Effect of Modeling Plume Chemistry on the Aerothermal and Aerodynamic Characterization of Supersonic Retro-Propulsion Nozzles

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Concept of Red Dragon

SuperDraco thrusters on SpaceX's Dragon 2 spacecraft[1]

Red Dragon mission[2]

[3]

- Dragon 2: "Crew transport and science delivery platform"
- Dragon + Falcon Heavy: Can explore the entire solar system
- Heat shield, parachutes and propulsive landing capabilities required to make this a reality

- Liquid Thrusters reach maximum thrust within 100 milliseconds of ignition
- Can be used for propulsive landings as well as for an abort during ascent if needed

[1] https://spaceflightnow.com/2016/04/27/spacex-announces-plan-to-send-mission-to-mars-in-2018; Credit: SpaceX
[2] http://imgur.com/gbOAmq5
[3] https://www.nasaspaceflight.com/2016/04/spacex-debut-red-dragon-2018-mars-mission

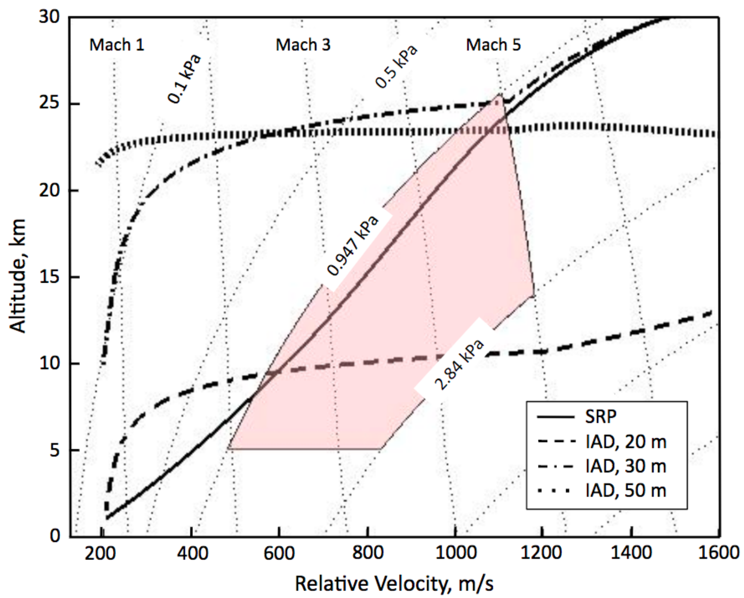
Supersonic Retro-Propulsion

'Forward-facing jets exhausting against the oncoming flow'

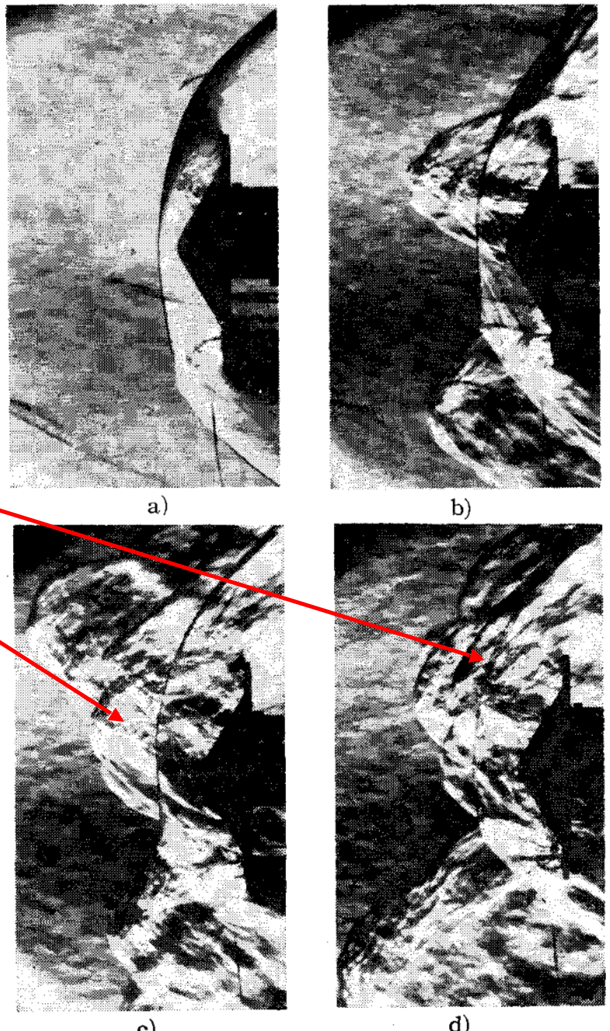
Primary Interests: Blunt body drag and Flow unsteadiness

- C_D calculations did not consider the thrust of the jets
- High degree of unsteadiness

POTENTIAL CANDIDATE FOR HIGH MASS PAYLOADS

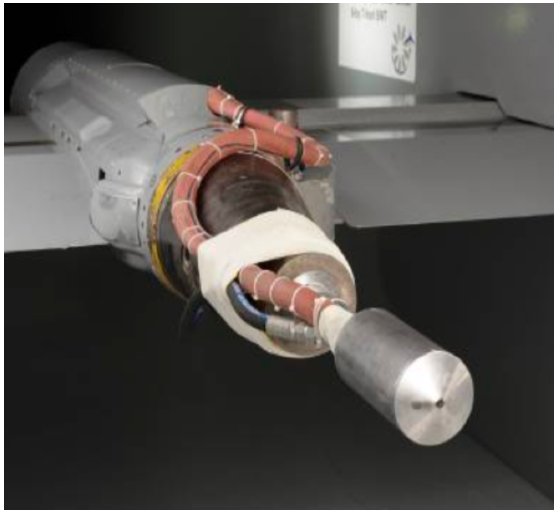


(Korzun and Braun, 2009)



Schlieren photographs (Keyes and Hefner, 1967)

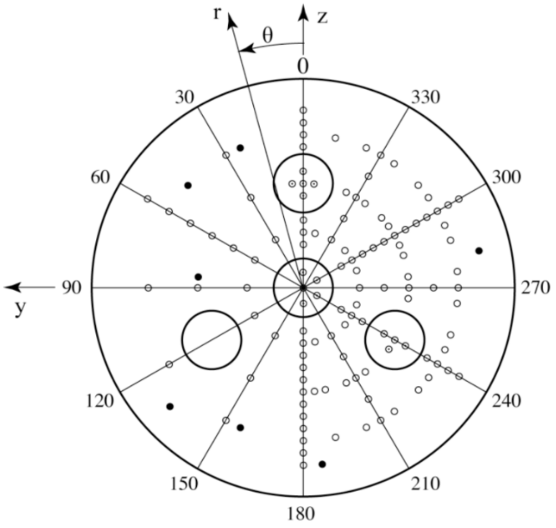
Unitary Plan Wind Tunnel Studies



NASA ARC 9' x 7' UPWT

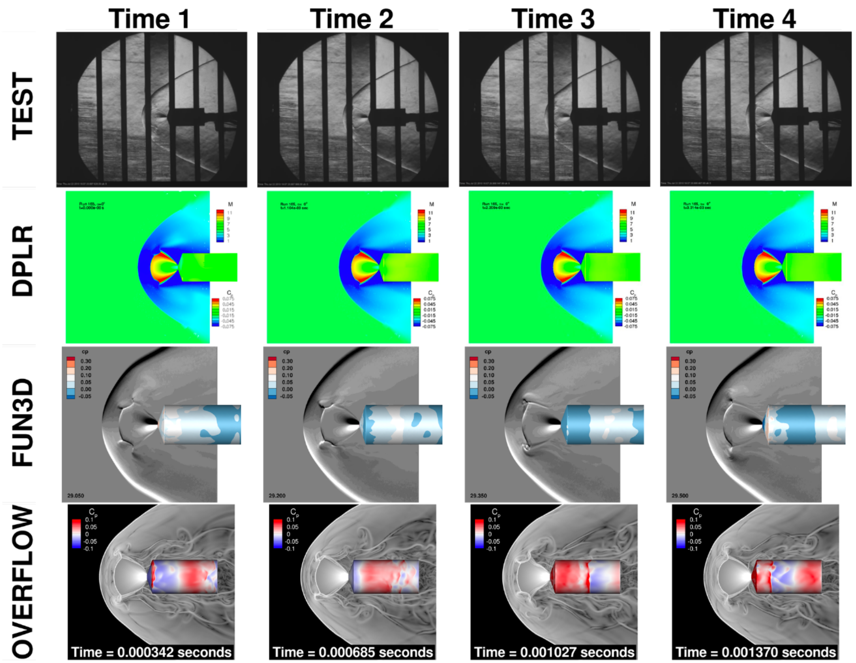
- Low p_j/p_∞ : Long-jet penetration mode; Jet exhaust unsteady
- Higher p_j/p_∞ : Short-penetration mode; Smaller shock stand-off distance
- At higher C_T (6): Steadier flow
- Tunnel interference limited C_T at LRC
- Liquefaction seen in plumes at ARC
- All UPWT tests were at small C_T and nozzle exhaust did not include hot combustion products

NASA LRC 4' x 4' UPWT



Pressure Taps on Forebody

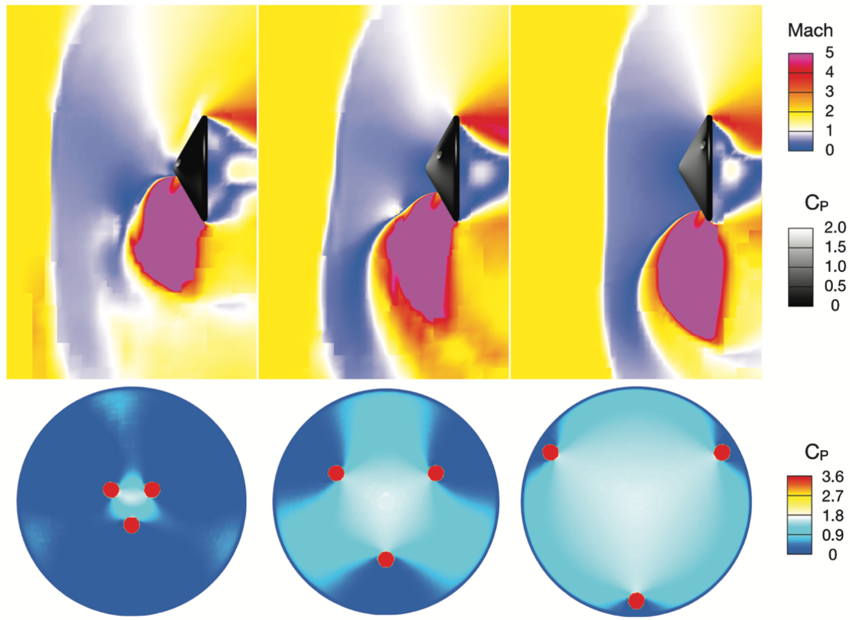
Numerical Studies



Periodic fluctuations at $\alpha = 0$ and $C_T = 2$

Perfect gas results
(Kleb et al.,2011)

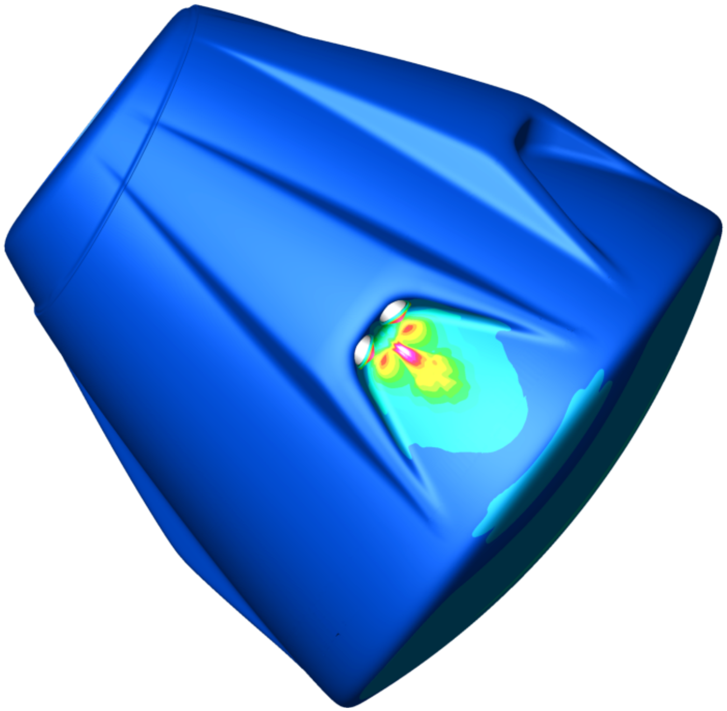
Aerothermal and aerodynamic characterization with finite rate chemistry effects not yet documented



Parametric studies
(Bakhtian and Aftosmis, 2010)

- Tri- and quad- nozzle capsule configurations studied using Cart3D
- Nozzle location, Orientation, Jet Strength: M, α

Objectives of Study



(Courtesy: Dr. Chun Tang)

- Codes such as Overflow do not compute chemically reacting flows
- Need to gain an understanding of the impact of missing databases on the results

I. EFFECTS OF CHEMISTRY ON THRUST OUTPUTS

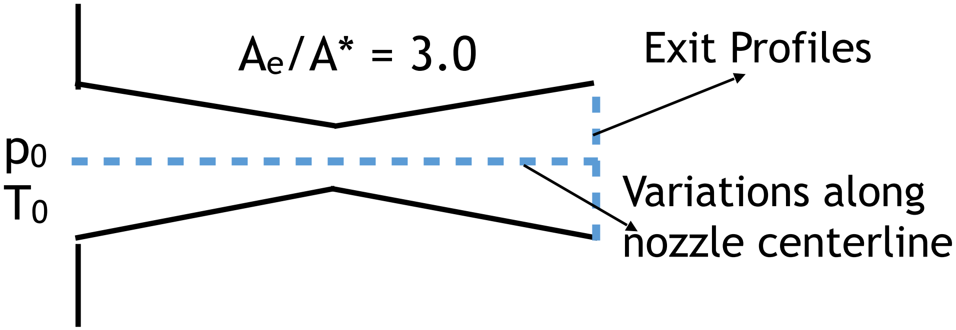
MULTIPLE ENGINE THROTTLE LEVELS

II. SENSITIVITY ANALYSIS TO QUANTIFY WALL HEATING DIFFERENCES DUE TO AN IMPINGING NOZZLE EXHAUST JET

CHEMISTRY MODELS

TURBULENCE EFFECTS

2-D Axisymmetric Nozzle Flow Simulations & Methodology



CEA

- Outputs used as Inputs to DPLR
- Used as comparisons to DPLR results

Grid generation

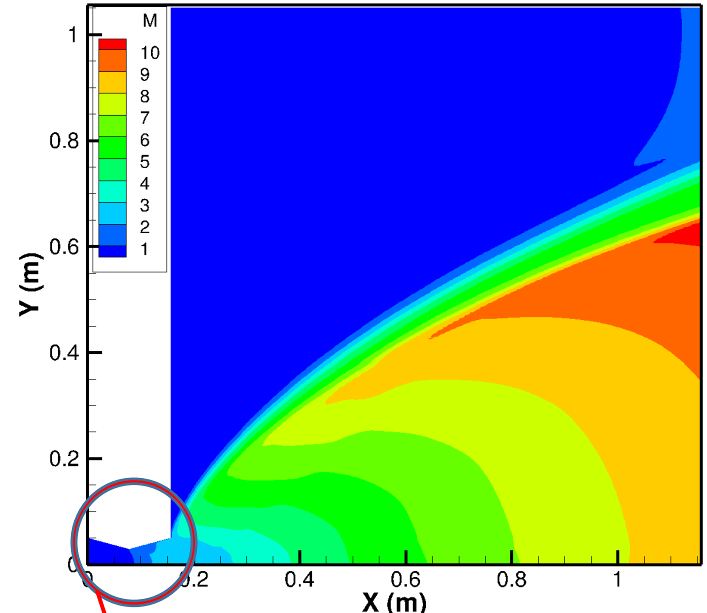
↓

Re-define domain depending upon plume behavior

↓

Solutions using DPLR & comparisons with CEA results

SENSITIVITY TO CHOICE OF CHEMISTRY MODELS

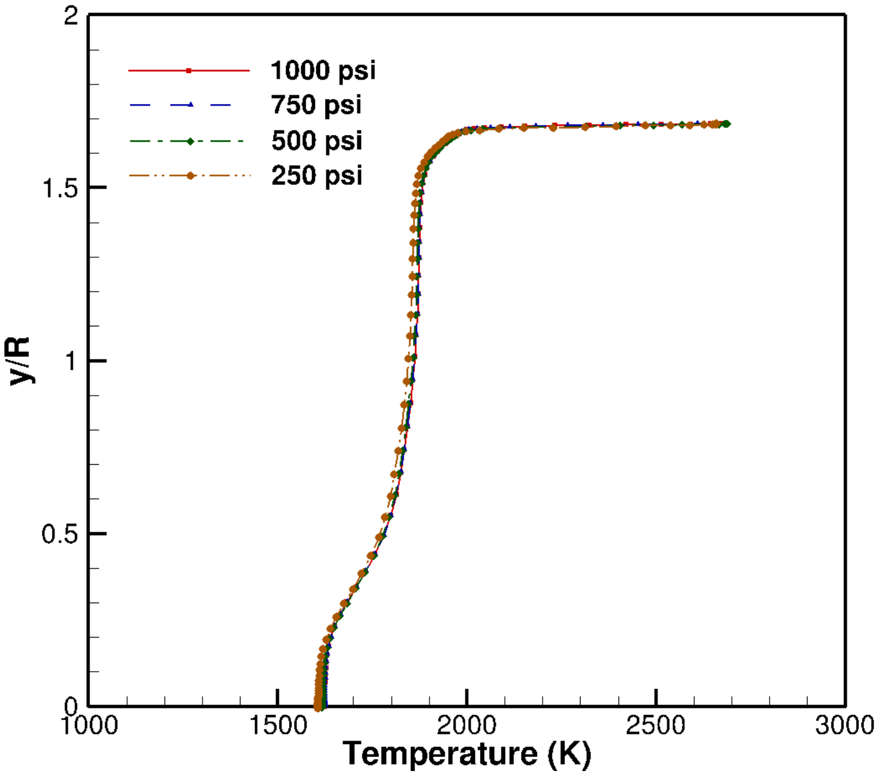


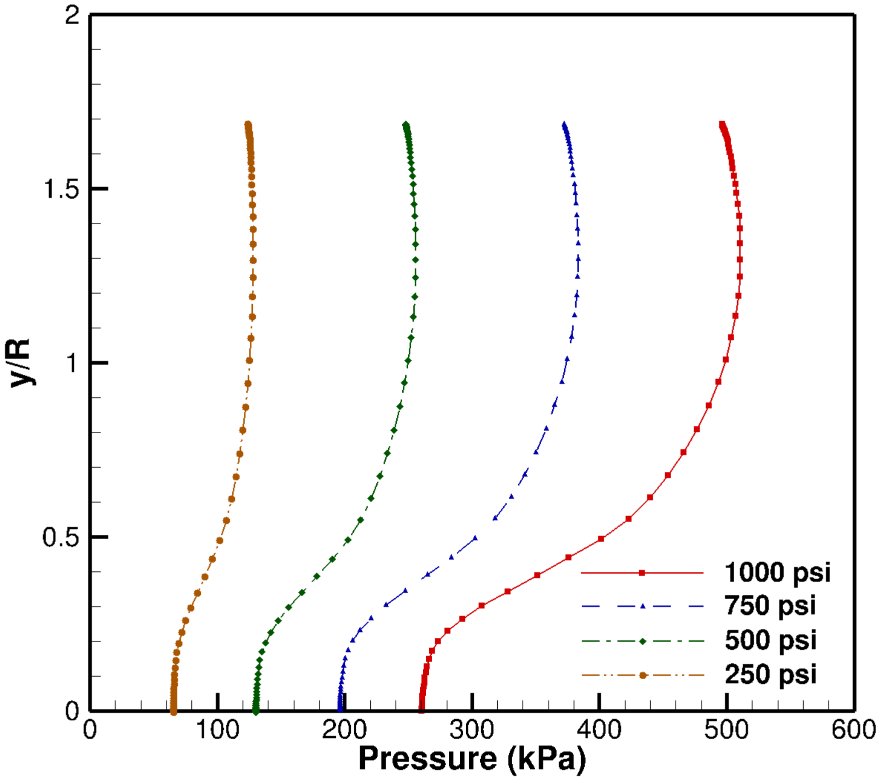
- Heat transfer to wall
- Spatial variation of flow variables and thermodynamic properties
- Numerically integrated thrust

Baseline Nozzle Case – Exit Plane Profiles (Adiabatic Wall)

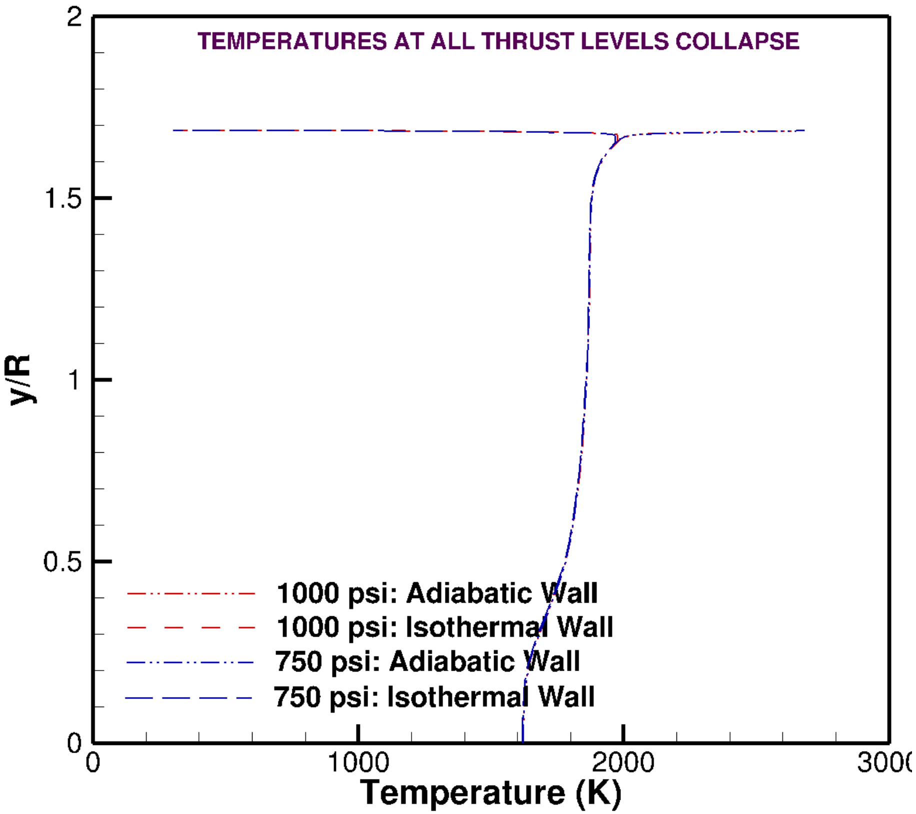
CEA inputs: O/F Ratio (1.5), Injector Pressure, Nozzle back pressure, Mixture composition
CEA outputs: First-order estimates of temperature, pressure & equilibrium composition at chamber exit, nozzle throat and exit.
DPLR inputs: CEA outputs at combustion chamber exit

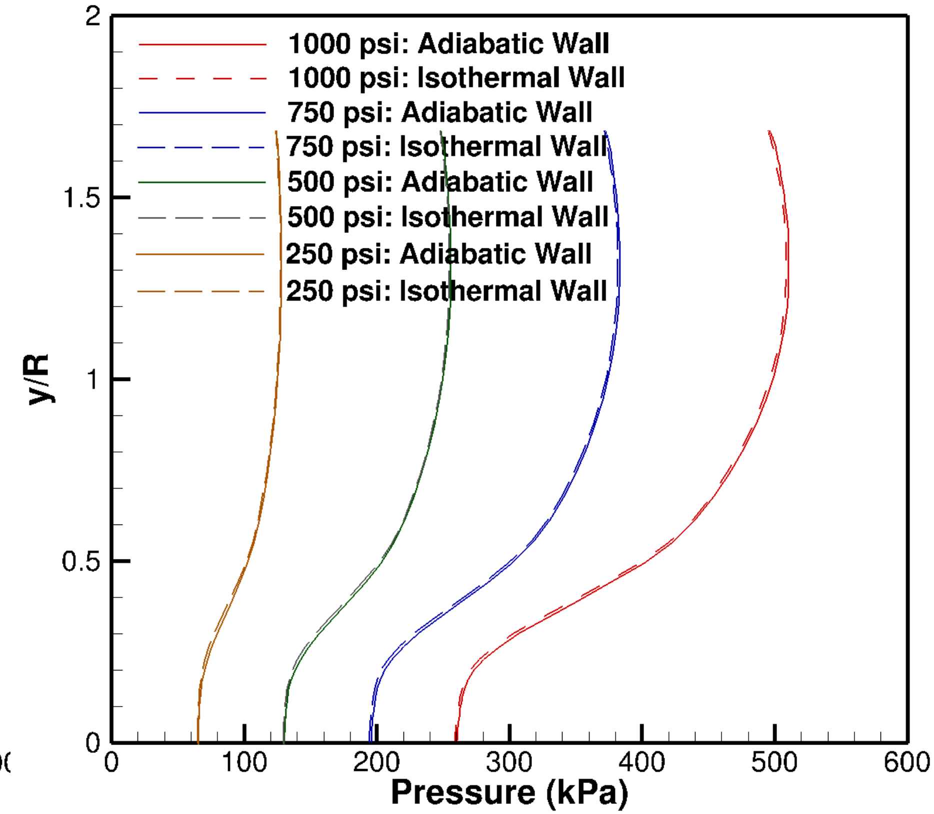
Chamber pressure varied to correspond to various engine throttle levels
Pressures chosen: 250 psi, 500 psi, 750 psi and 1000 psi





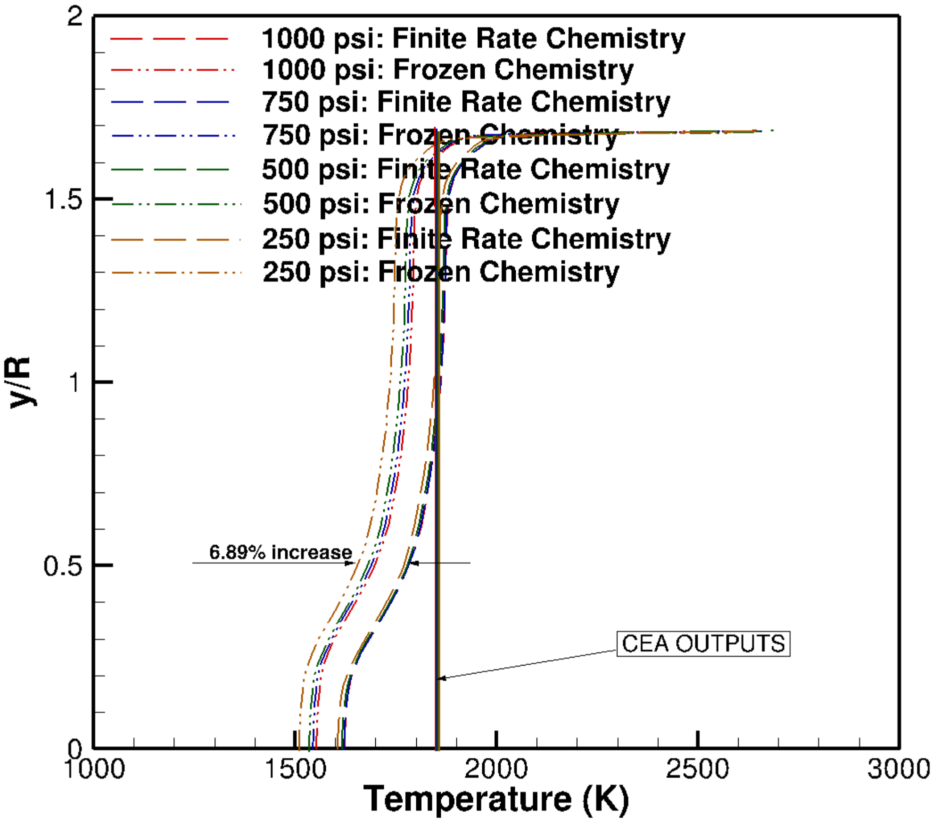
Baseline Nozzle Case - Wall BC Effects

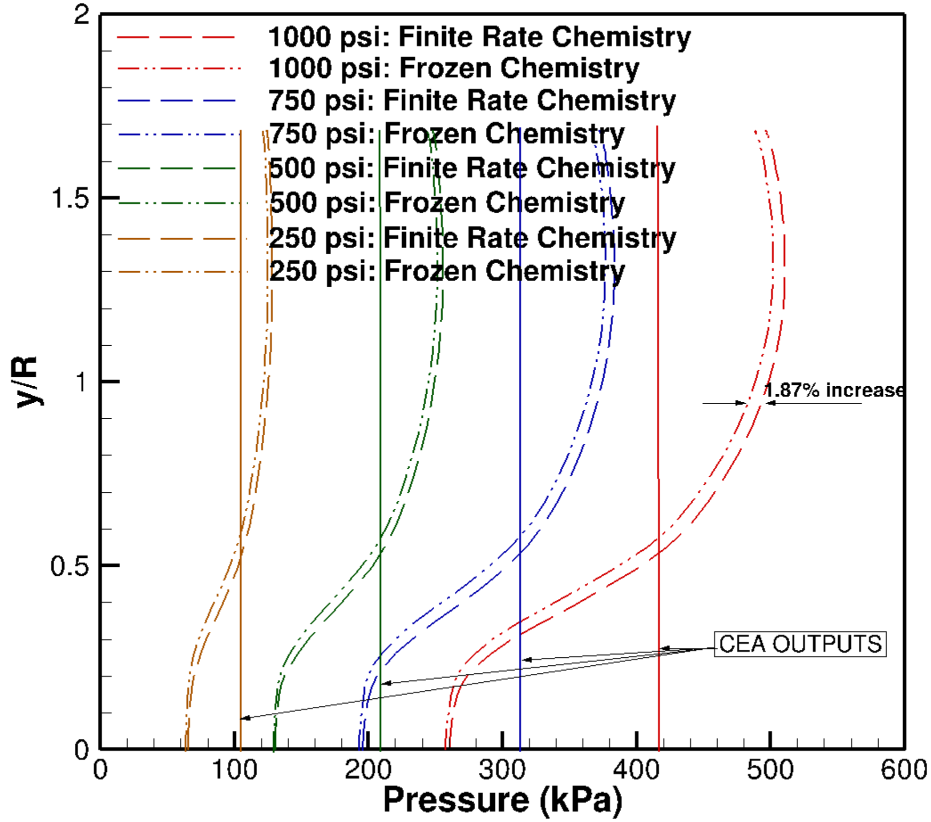




- Isothermal Wall BC: 300 K
- Any changes due to wall boundary condition are confined to the boundary layer
- *Thin boundary layers*

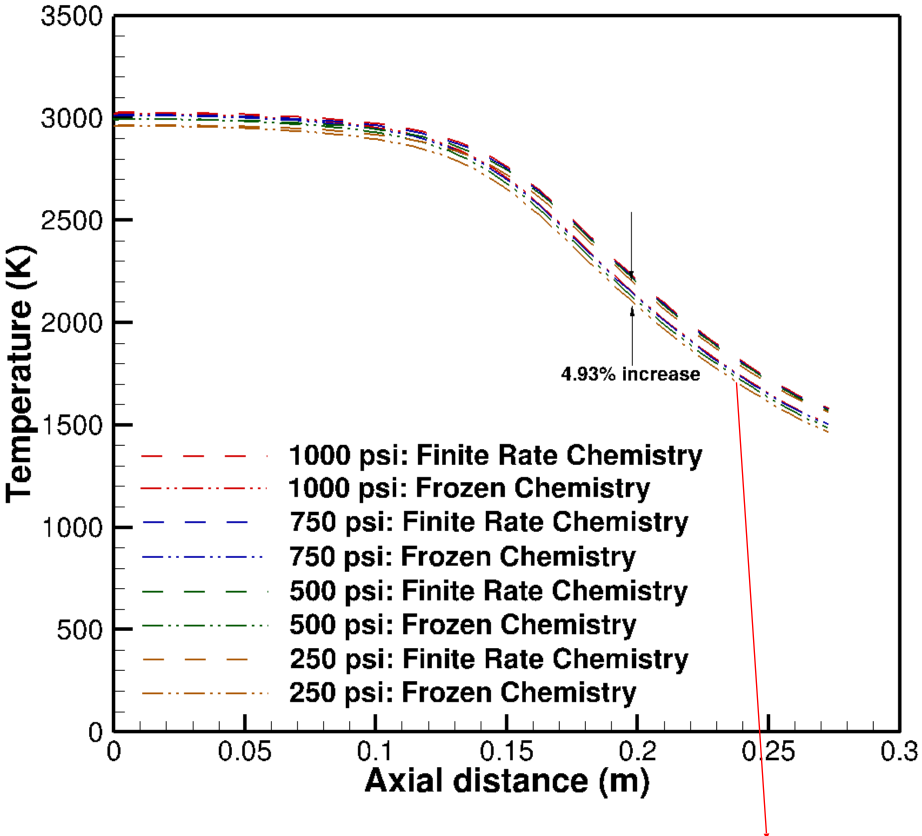
Chemistry Effects – Exit Plane Profiles

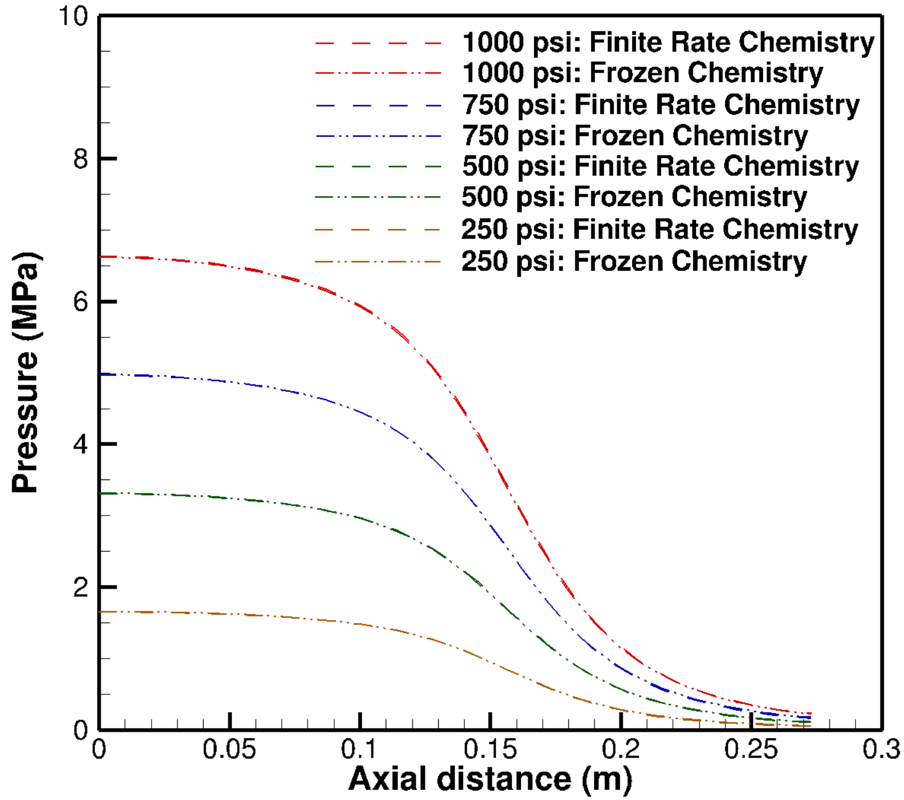




- Changed chemical fidelity; plenum conditions maintained
- Temperature predictions for finite rate chemistry using DPLR nearly similar for all thrust levels

Chemistry Effects – Centerline Profiles



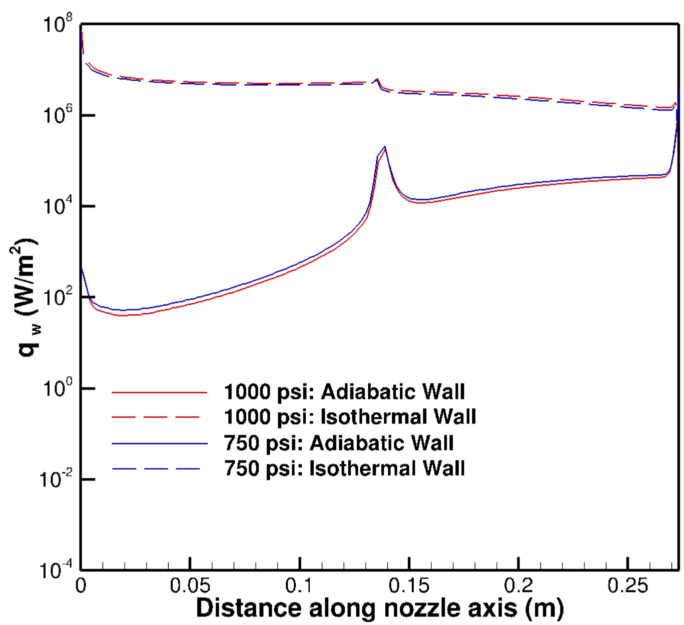


Frozen chemistry predicts lower temperatures than finite rate chemistry while marching along the axis

Axial pressure variations insensitive to choice of chemistry models

Heat Transfer to Nozzle Wall & Thrust Results

Chamber pressure (psi)	Thrust from CEA (kN)	FINITE RATE CHEMISTRY: ISOTHERMAL WALL		FINITE RATE CHEMISTRY: ADIABATIC WALL		FROZEN CHEMISTRY: ADIABATIC WALL	
		Thrust (kN)	% difference	Thrust (kN)	% difference	Thrust (kN)	% difference
1000	81.650	87.078	6.648	87.092	6.665	87.092	6.665
750	61.252	65.374	6.729	65.303	6.614	65.303	6.614
500	40.839	42.975	5.230	43.514	6.550	43.514	6.550
250	20.499	21.701	5.864	21.735	6.029	21.735	6.029

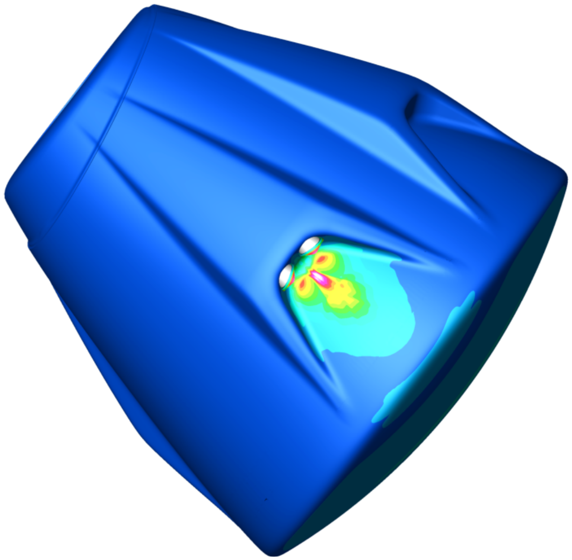


- CEA is a 1-D code
- For adiabatic wall BC: Finite rate chemistry and frozen chemistry yield similar thrust values
- No large scale effect seen: boundary layer effects

Jet Impingement Studies

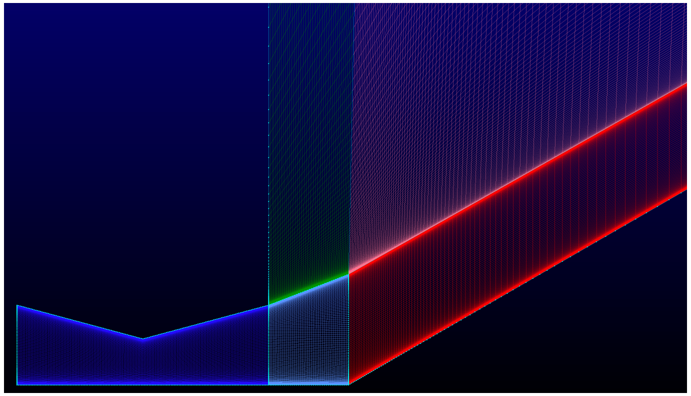
KEY PARAMETERS TYPICALLY VARIED:

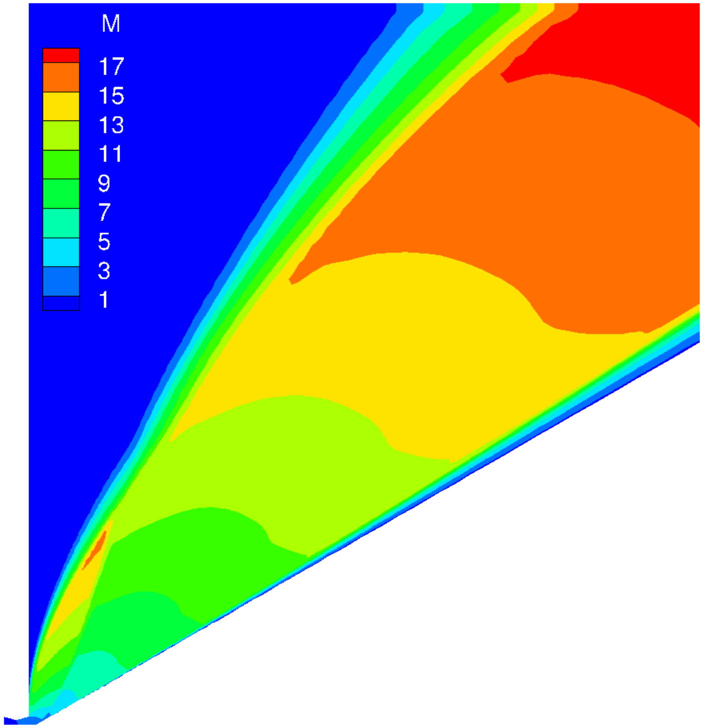
1. Nozzle to target spacing
2. Target material
3. Jet diameter
4. Jet inclination
5. Multiple target configurations: confined walls, rotating disks, etc …



(Courtesy: Dr. Tang)

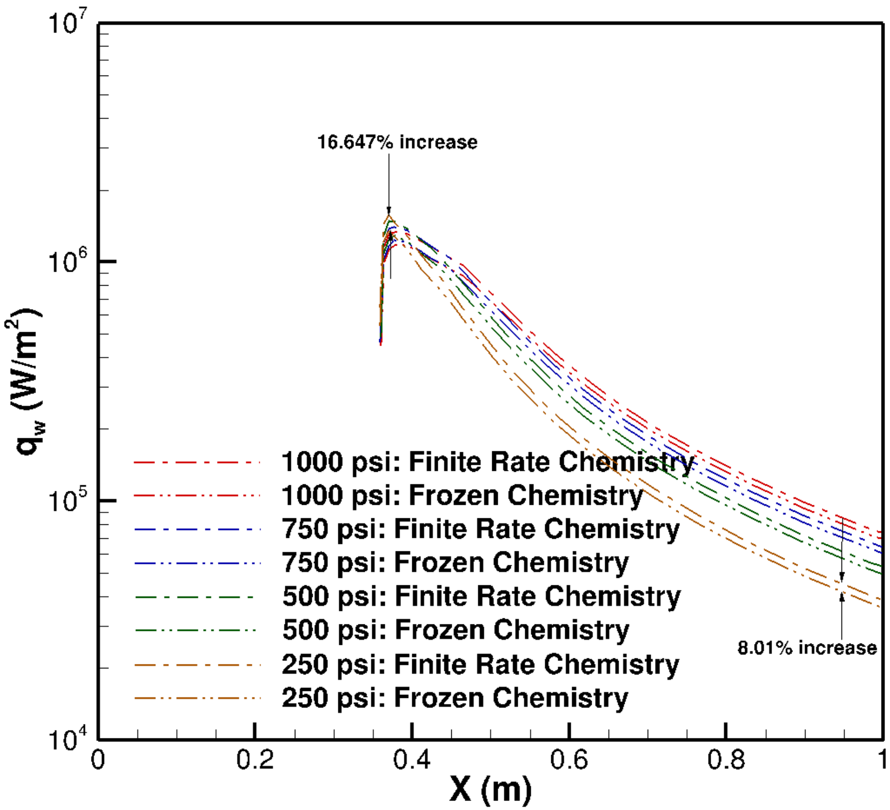
Effect of chemistry and turbulence on the wall heat transfer for the nozzle jets simulated in this study



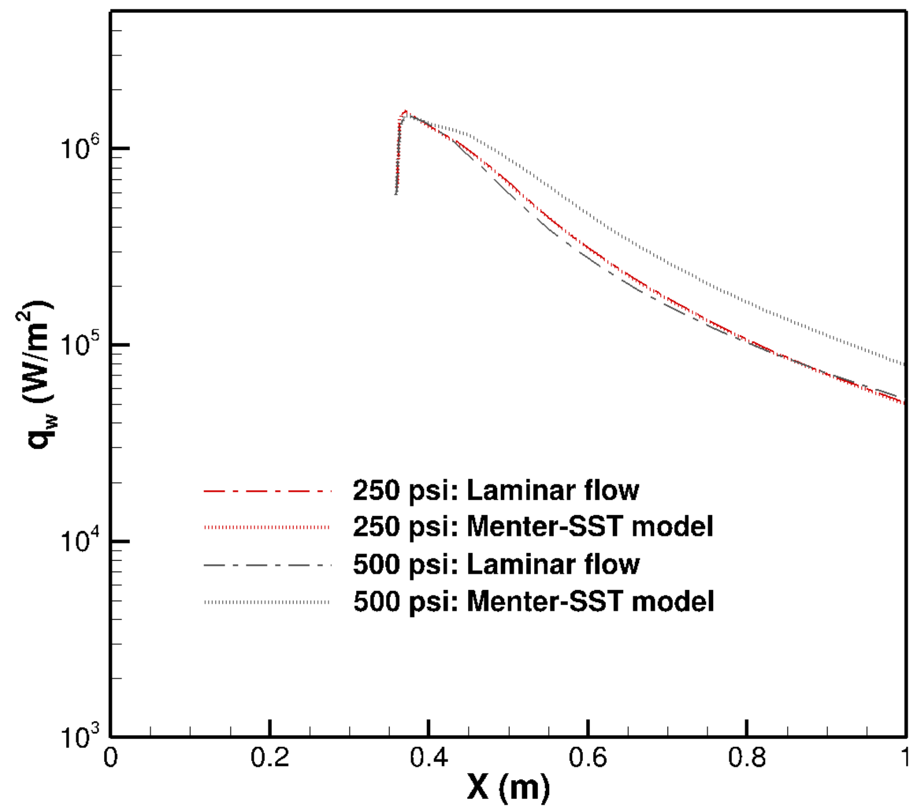


Jet Impingement Results – Heat Transfer

EFFECTS OF FULL AND FROZEN CHEMISTRY

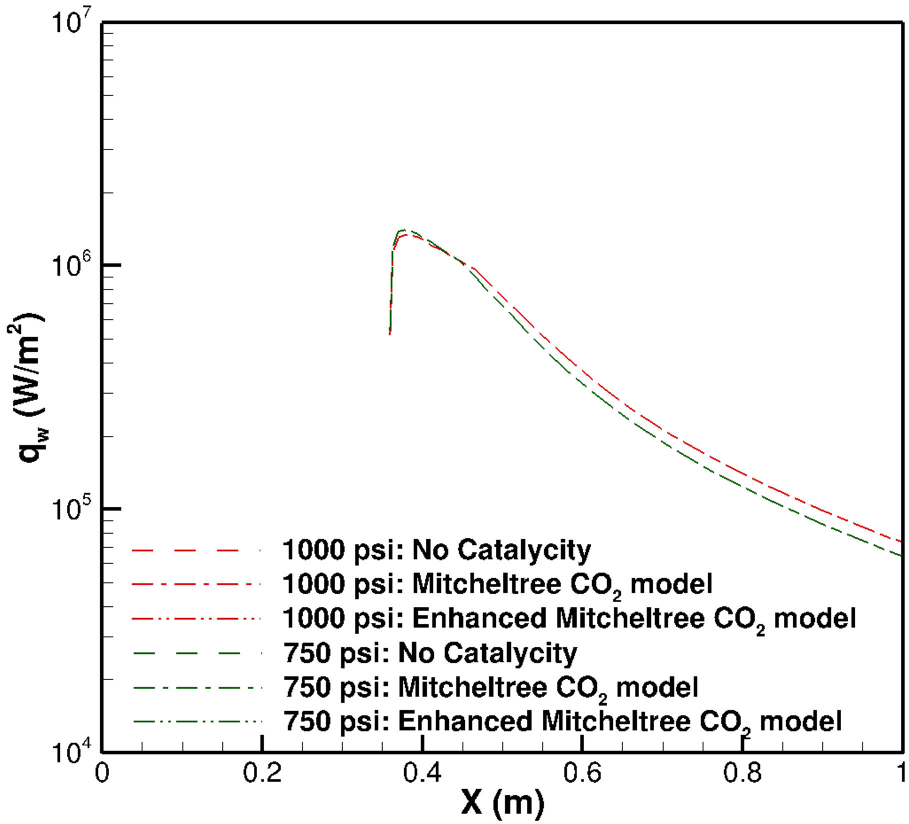


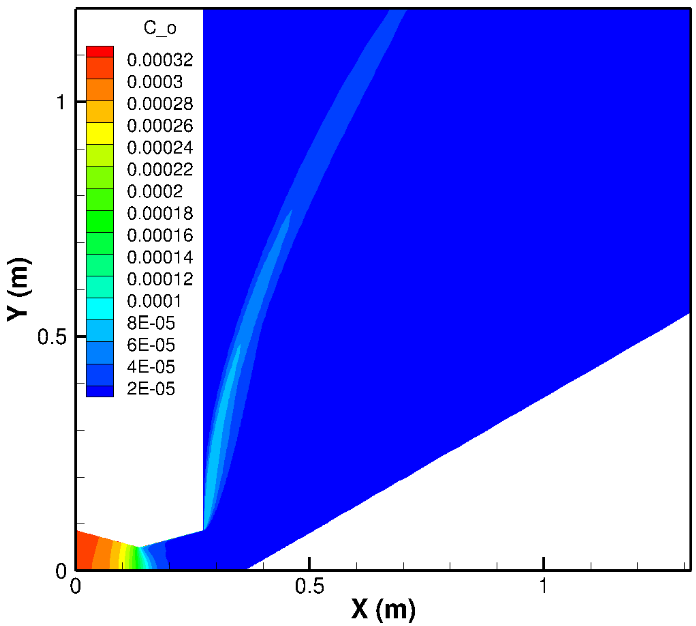
VARIATION WITH THUST LEVELS AND COMPARISONS TO LAMINAR RESULTS

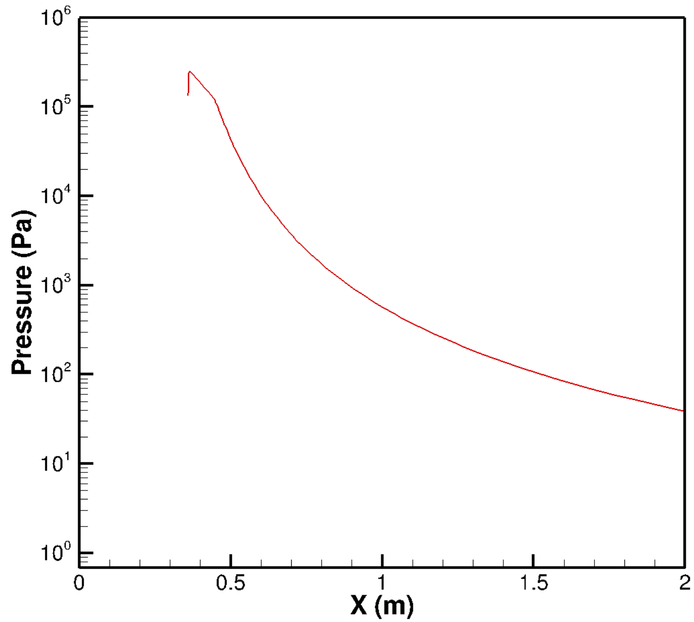


- Peak heating increases by ~17% by considering non-equilibrium effects
- Turbulence effects seen at pressures higher than 250 psi

Catalytic Wall Boundary Conditions







- High pressures encountered on the cone surface
- Near-equilibrium composition obtained upon plume expansion

Conclusions

- Aerothermal and aerodynamic characterization of 2-D axisymmetric nozzle flows completed
- Run matrix involved 4 throttle levels (100%, 75%, 50% and 25%) for every effect considered
- Wall BC effects for nozzle and variations in chemistry fidelity considered
- *Thin boundary layers lead to small variations in integrated thrust*

JET IMPINGEMENT STUDIES

- Heat transfer effects studied for varying levels of wall catalycity.
- Low levels of atomic oxygen and low adsorption rates result in no catalysis at the wall
- Peak heat flux does not change with turbulence modeling
- *Plume flows for flow conditions considered are at near-equilibrium conditions upon impingement*

Wall heating due to nozzle jet impingement is mainly due to convective heating and finite rate chemistry effects result in a 16%-17% increase in peak heat flux.

Questions?

National Aeronautics and
Space Administration

Ames Research Center
Entry Systems and Technology Division