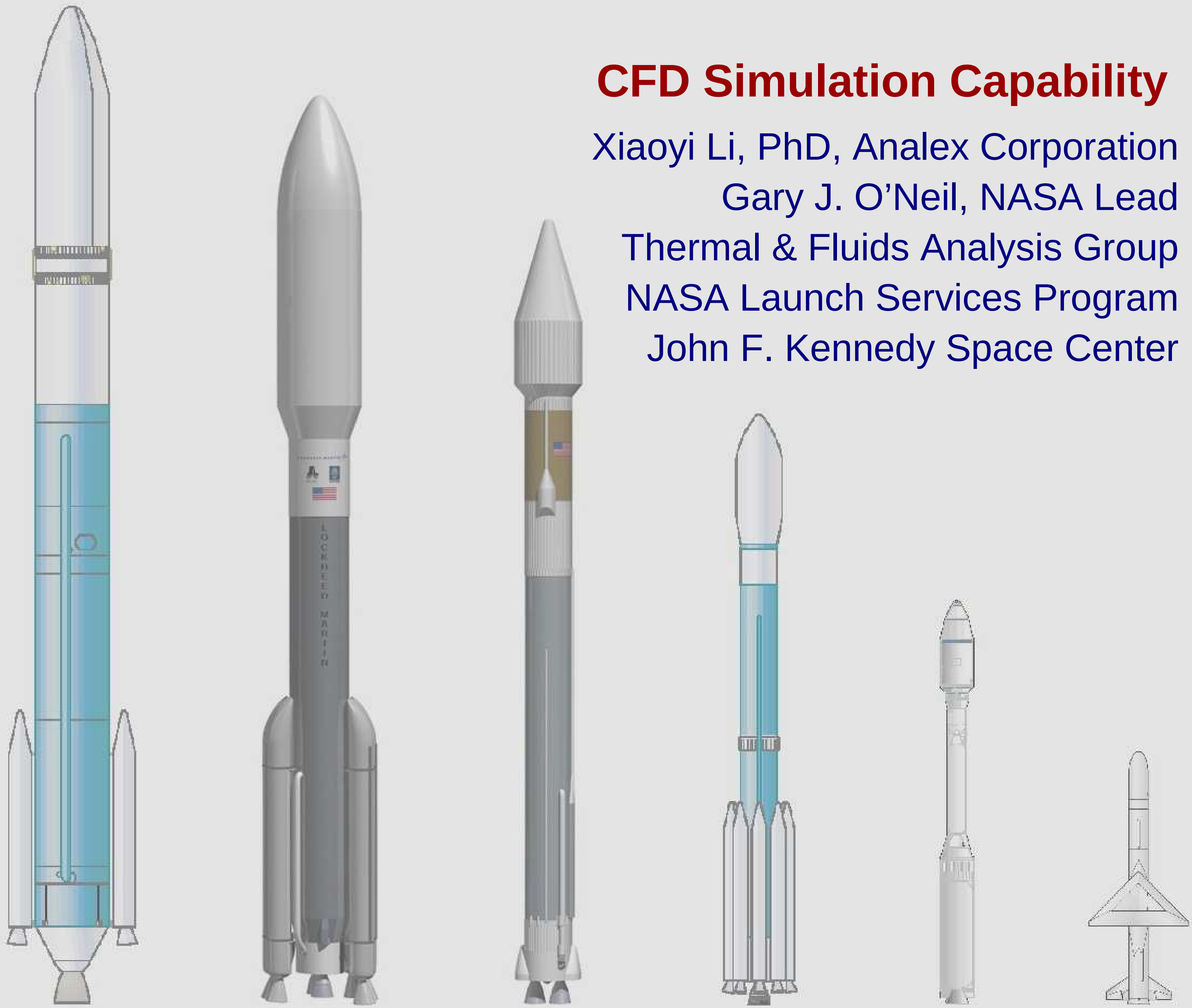
Launch Services Program

Thermal & Fluids Analysis Group



CFD Simulation Capability

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Content

- LSP Introduction
- Computational fluid dynamics capabilities overview
- Sample cases
  - Liquid fuel slosh
  - Lunar Lander plume study

Launch Services Program Introduction

Fleet Insight
-Vehicle Enhancements
-Anomaly Resolution
-Post Flight Data Review

Baseline Work

Mission Integration
-ICD Formulation & Verification
-Mission Unique Modifications
-Aeroheating Analysis
-Venting Analysis
-Integrated Thermal Analysis
-Launch Ops Support

Vehicle Certification
-Qualification review
-Independent Verification and Validation (IV&V) analyses

Studies
-as funding becomes available
- collaboration with other Centers, industry, academia

Computational Fluid Dynamics Capability at LSP

- Computational fluid dynamics (CFD) is commonly used to study thermal fluid problem. The CFD code solves continuity, momentum, energy equations using numerical methods.
- Problems solved using CFD at LSP
    - Liquid fuel slosh
    - Internal conjugate heat transfer
    - Exhaust plume impingement
    - External aerodynamics
- CFD code
    - Flow3D
    - Fluent
    - Overflow
    - USM3D

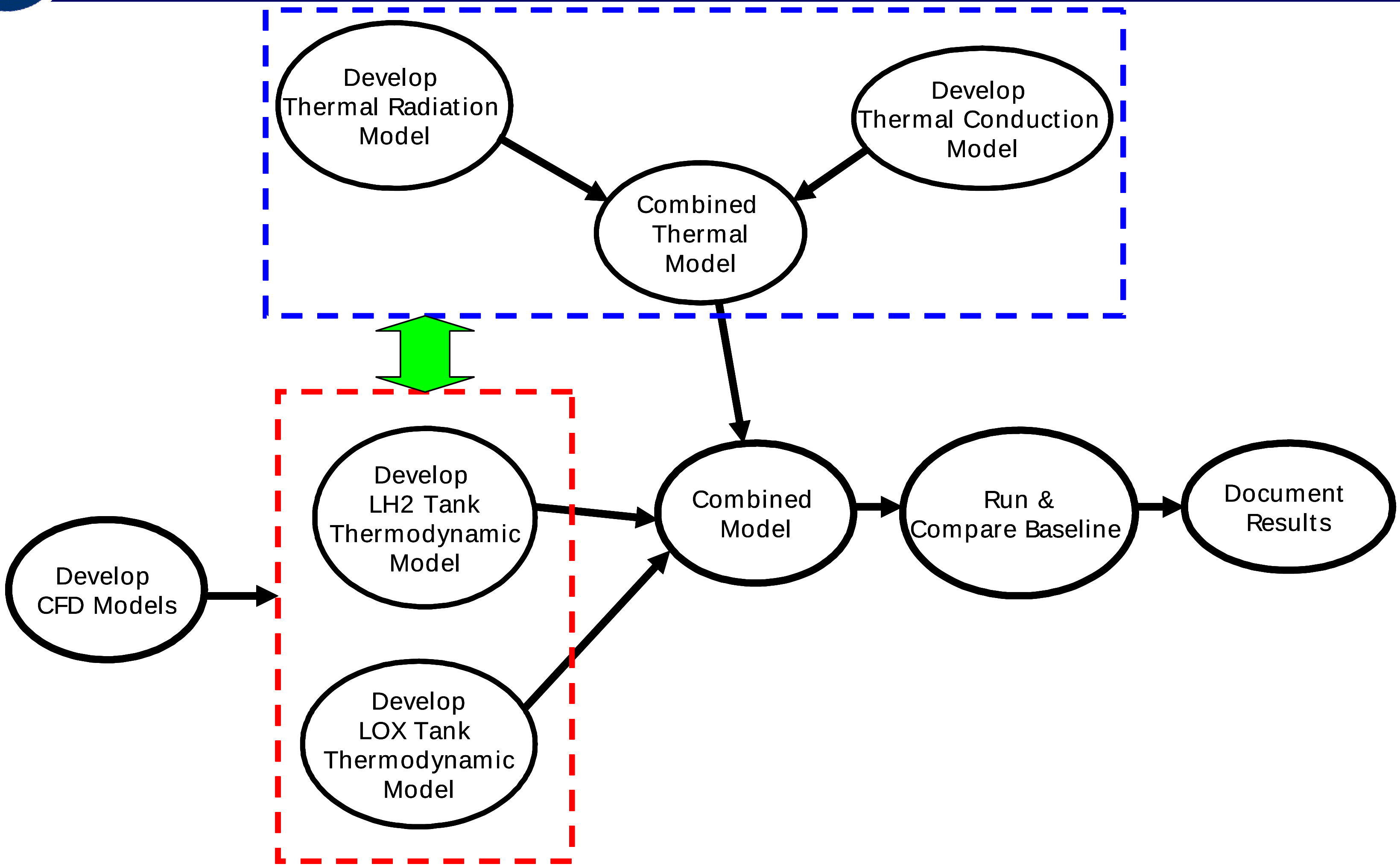
Example 1 – Liquid Fuel Slosh

- When the liquid fuel tank holds less fuel than full, the slosh dynamics plays an important role. This is critical especially when the gravity is small. Lack of body force, the fuel can be anywhere inside of the tank, and creates stability problem of the vehicle.

- In some mission, long coast with small amount of fuel in tank, the PTC roll can increase the contact surface area between wall and liquid fuel, as well as the interface between the ullage and liquid. Both can significantly increase heat tranfer and fuel evaporation. Not mention, that slosh during the maneuver, liquid fuel quenches on the warmer wall, and evaporates instantaneously. Knowing how much fuel is evaporated is important to know the tank pressure and predict how much fuel left in the tank for the next start of engine.

- Fuel tank slosh was studied using commercial CFD code - FLOW3D.

Example 1 – Liquid Fuel Slosh (cont'd)



Example 1 – Liquid Fuel Slosh (cont'd)

- Parametric study with different acceleration rates ,fill levels and rotating speeds.
- Turbulent model: k-ε model
- 4-DOF acceleration rates
- Predicted wetted wall area, and interface area between ullage and liquid fuel

Example 1 – Liquid Fuel Slosh (cont'd)

- Bond number: Ratio of the values of the surface forces to body forces. At higher altitudes it is thus possible to expect the surface tension force to become dominant.

$$B_O = \frac{F_g}{F_\sigma} = \frac{\rho g L^2}{\sigma}$$

If Bo ≈1, the surface tension force is included in the model

.

Example 1 – Liquid Fuel Slosh (cont'd)

Analytical solution of the liquid interface: $$h = \frac{\omega^2 r^2}{2g}$$

Interface area: $$A_{\text{interface}} = \int_0^r 2\pi r \,\mathrm{d}s$$

where $$\mathrm{d}s = \sqrt{1 + \left(\frac{\mathrm{d}h}{\mathrm{d}r}\right)^2}\,\mathrm{d}r$$

Therefore,

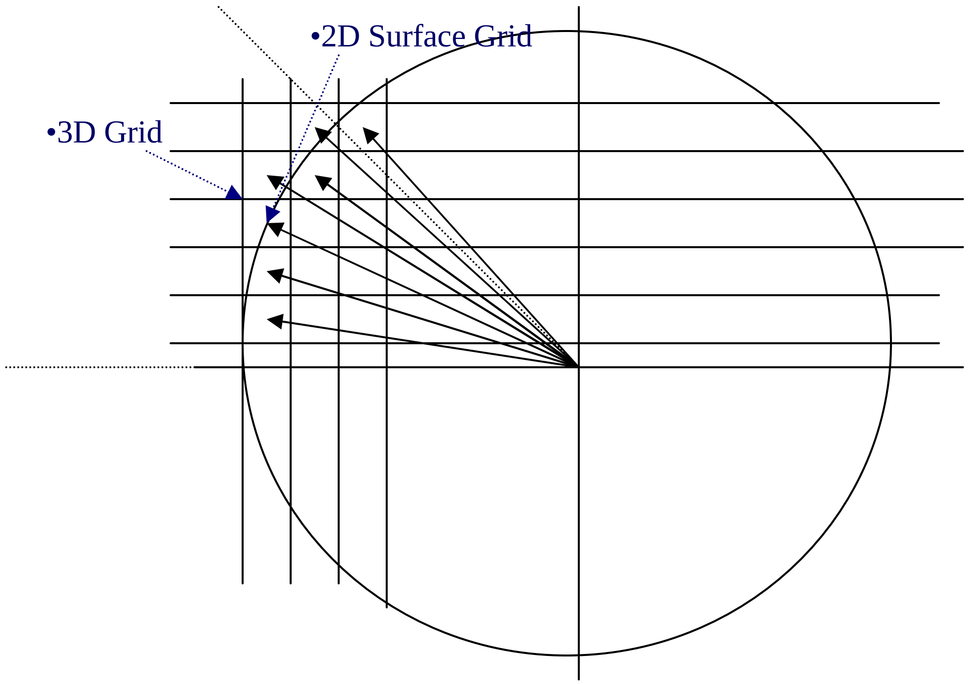
$$\frac{\mathrm{d}h}{\mathrm{d}r} = \frac{\omega^2 r}{g}$$

$$A_{\text{interface}} = \int_0^r 2\pi r \sqrt{1 + \left(\frac{\omega^2 r}{g}\right)^2}\,\mathrm{d}r$$

Analytical solution is used to compute interface at higher bonds number, and to validate the CFD

Example 1 – Liquid Fuel Slosh (cont'd)

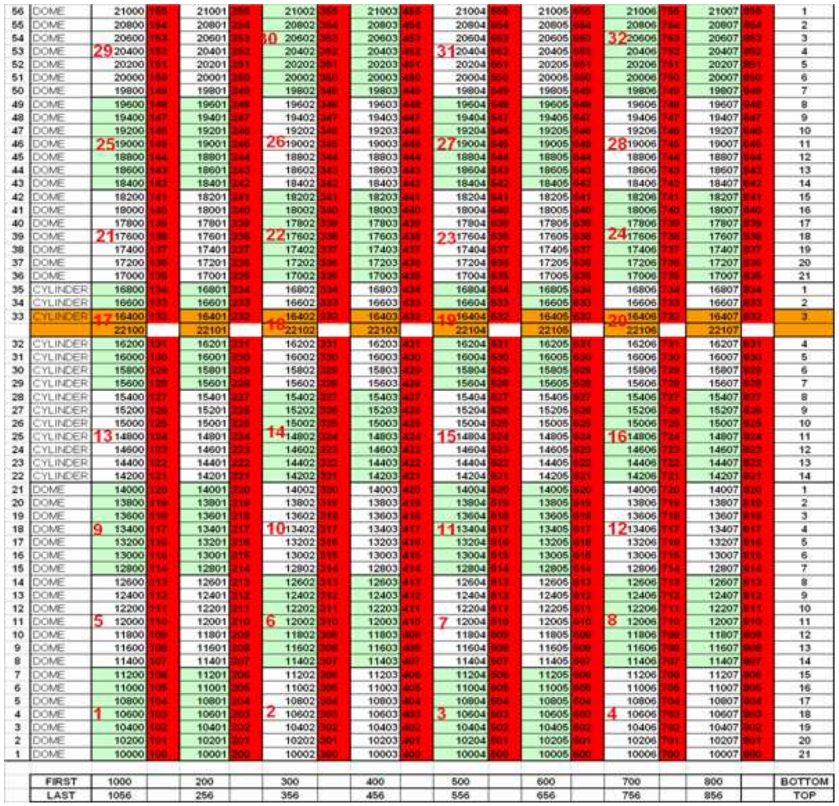
Mapping Scheme

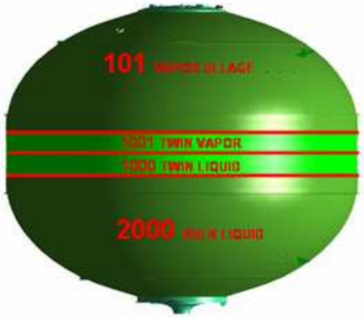


Mapping uses sweeping method.

For each layer of the CFD grids, sweeps a bar from negative x-axis clock

Example 1 – Liquid Fuel Slosh (cont'd)



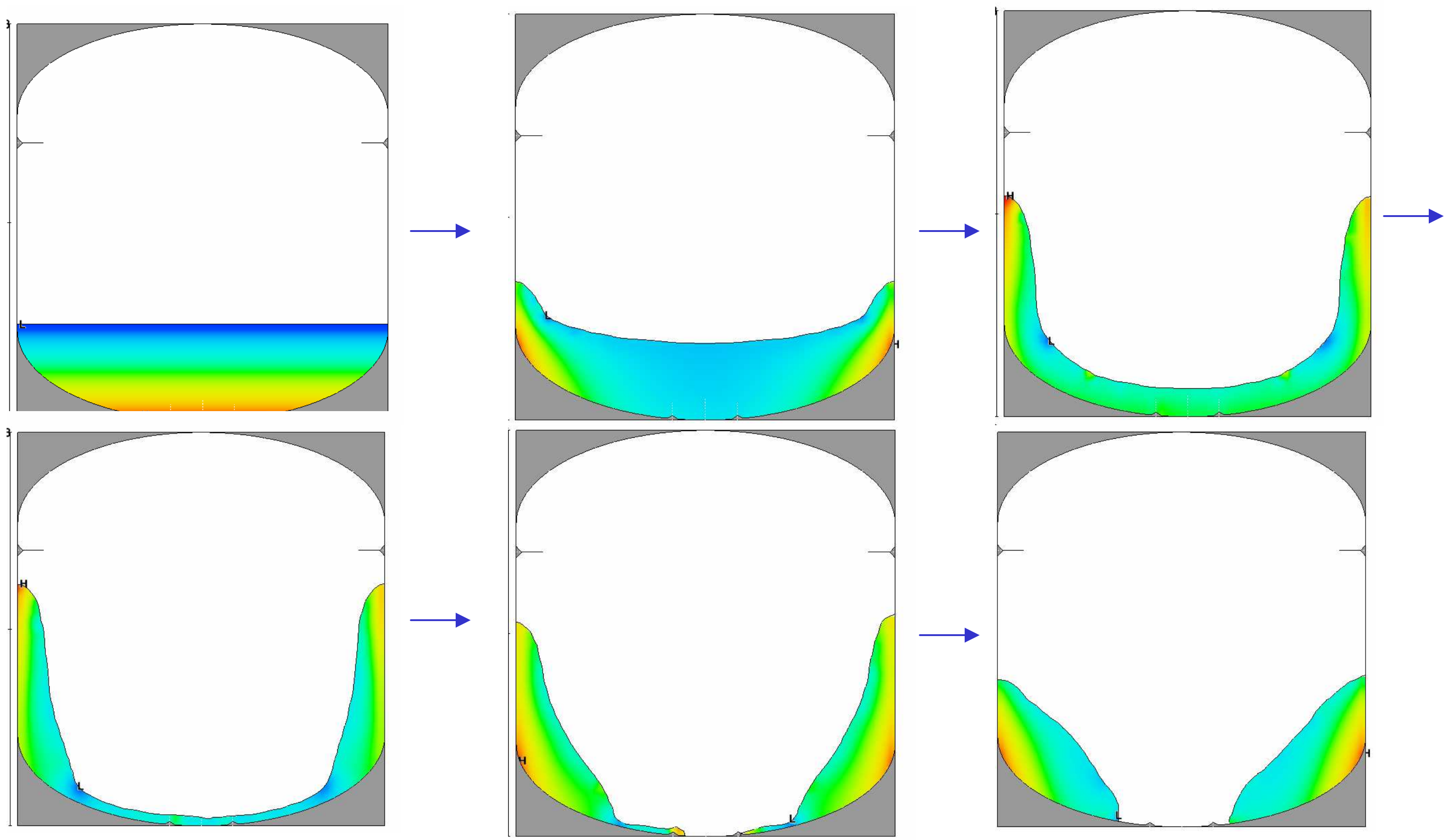


Mapping 3D CFD solution to 2D thermal nodes.

CFD grids are 3-dimensional, but thermal nodes are 2-dimensional.

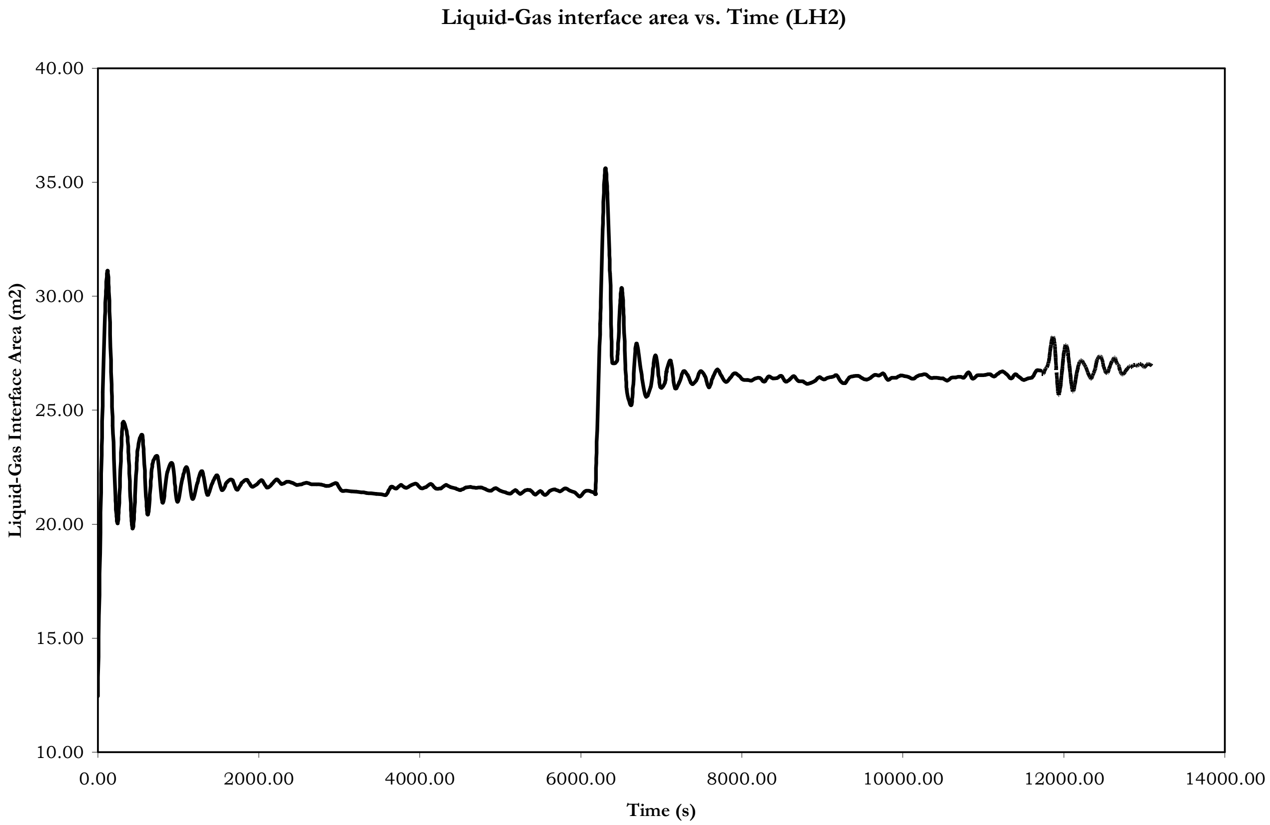
Example 1 – Liquid Fuel Slosh (cont'd)

Plot of Pressure



Change of interface shape during spin-up.

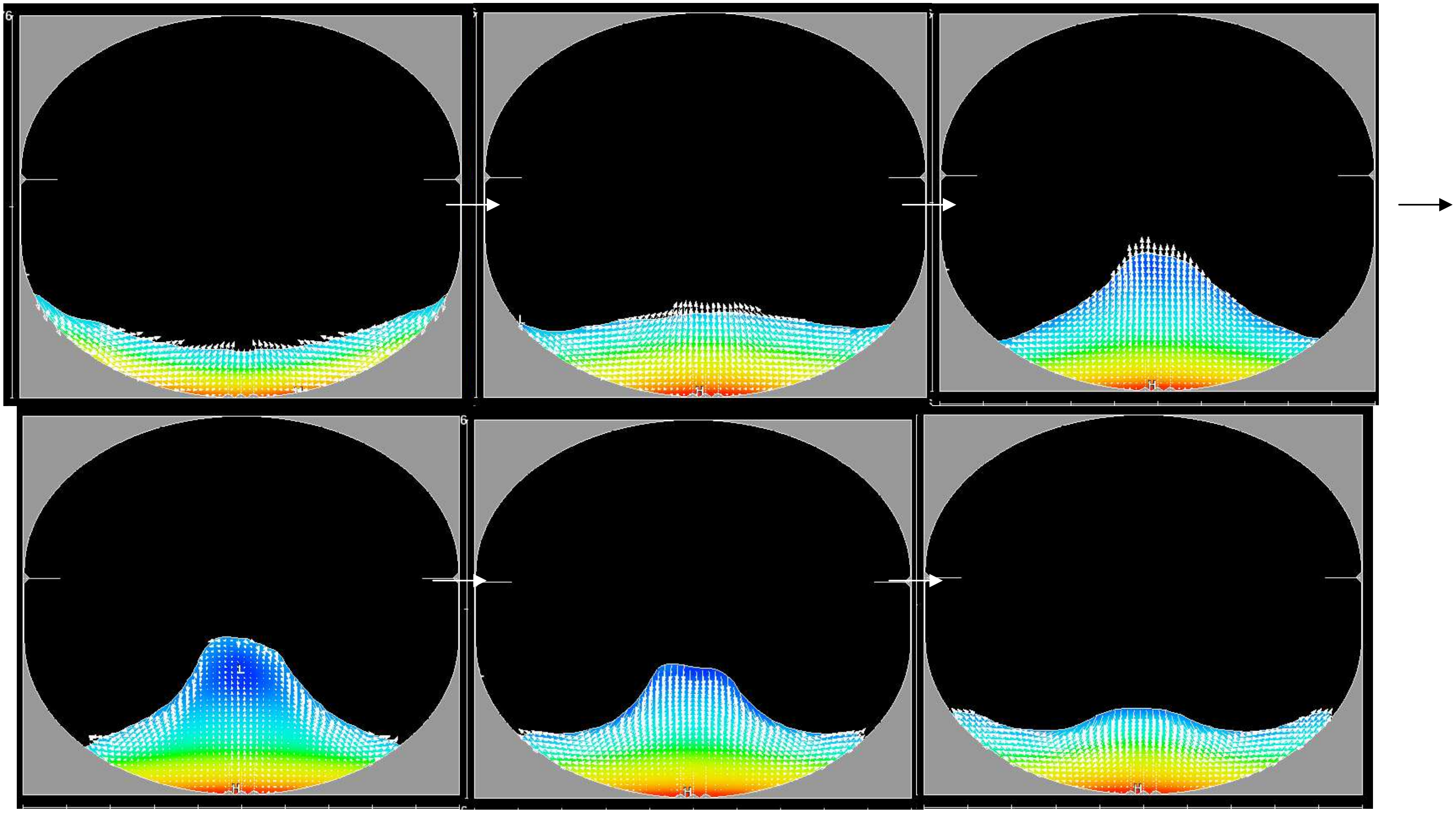
Example 1 – Liquid Fuel Slosh (cont'd)



The interface area oscillates while changing the direction of rotation.

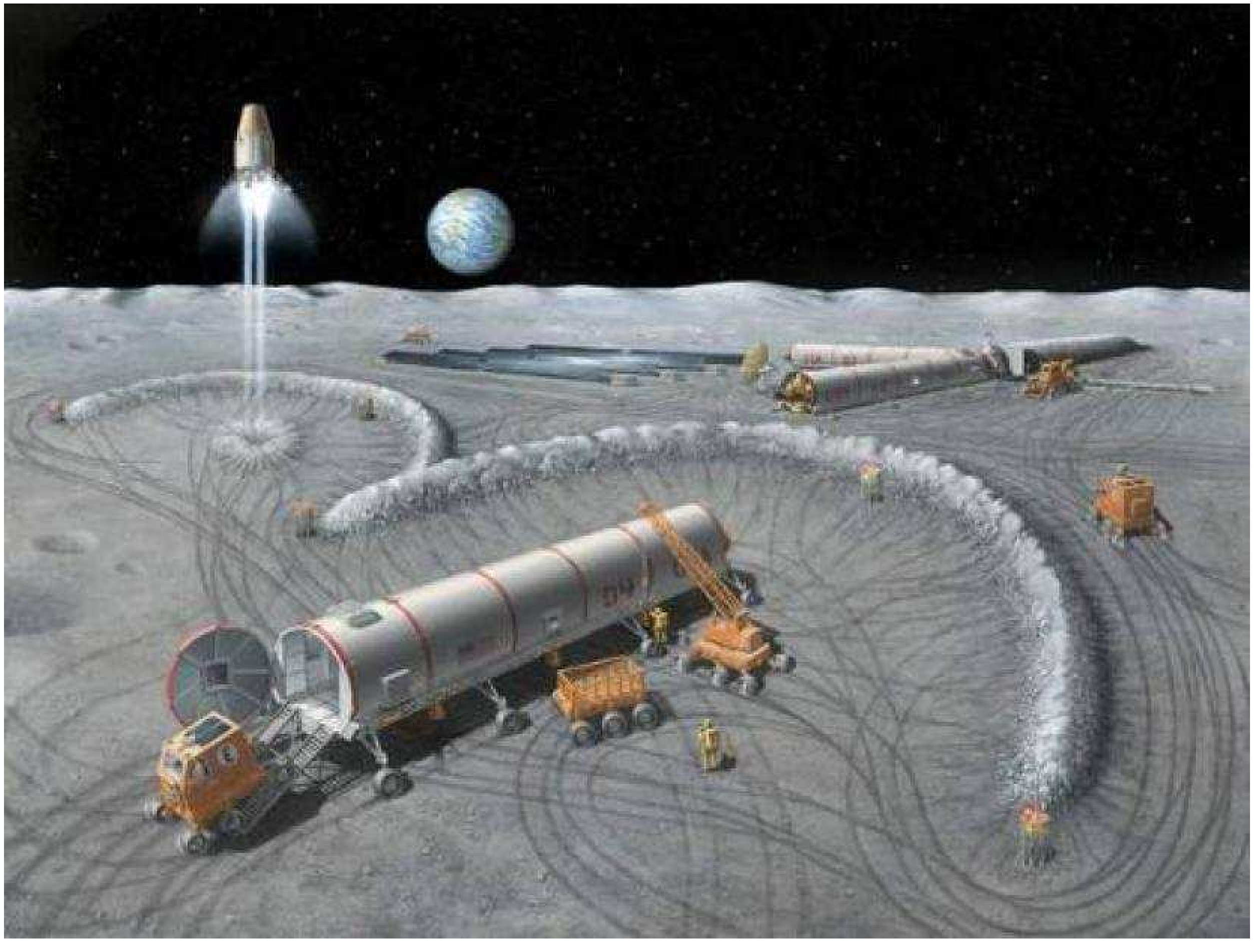
The first change of rotation used re-start, but the second one ran continuo

Example 1 – Liquid Fuel Slosh (cont'd)



Fuel slosh due to change of the linear acceleration. (accelera

Example 2 – Lunar Surface Plume Impingement



Example 2 – Lunar Surface Plume Impingement (cont'd)

- Particle Ballistic Study of Lunar Dust Particles
  - Purpose of the study
    - Supersonic jet of exhaust plume accelerates dust, soil, gravel, and small rocks on lunar surface to high velocities.
    - Low gravity and close to vacuum environment on lunar surface allows the particles to travel at the great distance unimpeded.
    - The sizes and kinetic energies of the particles can cause damage to the spacecraft and surrounding facilities.

Example 2 – Lunar Surface Plume Impingement (cont'd)

CFD (Computation Fluid Dynamics)

Gas:

- *Density*
- *Velocity*
- *Temperature*

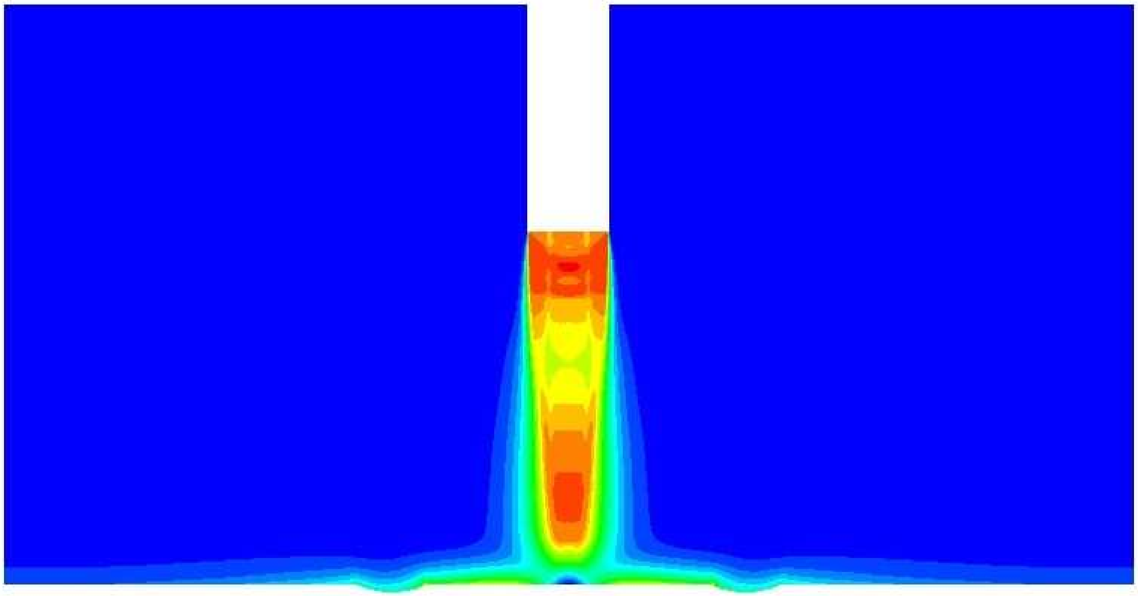
Particle Ballistics Simulation

Particle:

- *Forces*
- *Acceleration*
- *Velocity*
- *Position*

CFD simulation predicts pressure, temperature and gas velocity on the surface directly under the nozzle and immediate surroundings.

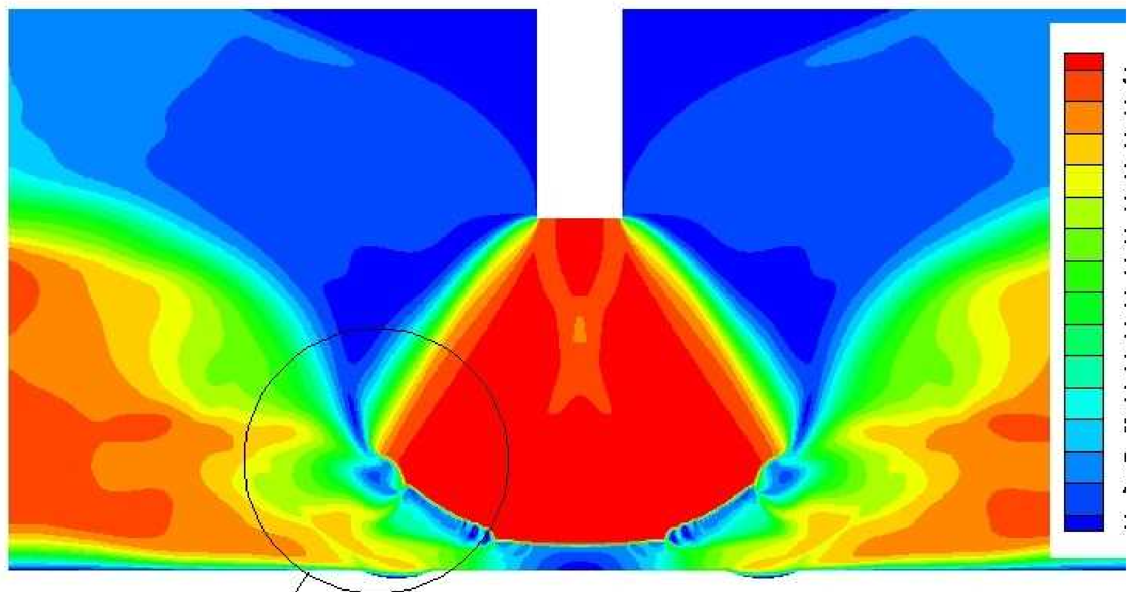
Example 2 – Lunar Surface Plume Impingement (cont'd)



Velocity Magnitude
Operating Pressure: 1 atm
Initial Pressure: 0 atm
Exit Pressure: 0 atm

Plume impingement in 1 atm environment.

Example 2 – Lunar Surface Plume Impingement (cont'd)

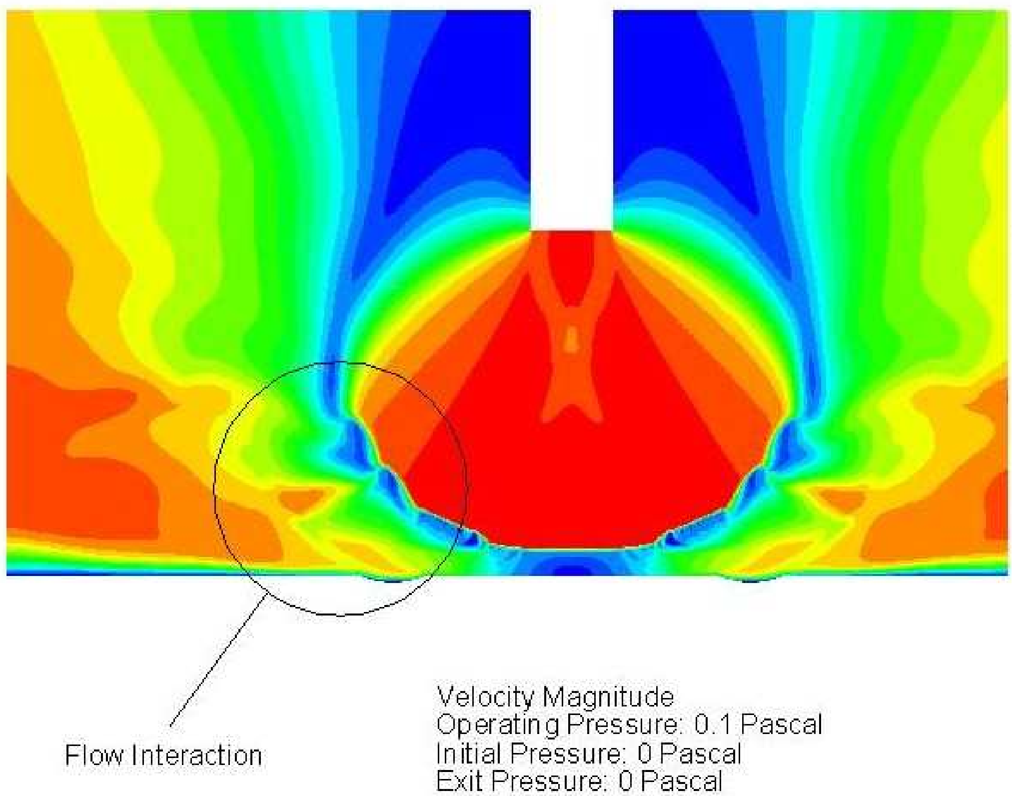


Velocity Magnitude
Operating Pressure: 1 Pascal
Initial Pressure: 0 Pascal
Boundary Condition at Exit: 0 Pascal

Flow interaction

Plume impingement in 1 Pascal environment.

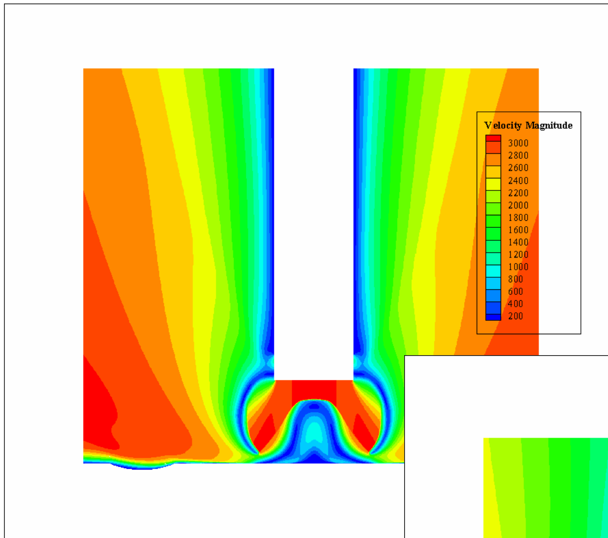
Example 2 – Lunar Surface Plume Impingement (cont'd)

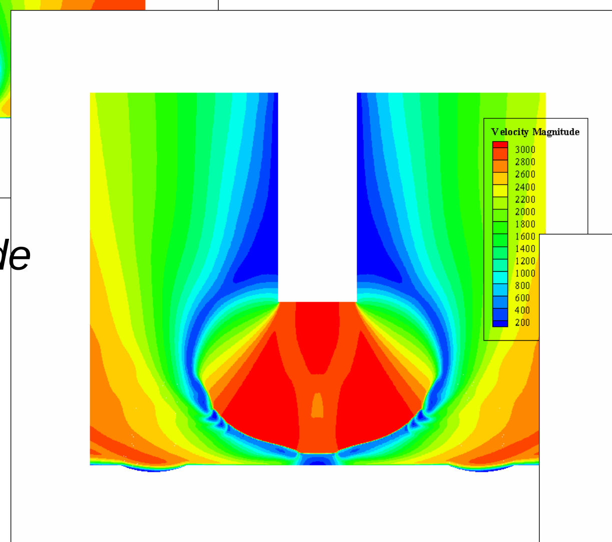


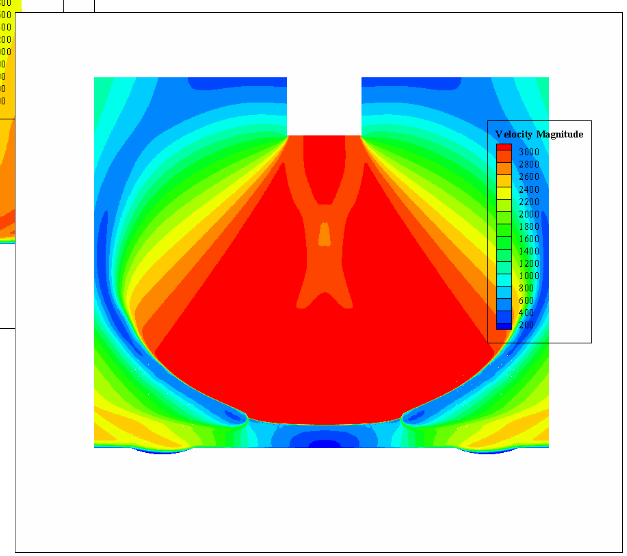
Plume impingement in 0.1 Pascal environment.

Example 2 – Lunar Surface Plume Impingement (cont'd)

Recirculation zone under the nozzle at lower altitude.



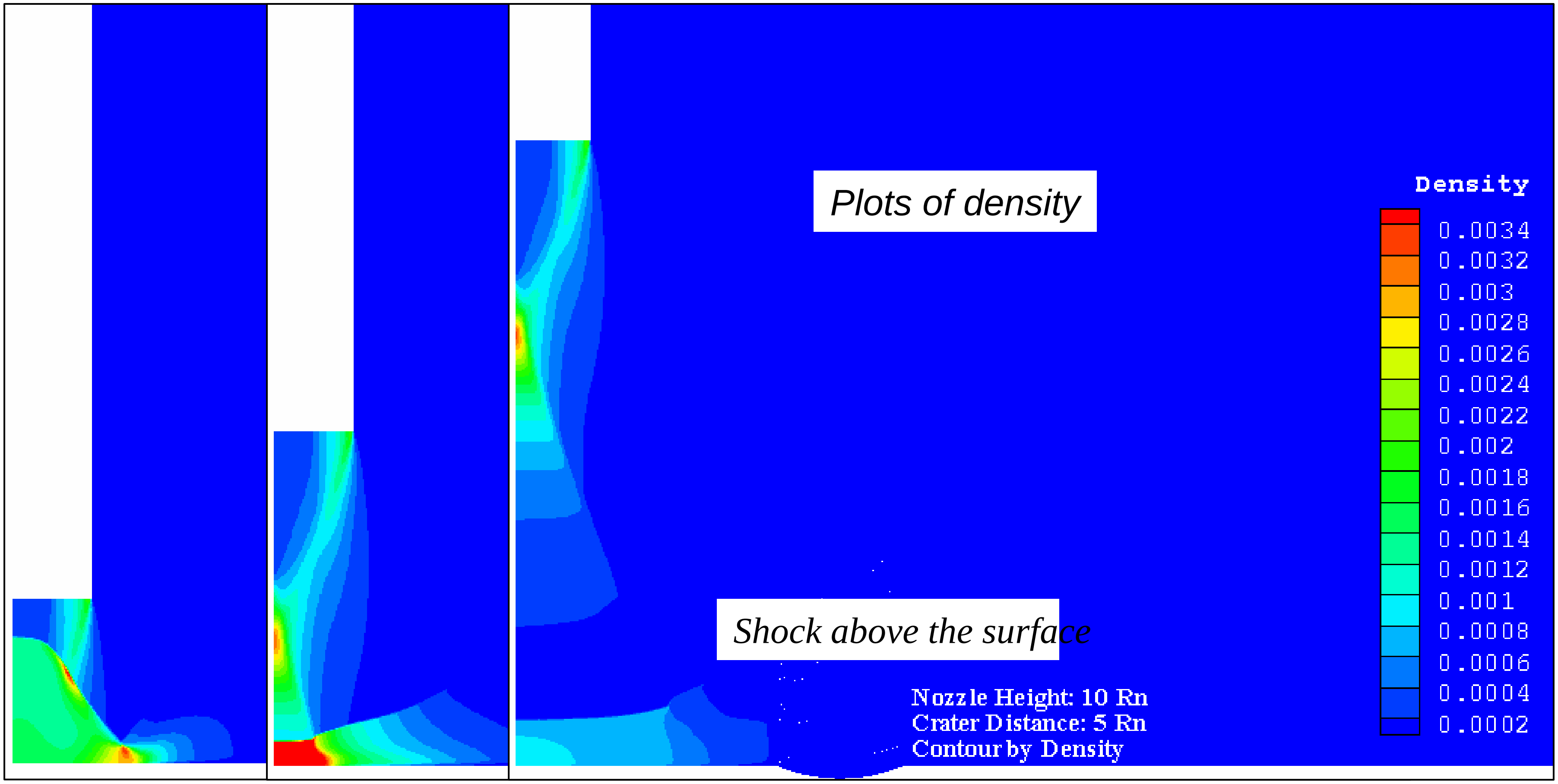




Plots of Velocity Magnitude

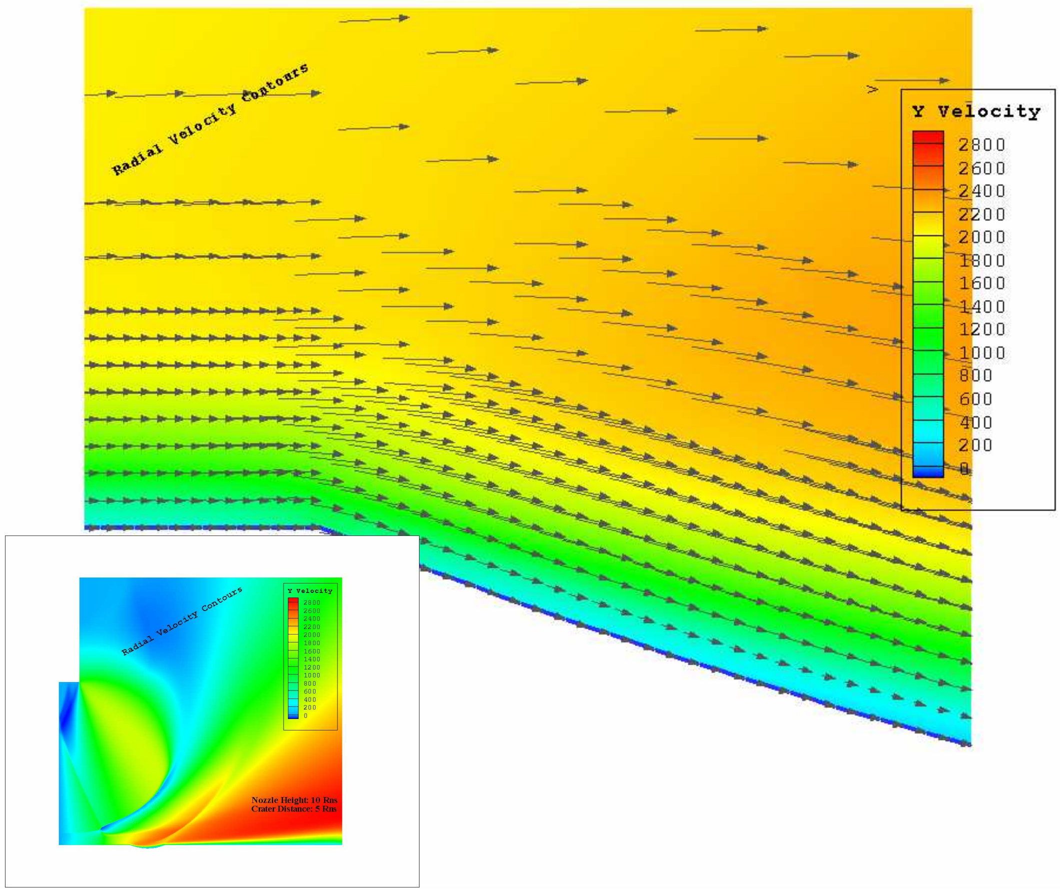
Plume impingement at different height.

Example 2 – Lunar Surface Plume Impingement (cont'd)



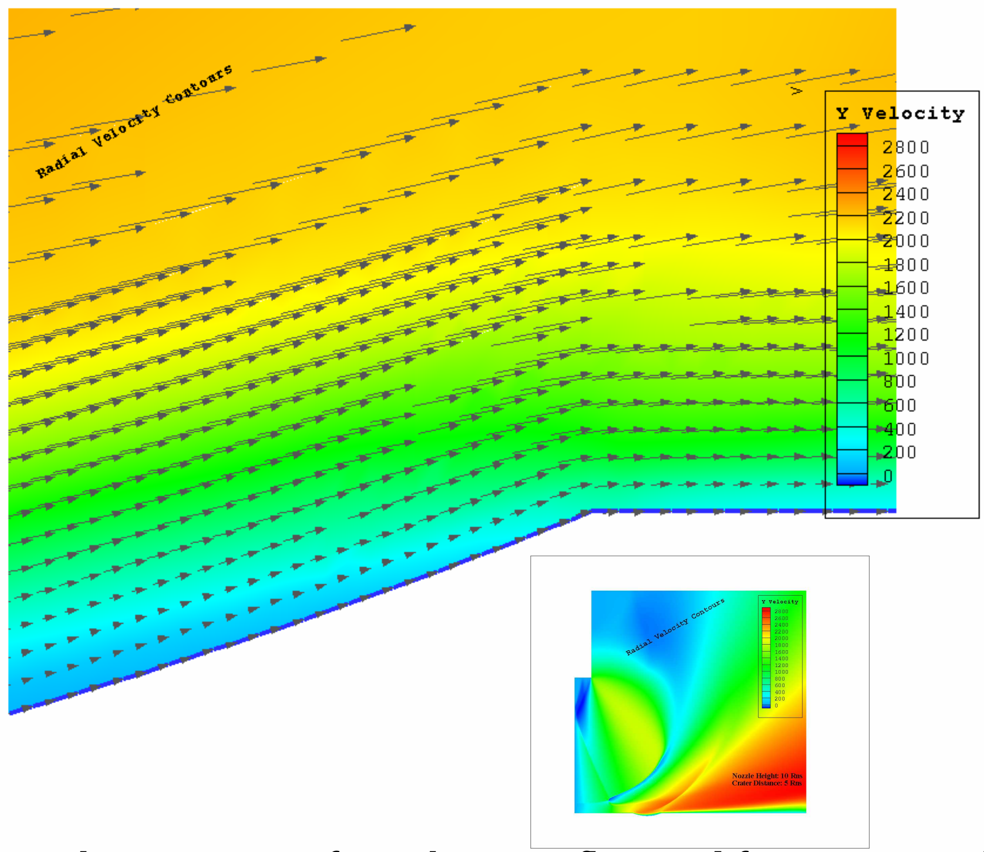
Example 2 – Lunar Surface Plume Impingement (cont'd)

Effect of Crater on the Surface- Flow entering the crater



Example 2 – Lunar Surface Plume Impingement (cont'd)

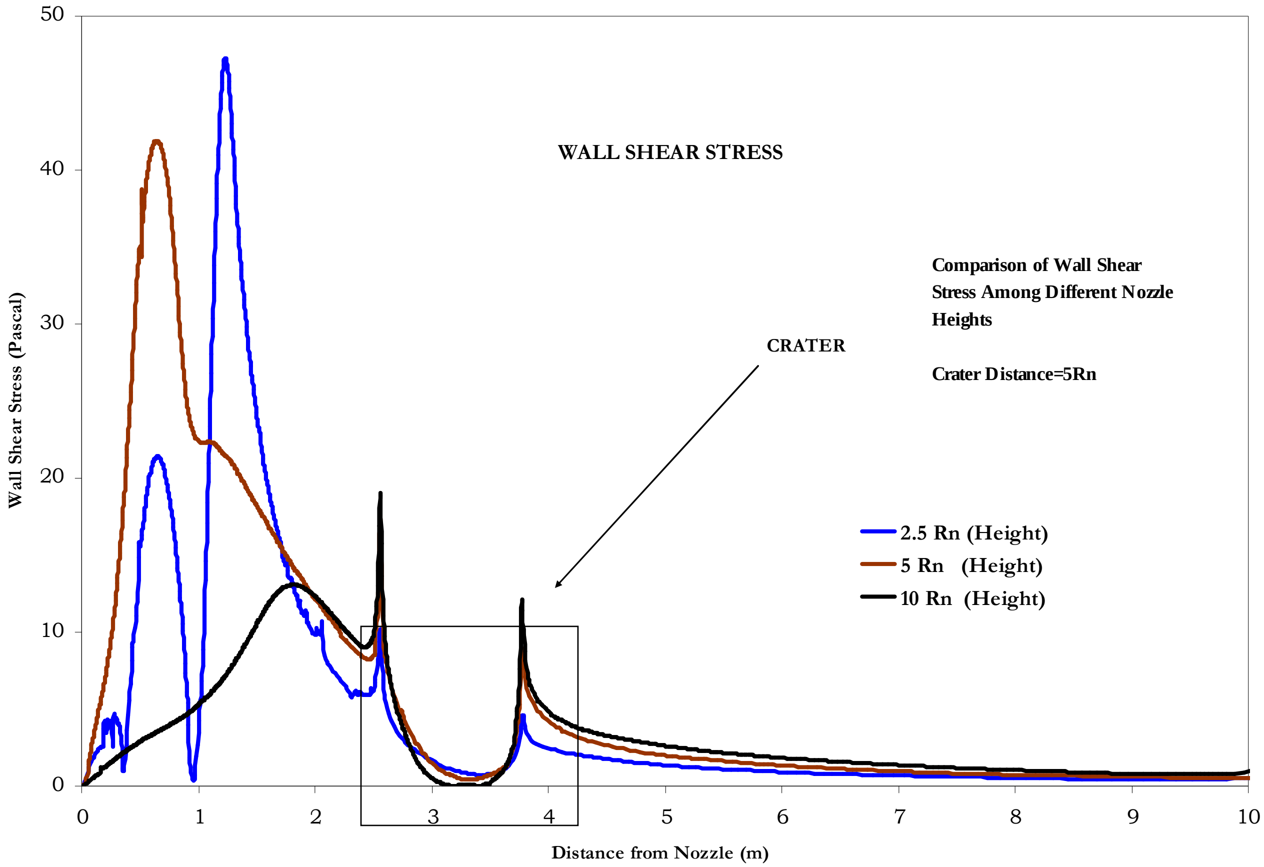
Effect of Crater on the Surface- Flow leaving the crater



Flow separates from the main flow and forms a secondary jet.

Example 2 – Lunar Surface Plume Impingement (cont'd)

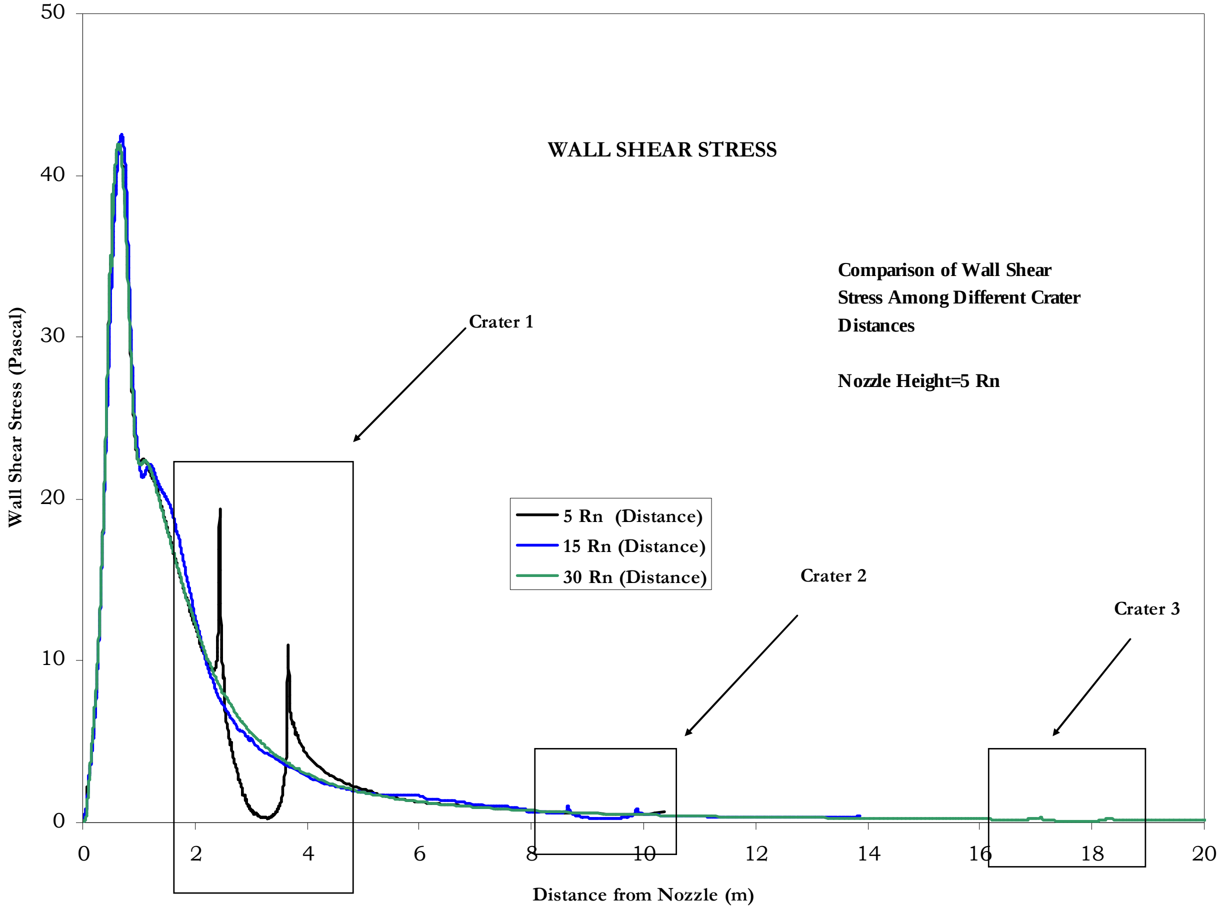
Plot of Shear Stress with Nozzle at Different Heights



The lower the nozzle, the pick shear stress is larger.
The higher the nozzle, the shear stress on the surface and around crater is higher.

Example 2 – Lunar Surface Plume Impingement (cont'd)

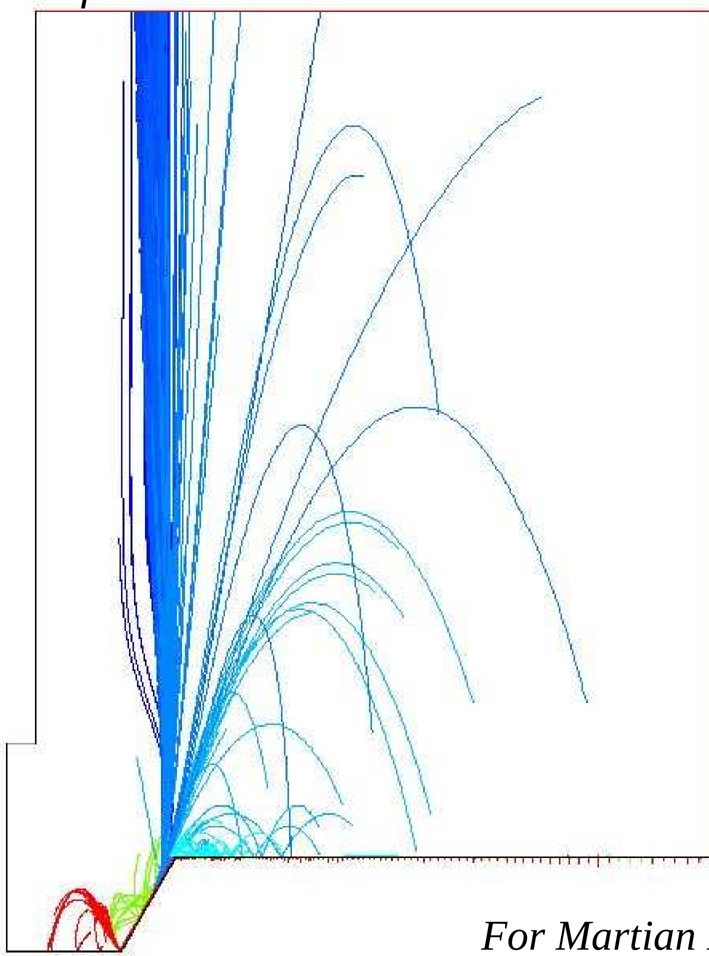
Plot of Shear Stress with Craters at Different Distances from Nozzle



The closer the crater to the nozzle, the crater has more effect on the shear stress.
The crater doesn't affect the shear stress down stream of the crater.

Example 2 – Lunar Surface Plume Impingement (cont'd)

Sample of Particle Trajectories
Colored by size of particles



For Martian Plume Study

Future work

- Fuel tank slosh
  - Structure Load
    - Predict pressure on the tank wall due to the fuel slosh
  - Solving control problem
    - Predict instability of vehicle caused by slosh dynamics of the fuel
- Martian plume study
  - 2D axisymetric (completed)
  - 3D three and four nozzles configurations (in progress)
  - LES turbulence model