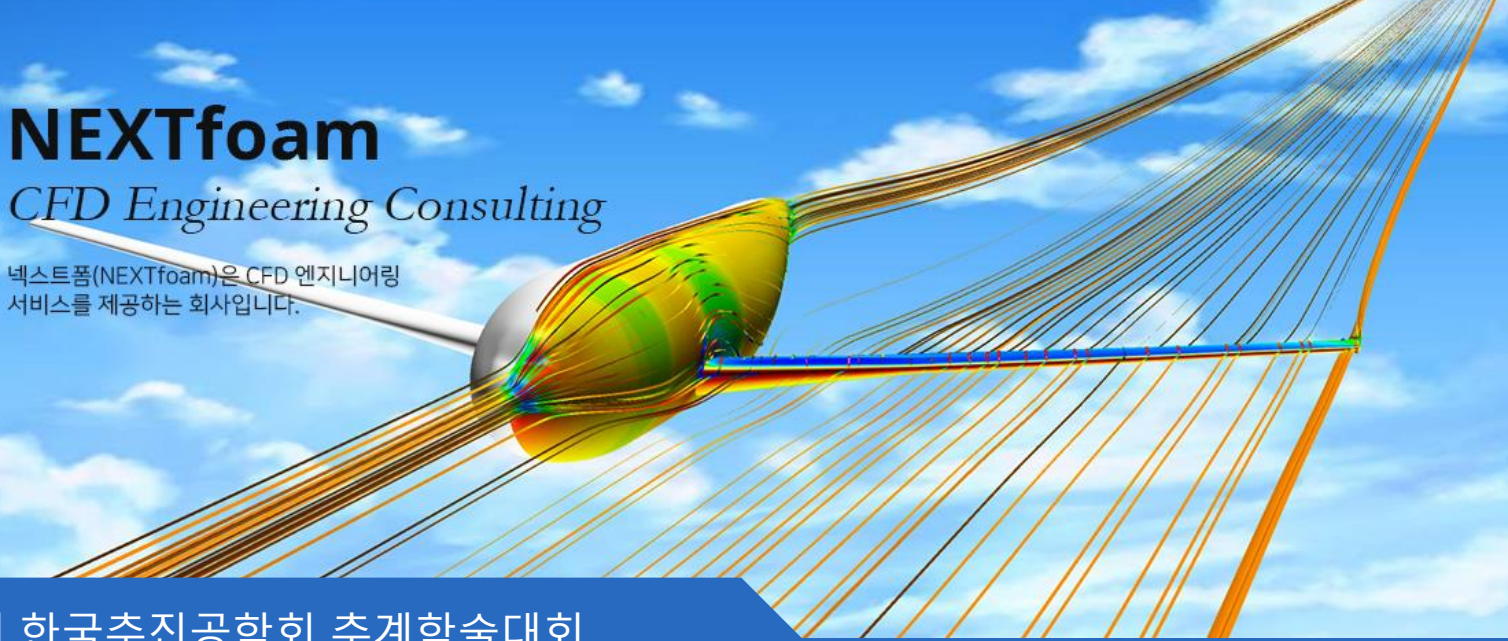


NEXTfoam

CFD Engineering Consulting

넥스트폼(NEXTfoam)은 CFD 엔지니어링 서비스를 제공하는 회사입니다.



2021년 한국추진공학회 추계학술대회

추력기의 액적 분사 해석을 위한 기초적인 수치연구

정황희¹, 신재렬^{1†}, 채종원²

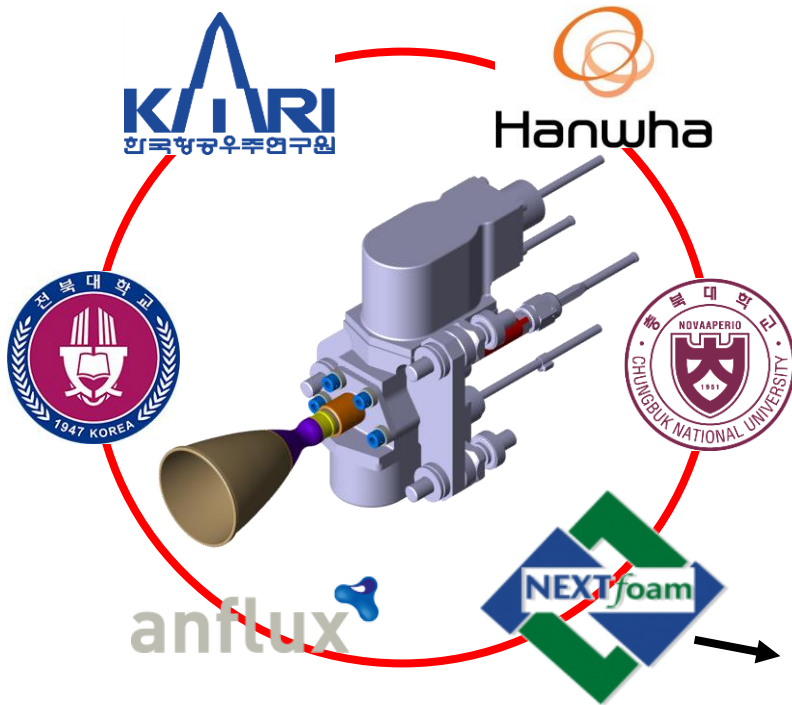
¹(주)넥스트폼 기술연구소, ²한국항공우주연구원

2021. 11. 26.

- 서론
 - 저장성 이원추진제 추력기
 - 개발 목표
 - rocFlamFoam
- 수치해석 시뮬레이션 & 결과
 - Spray Dynamics 액적 분사 거동
 - wall film formation 벽 필름 형성
- 결론 & 향후 연구

서론 – 이원추진제 추력기

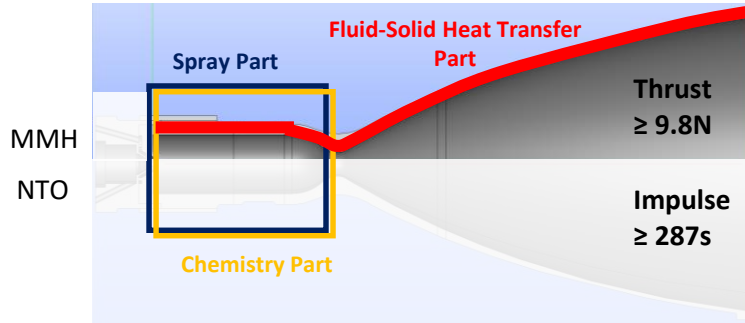
- 스페이스파이오니어 사업
 - 저장성 이원추진제 추력기 개발
 - 2021. 06. ~ 2025. 12. (55 개월)



이원추진제 추력기 연소 해석 소프트웨어 개발

서론 - 개발 목표

추력기 해석



[Section view of spp-k10]

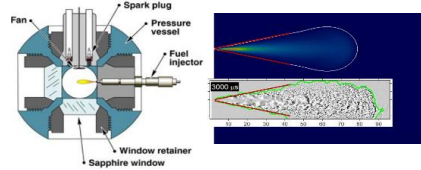
Hypergolic Chemistry

Characteristics	design (5 step, 11 species)	remarks
MMH Decomposition	$\text{CH}_3(\text{NH})\text{NH}_2 \rightarrow \text{CH}_4 + \text{H}_2 + \text{N}_2$	Ambiguous Arrhenius parameter
NTO Decomposition	$\text{N}_2\text{O}_4 \rightarrow 2\text{NO}_2$	
CH ₄ - NO ₂ reaction	$\text{CH}_4 + 2.3\text{NO}_2 + \text{H}_2 \rightarrow$ $3\text{H}_2\text{O} + 1.15\text{N}_2 + 0.4\text{CO} + 0.6\text{CO}_2$	
CH ₄ - CO ₂ reaction	$\text{CH}_4 + 0.5\text{CO}_2 + 0.5\text{H}_2\text{O} \rightarrow 1.5\text{CO} + 2.5\text{H}_2$	
H ₂ O Decomposition	$\text{H}_2\text{O} \leftrightarrow \text{H} + \text{OH}$	

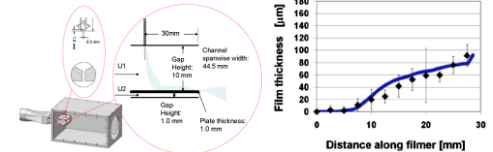
[Design focus, Xu (2006)]

Spray Dynamics

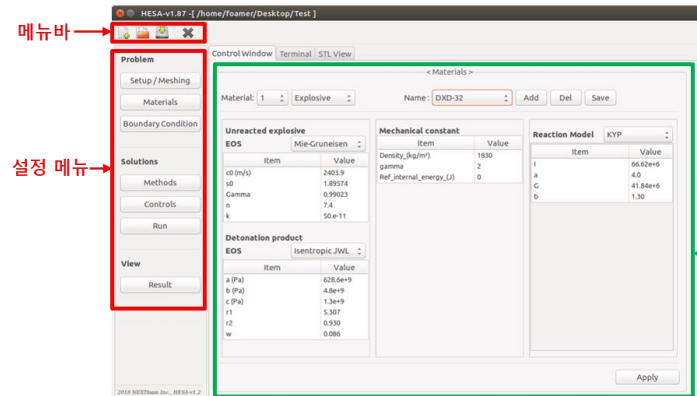
- Spray behavior
 - Sandia-A (heptane)



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

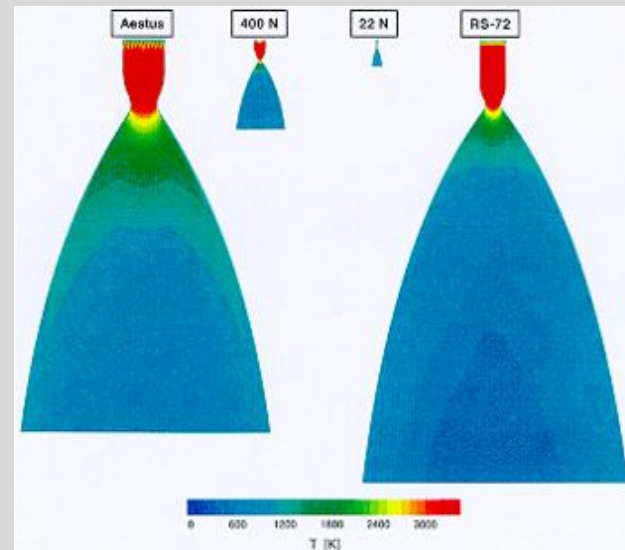


GUI Configuration



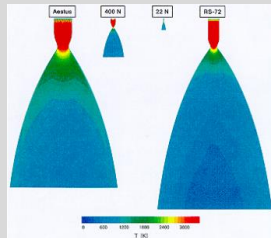
- 메뉴바 (New/Load/Save/Exit)
 - 프로젝트를 생성/읽기/저장하기 위한 메뉴
- 설정 메뉴 (Problem/Solution/View)
 - 진행 작업 또는 메뉴의 버튼에 따라 화면 전환

- 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



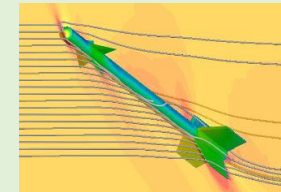
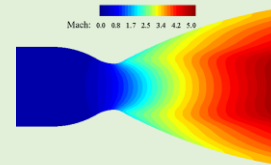
- ROCFLAM

- 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
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- Lagrangian
 - droplet-to-wall interaction model
 - secondary droplet break-up
 - annular film cooling model
 - viscous heating species diffusion
 - heat conduction in solid wall



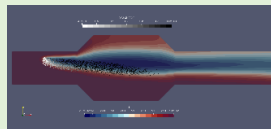
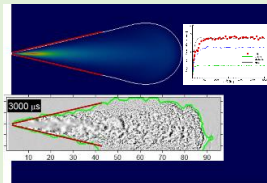
- PCNFoam(PISOCentralNFoam)

- 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



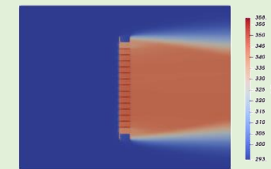
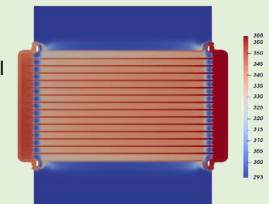
- SprayFoam

- 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

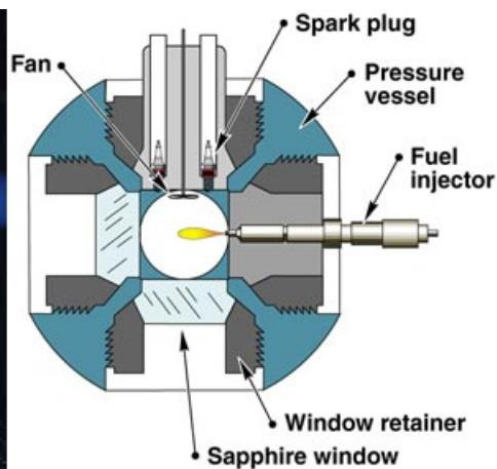
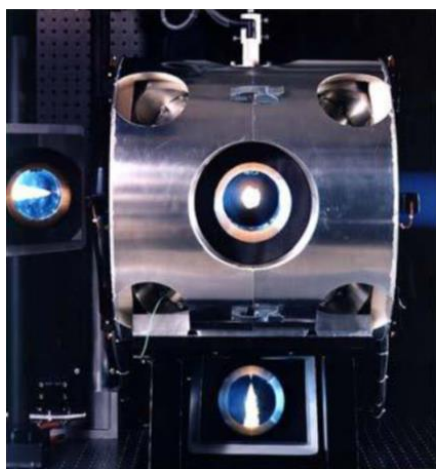


수치해석 시뮬레이션 & 결과

- **Spray Dynamics**
 - nonreacting spray
 - reacting spray
 - wall film formation

Spray Dynamics

- Spray modeling
 - SANDIA spray H n-heptane
 - 정적 연소 챔버



[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 ³

Diesel Data Search page

RESET Spray A Spray B n-heptane 1000K.42bar Cool vs Inj Press Cool vs Ambient CO Cool vs Orifice Diameter All Shot Measurements Units

Experimental Type	Ambient O ₂ (vol%)	Ambient Temperature (K)	Ambient Density (kg/m ³)	Nozzle Diameter (mm)	Serial Number	Injection Pressure (MPa)	Injection Duration (ms)	Fuel Type	Fuel Temperature (K)	Substituting Inhibitor
All	All	All	All	All	All	All	All	All	All	All
Shot	8	1000	14.8	0.100 ±	1009	150	6.8	n-hept	373	sandia
Shot Length	10									
Shot Delay	12									
All Parameters										

Copy Search Clear Search Parameters

Normal Ambient Special Experiment Dual Flow Uncertainty Stand Dev Search Show Empty

Use the data search by selecting desired parameters from the categories above. The white buttons next to the 'RESET' button are presets (except for 'Units'). The arrow on the left edge of the above table toggles 'Experimental Type' searching. To toggle single vs. double-click in the results window. Click on the column header above the data to read their definitions.

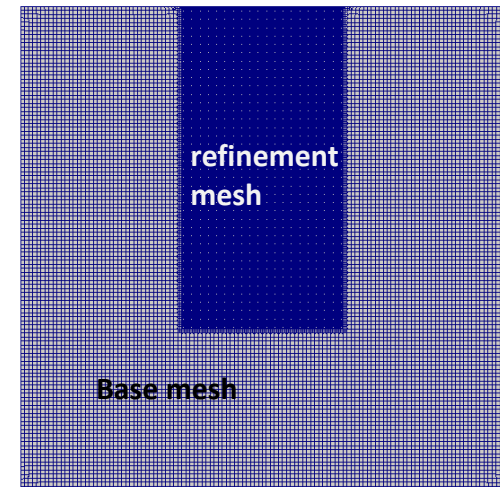
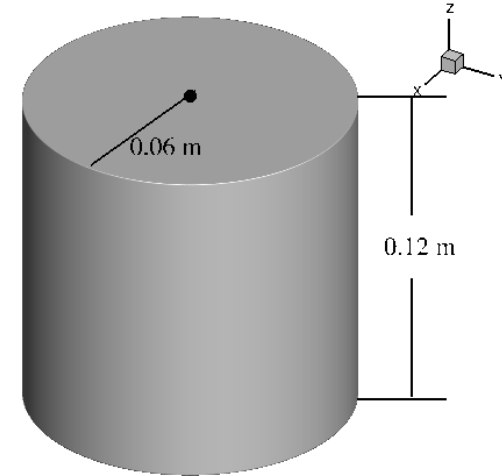
Shot	nozzleDia	theta	rhoAmb	rhoFuel	injPres	injDur	injRate	injMass	TaAmb	TaInj	TbInj	rhoInj	rhoFuel	Z	injP	injMFA	injDur	injMass	Ca	Ca	injGeo	needleDia	injDur	injMass	injRate
01	0	1000	14.8	0.100 ±	150	6.8	17.8	0.006	850	850	15.3	14.8	14.8	4.33	1.01	154.33	rate of injection	6.8	17.8	0.006	0.100 ±	6.807	17.8	0.006	17.8
02	21	1000	14.8	0.100 ±	150	6.8	17.8	0.006	850	850	15.3	14.8	14.8	4.33	1.009	150.21	rate of injection	6.8	17.8	0.006	0.100 ±	6.807	17.8	0.006	17.8
03	15	1000	14.8	0.100 ±	150	6.8	17.8	0.006	850	850	15.3	14.8	14.8	4.25	1.01	153.25	rate of injection	6.8	17.8	0.006	0.100 ±	6.807	17.8	0.006	17.8
04	12	1000	14.8	0.100 ±	150	6.8	17.8	0.006	850	850	15.3	14.8	14.8	4.27	1.01	153.27	rate of injection	6.8	17.8	0.006	0.100 ±	6.807	17.8	0.006	17.8
05	10	1000	14.8	0.100 ±	150	6.8	17.8	0.006	850	850	15.3	14.8	14.8	4.28	1.01	153.28	rate of injection	6.8	17.8	0.006	0.100 ±	6.807	17.8	0.006	17.8
06	8	1000	14.8	0.100 ±	150	6.8	17.8	0.006	850	850	15.3	14.8	14.8	4.29	1.01	152.29	rate of injection	6.8	17.8	0.006	0.100 ±	6.807	17.8	0.006	17.8

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

Spray Dynamics

- 액적 분사 모델링

- 실린더 형상
- 격자 도구: **cfMesh** (cartesianMesh)
- 베이스 격자 셀 크기: 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

- 수치해석 방법

 - 솔버: **sprayFoam** in OpenFOAM

 - Pimple** 알고리즘

 - 2nd breakup: **KHRT model**

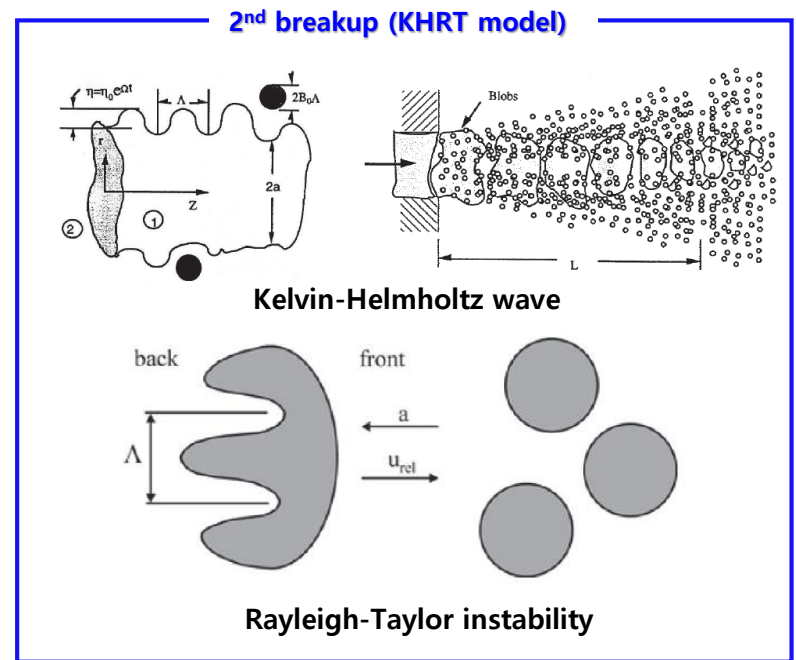
 - $B_0=0.61$, $B_1=40$, $C_\tau=1$, $C_{RT}=0.1$

- Spray injection model

 - Cone nozzle type

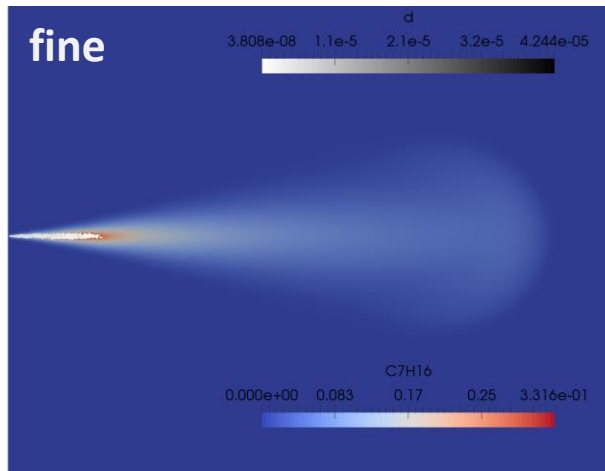
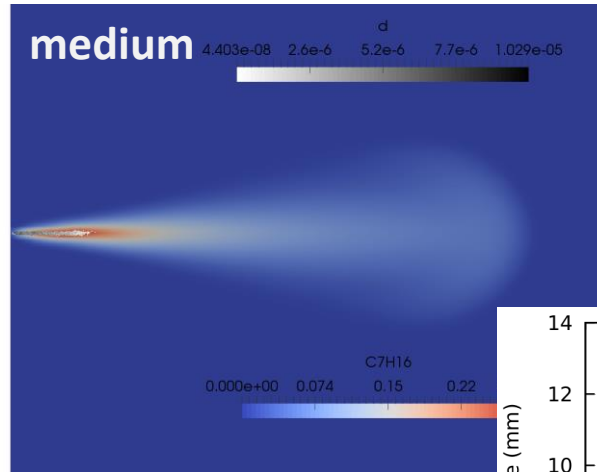
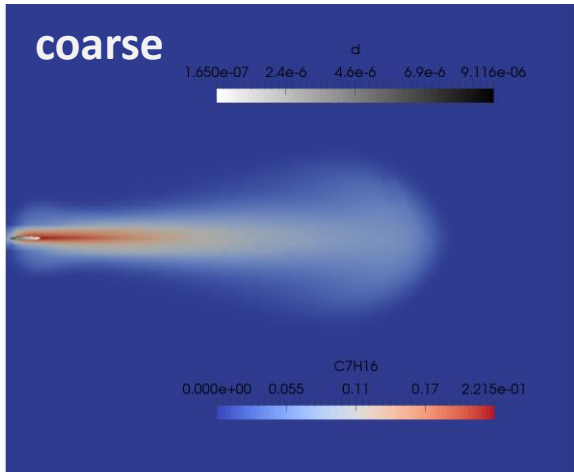
 - Spray half angle: 12.6°

 - Size distribution: Rosin Rammler (min: 1×10^{-3} , max: 9.27×10^{-2} [mm], $n = 2$)

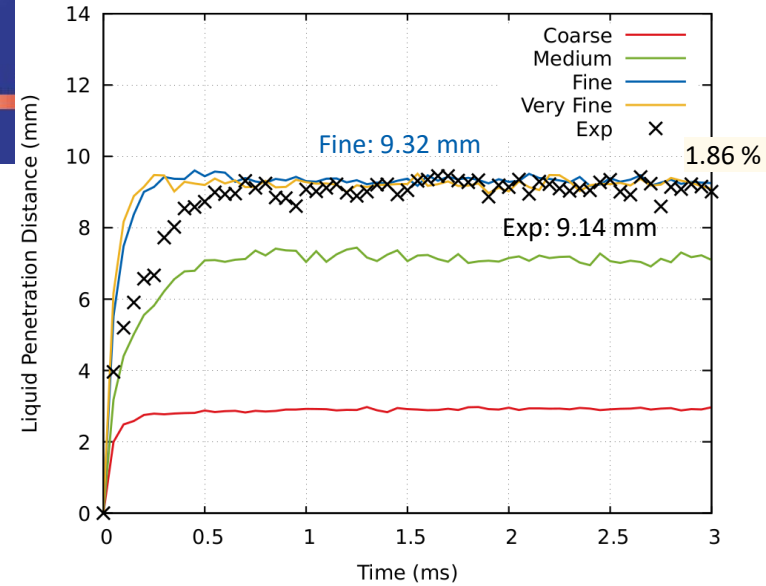


Spray Dynamics

- 결과 - 격자 해상도

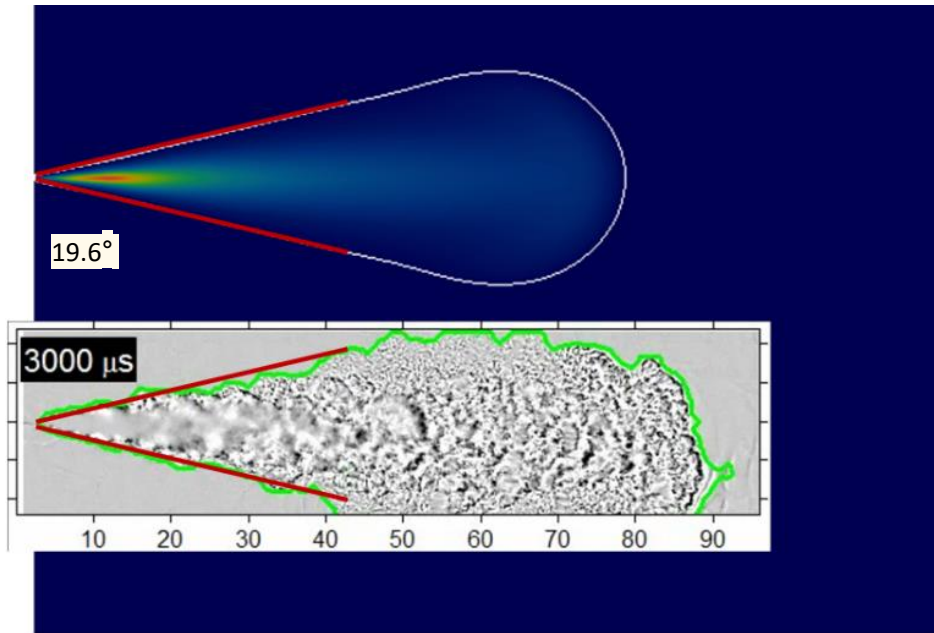


[liquid penetration]

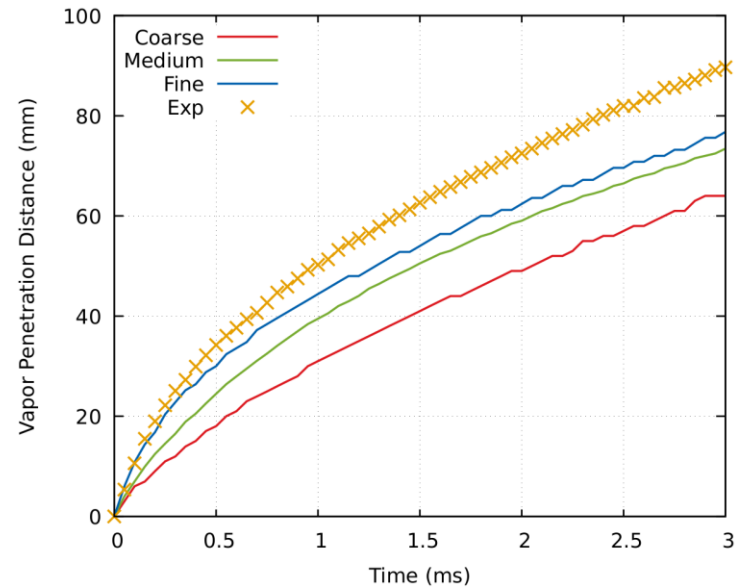


Spray Dynamics

- 증발 침투 거리 비교



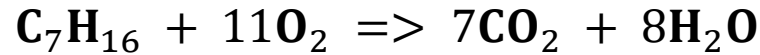
[vapor penetration]



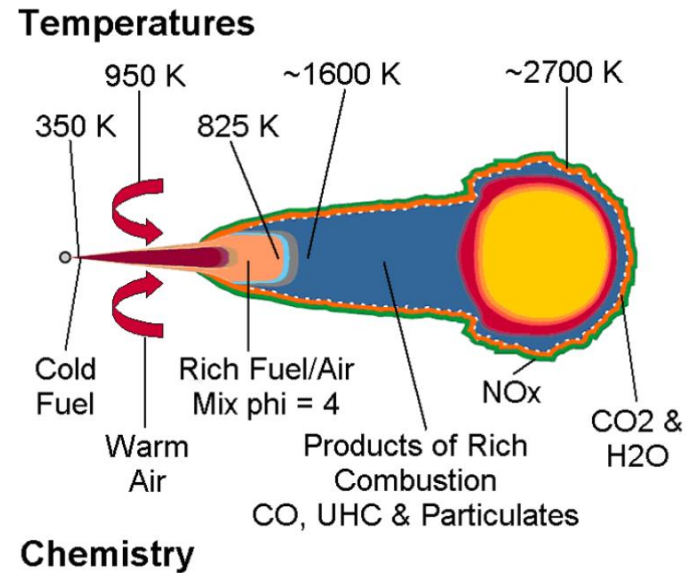
Spray Dynamics

- 반응 조건

- n-헵탄 총괄 반응식



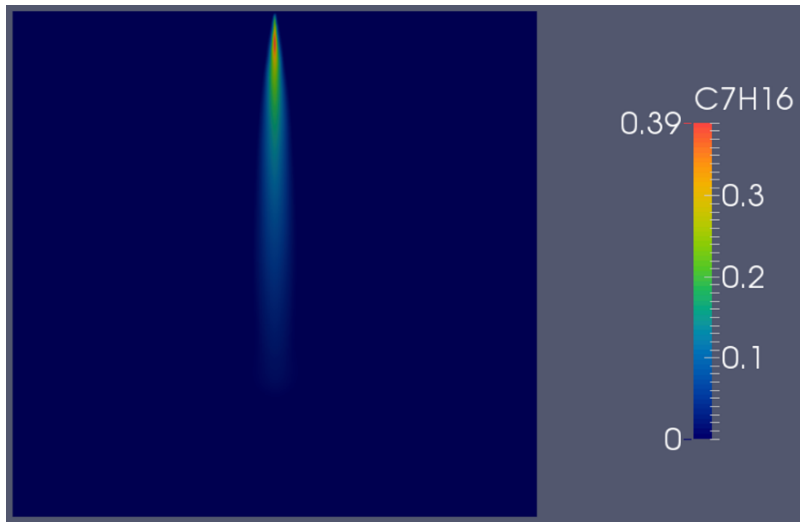
- CHEMKIN To Foam
- Mixture fraction
- Thermo: JANAF table
- Transport: Sutherland



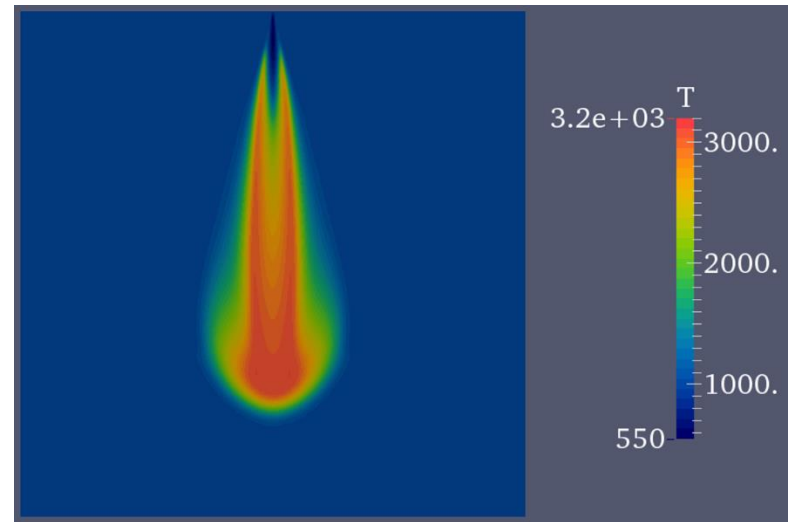
Spray Dynamics

- 반응 해석 결과

[n-heptane mass fraction]



[Temperature distribution]



Spray Dynamics

- Wall film formation

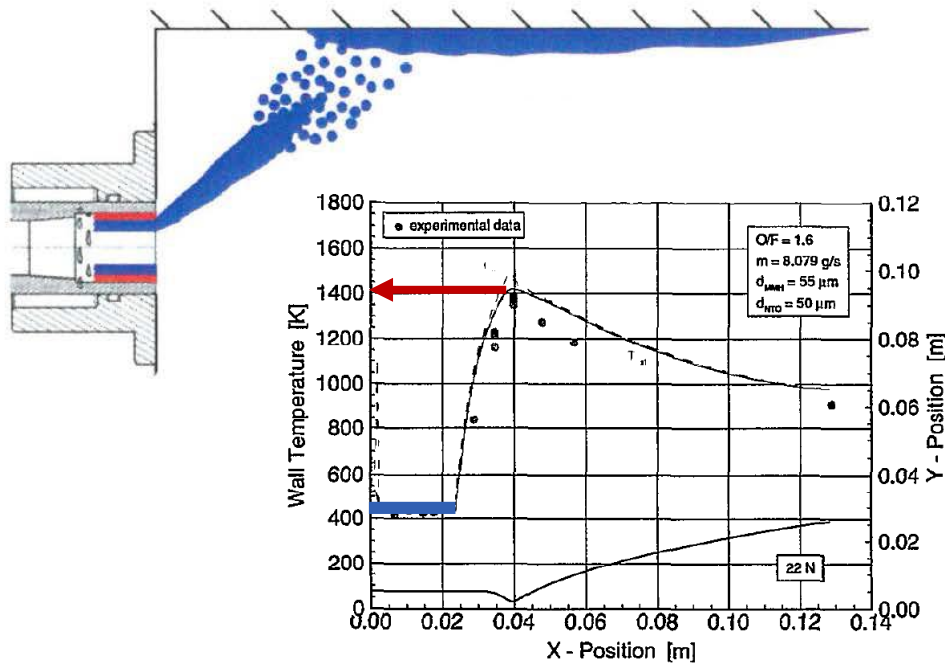


Figure 18: External and internal wall temperature distribution for the load point R2 of the 22 N thruster

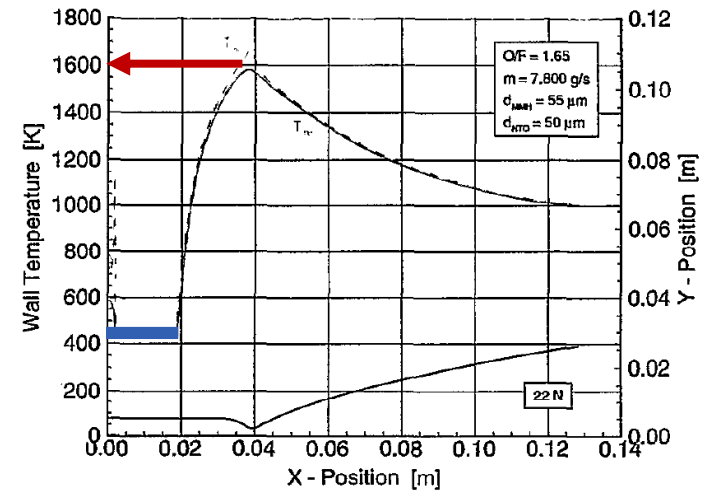


Figure 19: External and internal wall temperature distribution for the reference point R of the 22 N thruster

Spray Dynamics

- 벽 필름 형성

[shedd exp. AIAA 2009-998]

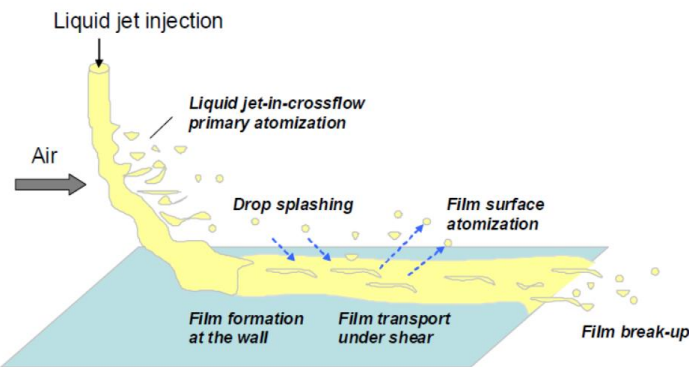
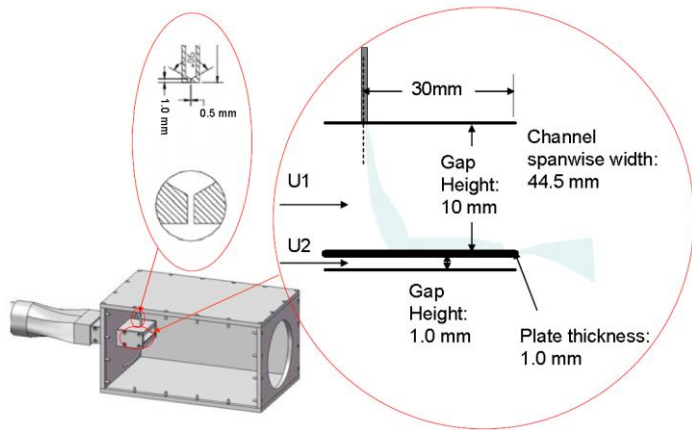


Table 1. List of operating conditions with specific cases highlighted for further discussion.

Case	Liquid Jet Velocity (m/s)	Crossflow Velocity (m/s)	Liquid Re _i	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	Sprays

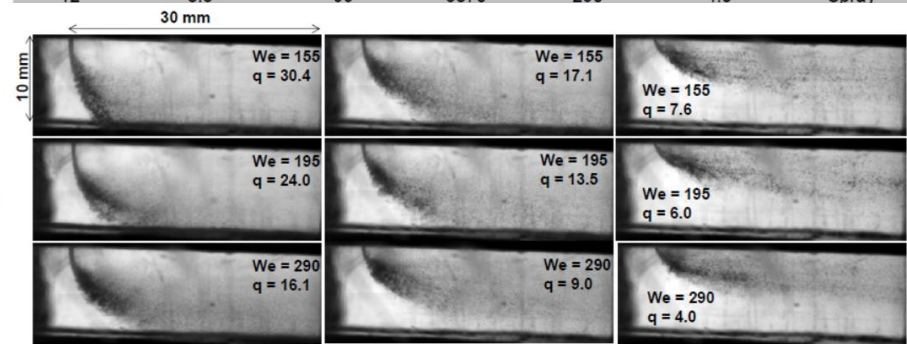
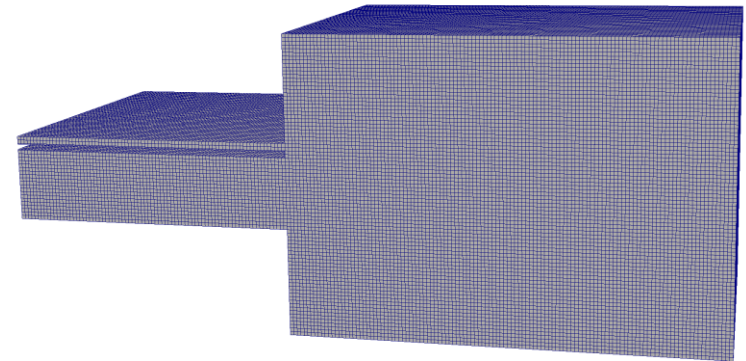


Figure 5. Spray trajectory and penetration as a function of Weber number (We) and momentum-flux ratio (q).

Spray Dynamics

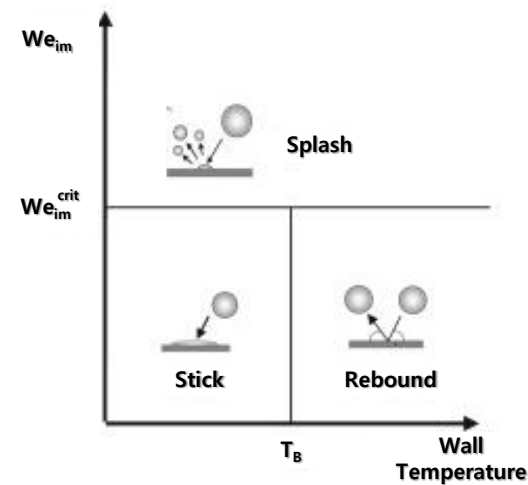
- **Wall film formation**

- **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



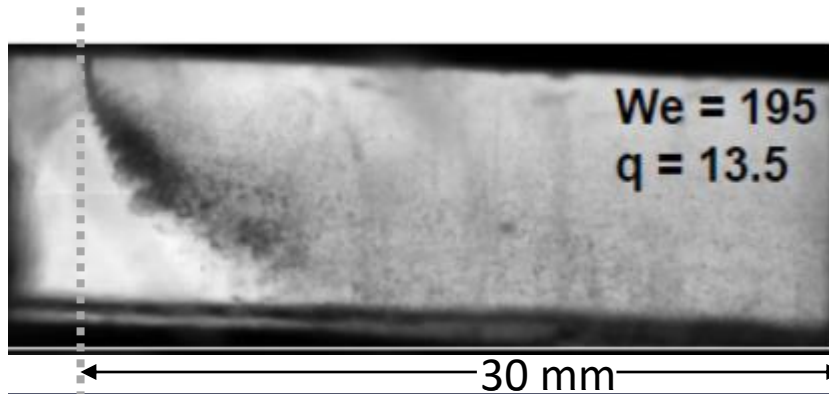
Grover and Assanis (2001)

Spray Dynamics

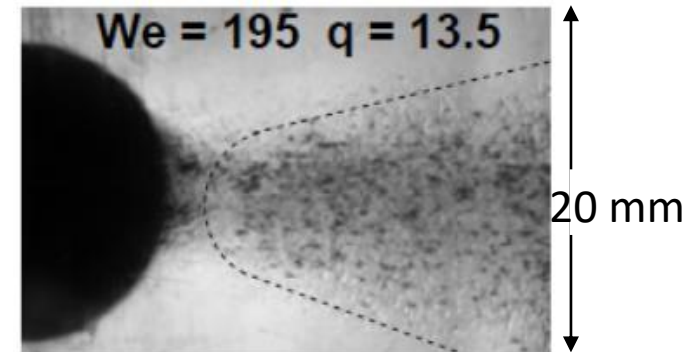
- Wall film formation
 - Spray trajectory

[Side view]

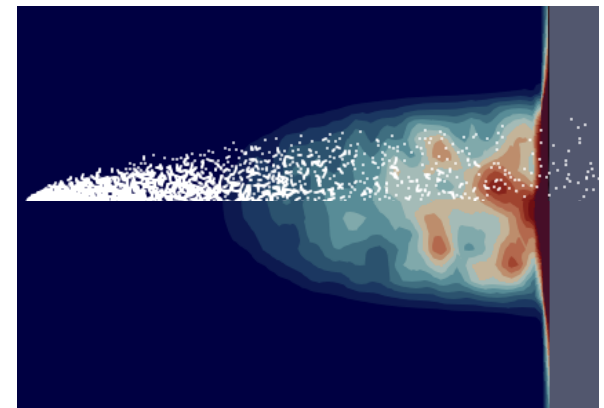
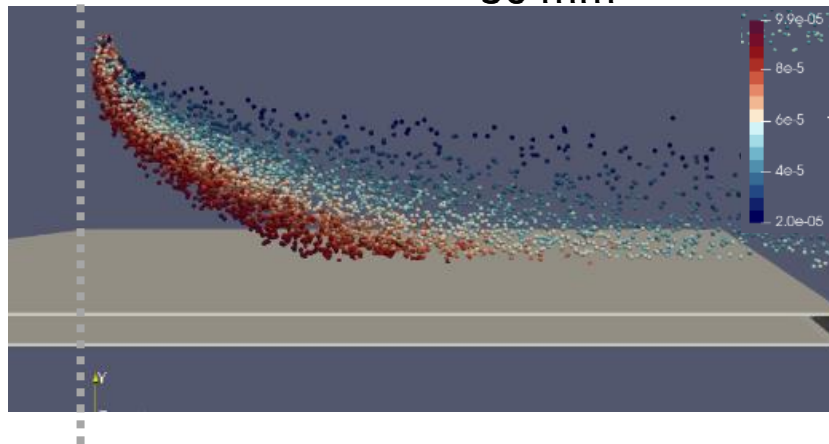
Experiment results



[Top view]



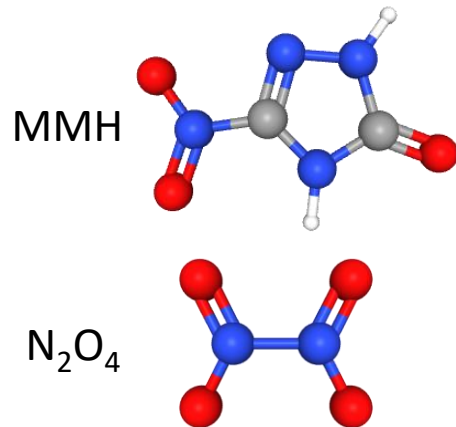
Simulation results



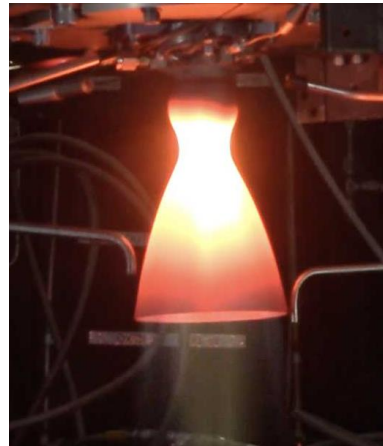
Conclusion & Future work

- Modify and development of SprayFoam, sprayPimpleCentralFoam
- Future work

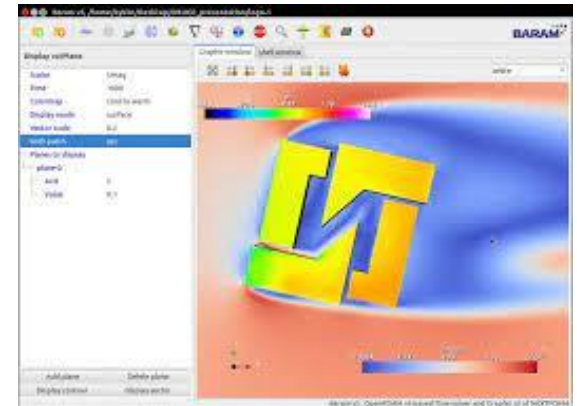
[Hypergolic chemistry]



[Conjugate Heat Transfer]



[Graphical User Interface]



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

Thank you for your attention.