Numerical Study of Lander Engine Plume Impingement on the Surface of Europa

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Team

- Simulation of Spacecraft engine’s exhaust plume is a multidisciplinary problem with applications in propulsion, thermal, and contamination control

- Team Members
  - Rebekah Lam, Propulsion Engineer
    - DSMC analyst
  - Elham Maghsoudi, AeroThermo Engineer
    - CFD analyst
  - William Hoey, Contamination Control Engineer
    - DSMC and Contamination Control Consultant

Agenda

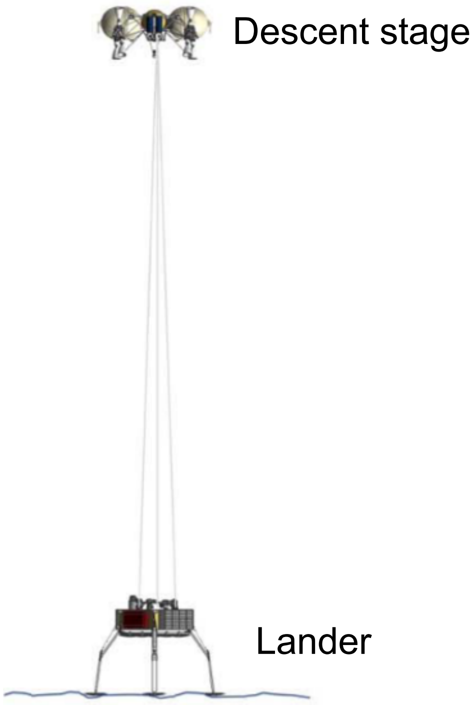
- Plume Concerns
- Landing Architecture
- Methodology
- CFD Domain
  - Overview
  - Code Validation
  - CFD/DSMC Interface
- DSMC Domain
  - Overview
  - Methodology
  - Code Validation
  - Results
- Summary and Conclusions

Plume Concerns for a Potential Europa Lander

- Impingement on the surface
  - Particle entrainment
  - Contamination of surface where science will be conducted
  - Heating → erosion or surface where science will be conducted
- On the lander vehicle
  - Direct impingement → vehicle torques
  - Direct heating
  - Contamination of vehicle surfaces

Landing Architecture Assumptions

- Four pairs of hydrazine monopropellant engines on descent stage
  - 30° and 5° canted engine in each pair
- All descent stage engines used above 30 m altitude
- Only 30° canted engines used during final Sky Crane stage used to lower lander onto Europa surface below 30 m altitude
- Descent stage at 12 m altitude when lander touches down

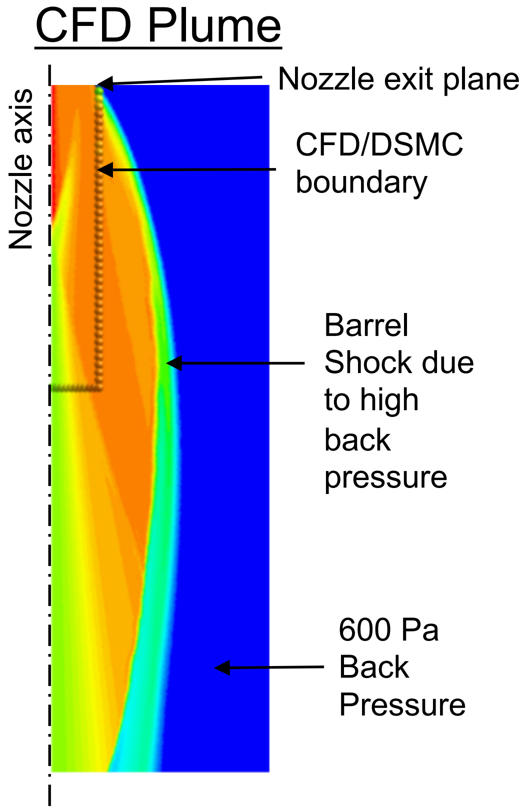


Artist's Concept

Hand, K.P. et al. ***Report of the Europa Lander Science Definition Team***, (Posted February, 2017).

Methodology for Plume Simulations

- One-way coupled CFD/DSMC approach
  - CFD alone cannot be used to solve plume in rarefied environment
- Build single nozzle in CFD
  - Solve flow with high background pressure in 2D axisymmetric simulation
- Establish boundary to transition to DSMC (Direct Simulation Monte Carlo) before continuum breaks down
- Transition to DSMC at boundary
- Validate using lunar lander engine simulation



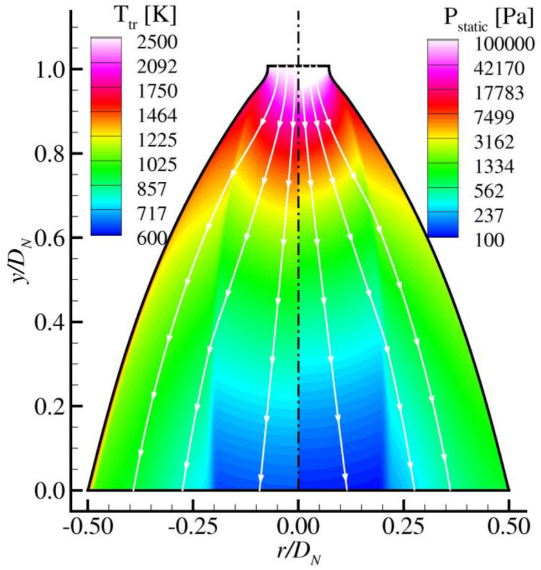
CFD Overview

- STAR-CCM+ commercial package used
  - 2D axisymmetric model
  - Non-reacting Eulerian multi-component gas model with real gas assumption
  - Specific heat (c_p) as a function of temperature for each constituent
  - K-omega turbulence model
  - Mesh refined to achieve T+ of 1 at nozzle walls
- Monopropellant hydrazine products (NH_3, H_2, N_2)
- 3D wedge model used to validate axisymmetric results
- Back pressure of 600 Pa
  - No back pressure sensitivity between 1000 Pa and 50 Pa (lowest achievable)
- Validated with lunar lander engine model

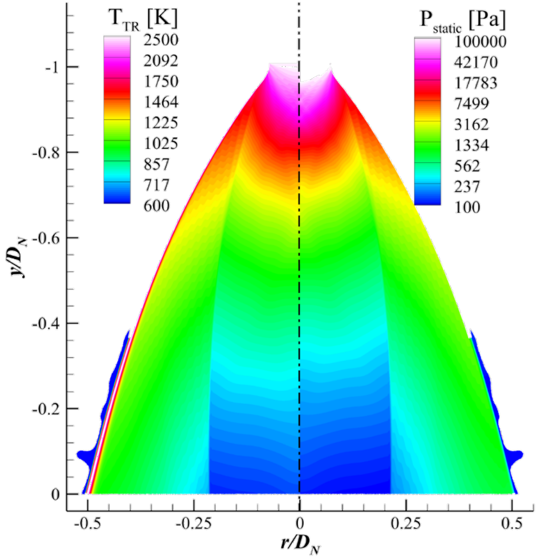
STAR-CCM+ Model Validation – Inside Nozzle

- Good agreement inside nozzle with LMDE (Lunar Module Descent Engine) simulation by Aaron Morris

Morris



STAR-CCM+



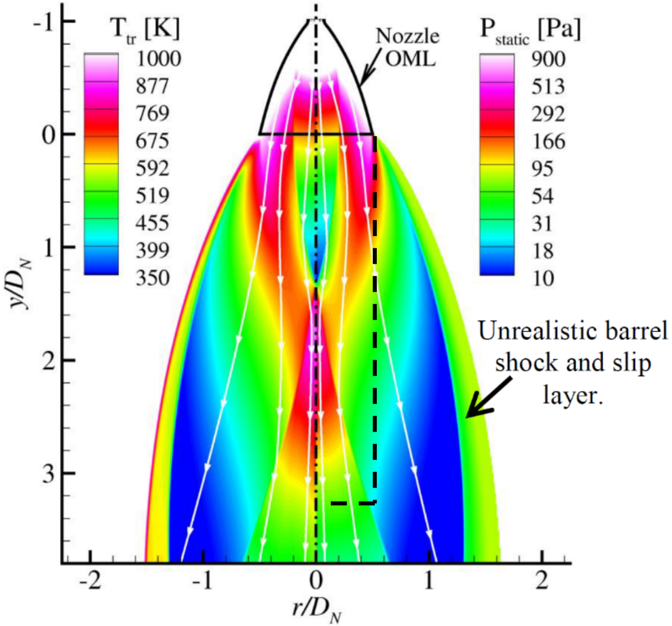
- Uses $c_p(T)$
- Single species H_2O Vapor

Morris, A., ***Simulation of Plume Impingement and Dust Dispersal on the Lunar Surface***, Ph.D. Dissertation, Aerospace Engineering Dept., Univ. of Texas at Austin, Austin, TX (2012). Solved using NASA DPLR Code.

STAR-CCM+ Model Validation – Downstream of Nozzle

- Good agreement just downstream nozzle with LMDE simulation

Morris



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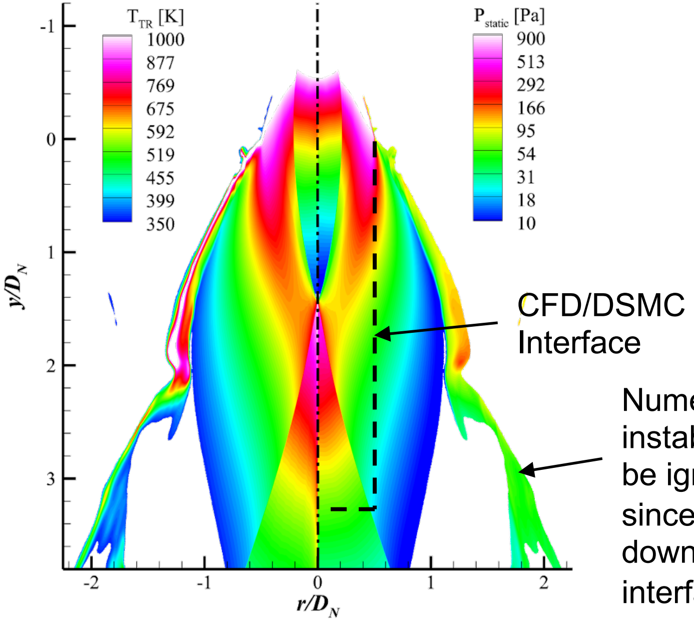
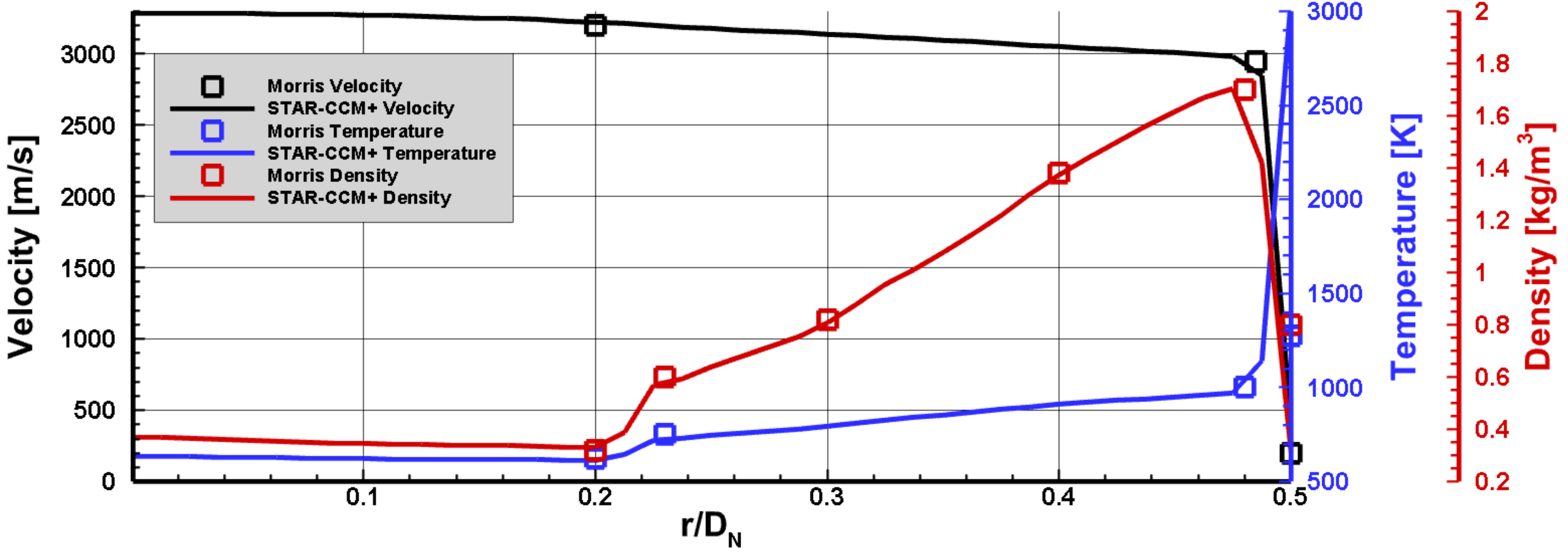
STAR-CCM+



Numerical instabilities can be ignored since they are downstream of interface

STAR-CCM+ Model Validation

- Very good agreement with LMDE simulation at exit plane



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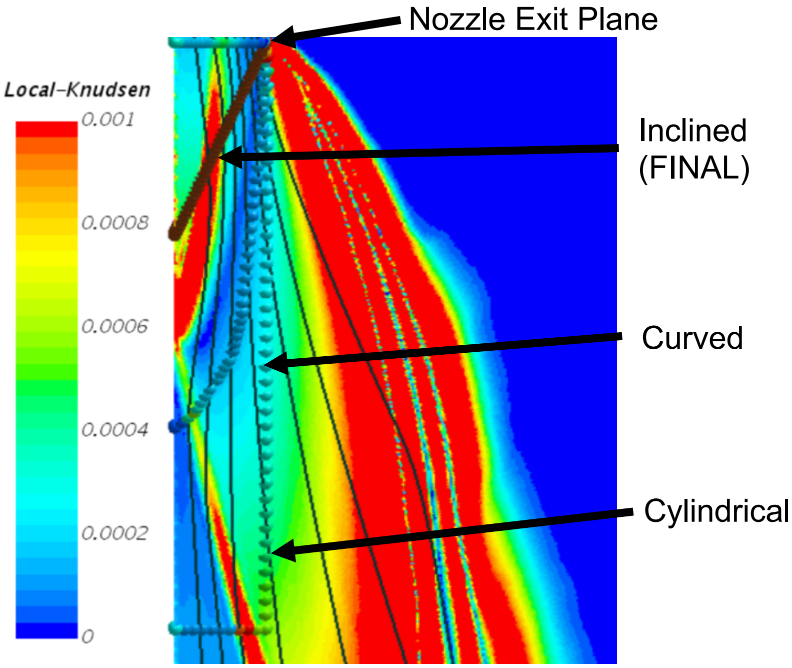
CFD/DSMC Interface Definition

- Requirements for CFD/DSMC Interface:
  - Within continuum regime, i.e. Kn < 0.001
    - Density gradient length scale based Kn
  - Interface-normal flow is supersonic
  - As far out from nozzle as possible to minimize DSMC computation size
- Iterated to satisfy all requirements – boundary sketched, then interface-normal Mach numbers computed
- Interface ends up as straight line extending 0.1 m downstream of nozzle exit



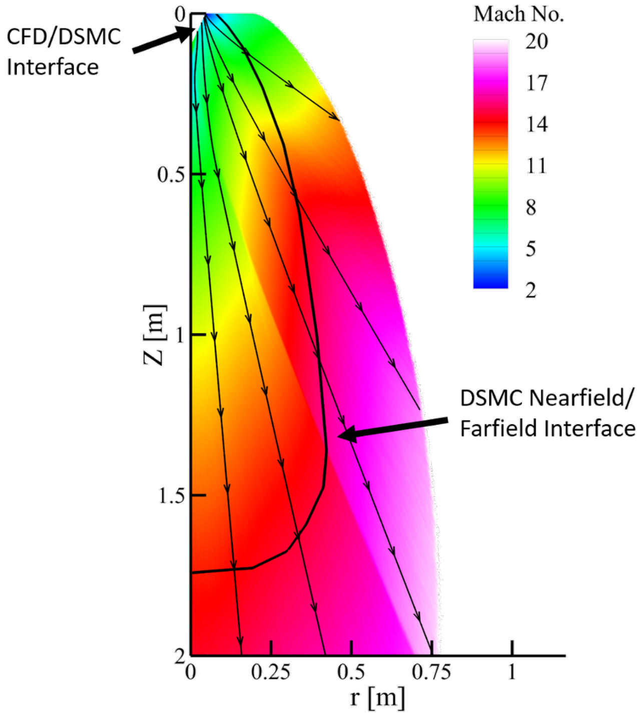
DSMC Plume Simulation Overview

- CFD is not valid at near-vacuum Europa conditions so a kinetic solver is required
- NASA's DAC (DSMC Analysis Code) used
- Inflow Boundary Condition at CFD/DSMC Interface using macroscopic flow properties from CFD
- Single engines simulated at altitudes spanning final stages of landing
    - 5° cant at 25 m
    - 30° cant at 25 m, 20 m, 15 m, 10 m altitudes

DSMC Plume Simulation Method

- Staged approach allows for cell size to be increased manually
  - Layer of smaller cells always used along surfaces
- DSMC domain broken into 2-3 stages:
  - Nearfield 2D axisymmetric simulation
    - No Europa surface
    - Second interface defined to transition to 3D
  - Farfield 3D simulation
    - Half-symmetry with cant
    - Inflow boundary condition uses Nearfield flow data
    - Domain extends to Europa surface
      - For altitudes greater than 10 m, second Farfield stage used before extending to surface

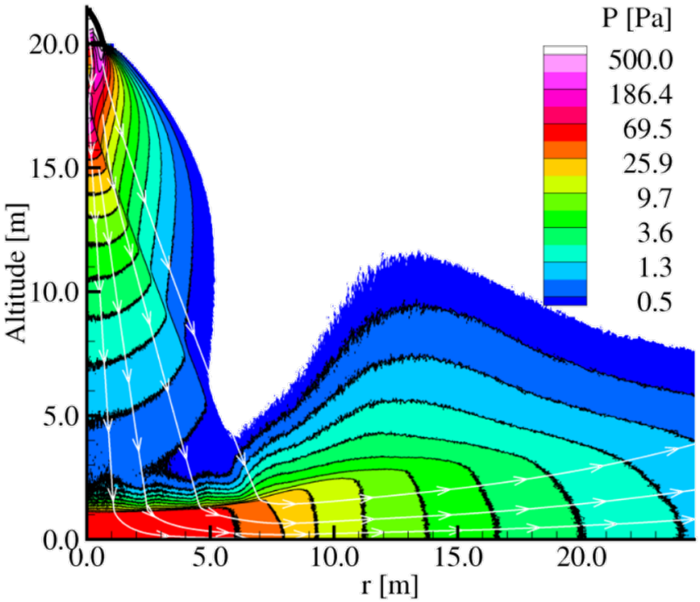
Nearfield DSMC Stage



DAC Validation – 2D, 0° Cant, 20 m Altitude

- Good agreement but DAC has recirculation zone and better resolved shock

MORRIS



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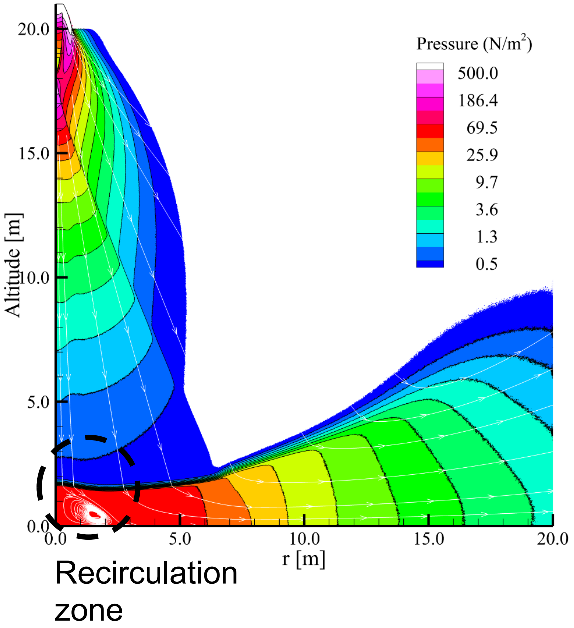
DAC



DAC Validation – 2D, 0° Cant, 5 m Altitude

- Good agreement but DAC has recirculation zone

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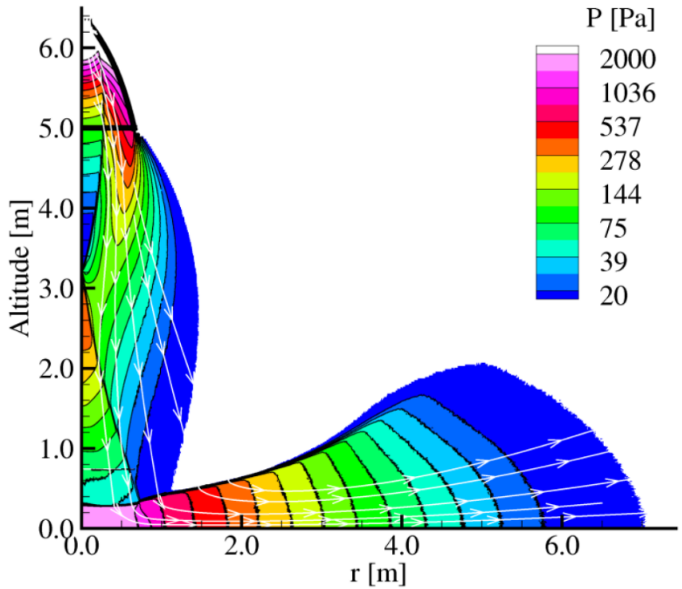

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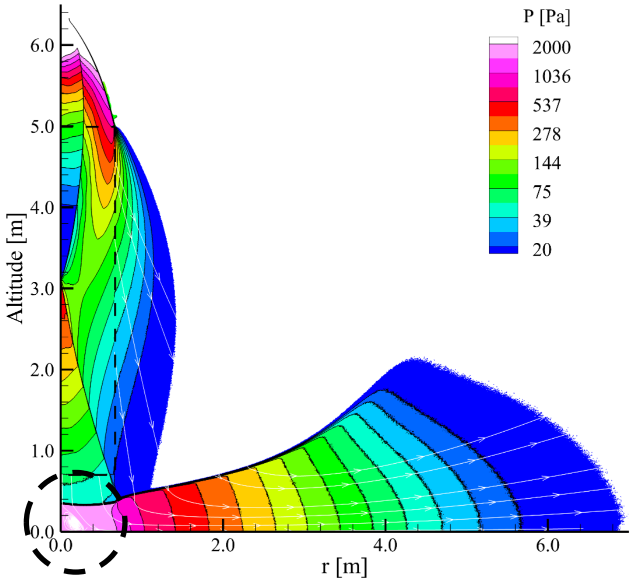
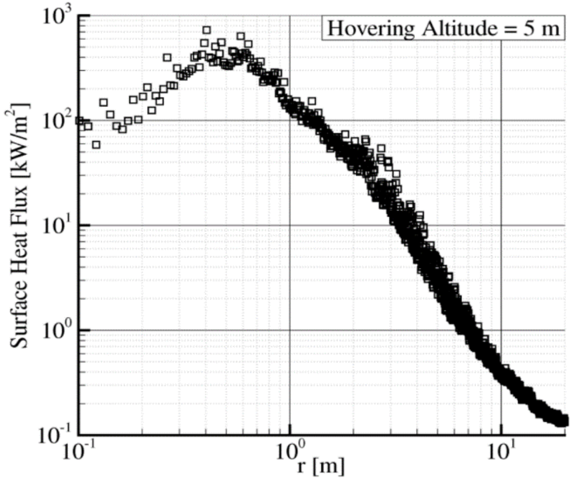
DAC



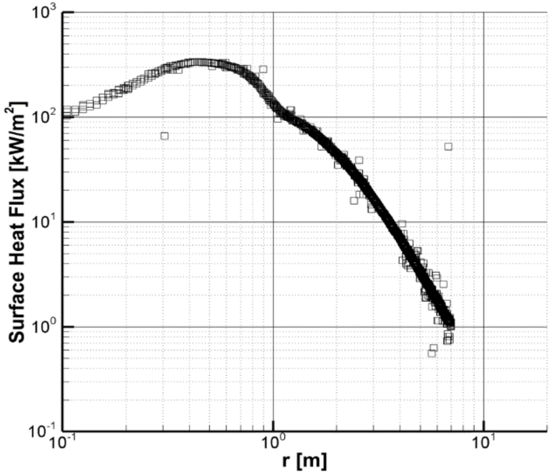
DAC Validation – 2D Surface Heat Flux

- At 5 m altitude, heat flux at surface agrees very well with Morris
  - Peak Heat rate ~300-400 kW/m^2 at r= ~0.5 m

MORRIS



DAC



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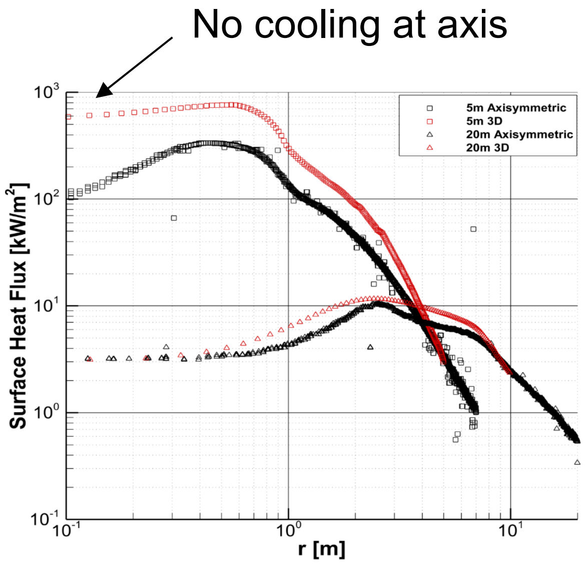
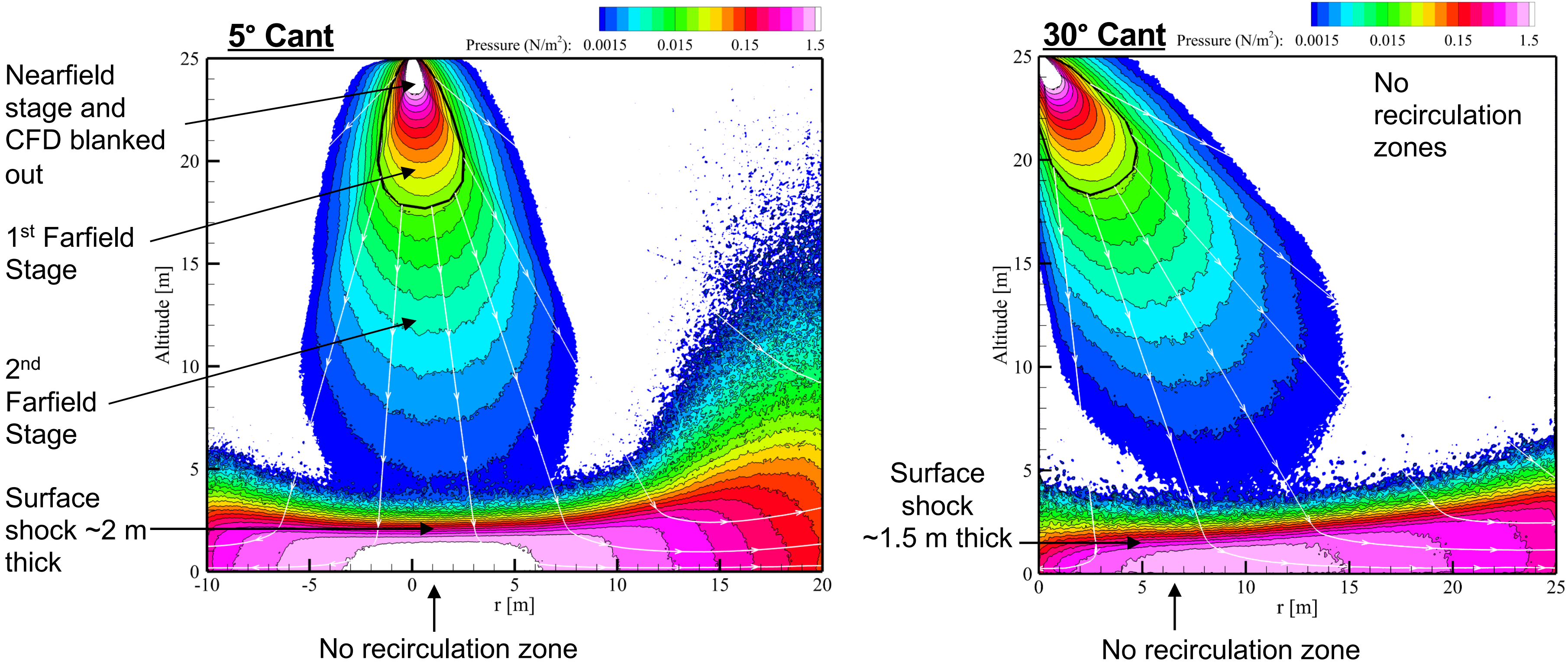
DAC Validation – 3D vs. 2D

- Europa simulations need to be in 3D due to cant, so 3D DAC must also be validated
- DAC simulations repeated in 3D using staged approach and compared to 2D solution
  - Pressure contours at both 20 m and 5 m altitude agreed well with 2D (and Morris)
    - At 5 m altitude, no recirculation zone seen in 3D
  - At 20 m altitude, 3D surface heat flux profile for 3D matches 2D well
  - At 5 m altitude, 3D surface heating is higher near axis due to lack of recirculation zone cooling
- Canted Europa lander engine simulations do not have recirculation zones

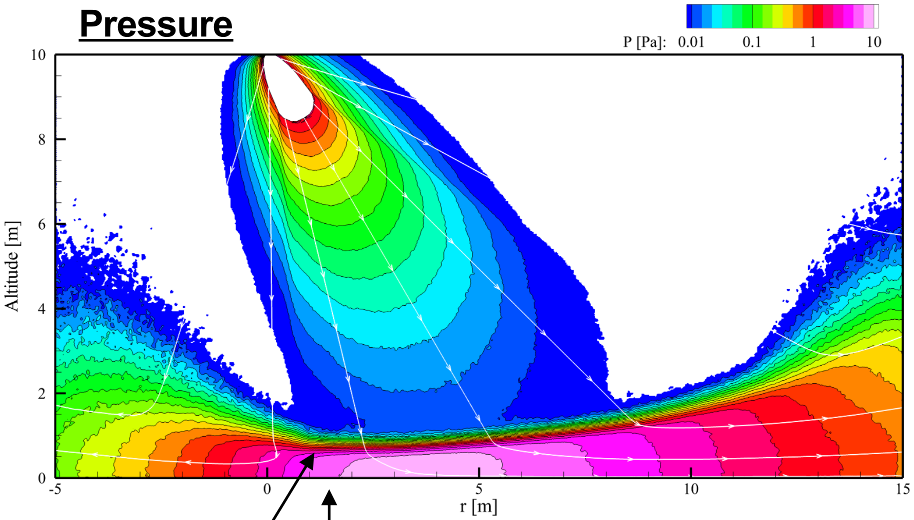


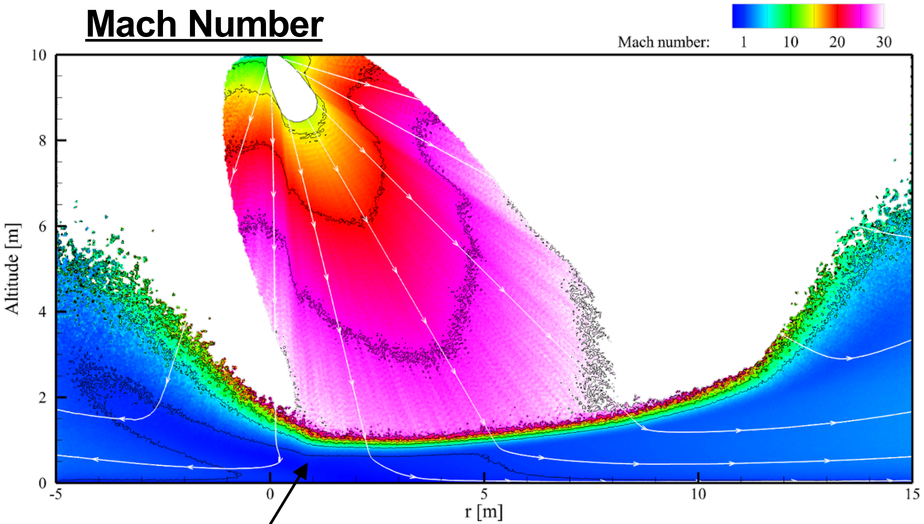
DAC Pressure Contours – 25 m Altitude



DAC Pressure & Mach – 10 m Altitude, 30° Cant

- Lowest altitude – worst case





Surface shock ~1.5 m thick

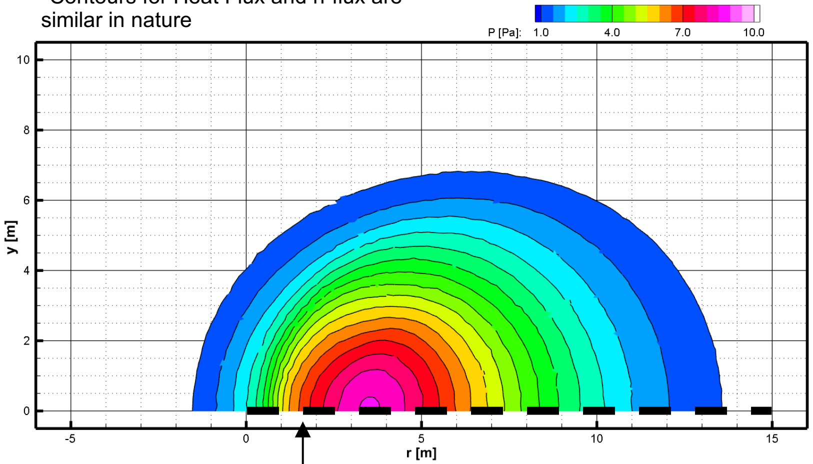
No recirculation zone

Subsonic region

DAC Surface Impingement Results

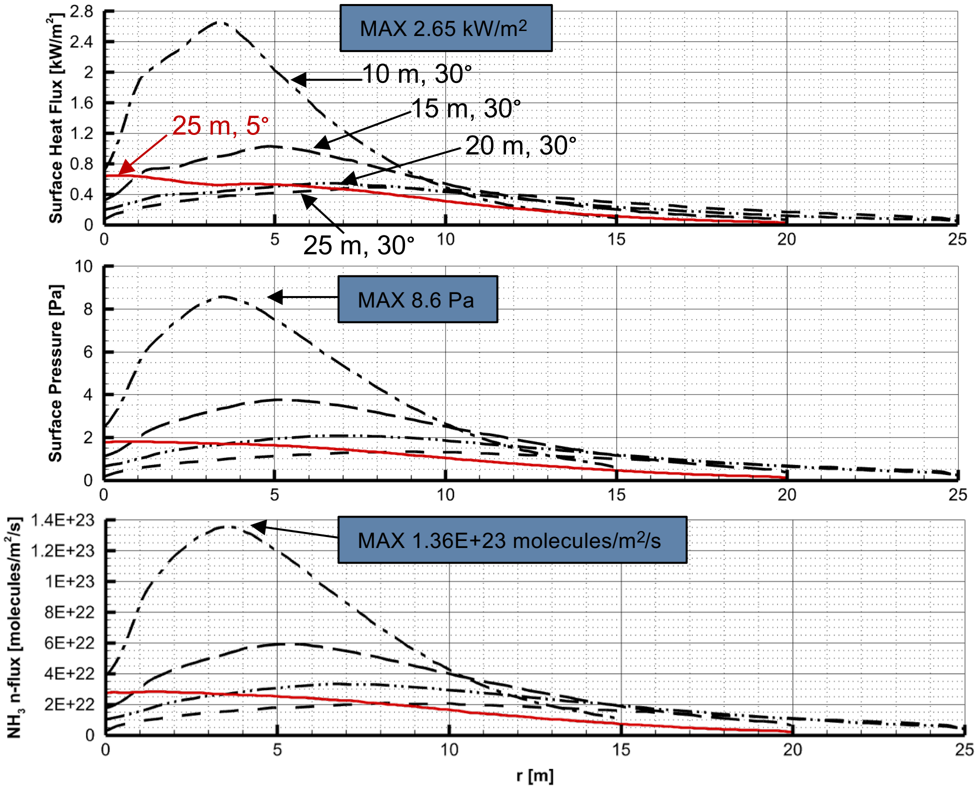
Surface Pressure - 10 m Altitude, 30° Cant

*Contours for Heat Flux and n-flux are similar in nature



Profiles along symmetry axis on plots to right

Surface Profiles – All altitudes & cants



Summary & Conclusions

- Potential Europa Lander engine plume was modelled using validated combination of CFD and DSMC with interface between the two defined within continuum region
- STAR-CCM+ and DAC well-validated with lunar lander engine simulation
  - $c_p(T)$ is important
  - Recirculation zones exist in DAC but irrelevant for canted Europa cases
- Plume impingement with Europa surface results in slightly angled surface shocks < 2 m from surface during final stages of landing (25 m to 10 m altitude)
- Worst plume impingement occurs 3.3 m out from cant axis at 10 m altitude

Summary & Conclusions

- Current results are meant to get a general idea of what plume environment is from single engine
- Results can be used to study plume effects in detail:
  - NH_3 accumulation and erosion of landing area
  - Particle entrainment and effects on lander and descent stage
  - Direct impingement/heating/contamination of lander and descent stage
  - Plume-plume interaction between engine pairs

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