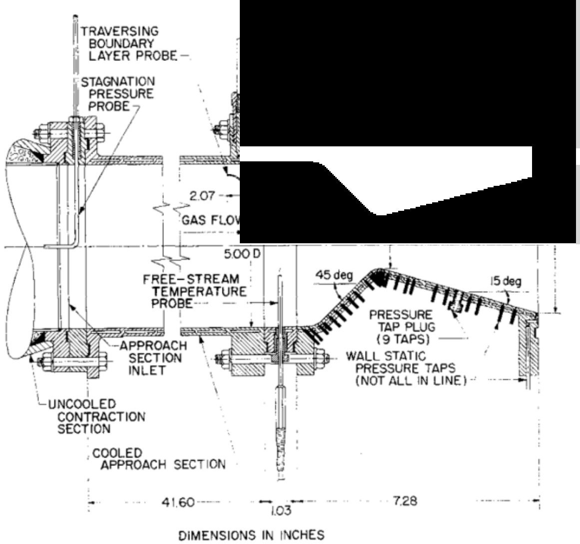


Validation

- JPL Nozzle Test

Boundary Name & Type





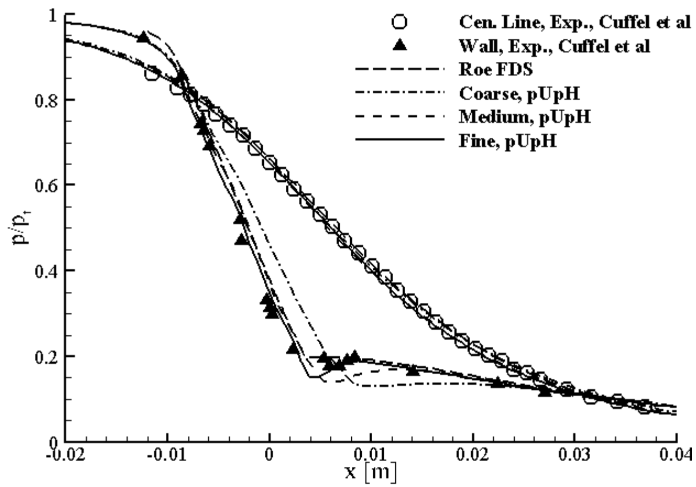
Experimental Configuration

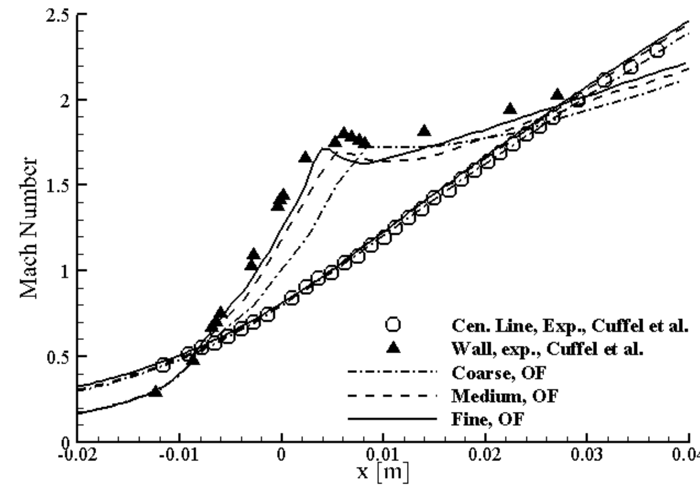
Cuffel et al, AIAA Journal, Vol.7, No. 7, pp. 1364-1366, 1969

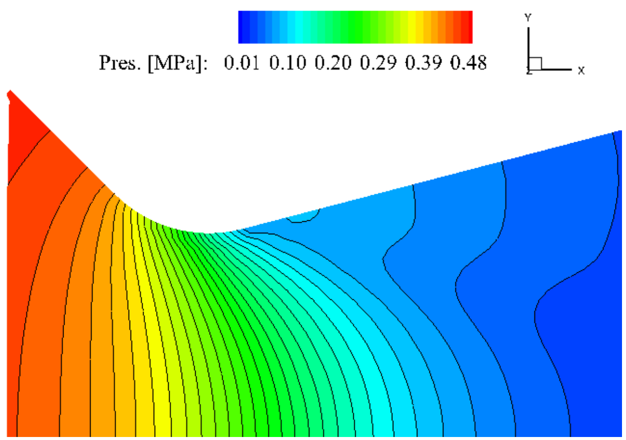
- Flux Scheme
  - 2nd-order Central difference type
  - Kurganov-Tadmor
- Reconstruction Method
  - minmod limiter
- Integration Method
  - Continuity: PCG
  - Moment. Energy: GMRES

Validation

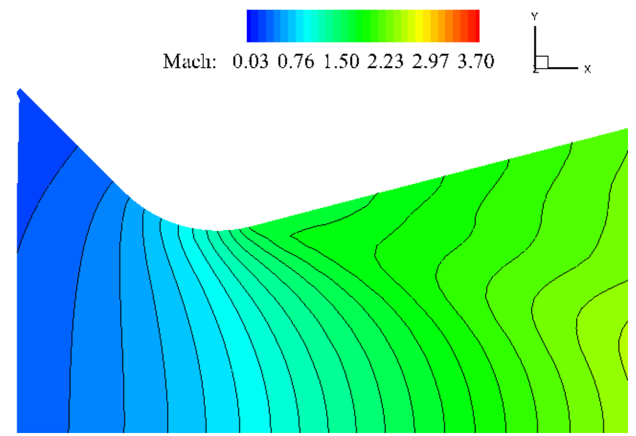
- JPL Nozzle Test







Pressure Contour

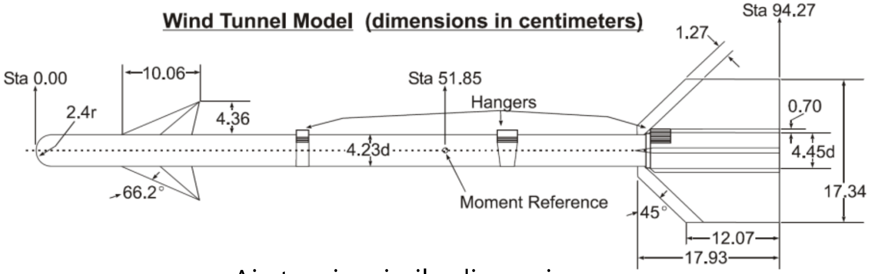


Mach Contour

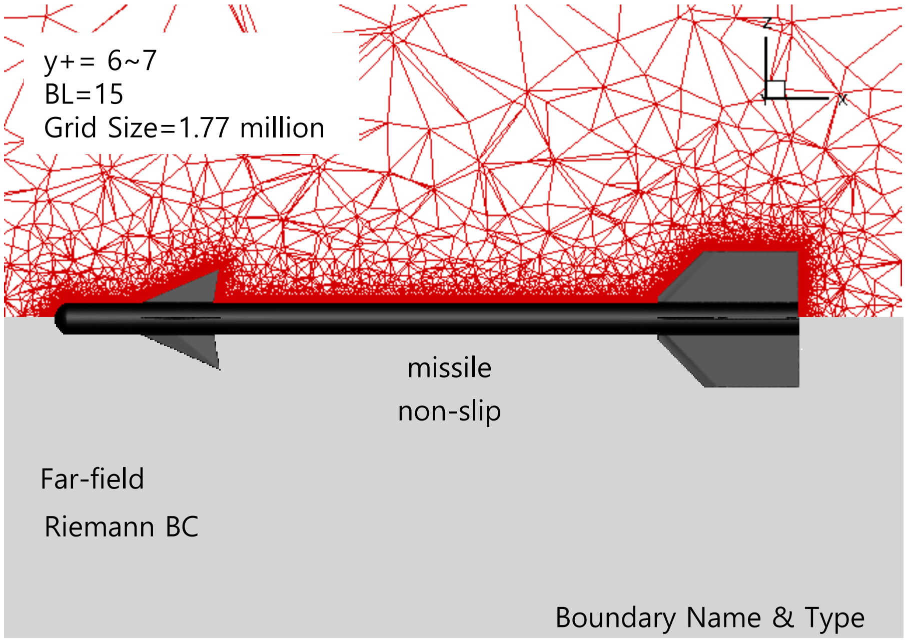
Aerodynamic Performance

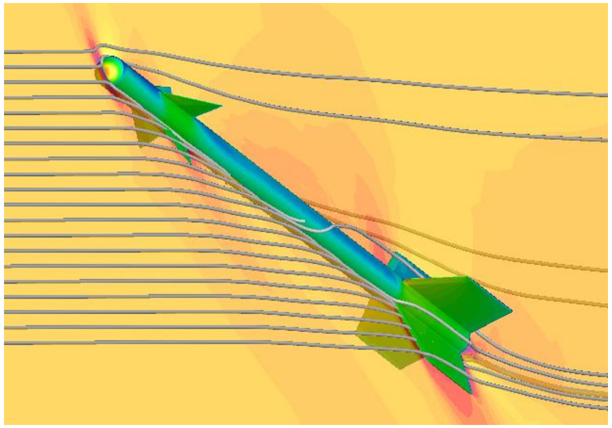
- Air-to-air Missile

Ref. Area= 1.408×10^{-3} m^2
Max Body Dia.= 4.238×10^{-2} m



Air-to-air missile dimension
Ernald et al, NASA TM X-3070, 1974



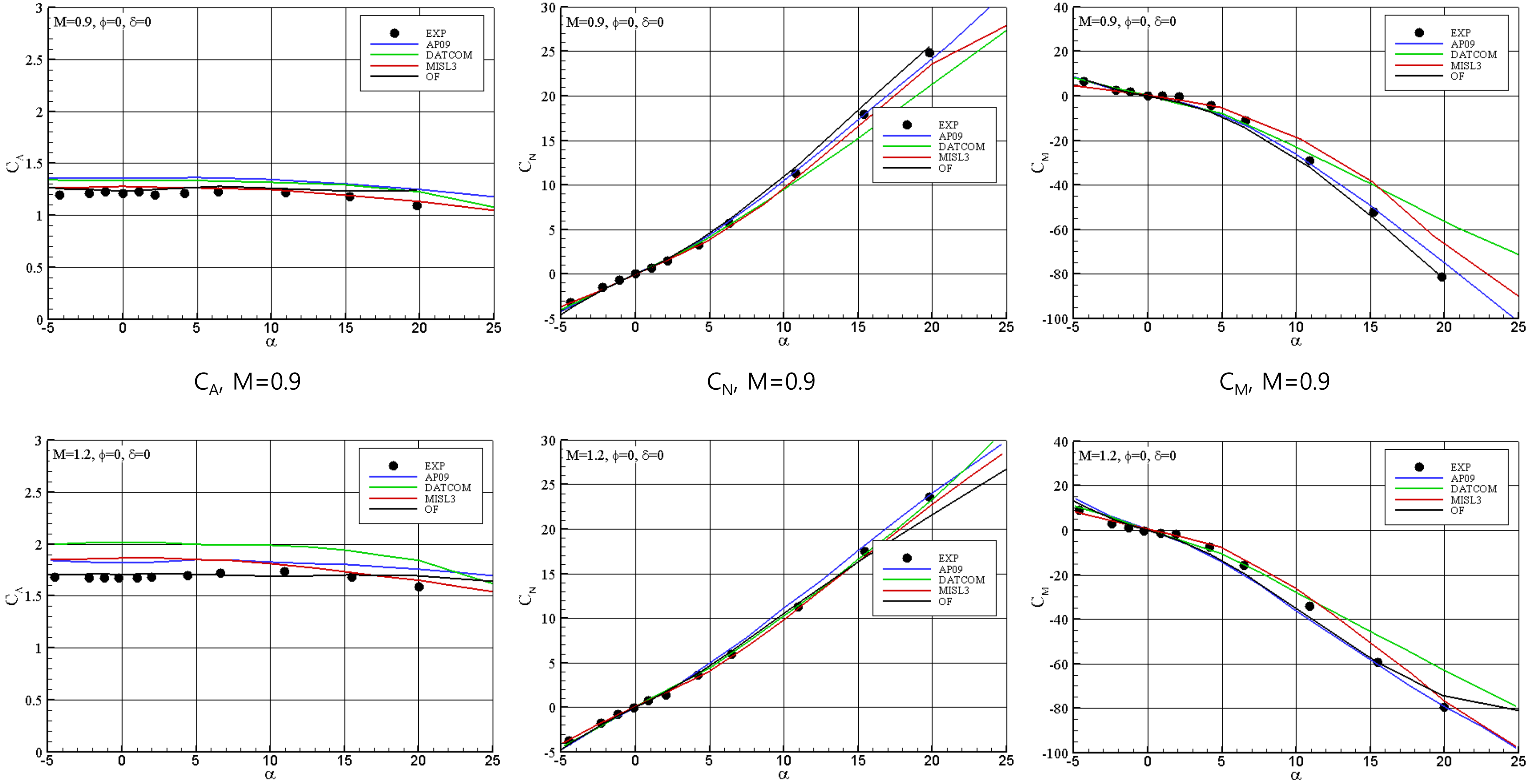


- Wind Tunnel Condition
  - Rex=6.56×10^6
  - T_t=332 K
- Far-field Condition
  - AOA Sweep (-5° ~ 25°)
- M0.9
  - P= 32.704 kPa
  - T= 285.71 K
  - U= 304.97 m/s
- M1.2
  - P= 22.068 kPa
  - T= 257.76 K
  - U= 386.22 m/s

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

Aerodynamic Performance

- Air-to-air Missile



C_A, M=0.9

C_N, M=0.9

C_M, M=0.9

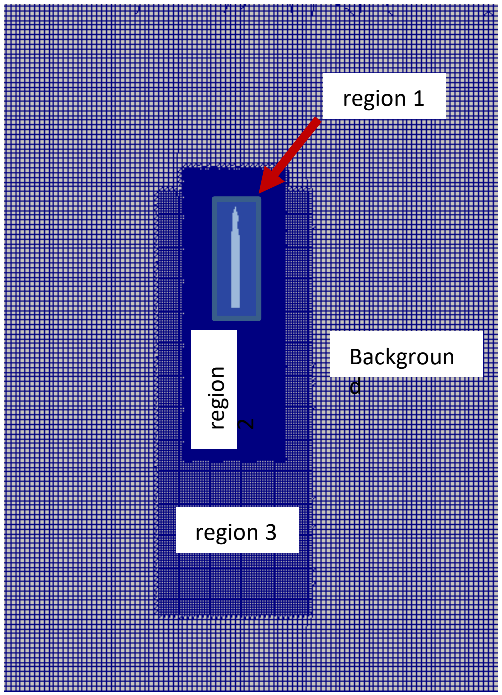
C_A, M=1.2

C_N, M=1.2

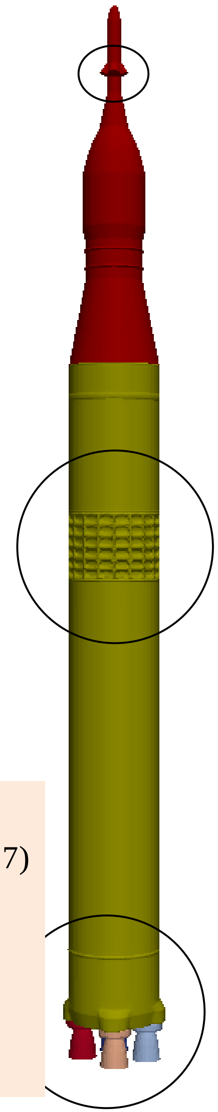
C_M, M=1.2

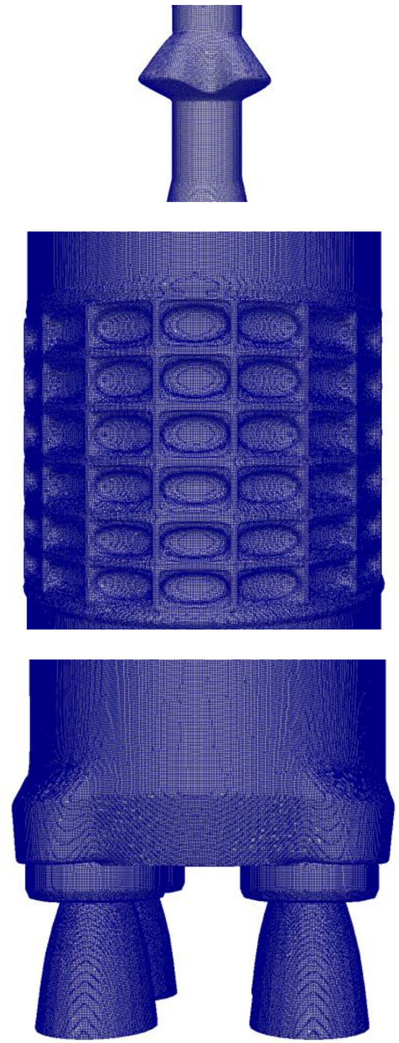
Aerodynamic Performance

- SLS Launch Vehicle



- Background: 8 m (level 0)
- Rocket Nozzle Surface: 0.0625m (level 7)
- 3 Refinement regions
  - Region 1 : 0.5m (level 4)
  - Region 2 : 2m (level 2)
  - Region 3 : 4m (level 1)
- 5 BL (first layer thickness = 0.003 m)





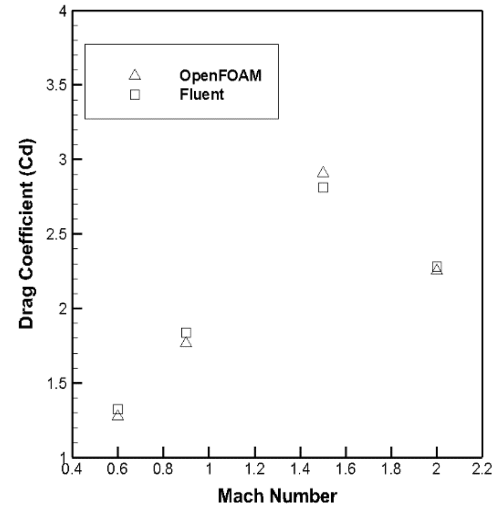
- Flux Scheme
  - 2nd-order Central difference type
  - Kurganov-Tadmor
- Reconstruction Method
  - minmod limiter
- Integration Method
  - Continuity: PCG
  - Moment. Energy: GMRES
  - Turbulence: k-ω SST: BiCGStab
- Far-field Condition
  - AOA Sweep (-5° ~ 15°)
  - Mach Sweep (0.6 ~ 2.0)

Aerodynamic Performance

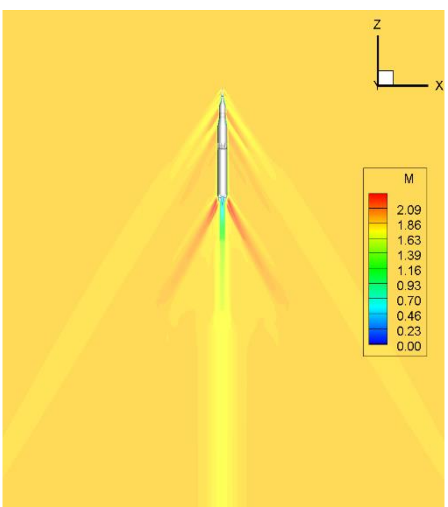
- SLS Launch Vel

OpenFOAM

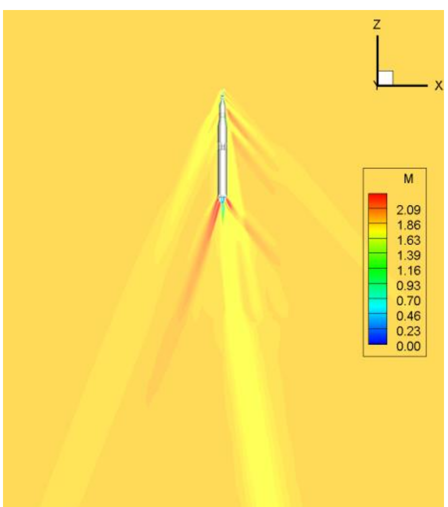
Fluent



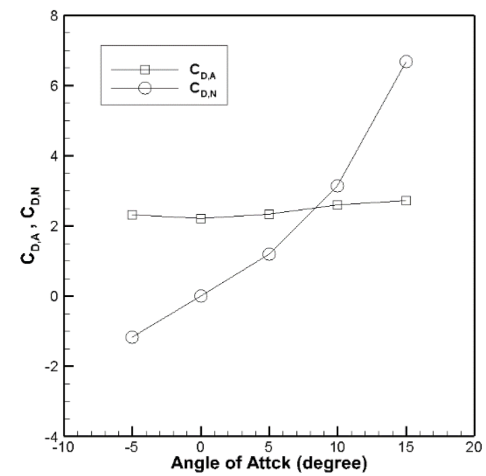
마하수에 따른 항력



AOA = 0



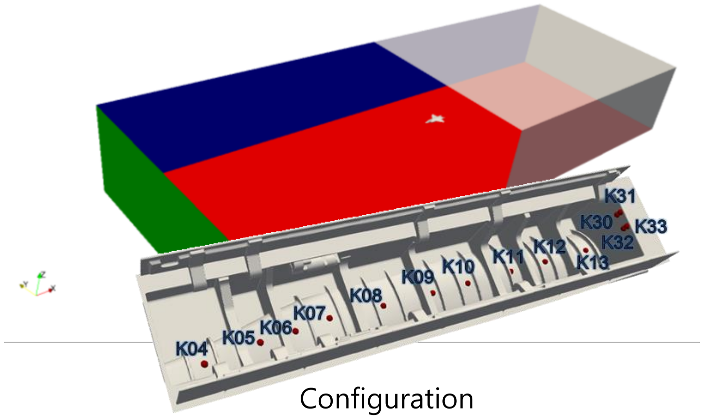
AOA = 10



AOA에 따른 공력계수

Practice Research

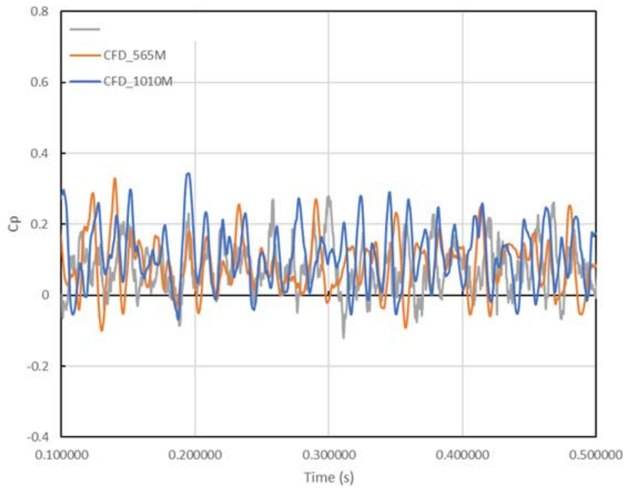
- 비행체 공동 유동



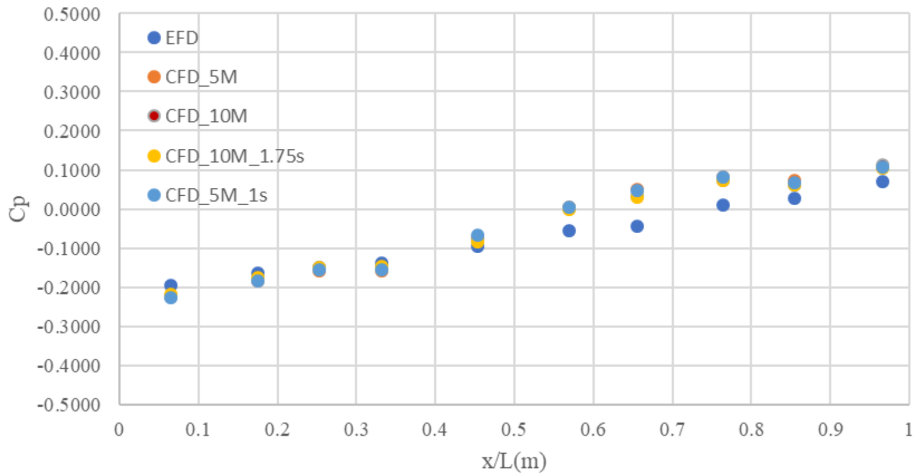
Configuration

- 5.6 million polyhedral cells
  - Δt=5e-5
  - hexa: 5.4 M, poly: 0.21 M
- 10 million polyhedral cells
  - Δt=4e-5
  - hexa: 9.9 M, poly: 0.48 M

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



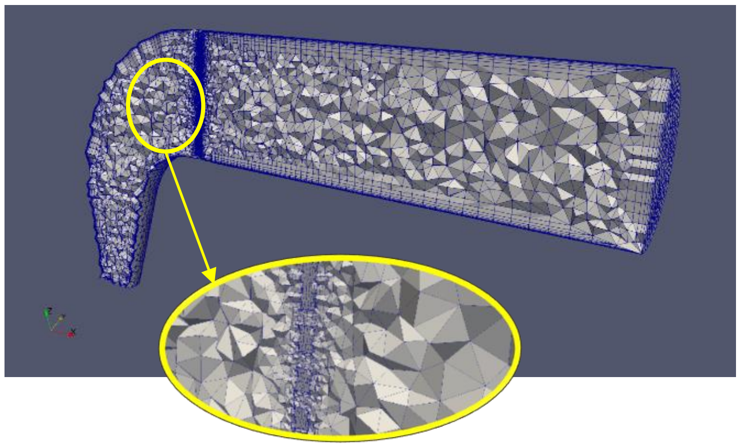
Cp time history



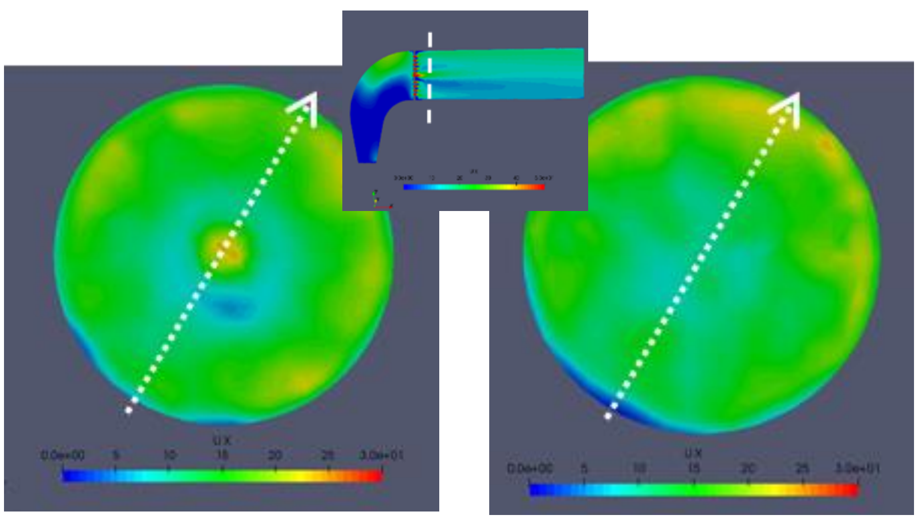
Grid dependency

Practice Research

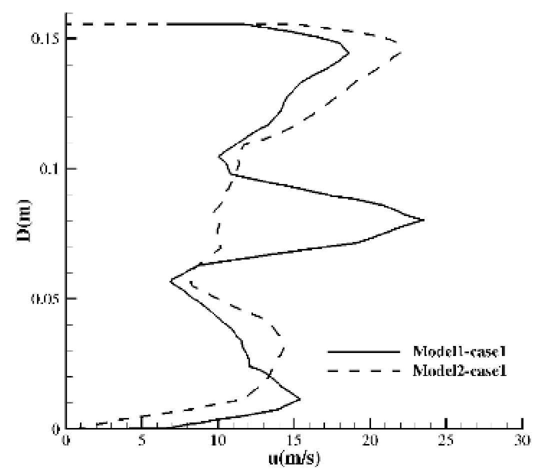
- KARI 산화제 유입부 유동



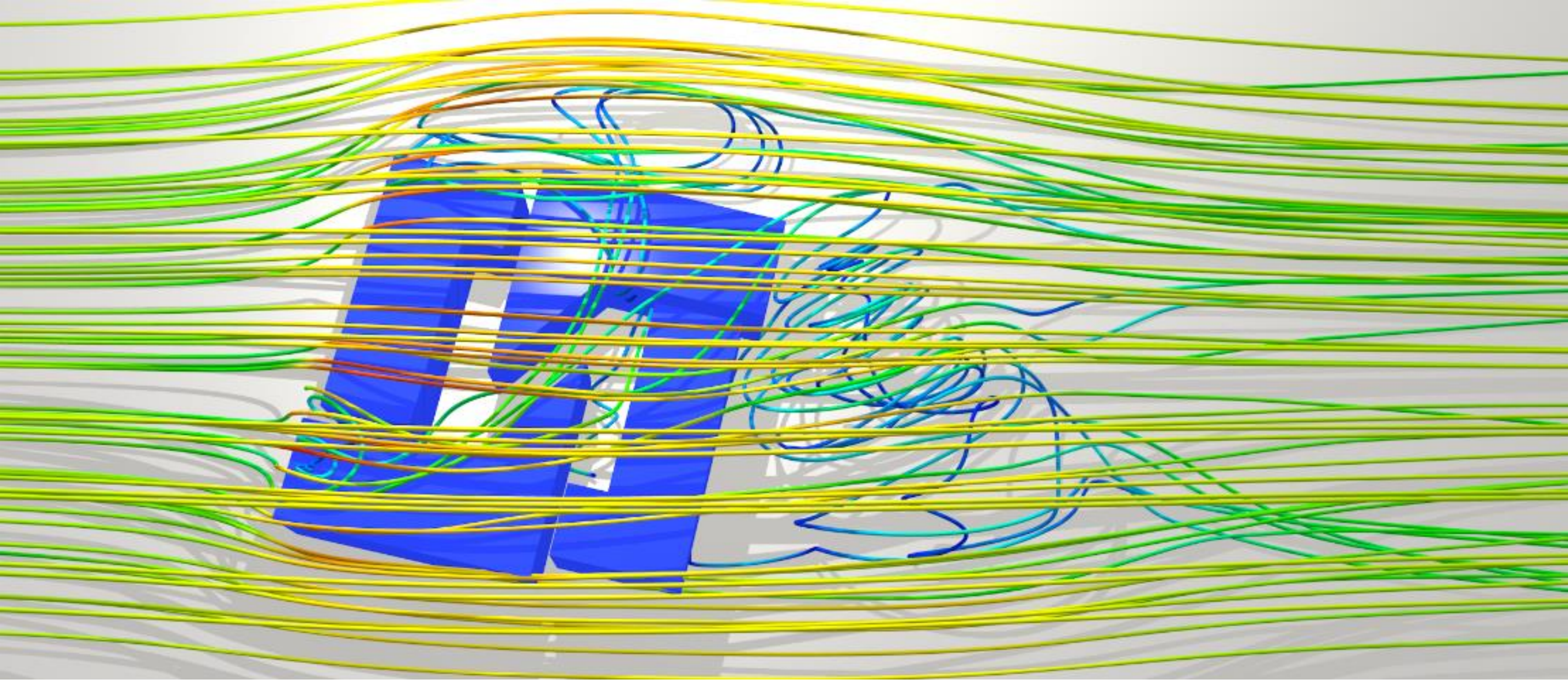
- Flux Scheme
  - 2nd-order Central difference type
  - Kurganov-Tadmor
- Reconstruction Method
  - minmod limiter
- Integration Method
  - Continuity: PCG
  - Moment. Energy: GMRES
  - Turbulence: realizable k-ε: BiCGStab
- Thermodynamics Properties
  - O_2



Model 1 Model 2



Velocity distribution

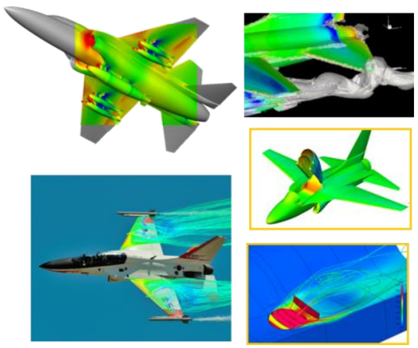


Density Based Compressible Solver

1. TSLAeroFoam

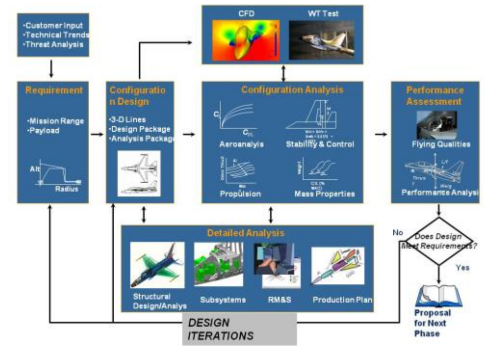
TSLAeroFoam

- Background
  - Increasing CFD analysis to development phase
  - Move problem resolution to massive computing in a design phase



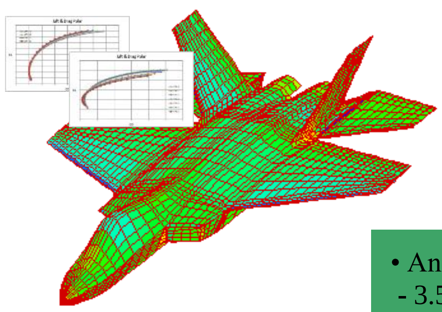
Problem Resolution

• Increasing CFD requirement



Design Phase Tool

- CFD Role
  - Able to build up aerodynamic DB by using CFD

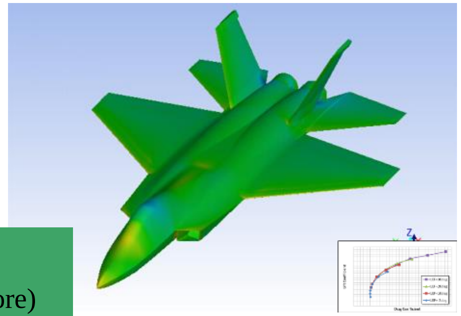


Panel Method

• Analysis time
- 3.5 days

• Analysis condition: 2,185 cases
- AOA (13), SSA (5), M (11), δ (4)

• Analysis time
- 121 days (32 core)
- 7.6 days (700 core)



CFD

TSLAeroFoam

- Governing Equations
  - Favre-averaged Navier-Stokes Equation

$$\int_V \frac{\partial Q}{\partial t} dv + \int_{\partial V} (F_c - F_v) ds = 0 \qquad W = \begin{bmatrix} \rho \\ \rho U \\ \rho E \end{bmatrix} \quad F_c = \begin{bmatrix} \rho U \\ \rho U_i U_j + PI \\ \rho HU \end{bmatrix} \quad F_v = \begin{bmatrix} 0 \\ \tau_{ij} \\ \nabla \cdot (\tau_{ij} U + \rho \alpha_{eff} \nabla h + (\mu + \frac{\mu_t}{\sigma_k}) \nabla k) \end{bmatrix}$$

- Turbulence Model
  - Two equation k-ω Shear Stress Transport with wall function model

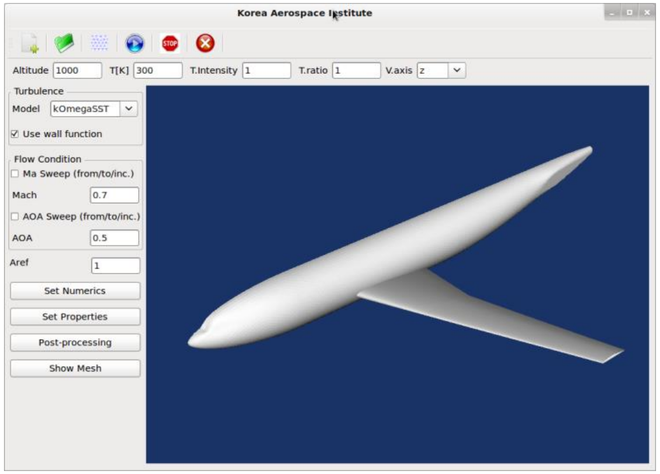
$$\frac{\partial(\rho k)}{\partial t} + \frac{\partial(\rho U_i k)}{\partial x_i} = \tilde{P}_k - \beta^* \rho k \omega + \frac{\partial}{\partial x_i}\left[(\mu + \sigma_k \mu_t)\frac{\partial k}{\partial x_i}\right]$$

$$\frac{\partial(\rho \omega)}{\partial t} + \frac{\partial(\rho U_i \omega)}{\partial x_i} = \alpha \rho S^2 - \beta \rho \omega^2 + \frac{\partial}{\partial x_i}\left[(\mu + \sigma_\omega \mu_t)\frac{\partial \omega}{\partial x_i}\right] + 2(1 - F_1)\rho \sigma_{w2}$$

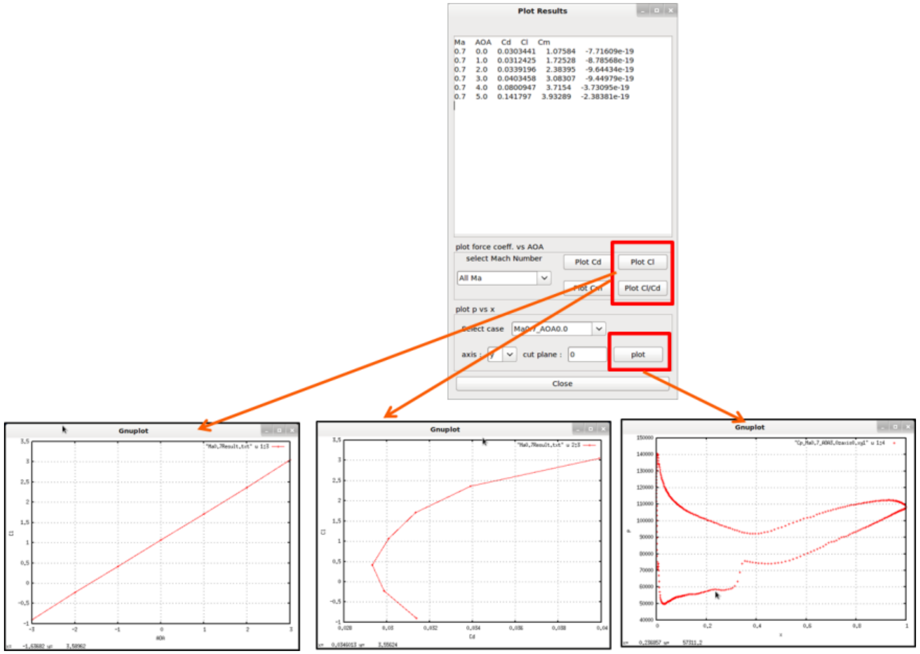
- Spatial Discretization
  - Roe FDS
  - Reconstruction: Least square method
- Temporal Integration
  - LU-SGS

TSLAeroFoam

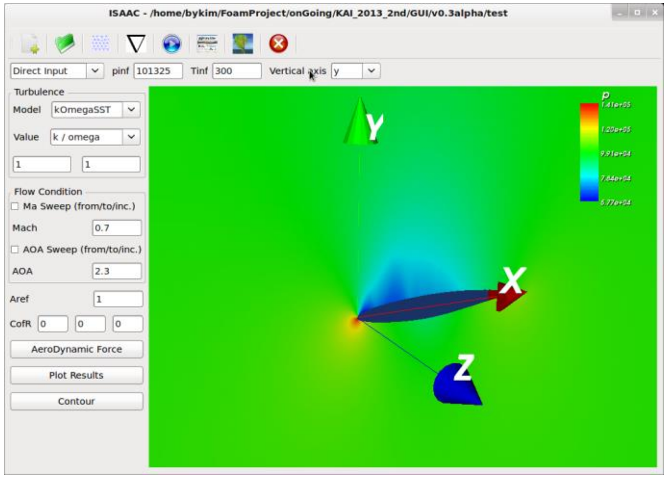
- Text User Interface
  - Batch job (e.g. Ma, AOA, SSA sweep)
- Graphic User Interface with 3D Graphic
  - Use VTK to generate mesh and contours



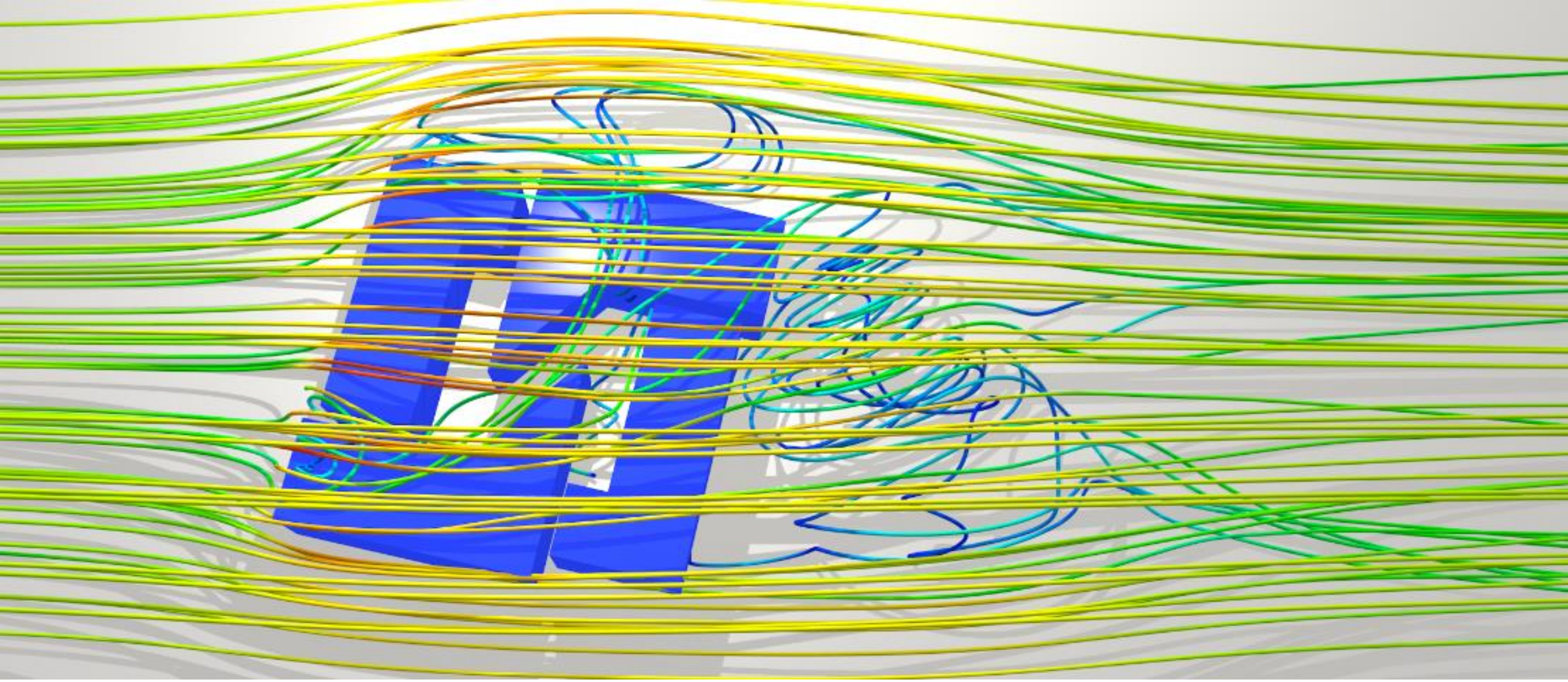
GUI graphic version



2D graphics post-processor



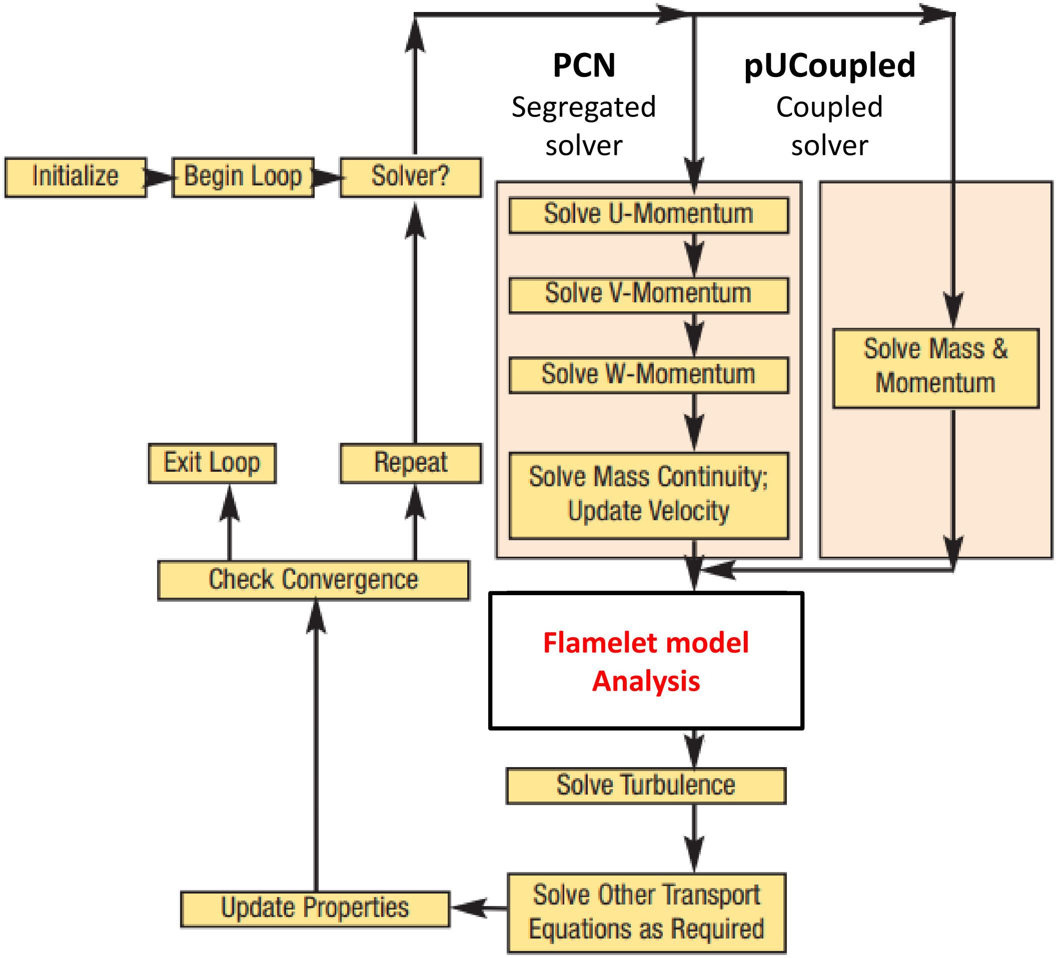
Embedded 3D graphic post-processor



Flamelet Solver

1. pUCoupledFCNFoam

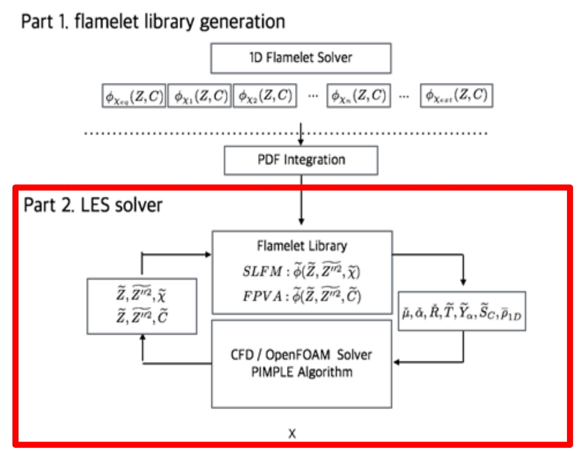
pUCoupledFCNFoam



- pressure based flux splitting central scheme
  - 격자 면에서의 flux 계산에 적용

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

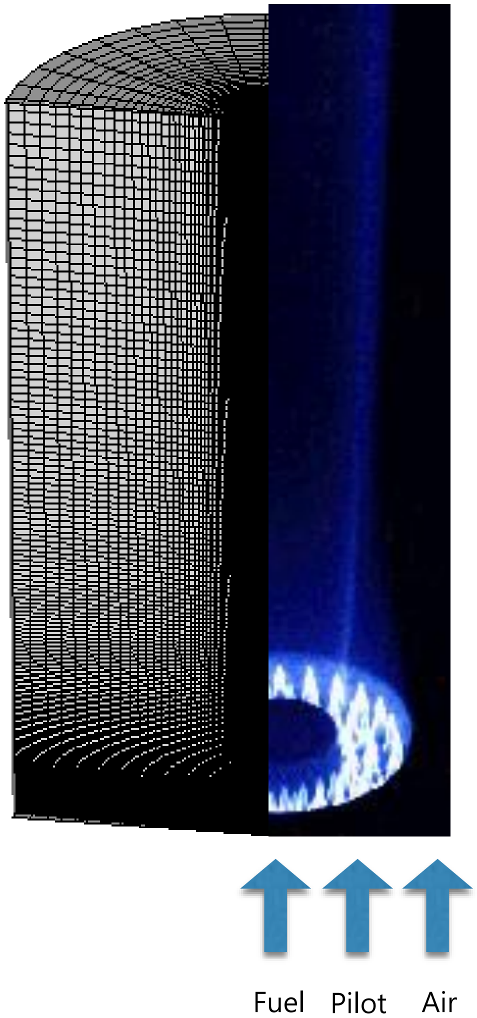
- Kurganov-Tadmor flux splitting scheme
  - Low Mach number correction
- Segregated 대비 압축성 영역 강건성
- 메모리 및 반복 시간 다소 손해



pUCoupledFCNFoam

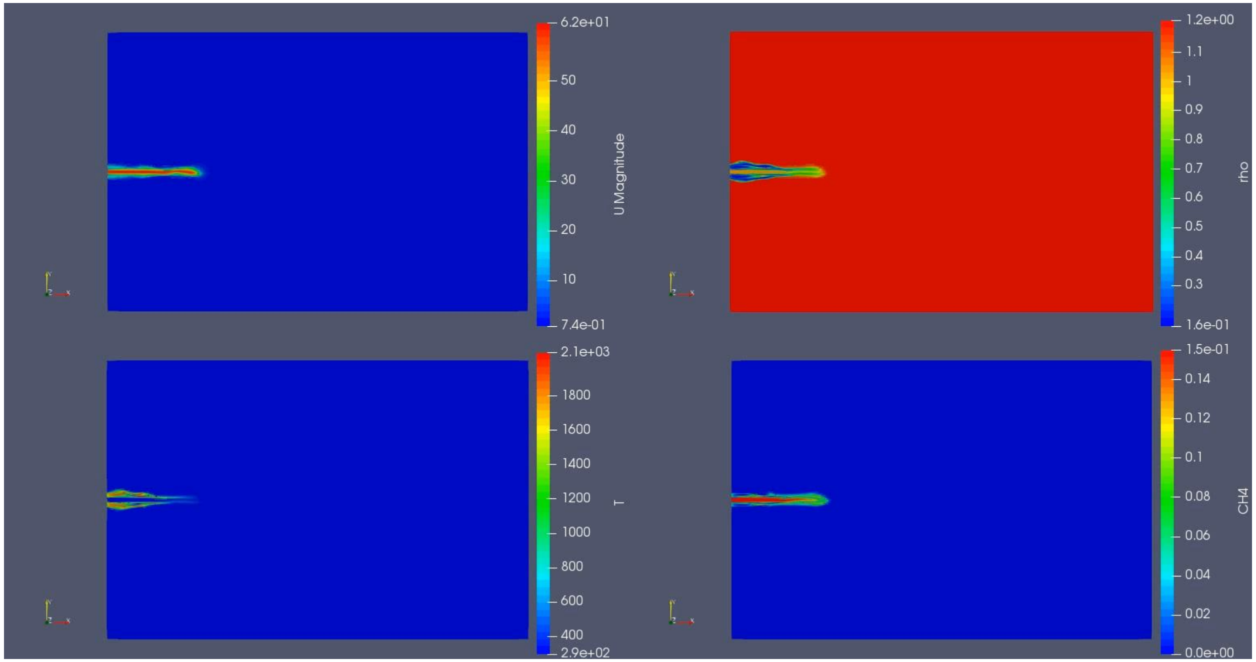
- Flamelet Test [Piloted CH4/air flame, SANDIA D]
  - Fuel : partially premixed CH_4(75%) and air(25%)
  - Oxidizer : air
  - Stoichiometric mixture fraction : 0.351
  - Reynolds number : 22400
- Dimension
  - Fuel nozzle diameter : 7.2 mm
  - Pilot nozzle diameter : 18.2 mm
- Pilot inlet condition
  - mixture fraction : 0.271
  - progress variable : 0.735
  - Temperature : 1880 K
- Turbulence model : Smagorinsky LES

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



pUCoupledFCNFoam

- Flamelet Library
  - FLAMEMASTER
    - https://www.itv.rwth-aachen.de/en/downloads/flamemaster/
  - Methane global chemistry
    - $CH_4 + 2O_2 = CO_2 + 2H_2O$
    - GRI 3.0
  - Scalar dissipation rate
    - csv Table



Thank you for your attention