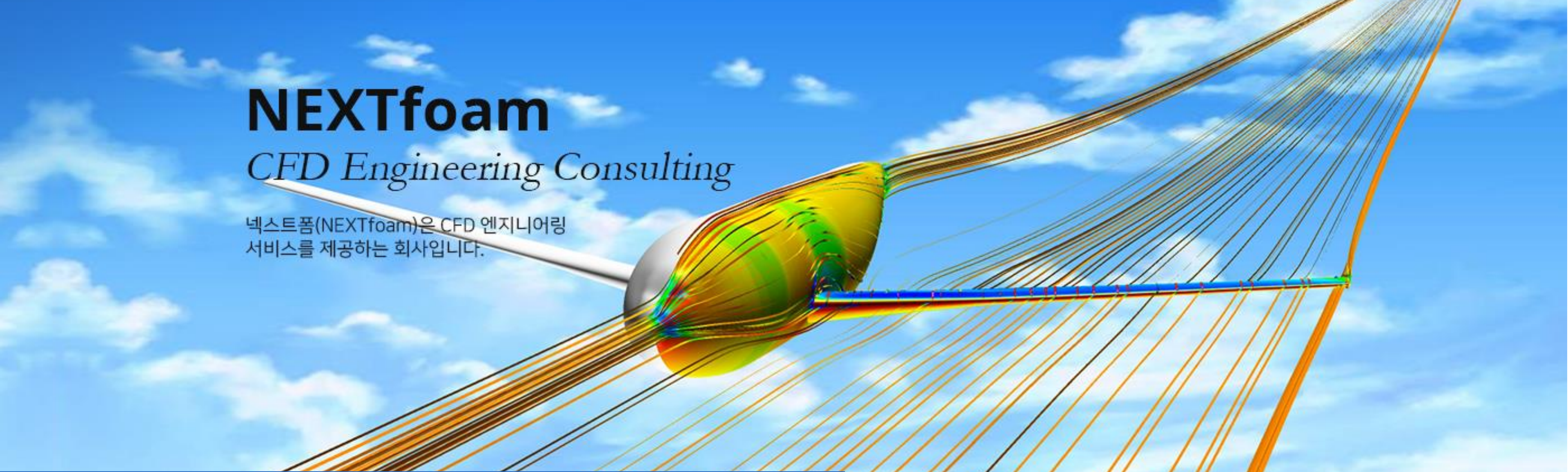


2021년 한국항공우주학회 추계학술대회

OpenFOAM을 활용한 액적분사 해석

정황희[1], 신재렬[1†], 채종원[2]

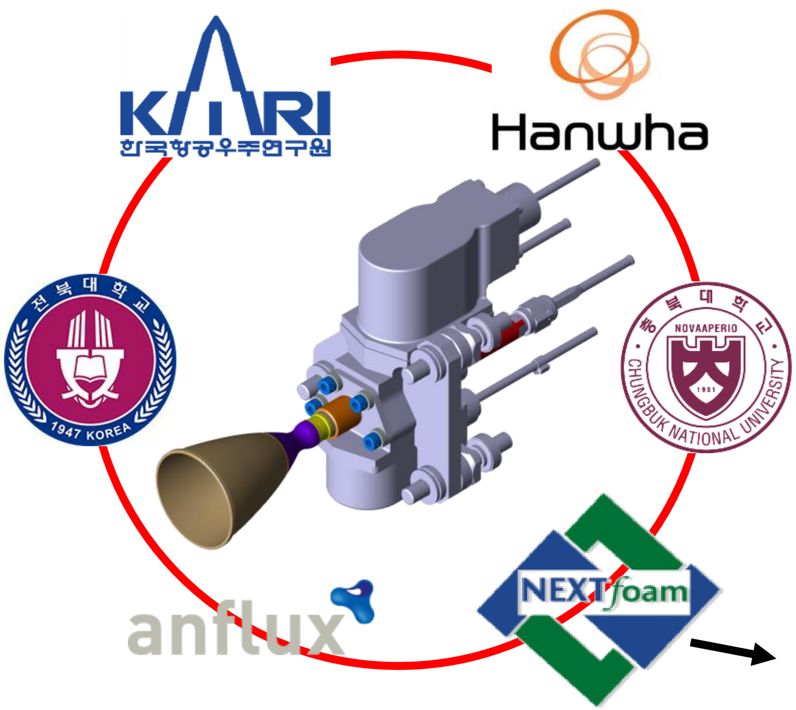
[1]㈜넥스트폼 기술연구소, [2]한국항공우주연구원

2021. 11. 19.

Contents

Introduction - Bipropellant thruster

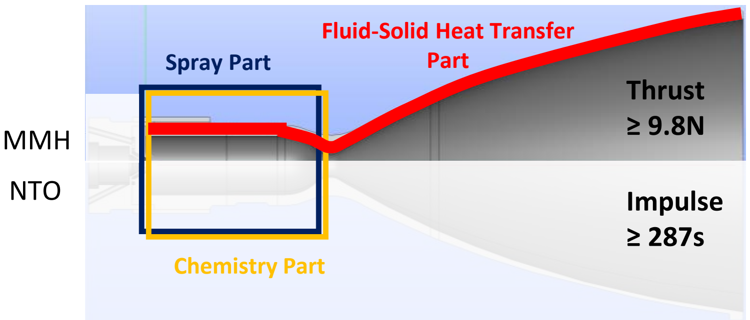
- **Space pioneer project**
  - **Storable bipropellant thruster**
  - 2021. 06. ~ 2025. 12. (55 month)



→ **Development of combustion analysis S/W**

Introduction – development goals

- **Thruster analysis**



[Section view of spp-k10]

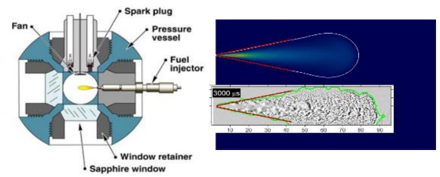
Hypergolic Chemistry

Characteristics	design (5 step, 11 species)	remarks
MMH Decomposition	$CH_3(NH)NH_2 \rightarrow CH_4+H_2+N_2$	Ambiguous Arrhenius parameter
NTO Decomposition	$N_2O_4 \rightarrow 2NO_2$	
CH4 – NO2 reaction	$CH_4+2.3NO_2+H_2 \rightarrow 3H_2O+1.15N_2+0.4CO+0.6CO_2$	
CH4 – CO2 reaction	$CH_4+0.5CO_2+0.5H_2O \rightarrow 1.5CO+2.5H_2$	
H2O Decomposition	$H_2O \leftrightarrow H+OH$	

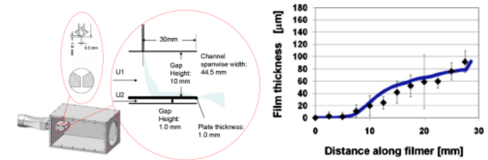
[Design focus, Xu (2006)]

Spray Dynamics

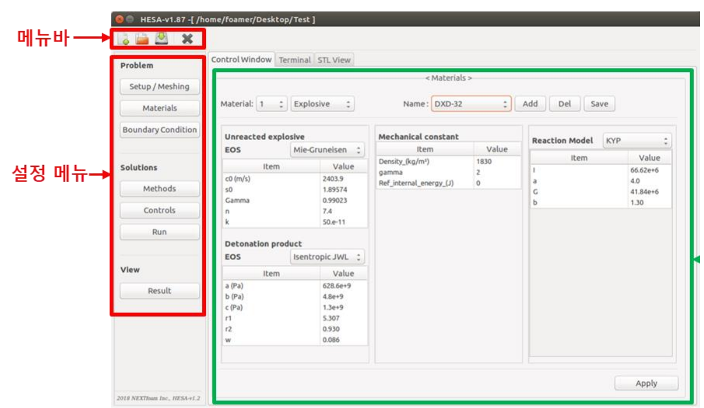
- Spray behavior
  - Sandia-A (heptane)



- Wall film model
  - Shedd exp. (urea), AIAA 2009-998



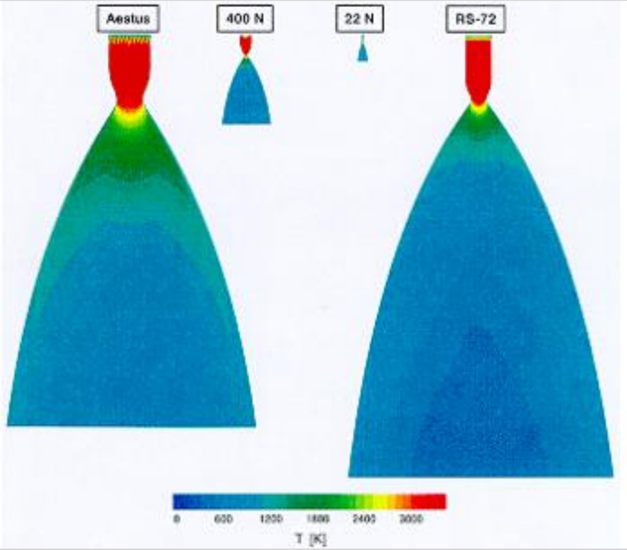
GUI Configuration



- 메뉴바 (New/Load/Save/Exit)
  - 프로젝트를 생성/읽기/저장하기 위한 메뉴
- 설정 메뉴 (Problem/Solution/View)
  - 진행 작업 또는 메뉴의 버튼에 따라 화면 전환

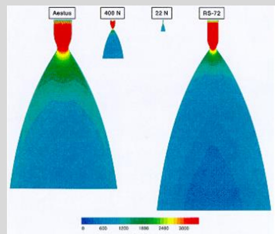
Development Target

- 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

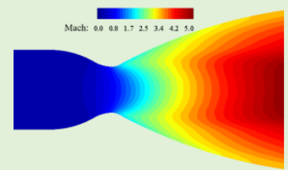


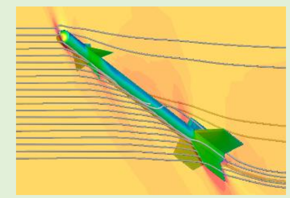
Development of rocFlamFoam

- 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

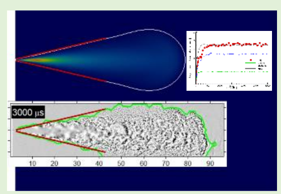


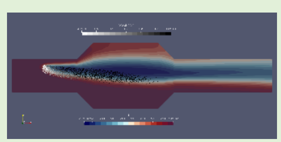
- PCNFoam(PISOCentralNFoam)
  - Compressible -sub, trans and supersonic
    - 3D finite volume, PIMPLE algorithm
    - Kurganov-Tadmor flux scheme
    - RANS/LES, wall function, 2 layer model
    - farField, Reimann boundary condition



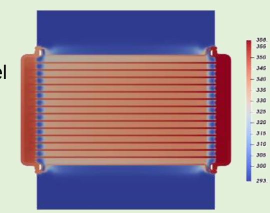


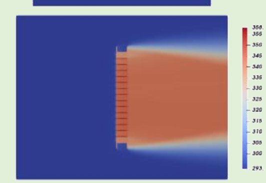
- SprayFoam
  - Compressible -sub, transonic
    - 3D finite volume, PIMPLE algorithm
    - RANS/LES, wall function
  - Multi-species chemistry
    - Arrhenius, EDC, EDM, PaSR
    - jannaf, CHEMKIN
  - Lagrangian
    - droplet-to-wall Patch Interaction Model
    - E/TAB, KHRT 2nd break-up
    - wall film model
  - Radiation
    - P1, fvDOM, viewFactor





- chtMultiRegionFoam
  - Conjugate heat transfer between regions
  - Incompressible
    - 3D finite volume, PIMPLE algorithm
    - RANS/LES, wall function, 2 layer model
    - Buoyancy effect
  - Multi-species chemistry
    - Arrhenius, EDC, EDM, PaSR
    - jannaf, CHEMKIN
  - Radiation
    - P1, fvDOM, viewFactor





Numerical simulation & Results

- Spray Dynamics

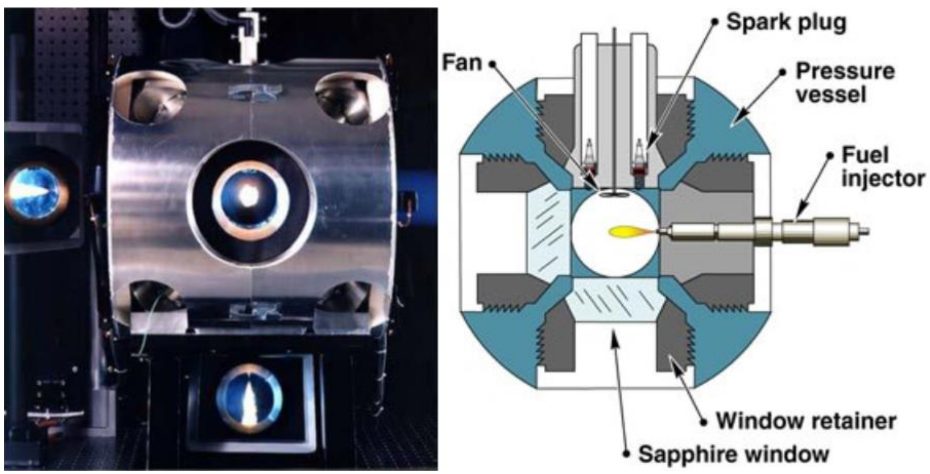
  - nonreacting spray

  - reacting spray

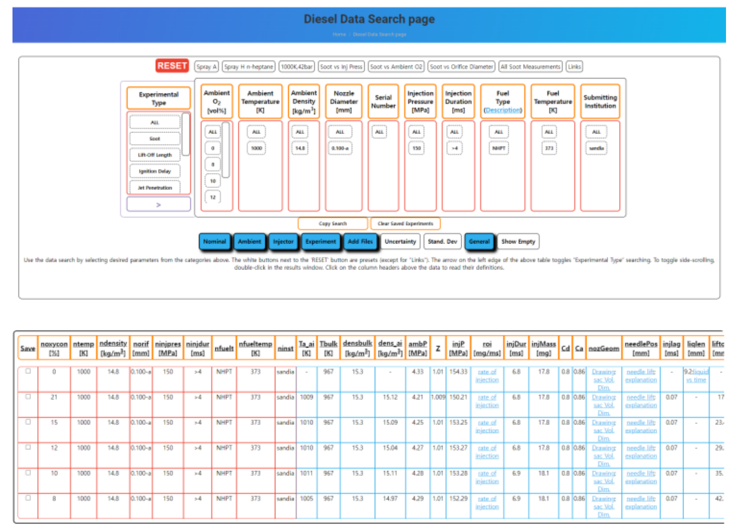
  - wall film formation

Spray Dynamics

- **Spray modeling**
  - SANDIA spray H n-heptane
  - Constant volume chamber



[SANDIA heptane spray experiment]



source: https://ecn.sandia.gov/ecn-data-search/

[Experiment condition]

Nozzle Dia.	Fuel temp.	Fuel Pres.	Total fuel mass	Injection duration	Amb. pres.	Amb. temp.	Amb. dens.
0.1 mm	373 K	150 Mpa	17.8 mg	6.8 ms	4.33 Mpa	850 K	14.8 kg/m^3

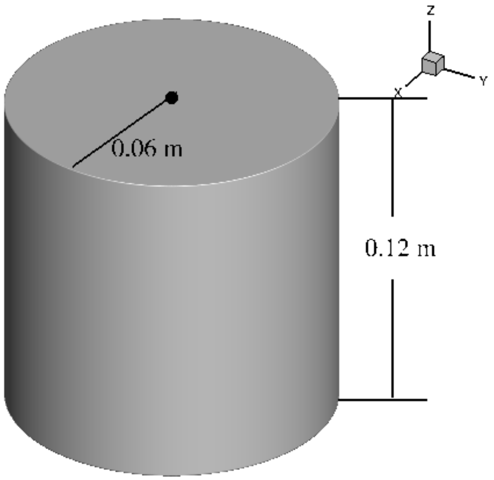
Spray Dynamics

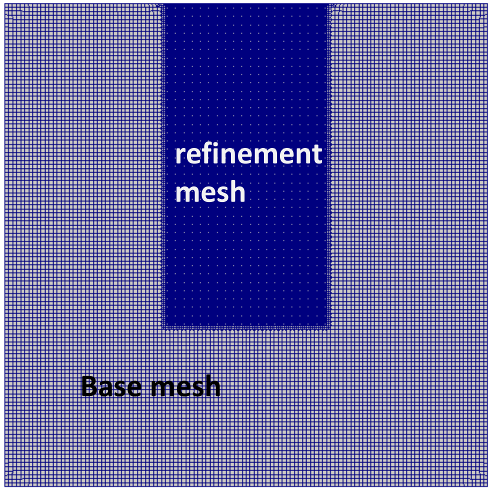
- **Spray modeling**
  - Cylinder shape
  - Mesh tool: **cfMesh** (cartesianMesh)
  - Base mesh cell size: 1 mm
  - Refinement cell size:

    coarse: 1 mm (1.38 M Cells)

    medium: 0.5 mm (2.1 M cells)

    fine: 0.25 mm (7.8 M cells)

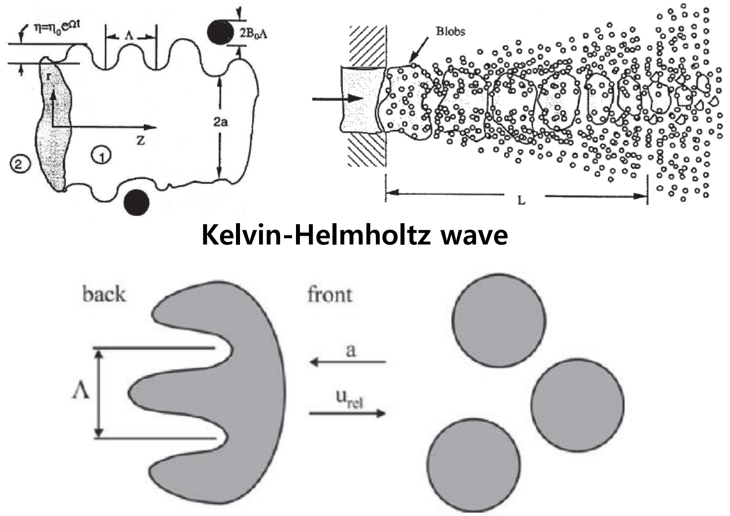




Spray Dynamics

- **Numerical method**
  - Solver: **sprayFoam** in OpenFOAM
  - **Pimple** algorism
  - 2nd breakup: **KHRT model**
    - B_0=0.61, B_1=40, C_τ=1, C_{RT}=0.1

2nd breakup (KHRT model)



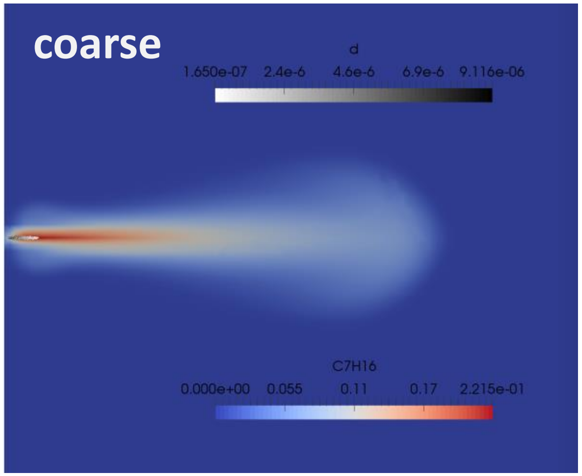
Kelvin-Helmholtz wave

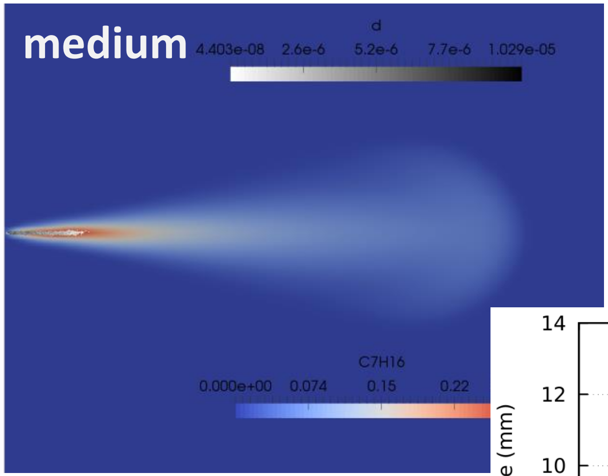
Rayleigh-Taylor instability

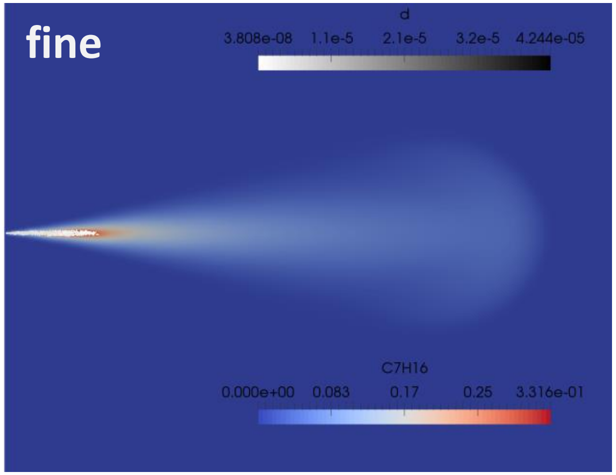
- Spray injection model
  - Cone nozzle type
  - Spray half angle: 12.6°
  - Size distribution: Rosin Rammler (min: 1x10^{-3}, max: 9.27x10^{-2} [mm], n =2)

Spray Dynamics

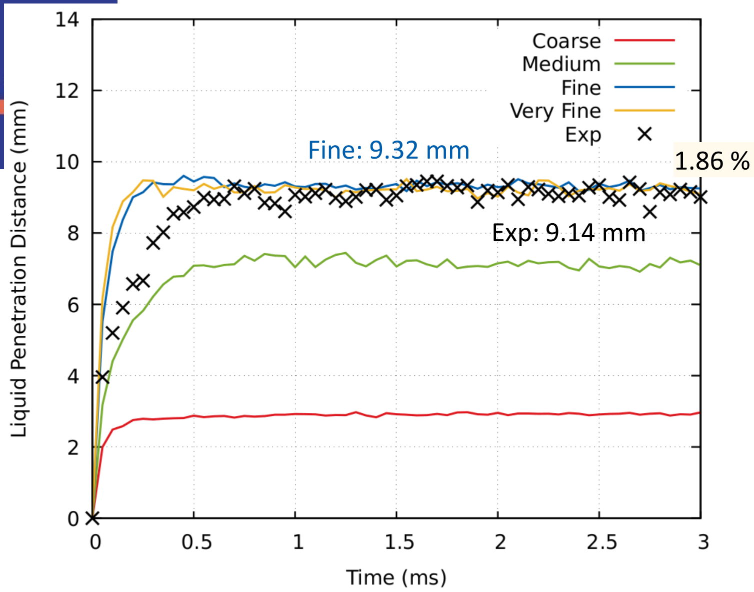
- **Results – grid resolution**





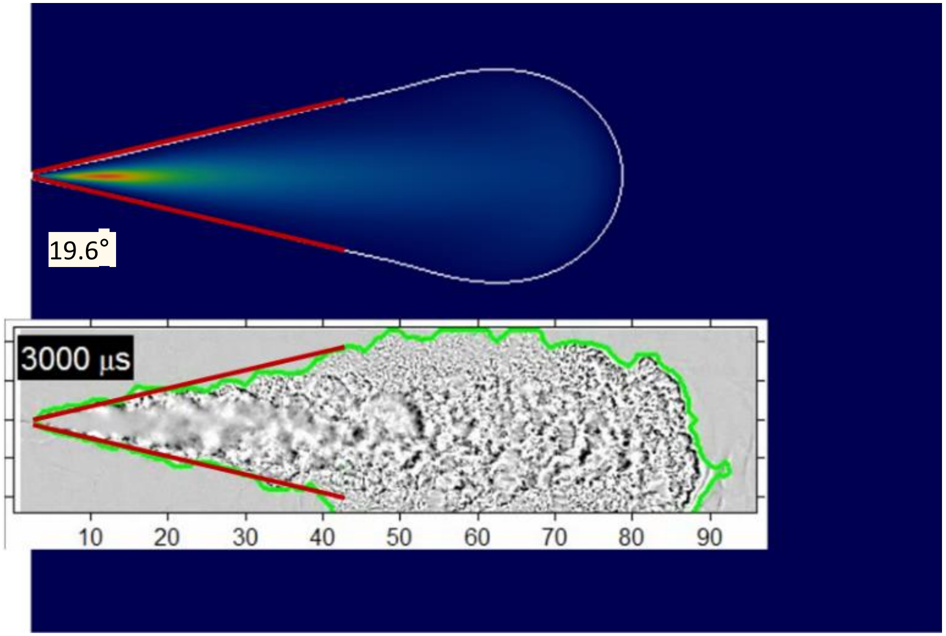


[liquid penetration]

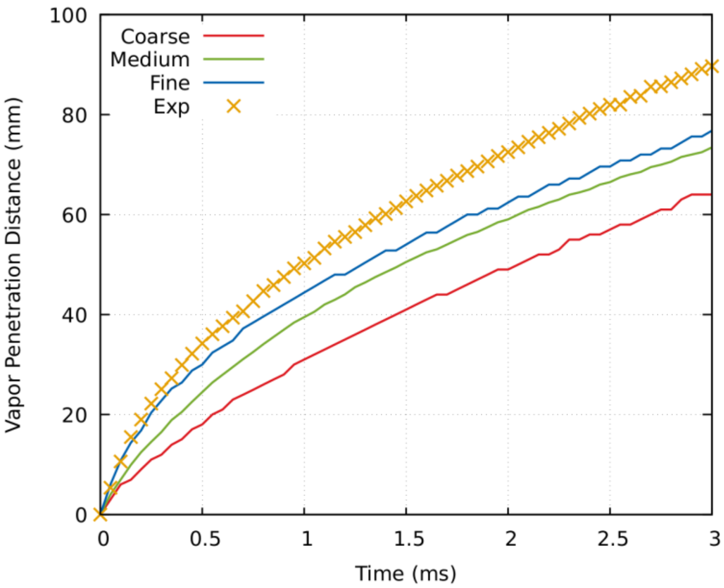


Spray Dynamics

- **Comparison of vapor penetration**



[vapor penetration]

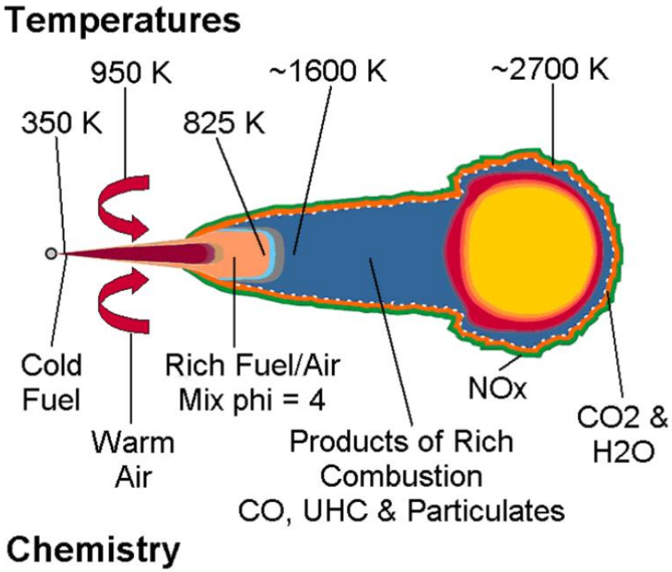


Spray Dynamics

- **Reacting condition**
  - n-heptane global reaction

$$C_7H_{16} + 11O_2 => 7CO_2 + 8H_2O$$

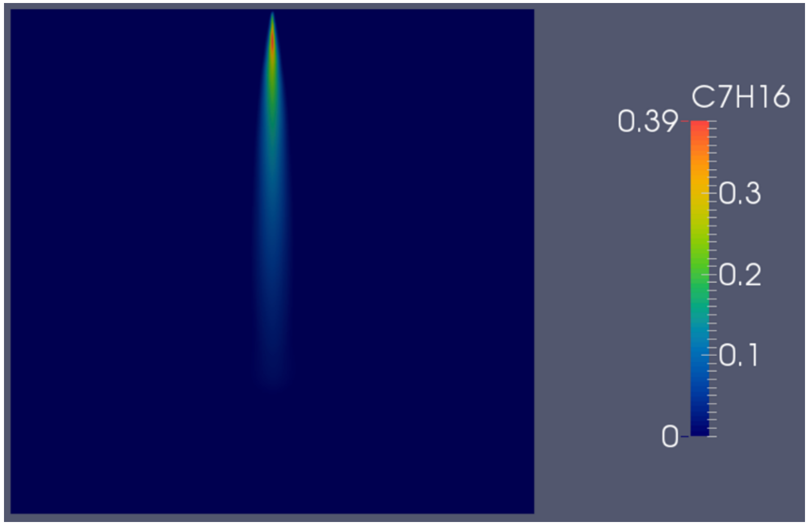
  - CHEMKIN To Foam
  - Mixture fraction
  - Thermo: JANAF table
  - Transport: Sutherland



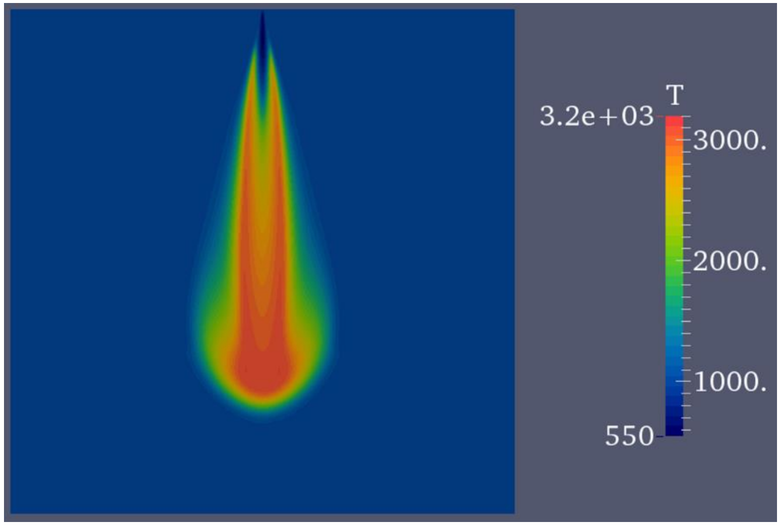
Spray Dynamics

- **Reacting results**

[n-heptane mass fraction]

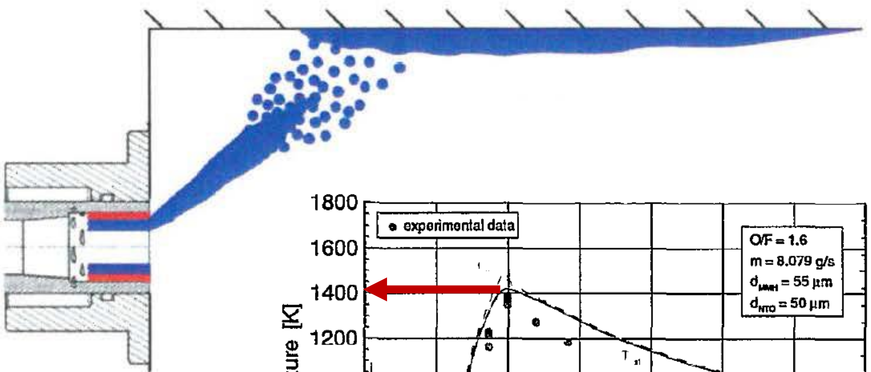


[Temperature distribution]



Spray Dynamics

- **Wall film formation**



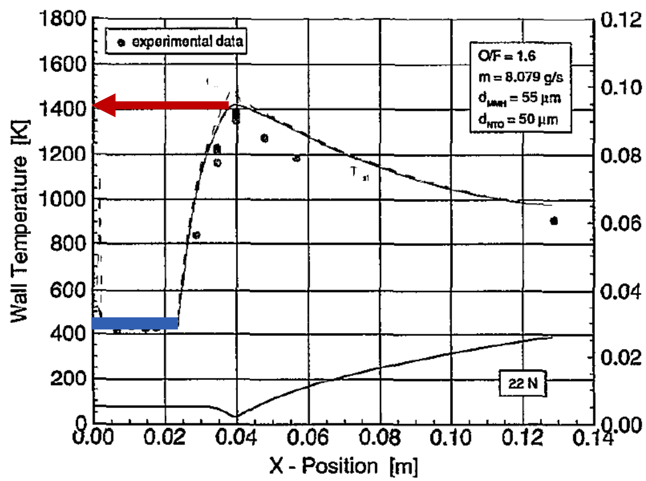


Figure 18: External and internal wall temperature distribution for the load point R2 of the 22 N thruster

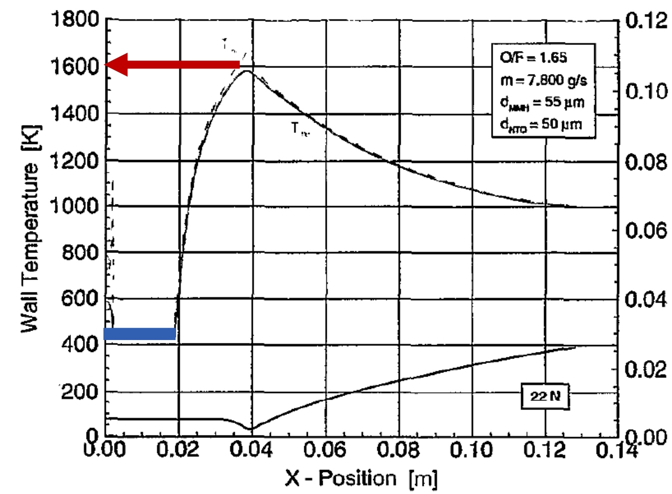
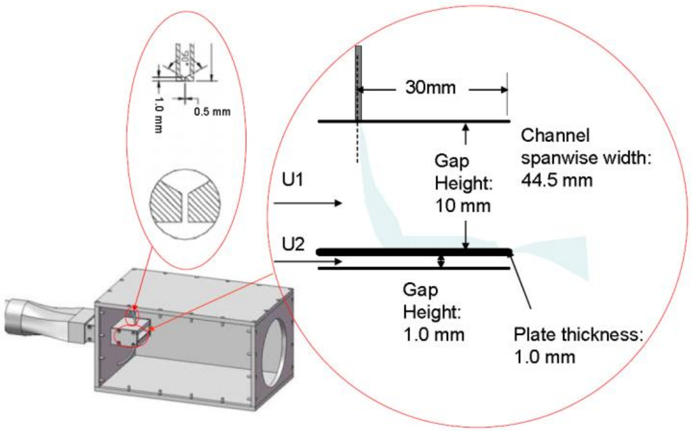


Figure 19: External and internal wall temperature distribution for the reference point R of the 22 N thruster

Spray Dynamics

- **Wall film formation**

[shedd exp. AIAA 2009-998]



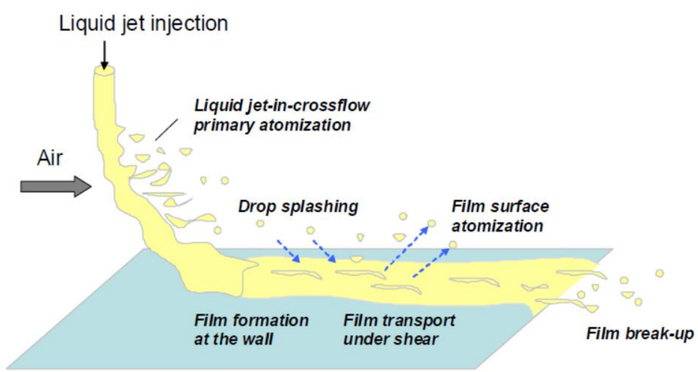


Table 1. List of operating conditions with specific cases highlighted for further discussion.

Case	Liquid Jet Velocity (m/s)	Crossflow Velocity (m/s)	Liquid Re_l	Aerodynamic We	q	Impingement Type
1	4.2	72	1935	155	1.9	Spray
2	8.5	72	3870	155	7.6	Spray
3	12.7	72	5800	155	17.1	Spray
4	17.0	72	7740	155	30.4	Jet
5	21.2	72	9670	155	47.4	Jet
6	4.2	81	1935	195	1.5	Spray
7	8.5	81	3870	195	6.0	Spray
8	12.7	81	5800	195	13.5	Spray
9	17.0	81	7740	195	24.0	Jet
10	21.2	81	9670	195	37.5	Jet
11	4.2	99	1935	290	1.0	Spray
12	8.5	99	3870	290	4.0	Spray

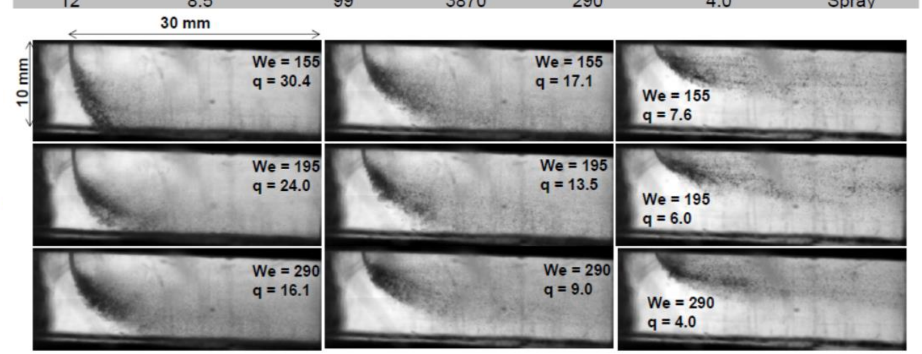
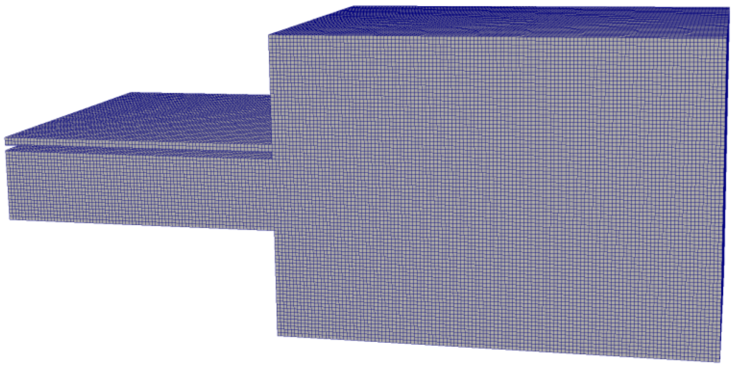


Figure 5. Spray trajectory and penetration as a function of Weber number (We) and momentum-flux ratio (q).

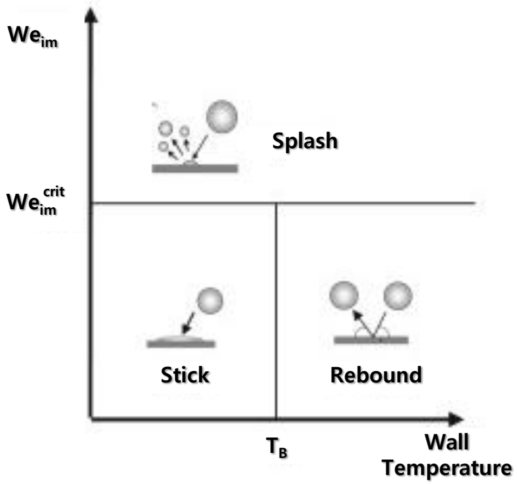
Spray Dynamics

- **Wall film formation**
  - **cfMesh** (cartesianMesh)
  - Coarse: **0.52 M cells**
  - Solver: **sprayPimpleCentralFoam**
  - **ETAB breakup model**



[case condition]

	values
mDot	1.945 g/s
Uinj	12.7 m/s
Uinf	81 m/s



Grover and Assanis (2001)

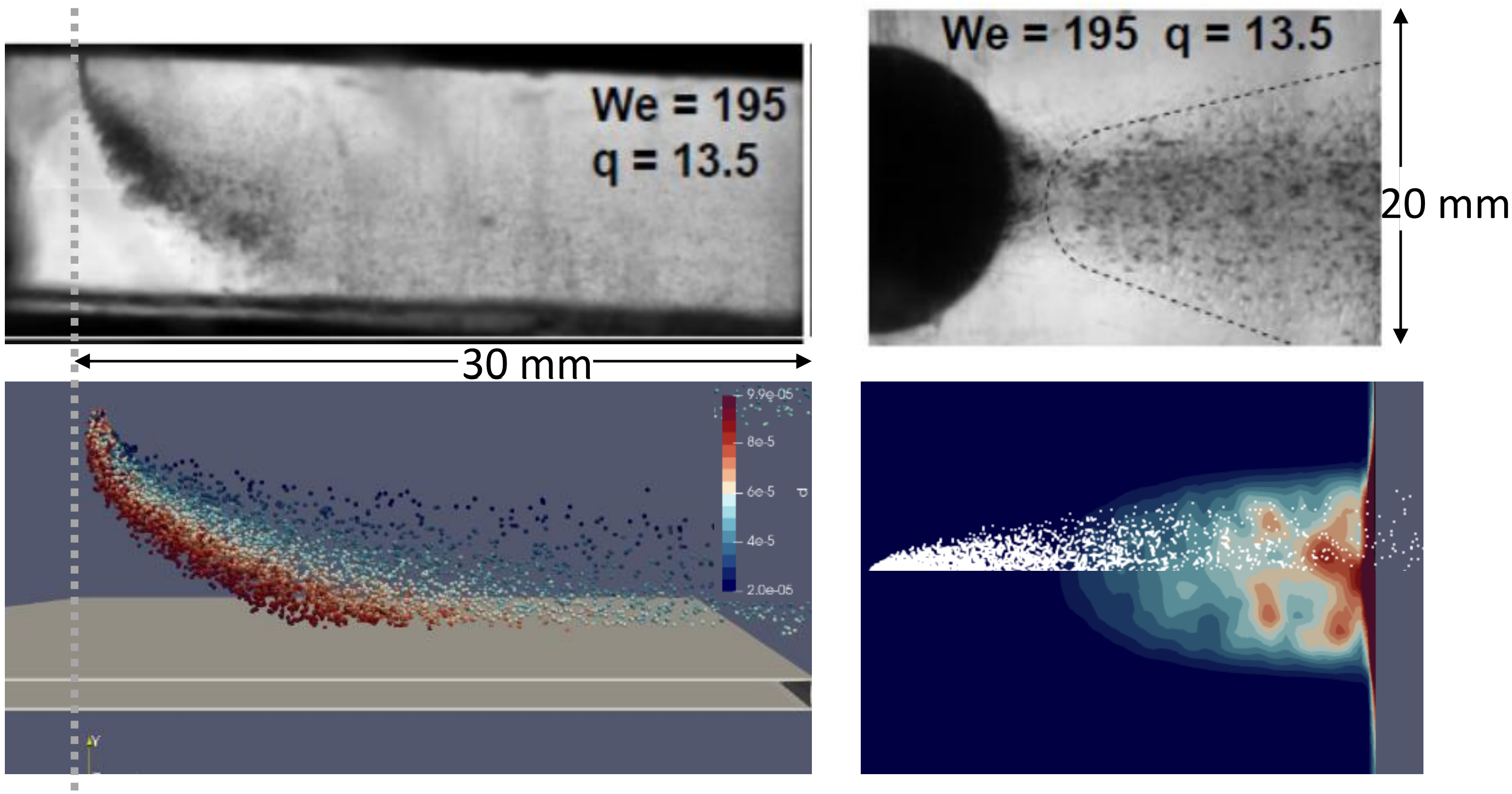
Spray Dynamics

- **Wall film formation**
  - **Spray trajectory**

[Side view] [Top view]

Experiment results

Simulation results



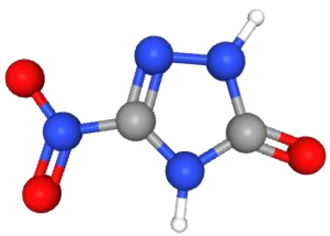
Conclusion & Future work

- Modify and development of SprayFoam, sprayPimpleCentralFoam

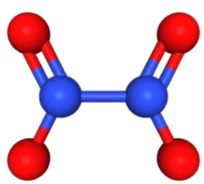
- Future work

[Hypergolic chemistry]

MMH

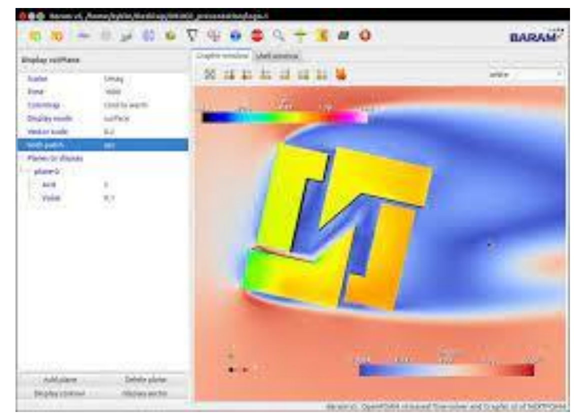


N_2O_4



[Conjugate Heat Transfer]

[Graphical User Interface]



- Localization of storable bipropellant thruster (analysis S/W)

Thank you for your attention.