

# NEXTfoam

CFD Engineering Consulting

넥스트폼(NEXTfoam)은 CFD 엔지니어링  
서비스를 제공하는 회사입니다.

2021년 한국항공우주학회 추계학술대회

## OpenFOAM을 활용한 액적분사 해석

정황희<sup>1</sup>, 신재렬<sup>1†</sup>, 채종원<sup>2</sup>

<sup>1</sup>(주)넥스트폼 기술연구소, <sup>2</sup>한국항공우주연구원

2021. 11. 19.

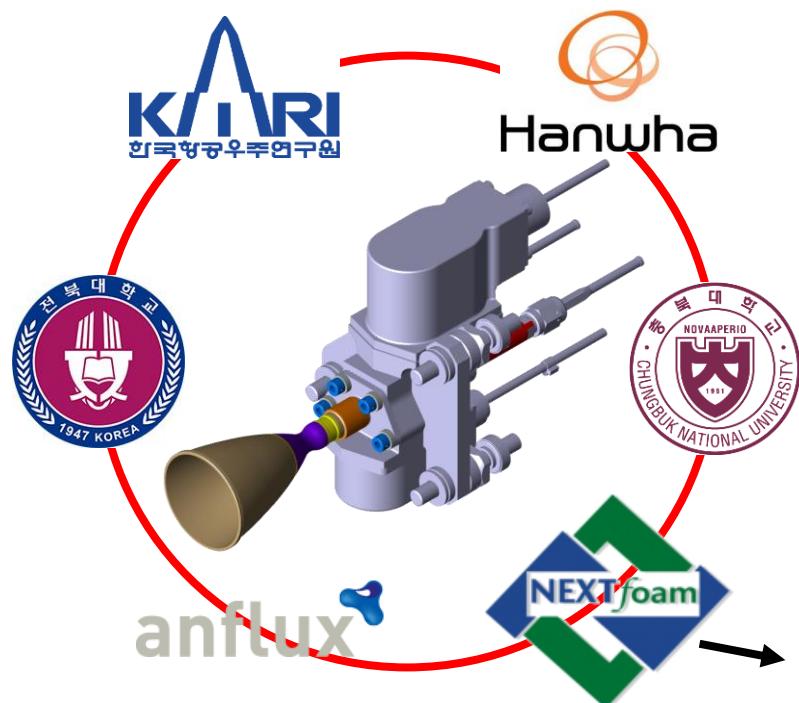
# Contents

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- **Introduction**
  - Storable Bipropellant Thruster
  - Development Goals
  - rocFlamFoam
- **Numerical simulation & Results**
  - Spray Dynamics
  - wall film formation
- **Conclusion & Future work**

# Introduction - Bipropellant thruster

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

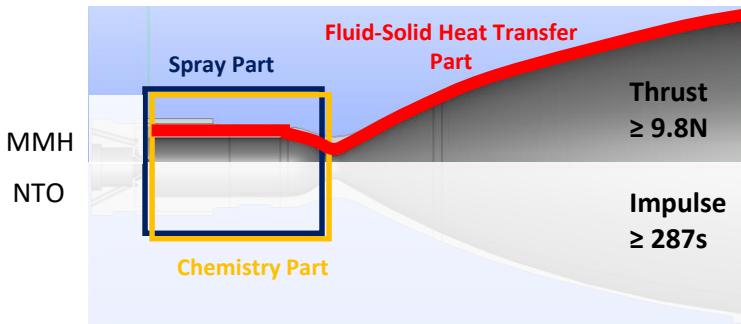


Development of combustion analysis S/W



# Introduction – development goals

## • Thruster analysis



[Section view of spp-k10]

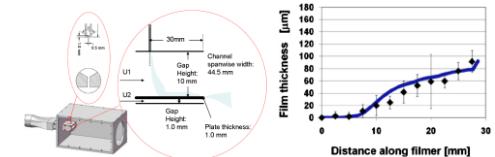
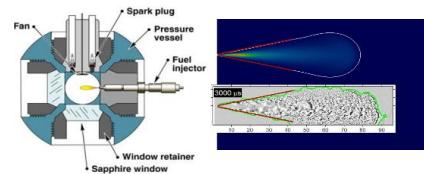
## ▪ Hypergolic Chemistry

Characteristics	design (5 step, 11 species)	remarks
MMH Decomposition	$\text{CH}_3(\text{NH})\text{NH}_2 \rightarrow \text{CH}_4 + \text{H}_2 + \text{N}_2$	
NTO Decomposition	$\text{N}_2\text{O}_4 \rightarrow 2\text{NO}_2$	Ambiguous
CH4 – NO2 reaction	$\text{CH}_4 + 2.3\text{NO}_2 + \text{H}_2 \rightarrow 3\text{H}_2\text{O} + 1.15\text{N}_2 + 0.4\text{CO} + 0.6\text{CO}_2$	Arrhenius parameter
CH4 – CO2 reaction	$\text{CH}_4 + 0.5\text{CO}_2 + 0.5\text{H}_2\text{O} \rightarrow 1.5\text{CO} + 2.5\text{H}_2$	
H2O Decomposition	$\text{H}_2\text{O} \leftrightarrow \text{H} + \text{OH}$	

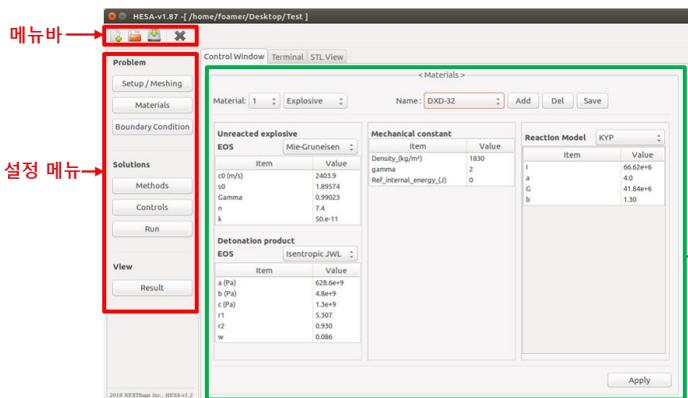
[Design focus, Xu (2006)]

## ▪ Spray Dynamics

- Spray behavior
- Sandia-A (heptane)
- Wall film model
- Shedd exp. (urea), AIAA 2009-998



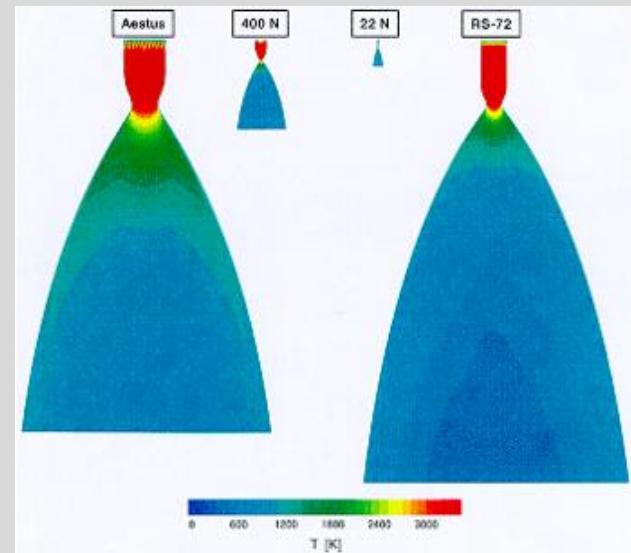
## ▪ GUI Configuration



- ▶ 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

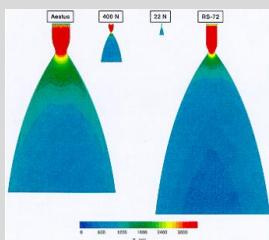
- ROCFLAM
  - Compressible -sub, trans and supersonic
    - 2D axisymmetric finite volume, SIMPLE algorithm
    - standard k- $\epsilon$  with wall function, 2 layer model
  - Multi-gaseous species chemistry
    - Arrhenius, EDC, global chemistry
    - standard jannaf property data
  - Lagrangian
    - 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

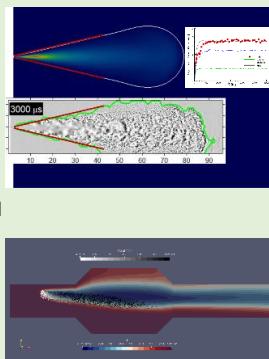
## • ROCFLAM

- Compressible -sub, trans and supersonic
  - 2D axisymmetric finite volume, SIMPLE algorithm
  - standard k- $\epsilon$  with wall function, 2 layer model
- Multi-gaseous species chemistry
  - Arrhenius, EDC, global chemistry
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  - droplet-to-wall interaction model
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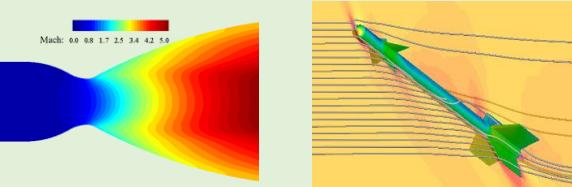
## • SprayFoam

- 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



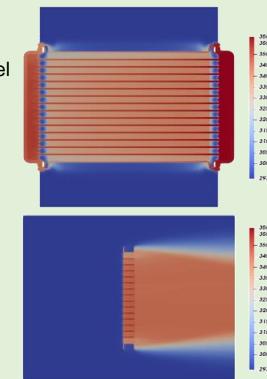
## • PCNFoam(PISOCentralNFOam)

- 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



## • 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

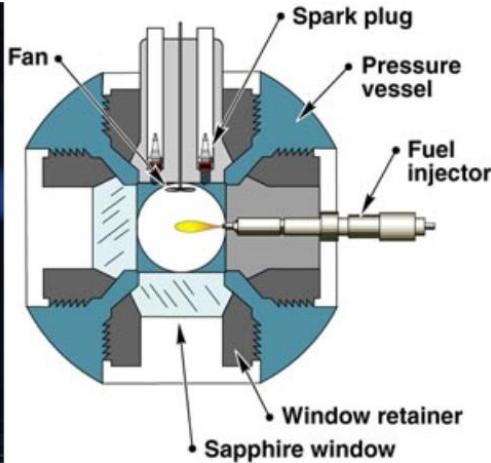
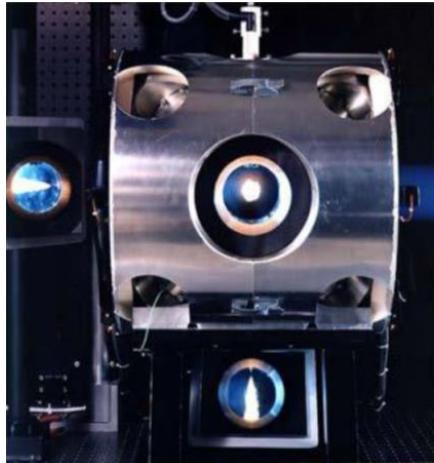


# Numerical simulation & Results

- 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]

[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 <sup>3</sup>

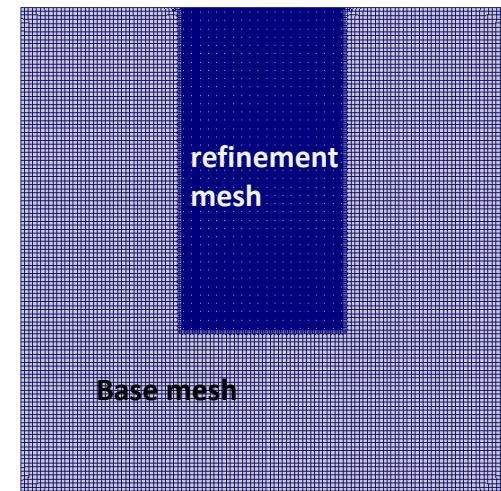
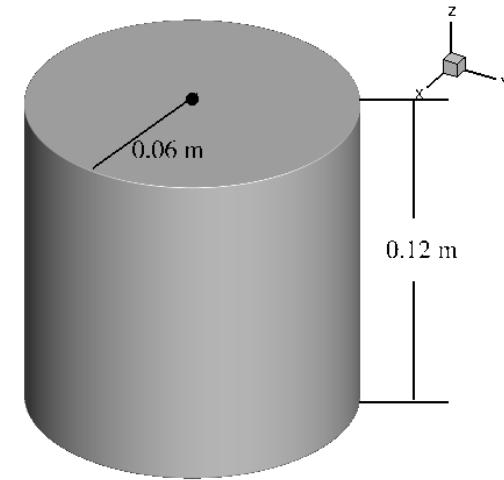


Diesel Data Search page																								
<small>Use the data search by selecting desired parameters from the categories above. The white buttons apply to the ECNTT button and green buttons for "Links". The arrow on the left edge of the above table toggles "Experimental Type" searching. To toggle side-scrolling double-click in the results window. Click on the column headers above the data to read their definitions.</small>																								
<small>RESET Spray A Spray H n-heptane 1000K,42bar Soot vs In Press Soot vs Ambient CO<sub>2</sub> Soot vs Orifice Diameter All Soot Measurements Links</small>																								
Size	nozzleDiameter (mm)	stems (K)	intensity (kg/m²)	nozL (MPa)	minPress (MPa)	similar (ms)	similar (ms)	inletTemp (K)	inletTemp (K)	airTemp (K)	Thick (kg/m³)	densH (kg/m³)	densL (kg/m³)	Z (Mpa)	tau (ms)	tauH (ms)	tauL (ms)	Cd	Ca	maxGross	needlePos (mm)	inlet (mm)	holes (mm)	Mfc (ms)
0	1000	14.8	0.100±0	150	-4	NHPT	373	sandia	-	967	15.3	-	4.33	1.021	154.5	0.01	6.8	17.8	0.0 0.06	Crossflow Nozzle Data	needleUp extraction	-	Reduced in. time	
21	1000	14.8	0.100±0	150	-4	NHPT	373	sandia	1009	967	15.3	15.12	4.21	1.009	150.2	0.01	6.8	17.8	0.0 0.06	Crossflow Nozzle Data	needleUp extraction	0.07	-	
15	1000	14.8	0.100±0	150	-4	NHPT	373	sandia	1010	967	15.3	15.09	4.25	1.021	153.25	0.01	6.8	17.8	0.0 0.06	Crossflow Nozzle Data	needleUp extraction	0.07	-	
12	1000	14.8	0.100±0	150	-4	NHPT	373	sandia	1010	967	15.3	15.04	4.27	1.021	153.27	0.01	6.8	17.8	0.0 0.06	Crossflow Nozzle Data	needleUp extraction	0.07	-	
10	1000	14.8	0.100±0	150	-4	NHPT	373	sandia	1011	967	15.3	15.11	4.28	1.021	153.28	0.01	6.8	18.1	0.0 0.06	Crossflow Nozzle Data	needleUp extraction	0.07	-	
8	1000	14.8	0.100±0	150	-4	NHPT	373	sandia	1005	967	15.3	14.97	4.29	1.021	152.29	0.01	6.9	18.1	0.0 0.06	Crossflow Nozzle Data	needleUp extraction	0.07	-	

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

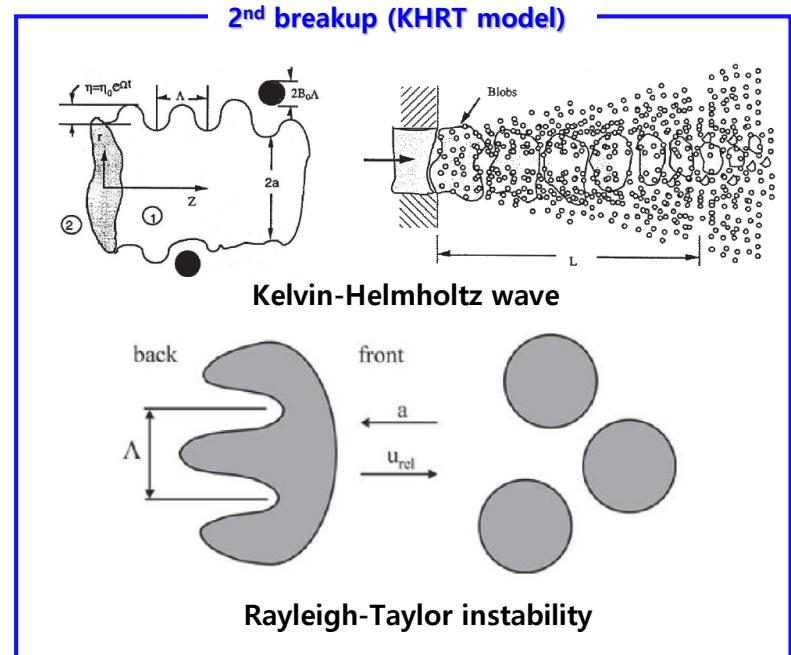
# Spray Dynamics

- 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)**



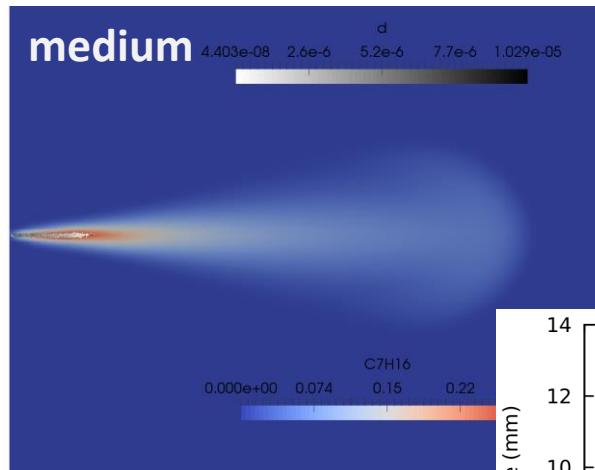
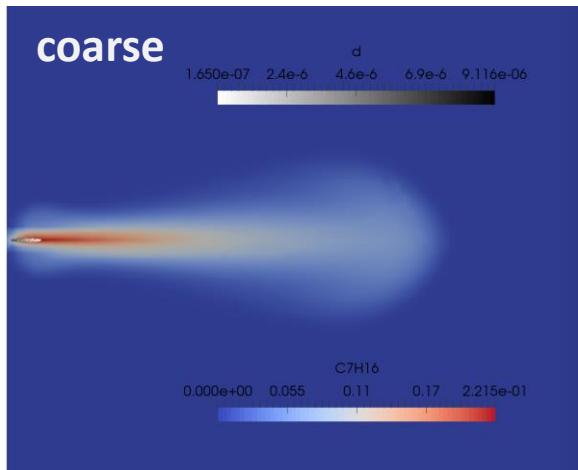
# Spray Dynamics

- Numerical method
  - Solver: **sprayFoam** in OpenFOAM
  - **Pimple** algorism
  - 2<sup>nd</sup> breakup: **KHRT model**
    - $B_0=0.61, B_1=40, C_\tau=1, C_{RT}=0.1$
- Spray injection model
  - Cone nozzle type
  - Spray half angle: 12.6°
  - Size distribution: Rosin Rammler (min:  $1 \times 10^{-3}$ , max:  $9.27 \times 10^{-2}$  [mm], n = 2)

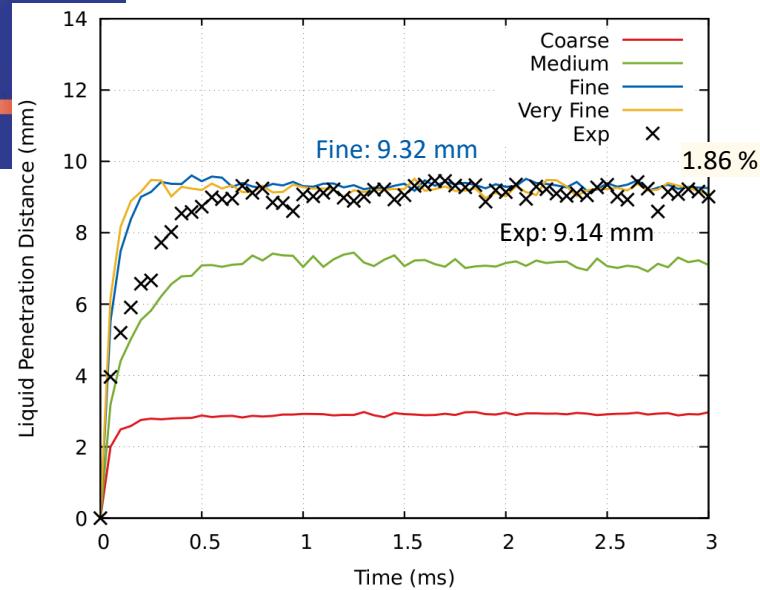
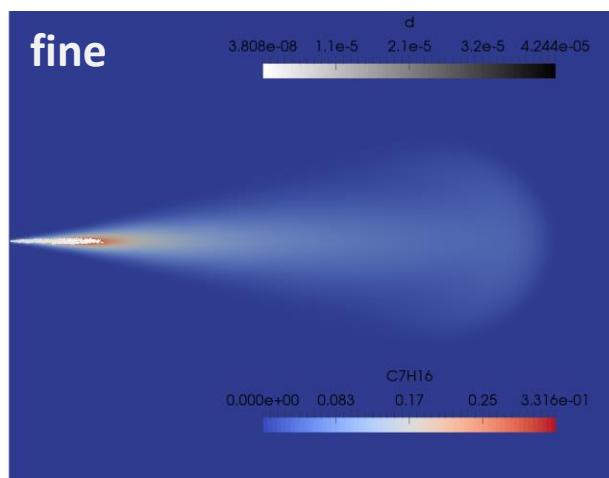


# Spray Dynamics

- Results – grid resolution

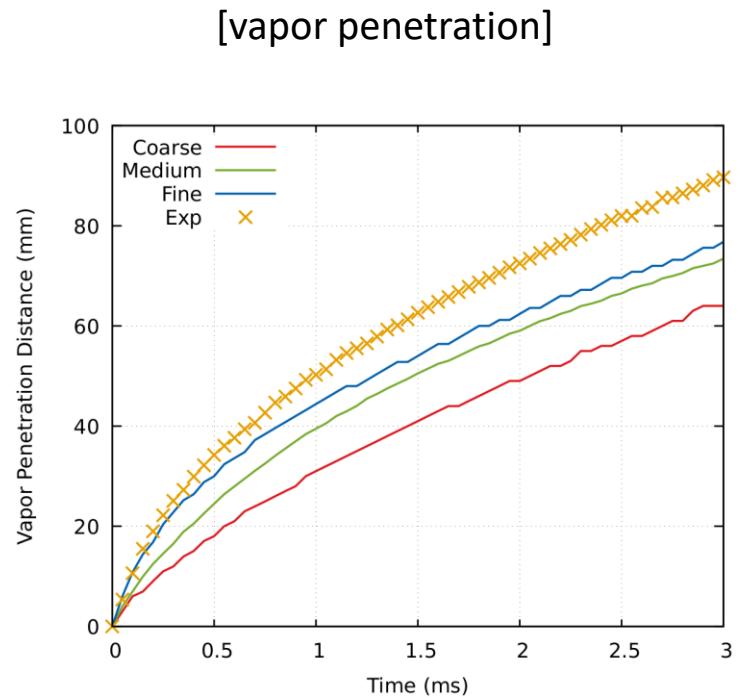
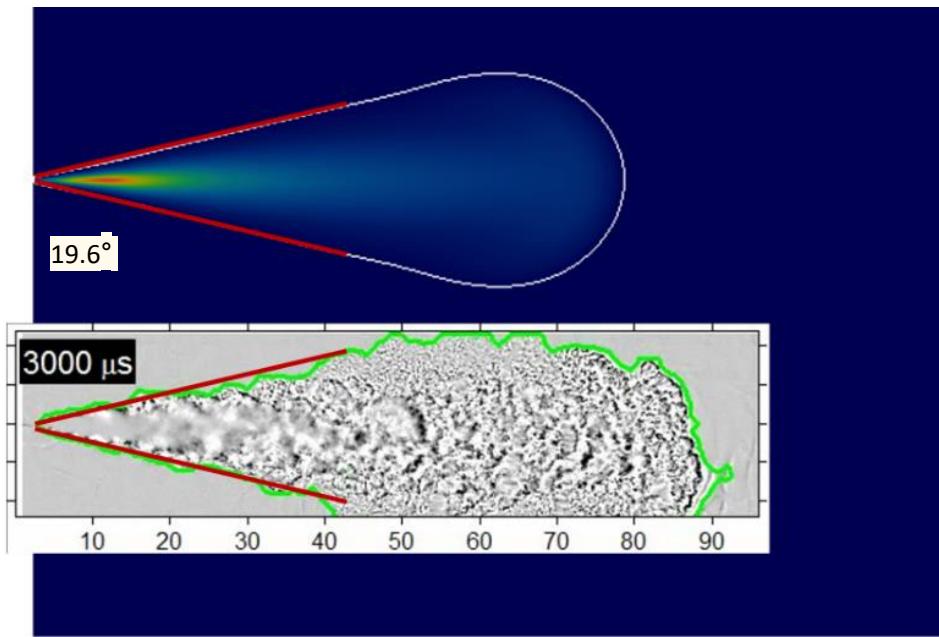


[liquid penetration]



# Spray Dynamics

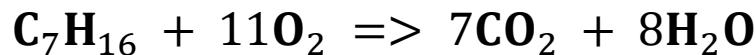
- Comparison of vapor penetration



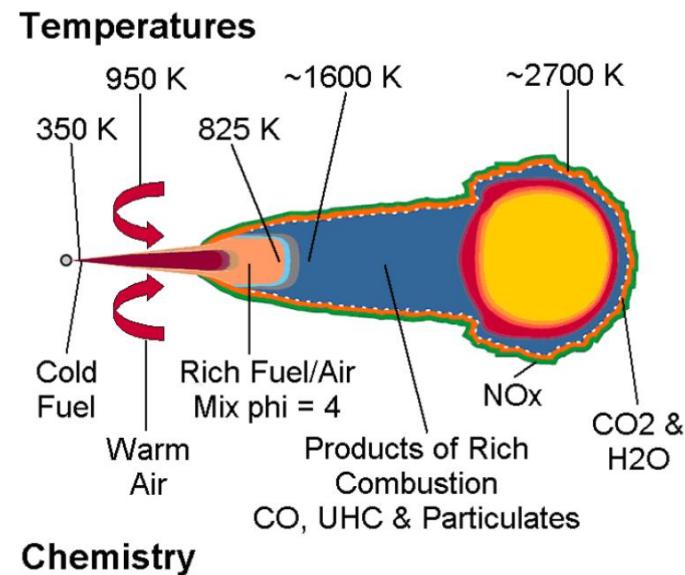
# Spray Dynamics

- Reacting condition

- n-heptane global reaction



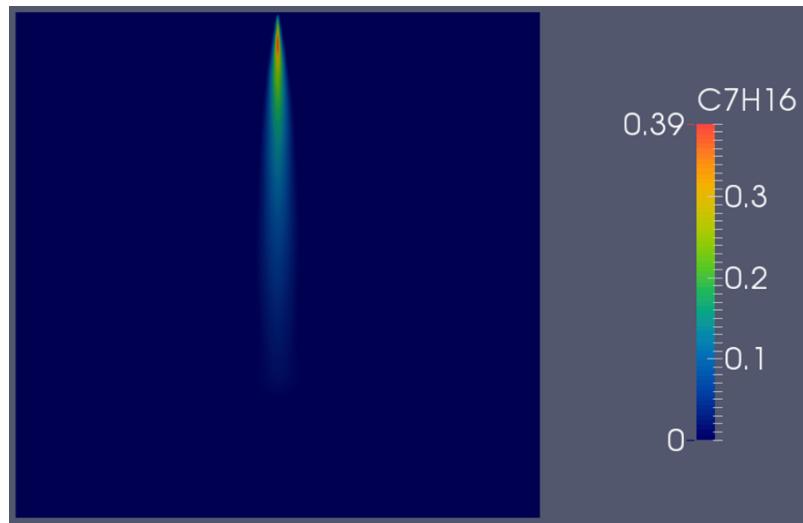
- CHEMKIN To Foam
- Mixture fraction
- Thermo: JANAF table
- Transport: Sutherland



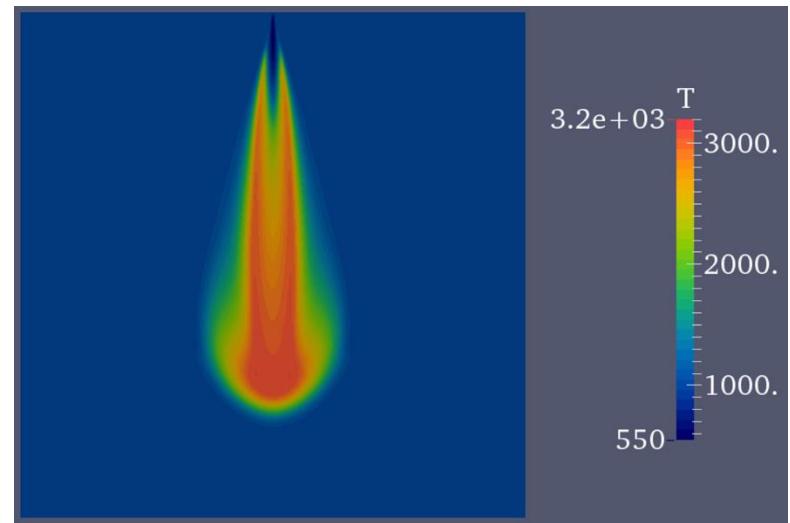
# Spray Dynamics

- Reacting results

[n-heptane mass fraction]



[Temperature distribution]



# Spray Dynamics

- Wall film formation

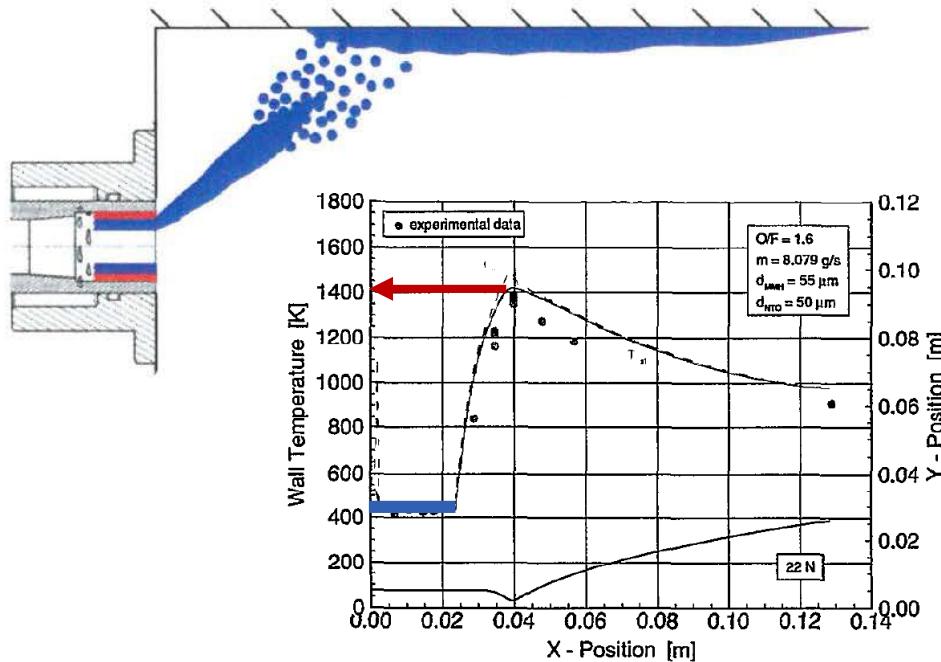


Figure 18: External and internal wall temperature distribution for the load point R2 of the 22 N thruster

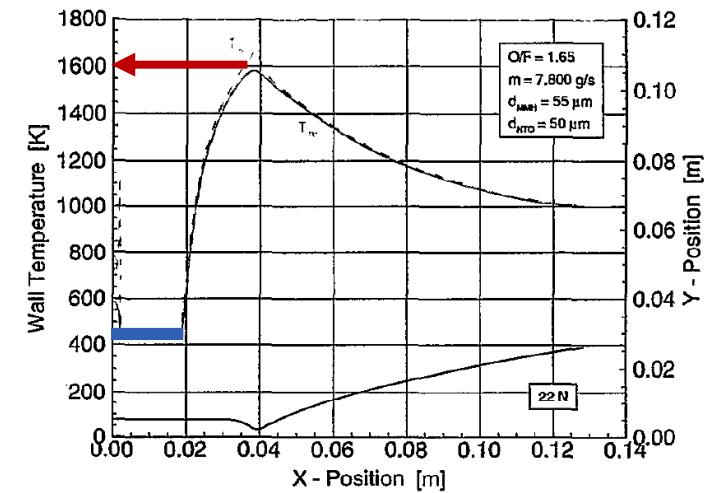
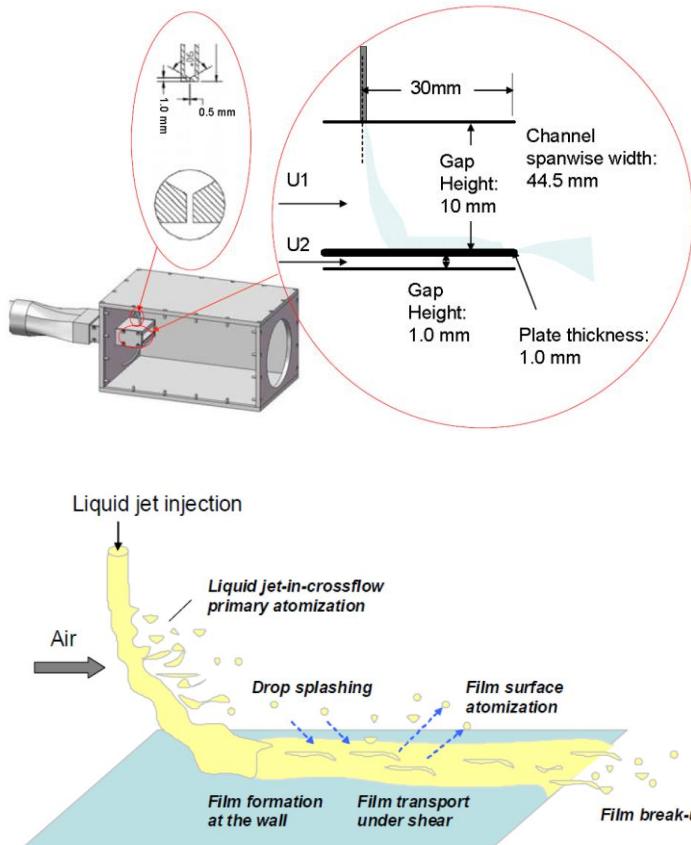


Figure 19: External and internal wall temperature distribution for the reference point R of the 22 N thruster

# Spray Dynamics

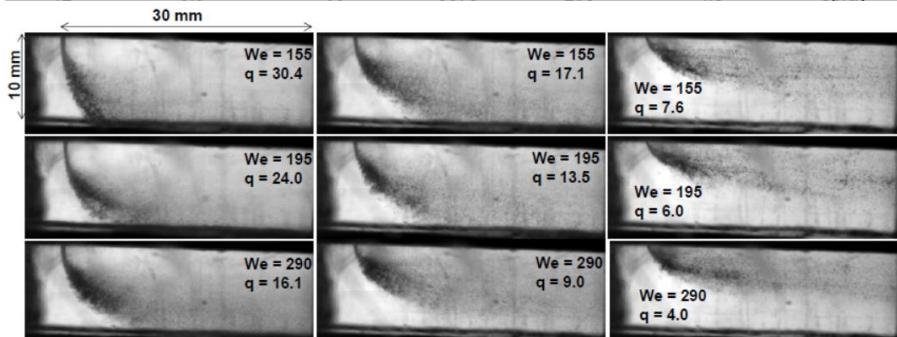
- Wall film formation

[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 <sub>l</sub>	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



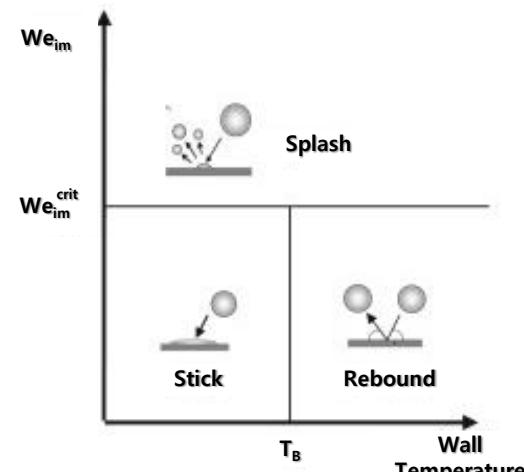
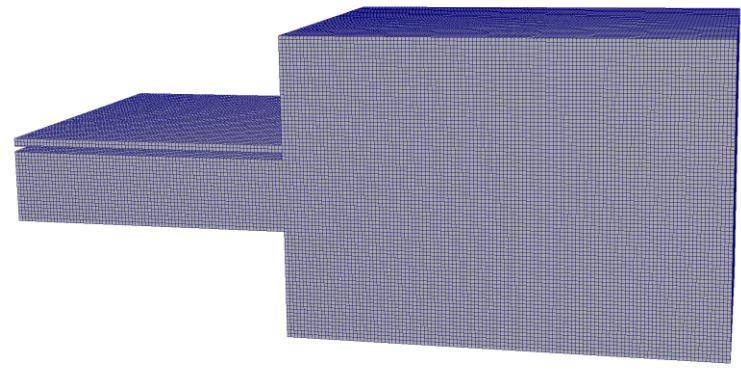
**Figure 5.** Spray trajectory and penetration as a function of Weber number (We) and momentum-flux ratio (q).

# 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

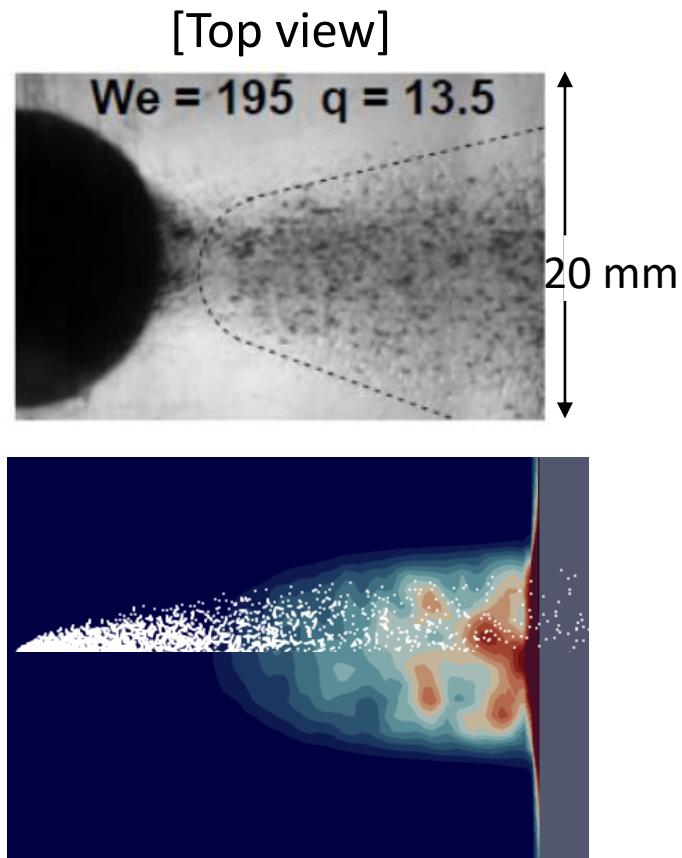
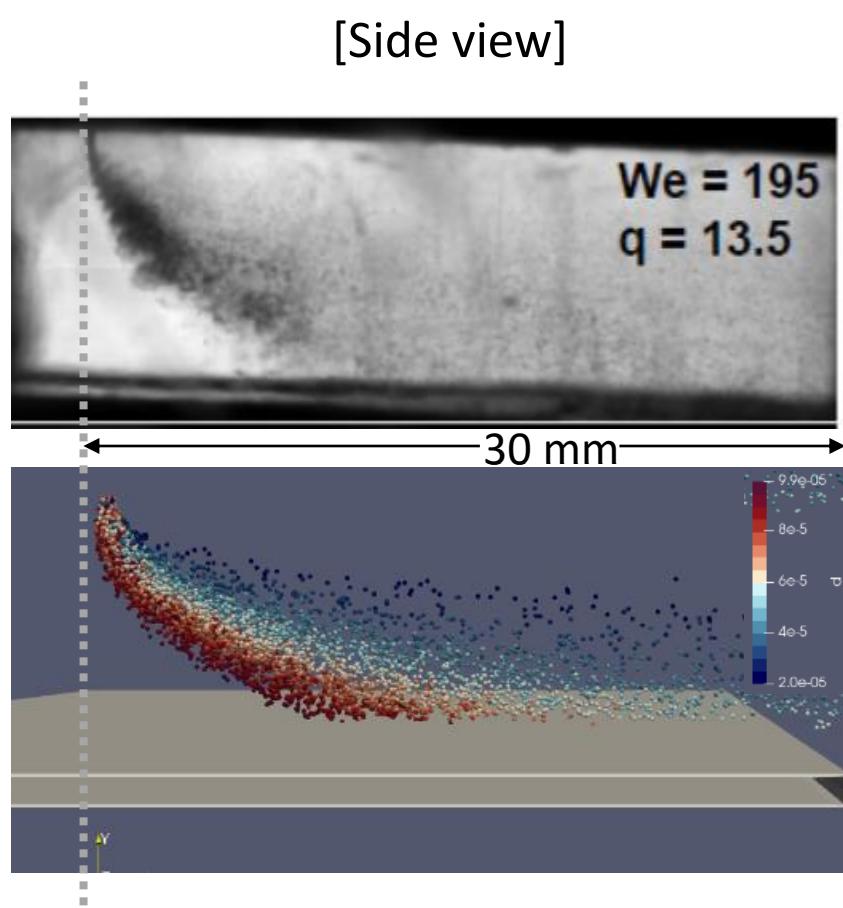


Grover and Assanis (2001)

# Spray Dynamics

- Wall film formation
  - Spray trajectory

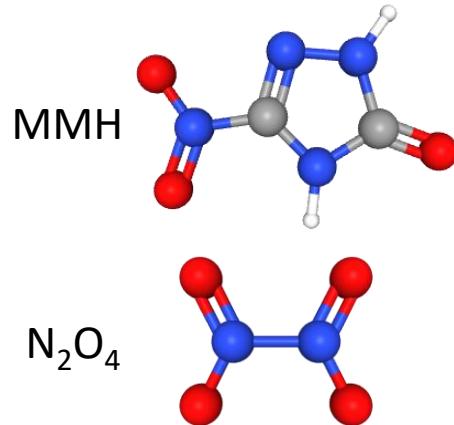
Experiment results



# Conclusion & Future work

- Modify and development of SprayFoam, sprayPimpleCentralFoam
- Future work

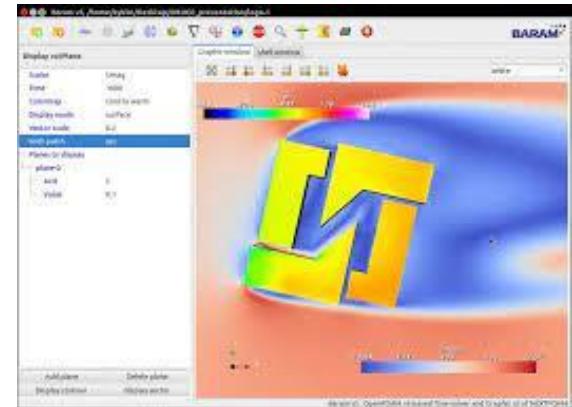
[Hypergolic chemistry]



[Conjugate Heat Transfer]



[Graphical User Interface]



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

# Thank you for your attention.