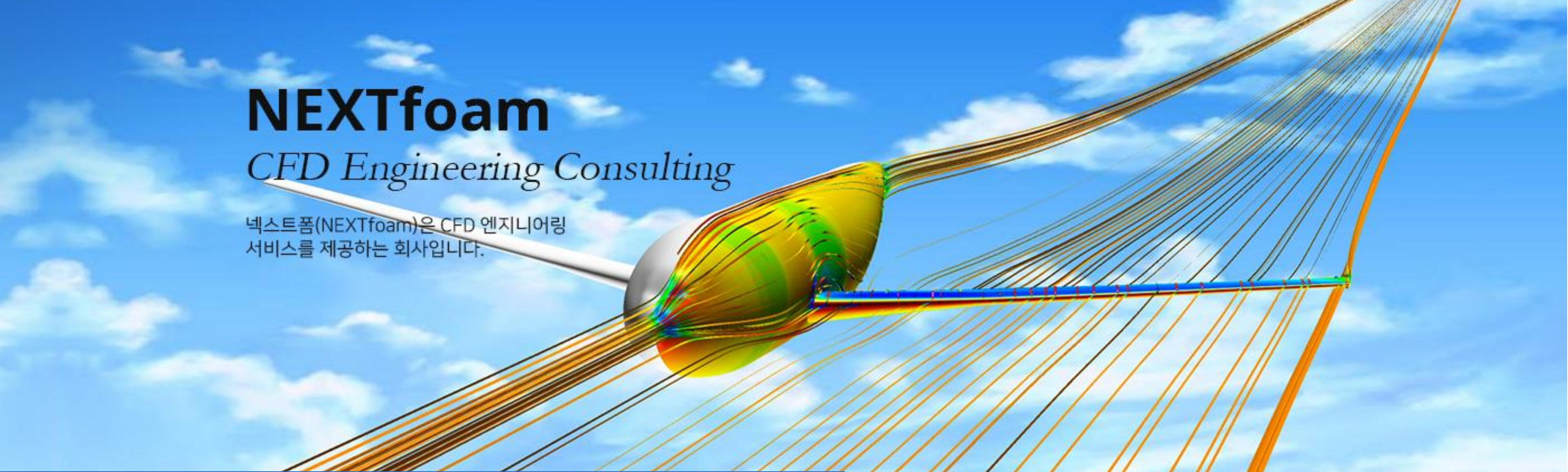

2022년 한국추진공학회 춘계학술대회

10 N 추력기의 노즐 성능 해석을 위한 수치 연구

정황희[1], 신재렬 [1†], 채종원[2]

[1]㈜넥스트폼 기술연구소

[2]한국항공우주연구원 위성기술연구부

2022. 05. 27.

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- 수치해석 시뮬레이션 & 결과
  - CEA 분석
  - 2D, 3D 유동 해석
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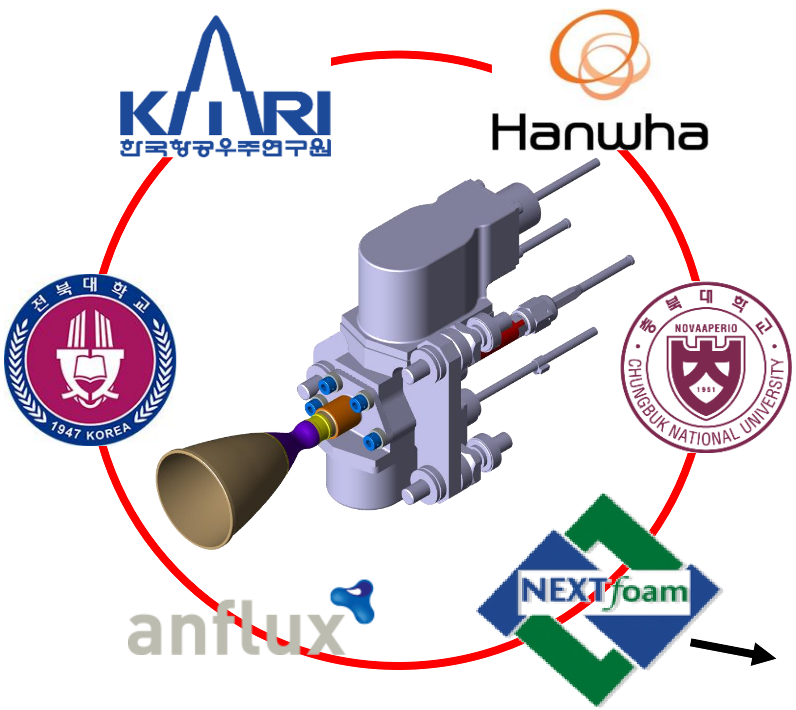
10N 저장성 이원추진제 추력기

- 스페이스파이오니어 사업
  - 저장성 이원추진제 추력기 개발
  - 2021. 06. ~ 2025. 12. (55 개월)

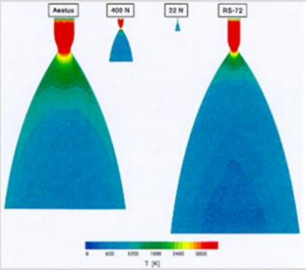


→ 이원추진제 추력기 연소 해석 소프트웨어 개발

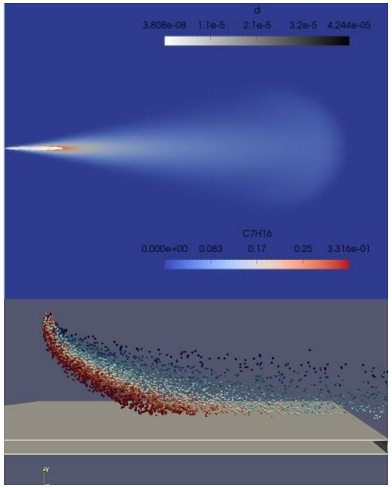
연구 목표

- **추력기 연소 해석 S/W 개발**
  - 연소 해석 솔버 개발
  - 사용자 GUI 환경 개발
  - 추력기 연소 해석

- ROCFLAM
  - Compressible -sub, trans and supersonic
    - 2D axisymmetric finite volume, SIMPLE algorithm
    - standard k-ε with wall function, 2 layer model
  - Multi-gaseous species chemistry
    - Arrhenius, EDC, global chemistry
    - standard jannaf property data
  - Lagrangian
    - droplet-to-wall interaction model
    - secondary droplet break-up
    - annular film cooling model
    - viscous heating species diffusion
    - heat conduction in solid wall

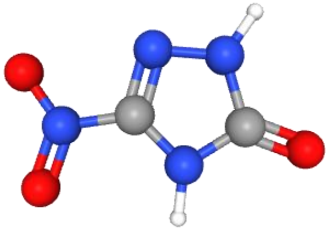


[Spray]

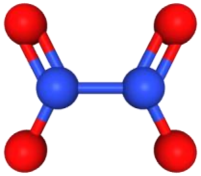


[Hypergolic chemistry]

MMH



N_2O_4



[Conjugate Heat Transfer]

수치해석 내용

- 해석 솔버 검증
  - JPL 노즐 해석
- 수치해석 시뮬레이션 & 결과
  - CEA 분석
  - 2D, 3D 유동 해석
  - 추력/비추력 계산

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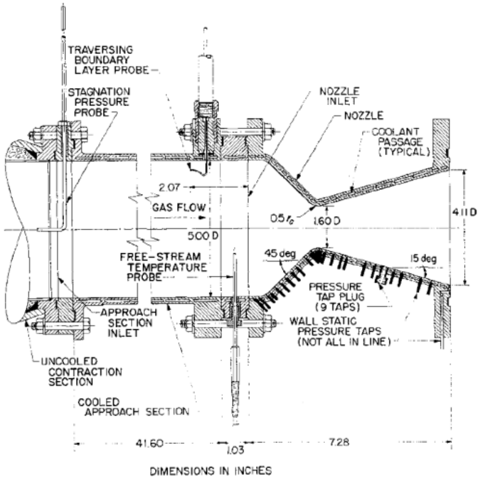
코드 검증

- **Kurganov 및 Tadmor의 central-upwind 기반 OpenFOAM 솔버**
  - hybrid central solvers – ISPRAS(Institute for System Programming of the Russian Academy of Sciences)
  - pressure-based semi-implicit compressible viscous flow of perfect gas
  - https://github.com/unicfdlab/hybridCentralSolvers

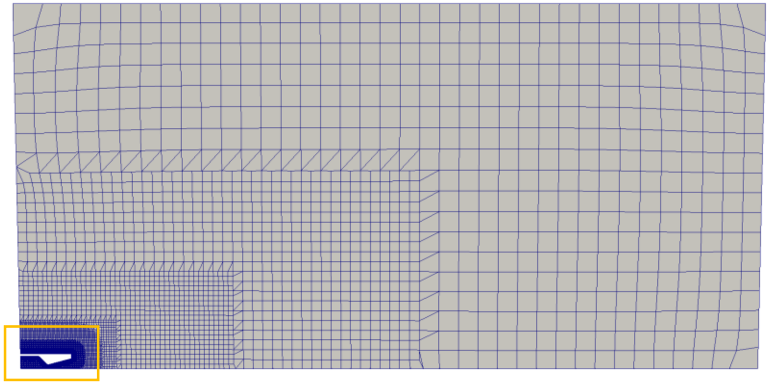
- **검증 케이스: JPL 노즐**
  - L. H. Back and R. F. Cuffel (1966)
    - Jet Propulsion lab., California Institute of Technology

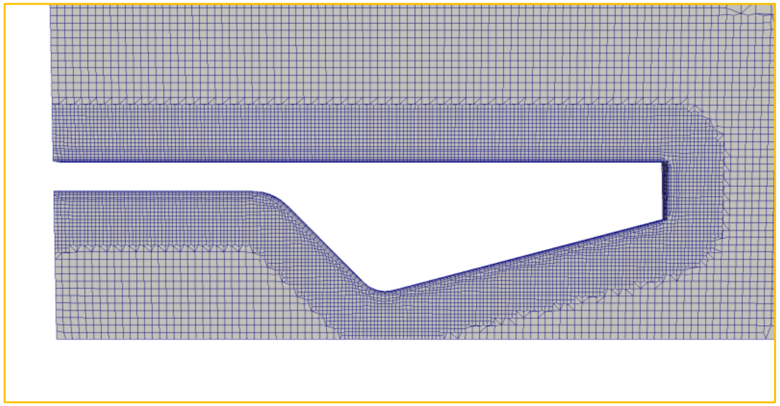


코드 검증 - JPL 노즐

- **해석 격자 및 조건**

JPL 해석격자: 2D axisymmetric





해석 조건

- Inlet pressure: 482,633 Pa
- Ambient pressure: 101,325 Pa

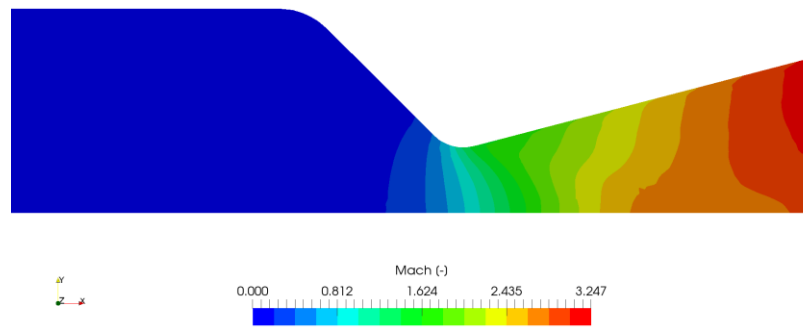
- Inlet Temperature: 2000 K
- Ambient Temperature: 300 K

- Cp: 1005 J/kg-K
- mu: 1.827e-5
- Pr: 0.7

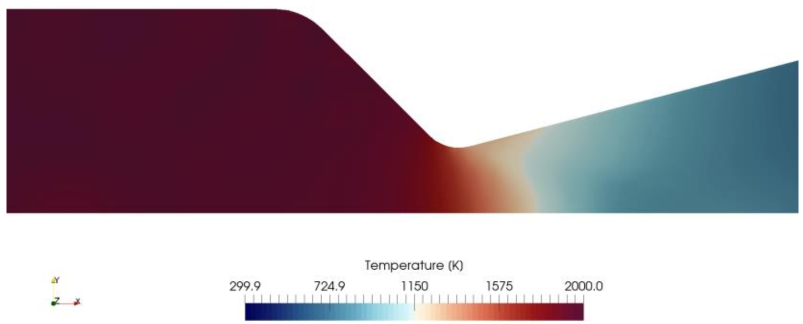
코드 검증 - JPL 노즐

- 해석 결과

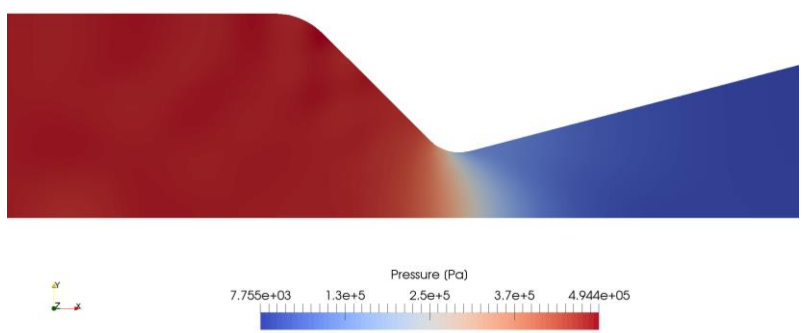
Mach



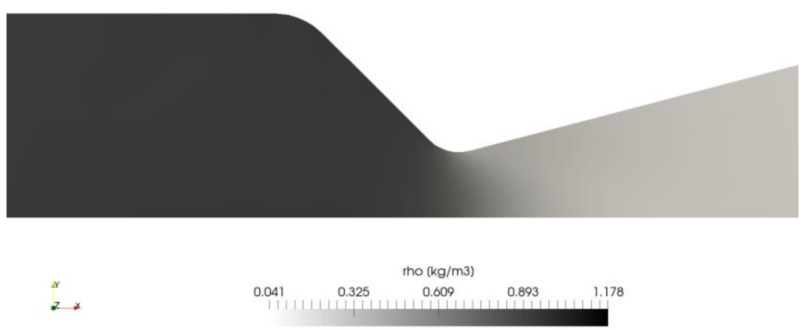
Temperature



Pressure



Density



코드 검증 - JPL 노즐

- 해석 결과 비교

Ref - R. F. Cuffel(1969)

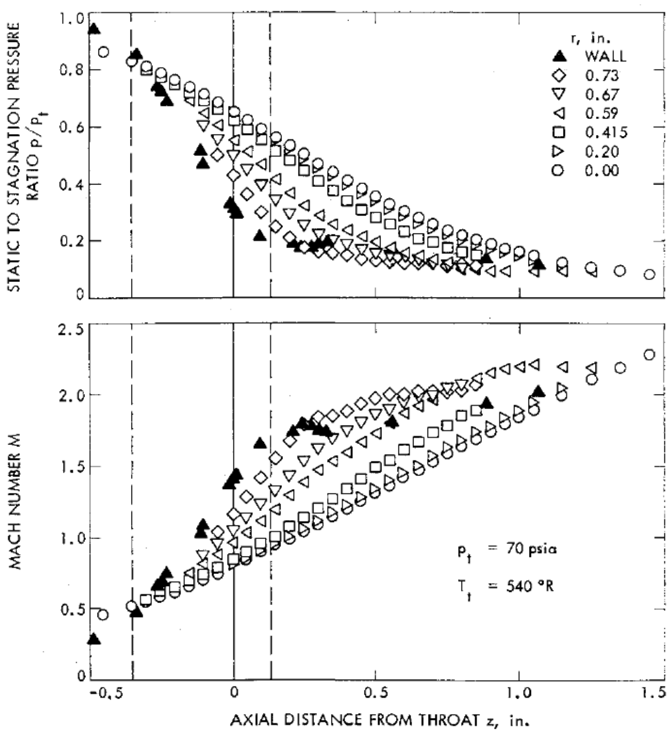
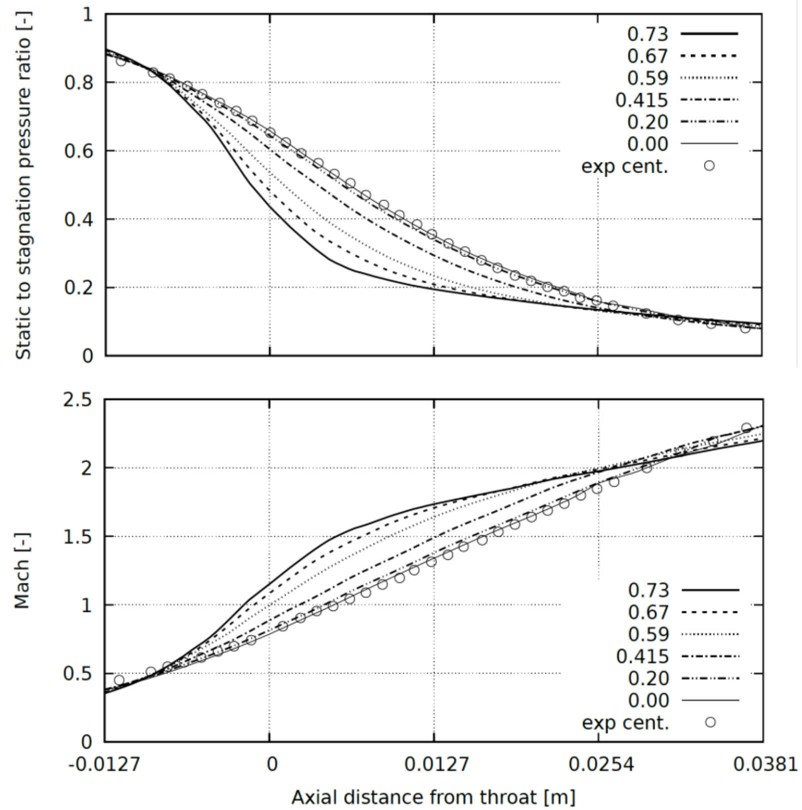


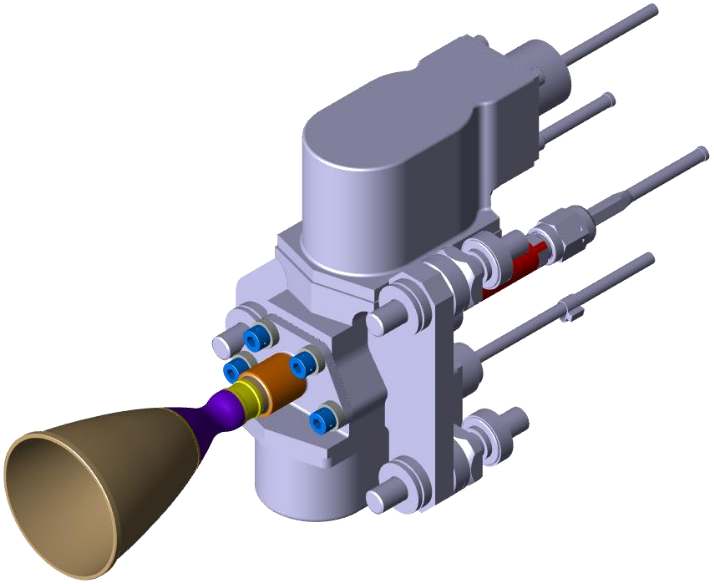
Fig. 1 Experimentally measured static pressure and calculated Mach number distributions in the transonic region.

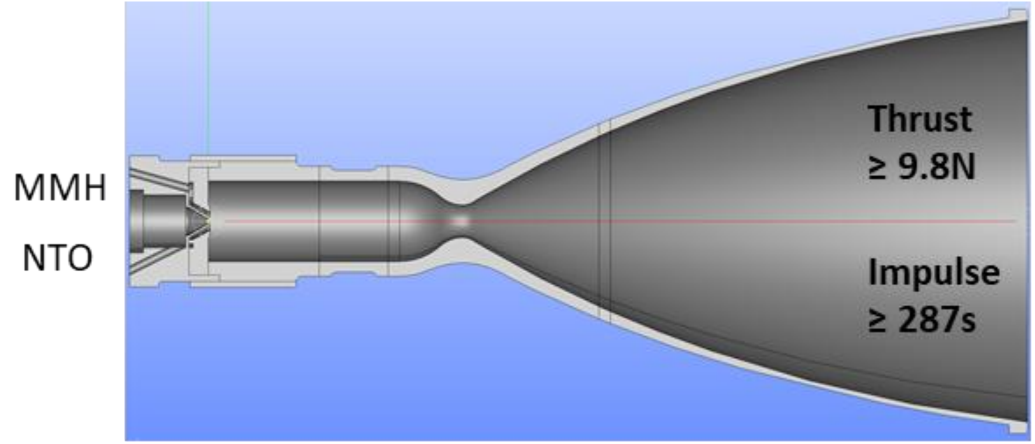
present results



10N 추력기 목표 성능

- **목표 성능**
  - 진공 추력 9.9 N ± 0.2 N
  - 진공 비추력 ≥ 287 s





[Section view of spp-k10]

10N 추력기 해석

- **CEA 해석**
  - MMH/NTO 총괄 반응식

    4 CH3NHNH2 + 5 N2O4 => 4 CO2 + 12 H2O + 9 N2

  - 챔버 압력: 9 bar, 연료/산화제 온도: 298.15 K, 면적비(Ae/At): 150.816

- **CEA 해석 결과**

	Chamber	Throat	Exit
T, [K]	3163.25	3015.06	1277.22
Cp, [kJ/(kg)(k)]	6.5496	6.3513	1.6774
Gamma, [-]	1.1274	1.1246	1.2386
Pr, [-]	0.4649	0.476	0.7769
Viscosity, [mP]	1.0127	0.98159	0.54574

Chemical Equilibrium with Applications

- MMH 물성치 추가
  - thermodynamic properties 및 transport properties
  - **Burcat**'s thermodynamic data

thermo.inp

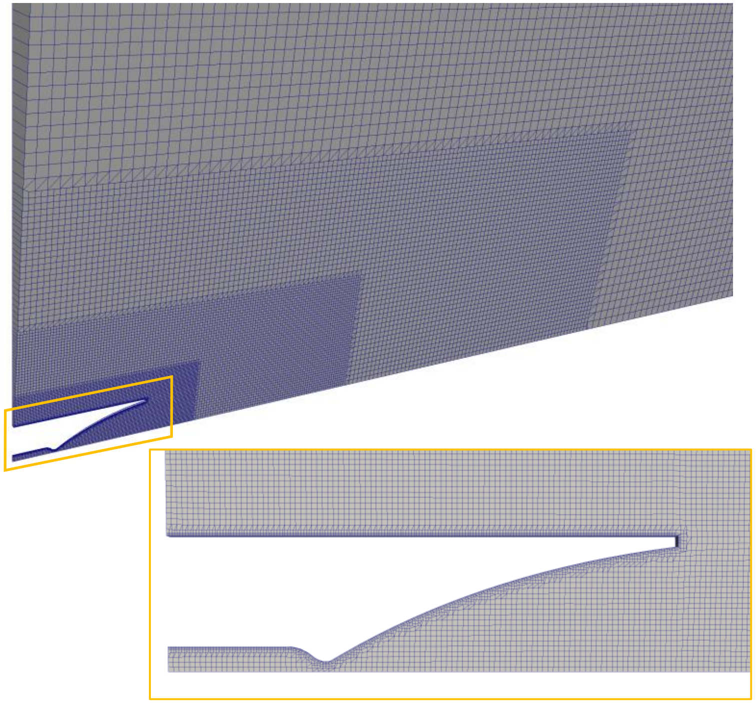
```
CH6N2                Methyl-Hydrazin Burcat G3B3 calc HF298=26.150 kcal
 3 tpis78 C   1.00H   6.00N   2.00    0.00    0.00 0   46.0718200     109411.600
     50.000    200.0007 -2.0 -1.0  0.0  1.0  2.0  3.0  4.0  0.0         14096.674
-5.202183790D+03 3.742586550D+02-6.113676640D+00 1.210088925D-01-5.874013570D-04
 1.553546694D-06-1.463918516D-09                 1.027252125D+04 4.826497170D+01
    200.000   1000.0007 -2.0 -1.0  0.0  1.0  2.0  3.0  4.0  0.0         14096.674
-2.135584394D+05 4.136686700D+03-2.671497318D+01 1.145823712D-01-1.472913038D-04
 1.012614835D-07-2.813944157D-11                -7.139610730D+03 1.694064181D+02
   1000.000   6000.0007 -2.0 -1.0  0.0  1.0  2.0  3.0  4.0  0.0         14096.674
 5.198347430D+06-2.031816040D+04 3.514801630D+01-2.810314928D-03 4.377350080D-07
-3.550932250D-11 1.150144154D-15                 1.344868648D+05-2.094181853D+02
```

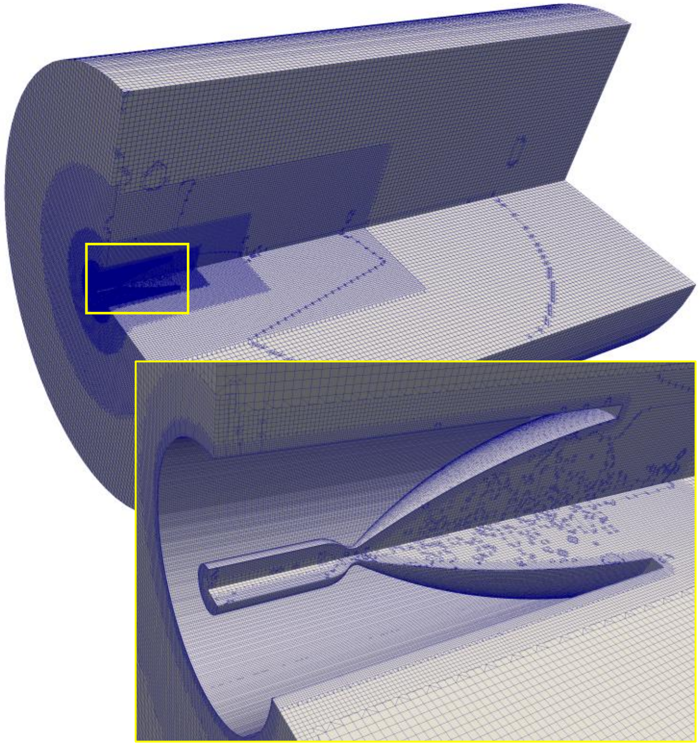
trans.inp

```
CH6N2                             V1C2
 V   300.0    5000.0    5.92241336E-01-2.22179762E+02 8.28721494E-01 1.62442137E+00
 C   300.0    1500.0    1.25083173E+00 9.50635709E-01 9.99812473E-01-1.79184981E+00
 C  1500.0    5000.0    8.00436222E-01 9.99071151E-01 9.99997106E-01 1.53496259E+00
```

10N 추력기 해석

- **격자 생성** – snappyHexMesh(unstructured)
- 2D 축대칭 해석 격자
  - 25,000 cells
- 3D 해석 격자
  - 5,440,000 cells





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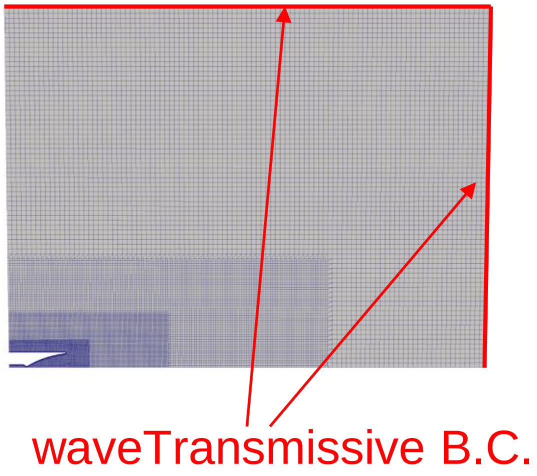
10N 추력기 해석

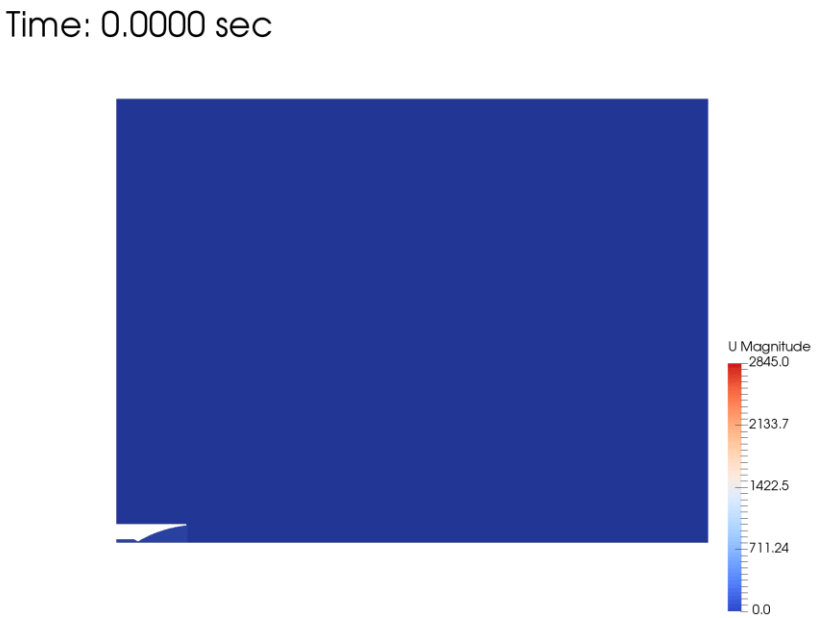
- 해석 솔버: pimpleCentralFoam
- 난류 모델: k-ω SST
- 단일 화학종 비반응 해석
- 해석 조건
  - Chamber pressure: 9 bar waveTransmissive
  - Chamber temperature: 3163.25 K
  - Ambient pressure: 5 mbar
  - waveTransmissive boundary condition



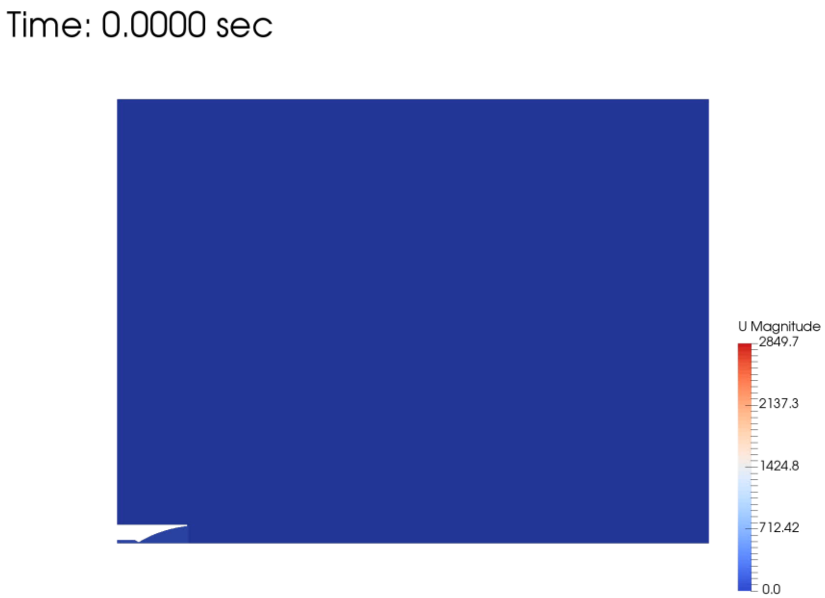
10N 추력기 해석

- **waveTransmissive** boundary condition
    - Non-reflecting B.C.

Non-waveTransmissvie B.C.



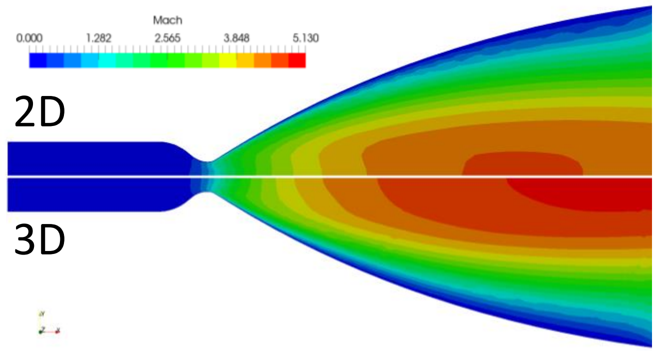
waveTransmissvie B.C.

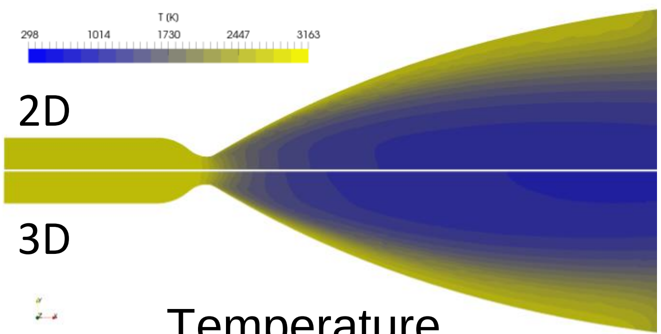


10N 추력기 해석

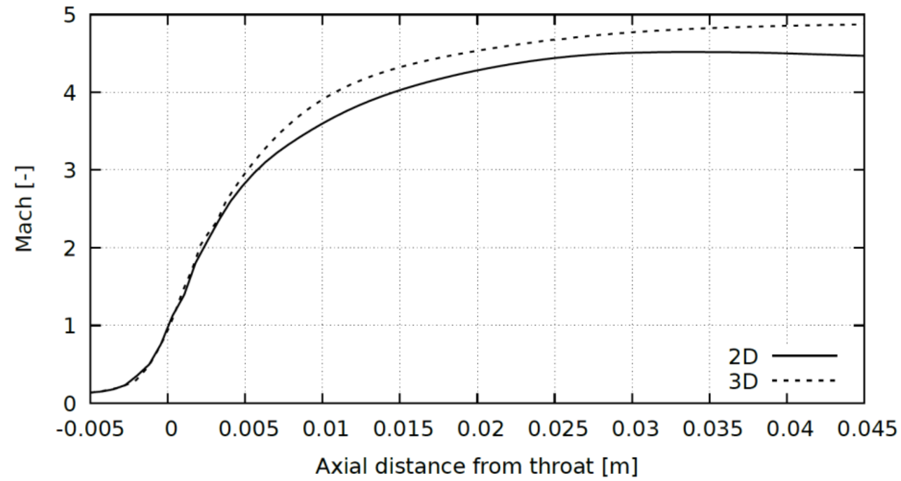
- **Mach & Temperature**

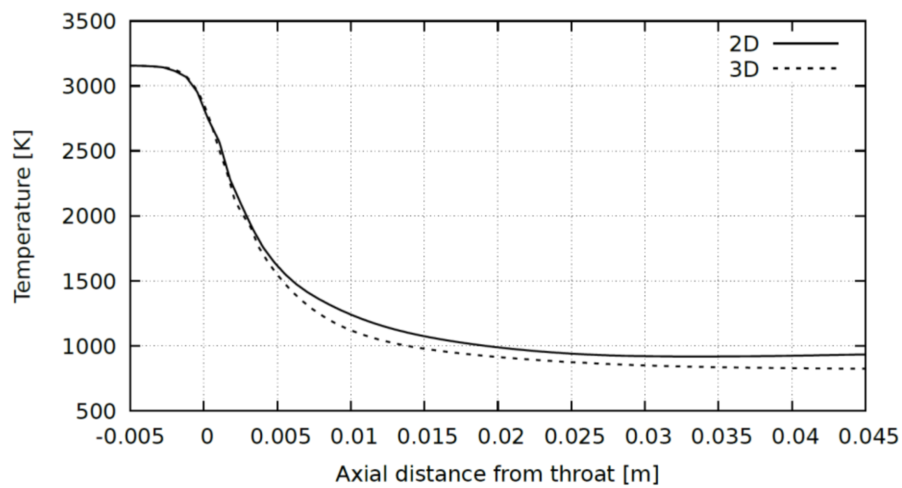
Mach





Temperature





10N 추력기 해석

- **추력/비추력**

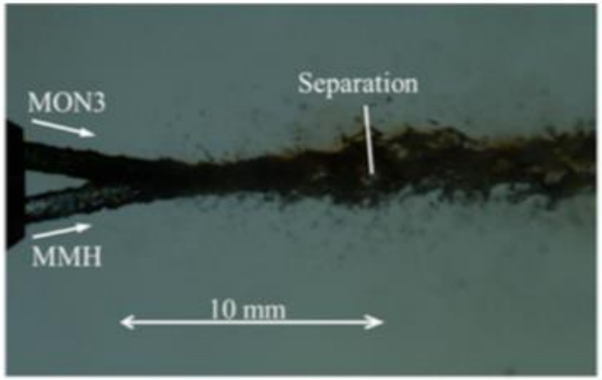
추력 계산 식: $I_{\mathrm{sp}} = \frac{v_{\mathrm{e}}}{g_0}$; g_0 는 표준 중력가속도

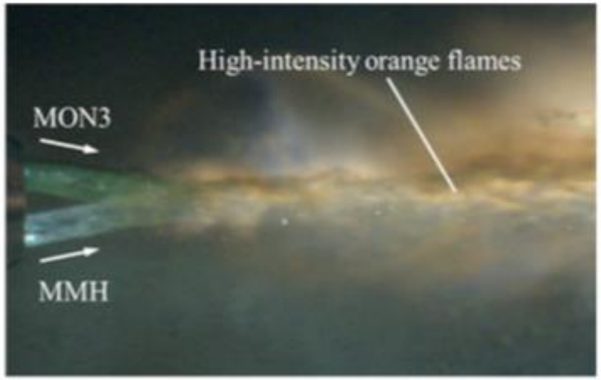
비추력 계산 식: $F_{\mathrm{thrust}} = g_0 \cdot I_{\mathrm{sp}} \cdot \dot{m}$

	목표 성능	2D 해석결과	3D 해석결과
비추력	287 s	278 s	285 s
추력	9.9 N	9.54 N	9.78 N

향후 연구

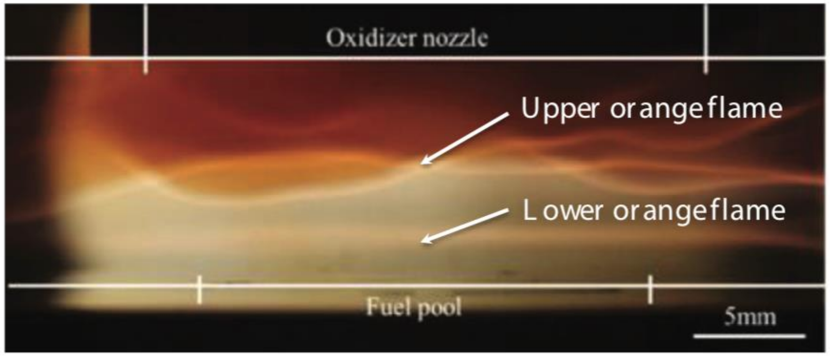
- 이원 추진제 미립화 및 분사 궤적 해석





Japan Aerospace Exploration Agency(JAXA), Japan, 2017

- 대향류 화염을 통한 이원추진제 연소특성 파악



Kyoto University, japan, 2019

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Thank you for your attention.