

Numerical Implementation of Source Terms to Evaluate Active Porosity Control using a Transpiration Cooled Thermal Protection System

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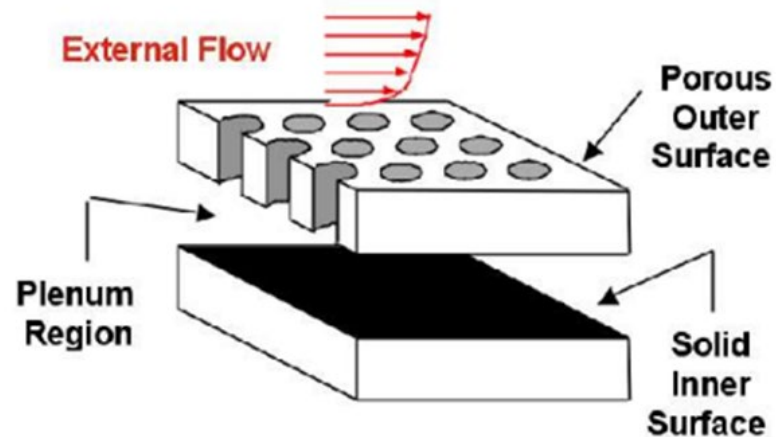
- Introduction
 - Porous surface impacts in high-speed flow
 - Thermal Protection System: Transpiration cooling
 - surface source terms
 - Cooling & Control in tandem
 - Study focus: Aerodynamics impacts
- Methods
 - Numerical Model
 - Source-term injection scheme
- Results & Discussion
- Next steps



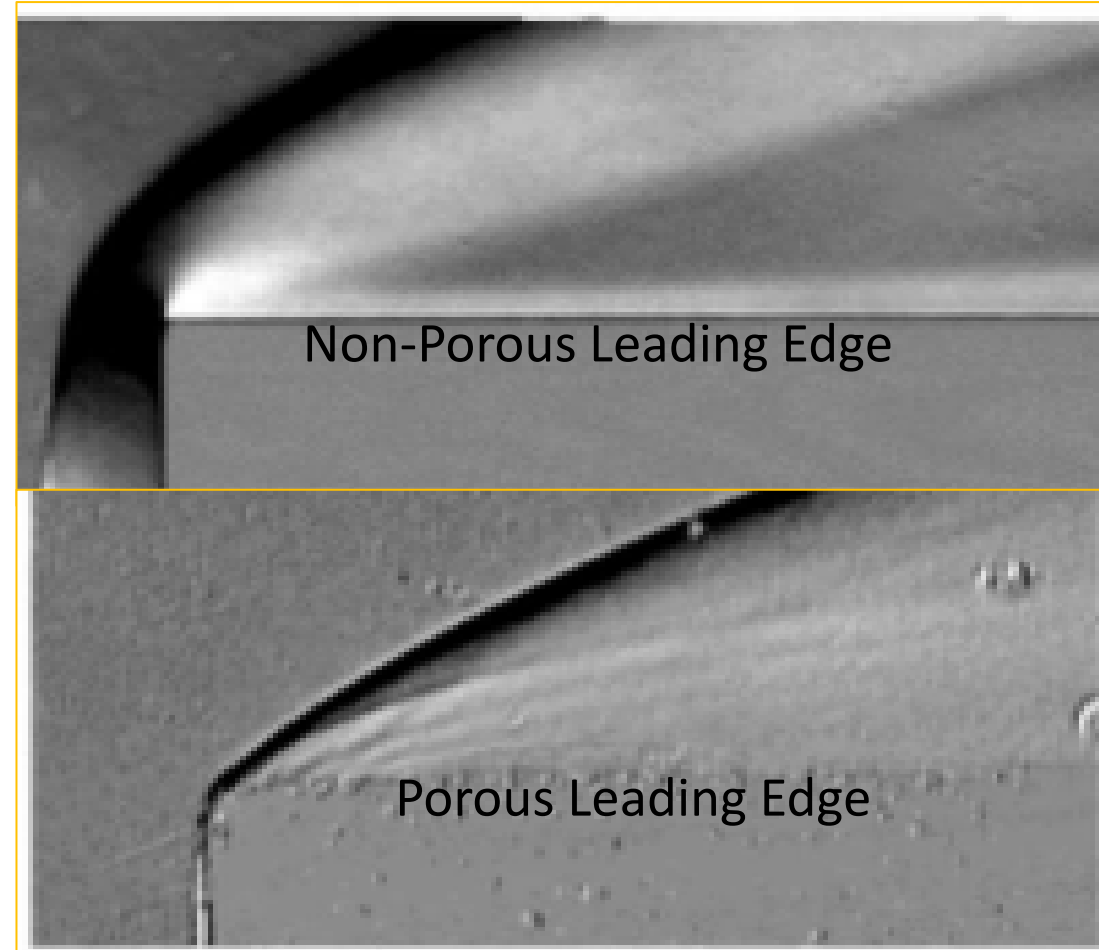
Introduction: Porous Surface Control

Porous Surface Control

- Shock Manipulation
- Pressure Gradient Distance



Schlieren Imaging of Cylinders in Mach 2



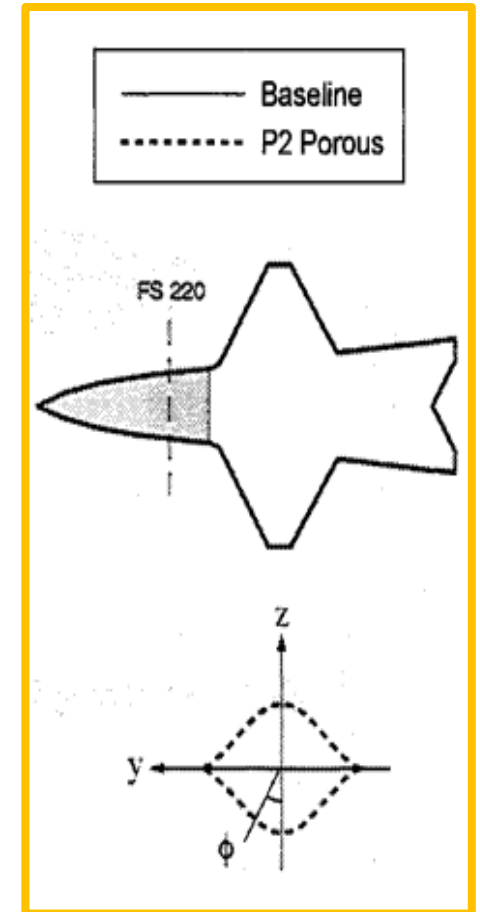
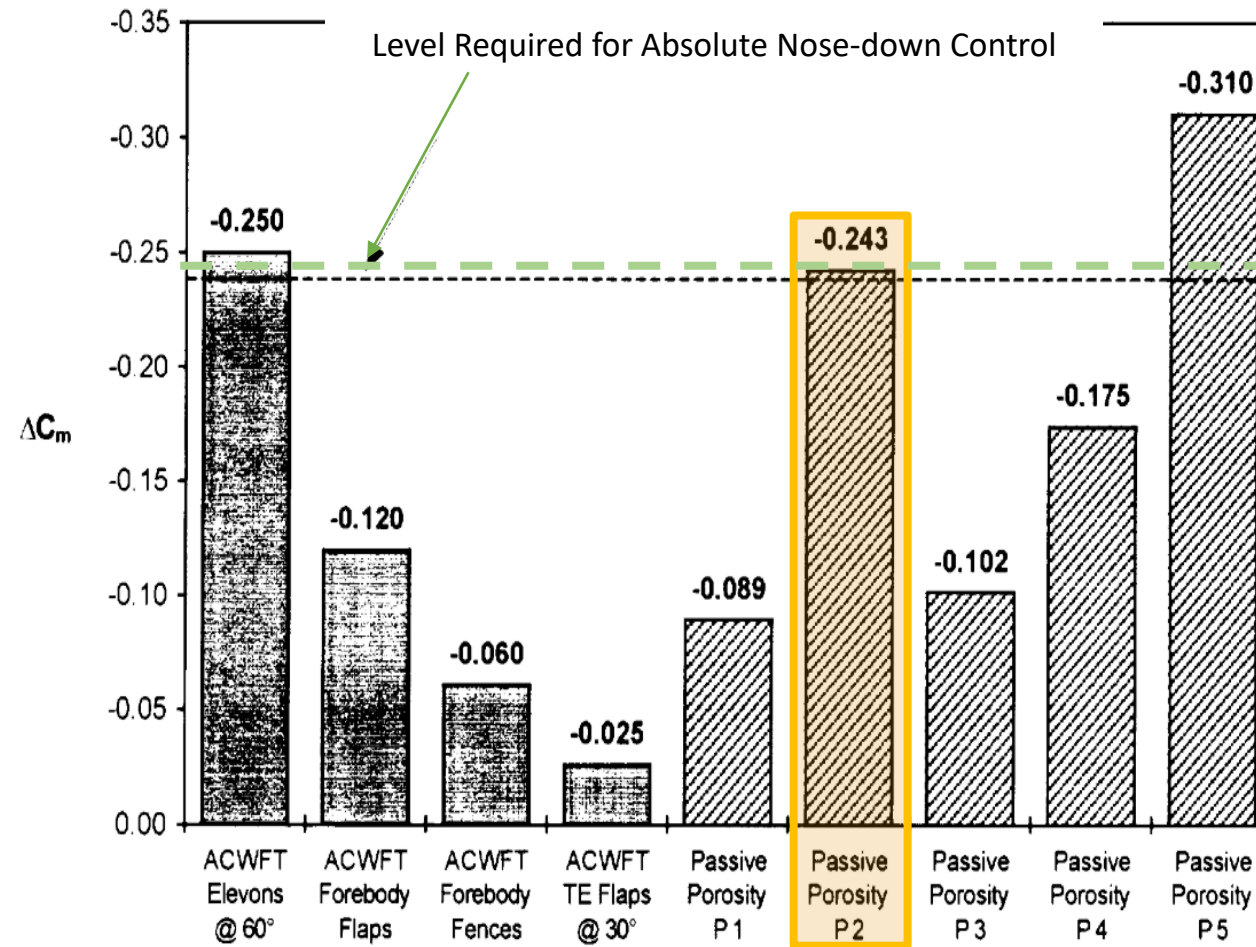
Maslov, A. A., Mironov, S. G., Poplavskaya, T. V., and Kirilovskiy, S. V., "Supersonic flow around a cylinder with a permeable high-porosity insert: Experiment and numerical simulation," 2019

Introduction: Porous Surface Control

Porous Surface Control

- Feasibility to replace traditional control surfaces

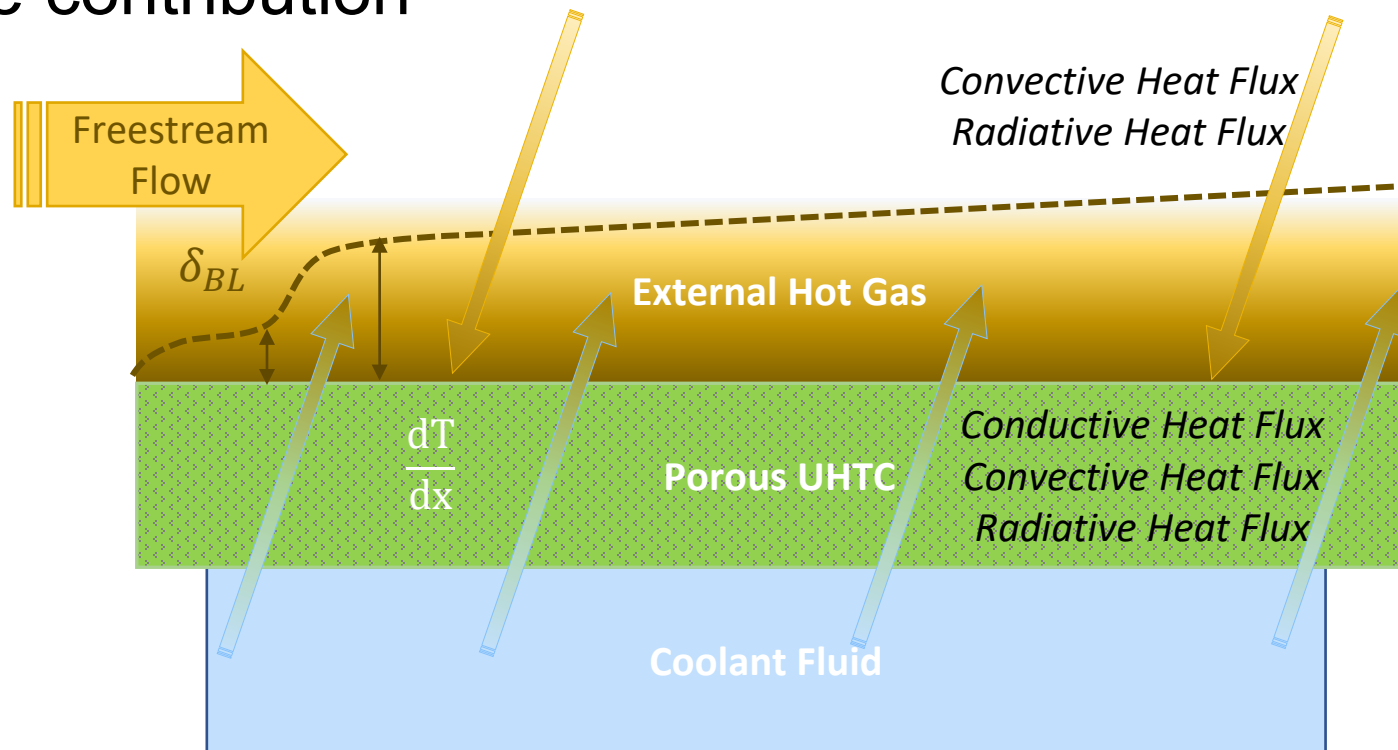
Nose Down Pitch Control Comparison



Introduction: Transpiration Cooling

Transpiration Cooling for Thermal Protection Systems

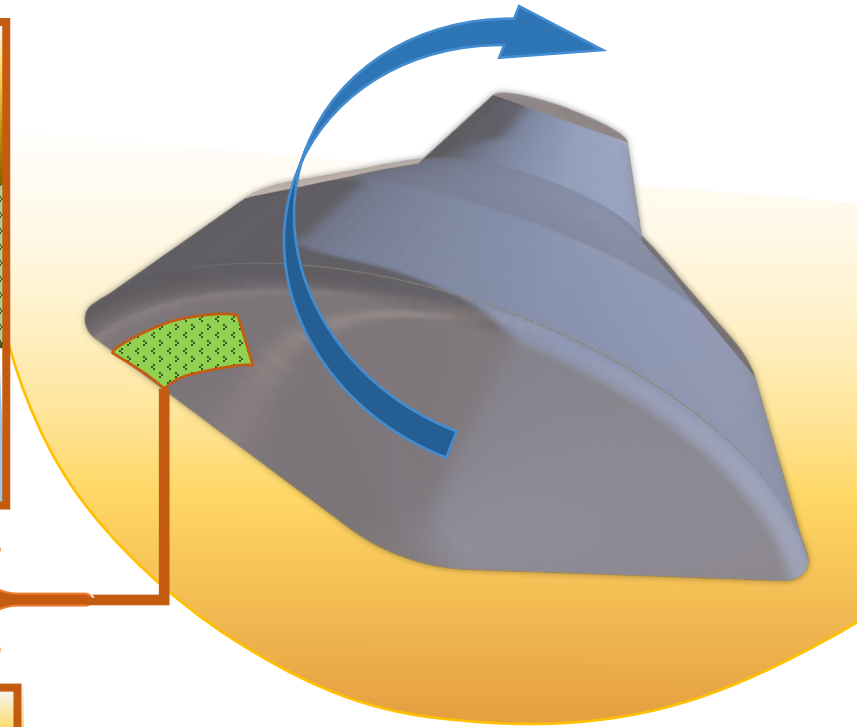
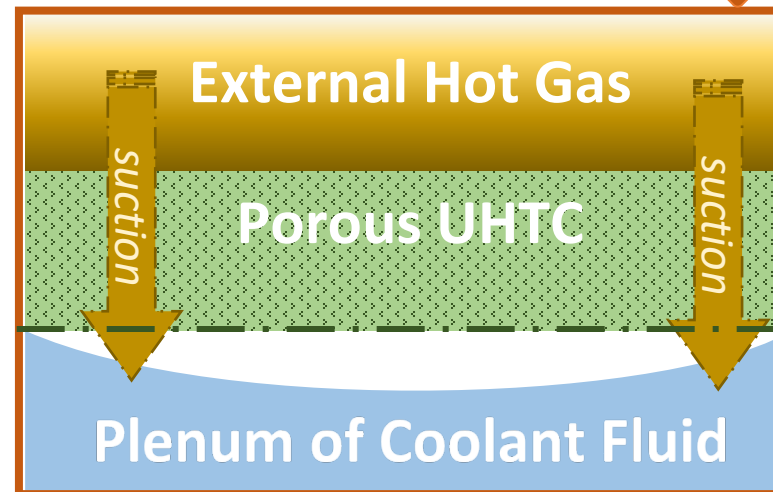
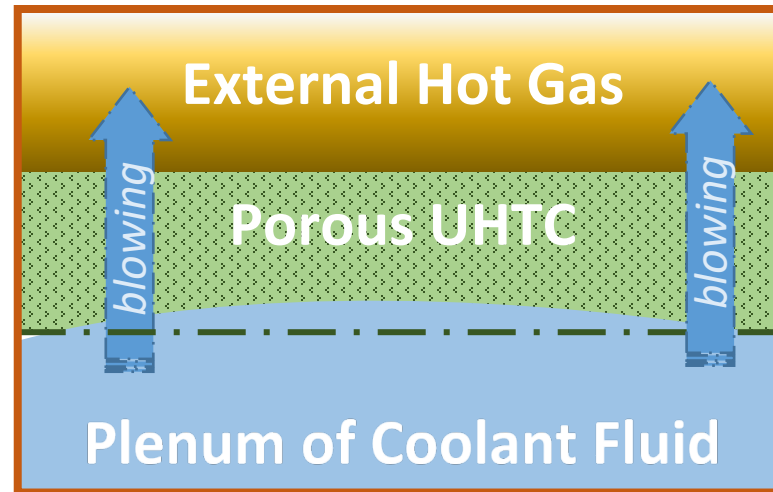
- Thermal Gradient (Passive) vs. Active Control
- Conductive transfer from solid to coolant, convective transfer from surface, and radiative contribution



Introduction: Proposed Dual System

Proposed Solution: The Dual System

- Combined TPS & Control Augmentation
- “Active” Regions create asymmetric scheme
- **Proof of Concept Study:** Evaluate effects of transpiration cooling products by implementing source terms of coolant properties at surface into external flow



NASA EDL Goal:
alter L/D
acceleration of
 $0.005-0.008 \text{ s}^{-2}$

“NASA Technology Roadmaps.” 2015

Methods: Numerical Model



$$\text{Continuity: } \frac{\partial \rho}{\partial t} + \frac{\partial(\rho u)}{\partial x} + \frac{\partial(\rho w)}{\partial z} = 0$$

$$\text{X-Momentum: } \frac{\partial(\rho u)}{\partial t} + \frac{\partial(\rho u^2)}{\partial x} + \frac{\partial(\rho uv)}{\partial y} + \frac{\partial(\rho uw)}{\partial z} = -\frac{\partial \rho}{\partial x} + \frac{1}{Re_r} \left[\frac{\partial \tau_{xx}}{\partial x} + \frac{\partial \tau_{xy}}{\partial y} + \frac{\partial \tau_{xz}}{\partial z} \right]$$

$$\text{Y-Momentum: } \frac{\partial(\rho v)}{\partial t} + \frac{\partial(\rho uv)}{\partial x} + \frac{\partial(\rho v^2)}{\partial y} + \frac{\partial(\rho vw)}{\partial z} = -\frac{\partial \rho}{\partial y} + \frac{1}{Re_r} \left[\frac{\partial \tau_{xy}}{\partial x} + \frac{\partial \tau_{yy}}{\partial y} + \frac{\partial \tau_{yz}}{\partial z} \right]$$

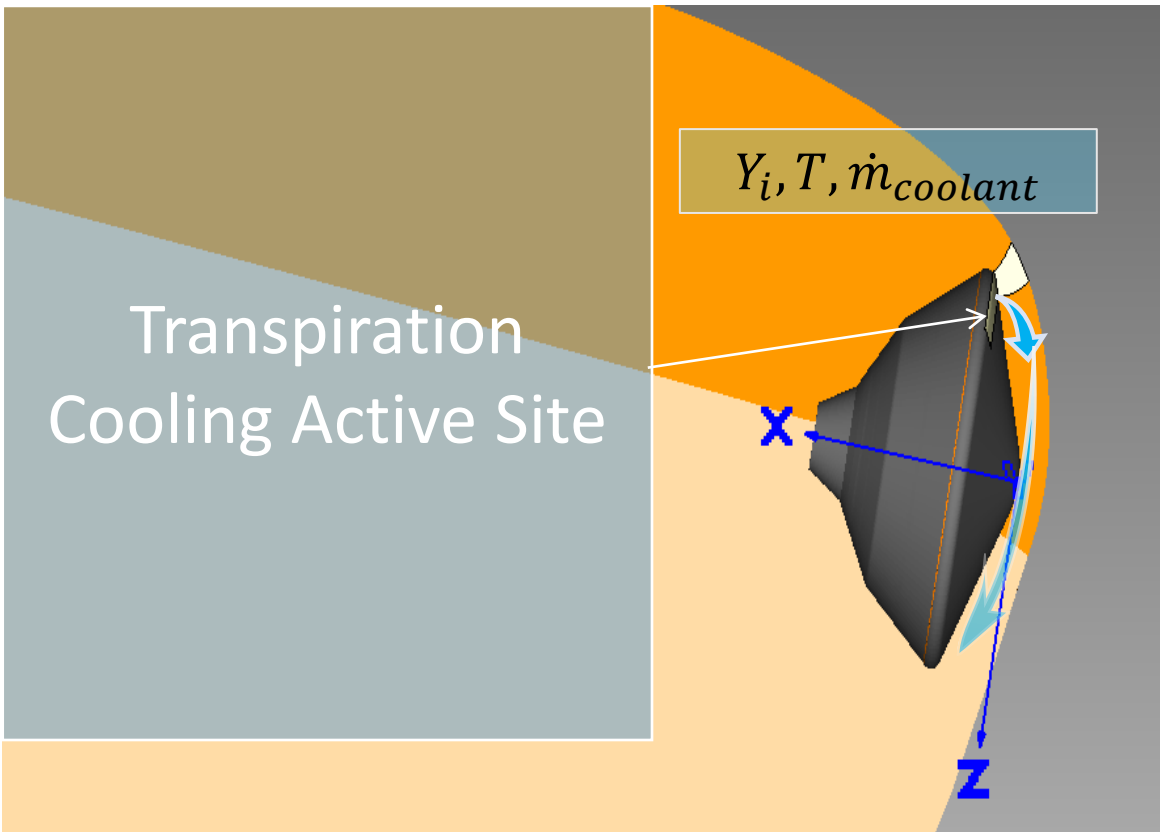
$$\text{Z-Momentum: } \frac{\partial(\rho w)}{\partial t} + \frac{\partial(\rho uw)}{\partial x} + \frac{\partial(\rho vw)}{\partial y} + \frac{\partial(\rho w^2)}{\partial z} = -\frac{\partial \rho}{\partial z} + \frac{1}{Re_r} \left[\frac{\partial \tau_{xz}}{\partial x} + \frac{\partial \tau_{yz}}{\partial y} + \frac{\partial \tau_{zz}}{\partial z} \right]$$

$$\begin{aligned} \text{Energy: } & \frac{\partial(E_t)}{\partial t} + \frac{\partial(uE_t)}{\partial x} + \frac{\partial(vE_t)}{\partial y} + \frac{\partial(wE_t)}{\partial z} \\ &= -\frac{\partial(up)}{\partial x} - \frac{\partial(vp)}{\partial y} - \frac{\partial(wp)}{\partial z} - \frac{1}{Re_r Pr_r} \left[\frac{\partial q_x}{\partial x} + \frac{\partial q_y}{\partial y} + \frac{\partial q_z}{\partial z} \right] \\ &+ \frac{1}{Re_r} \left[\frac{\partial}{\partial x} (u\tau_{xx} + v\tau_{xy} + w\tau_{xz}) + \frac{\partial}{\partial y} (u\tau_{xy} + v\tau_{yy} + w\tau_{yz}) + \frac{\partial}{\partial z} (u\tau_{xz} + v\tau_{yz} + w\tau_{zz}) \right] \end{aligned}$$

- Steady State
- Data parallel line relaxation scheme
- Constant Lewis/Schmidt number
- vibrational, electronic and translational energy neglected
- all species created/destroyed at the mixture energy state



Methods: Boundary Conditions



- Freestream outer boundaries
 - Mars Science Laboratory
- Catalytic Radiative Equilibrium Wall
- Species Term Application Boundary

El Time (s)	Altitude (km)	V_∞ (m/s)	T_∞ (K)	ρ_∞ (kg/m ³)	M_∞	α (deg)	$\bar{q}$ (kPa)
130	14.3	1263.5	192.2	0.004396	5.7	-18.58	3.51

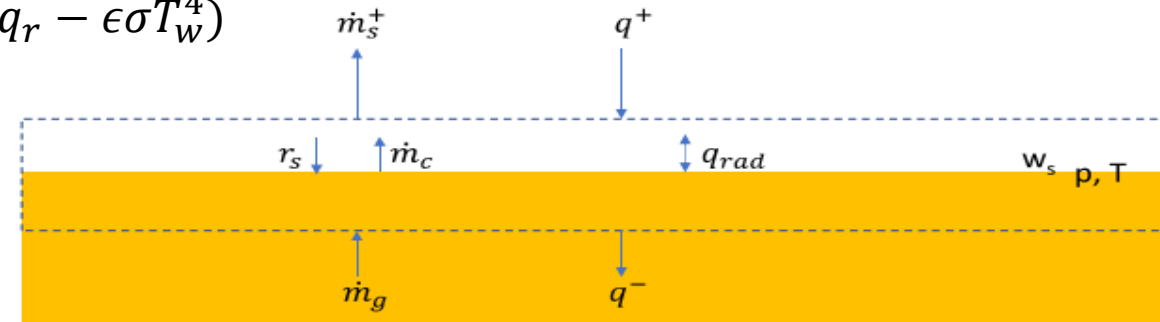


Methods: Boundary Conditions

Species Term Application Boundary:

$$(1) \quad \sum_i h_i J_i + q_v^+ - \dot{m}_g \sum_i h_i (Y_i - Y_i^g) - \dot{m}_c \left(\sum_i h_i Y_i - h_c \right) + \alpha q_r - \epsilon \sigma T_w^4$$

$$(2) \quad q_e^+ = q_c^+ + q_v^+ + \sum_i h_i J_i$$



Y = mass fraction

q^+ = heat flux in, W/m^2

q^- = heat flux out, W/m^2

h = specific enthalpy, J/kg

$\dot{m}$ = mass flux, $kg/m^2 s$

J = diffusive flux, $kg/m^2 s$

α = absorptivity

q_r = radiation heat flux, W/m^2

ϵ = emissivity

σ = Stefan-Maxwell constant, $W/m^2 K^4$

T = Temperature, K

Scripts

i = species

c = conductive for heat flux, char for mass flux and enthalpy

g = pyrolysis

r = radiation

v = viscous

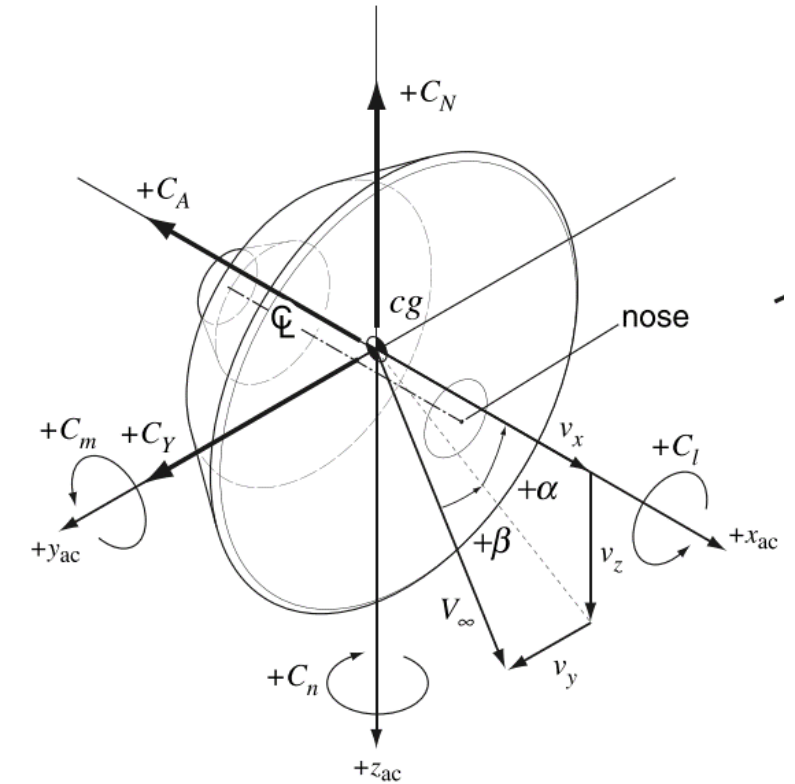
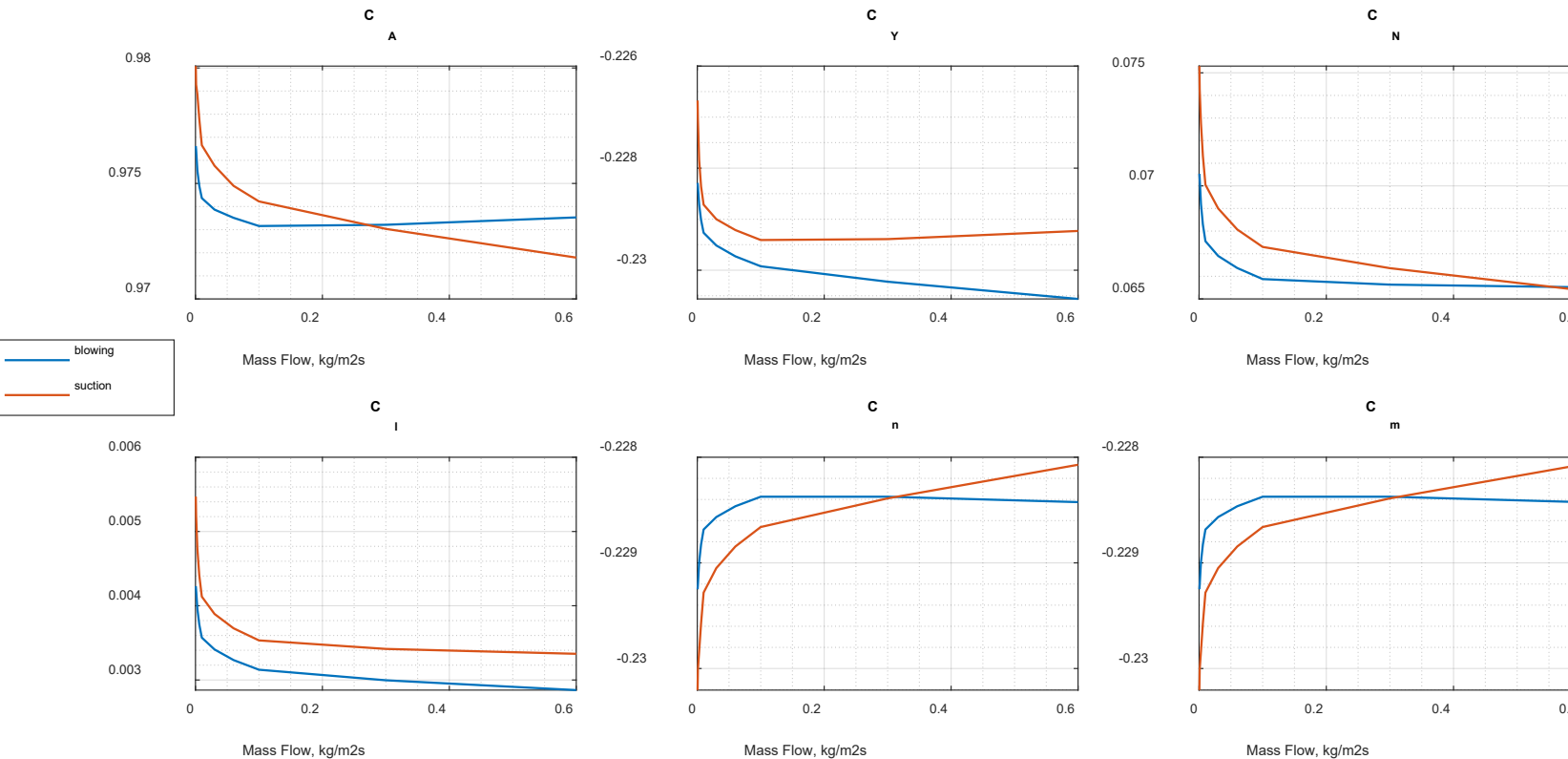
e = boundary layer edge

w = wall

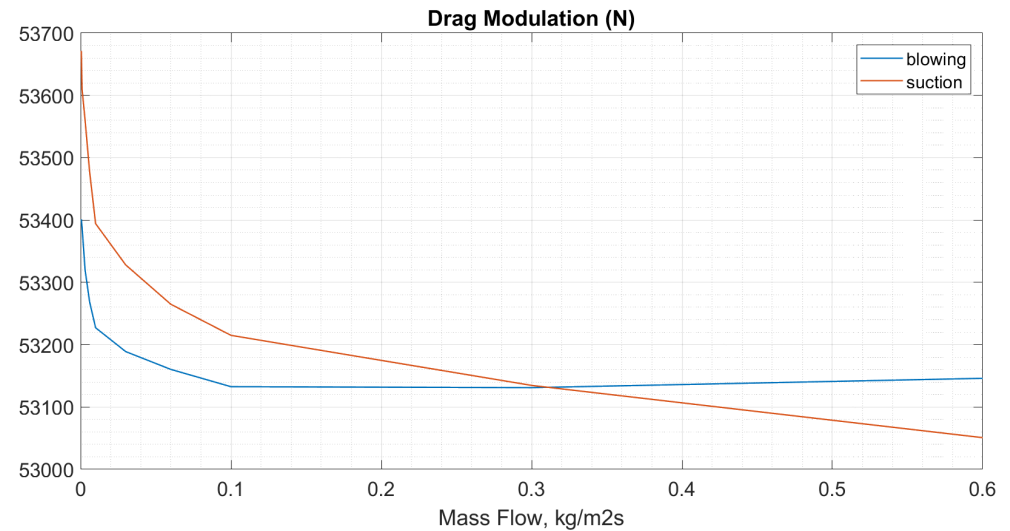
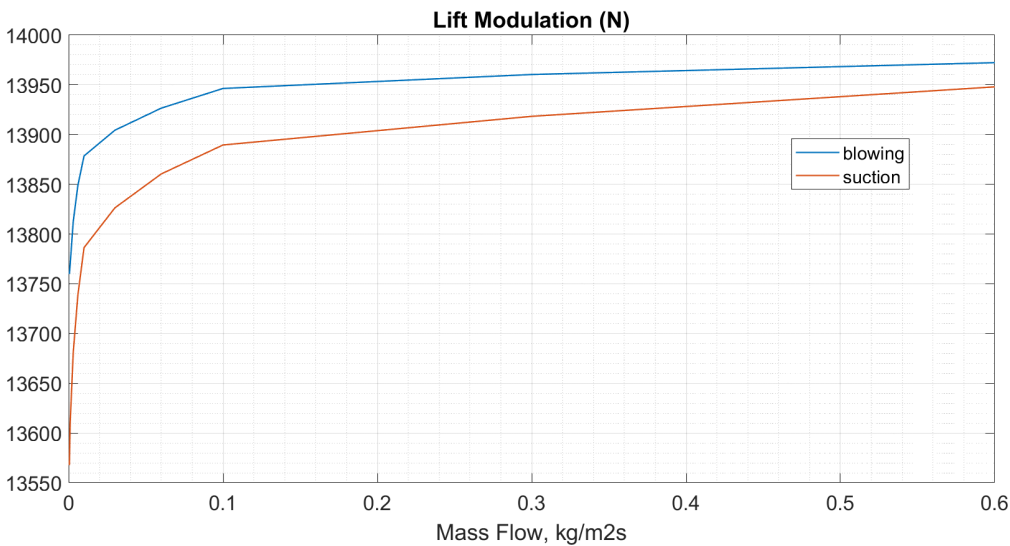
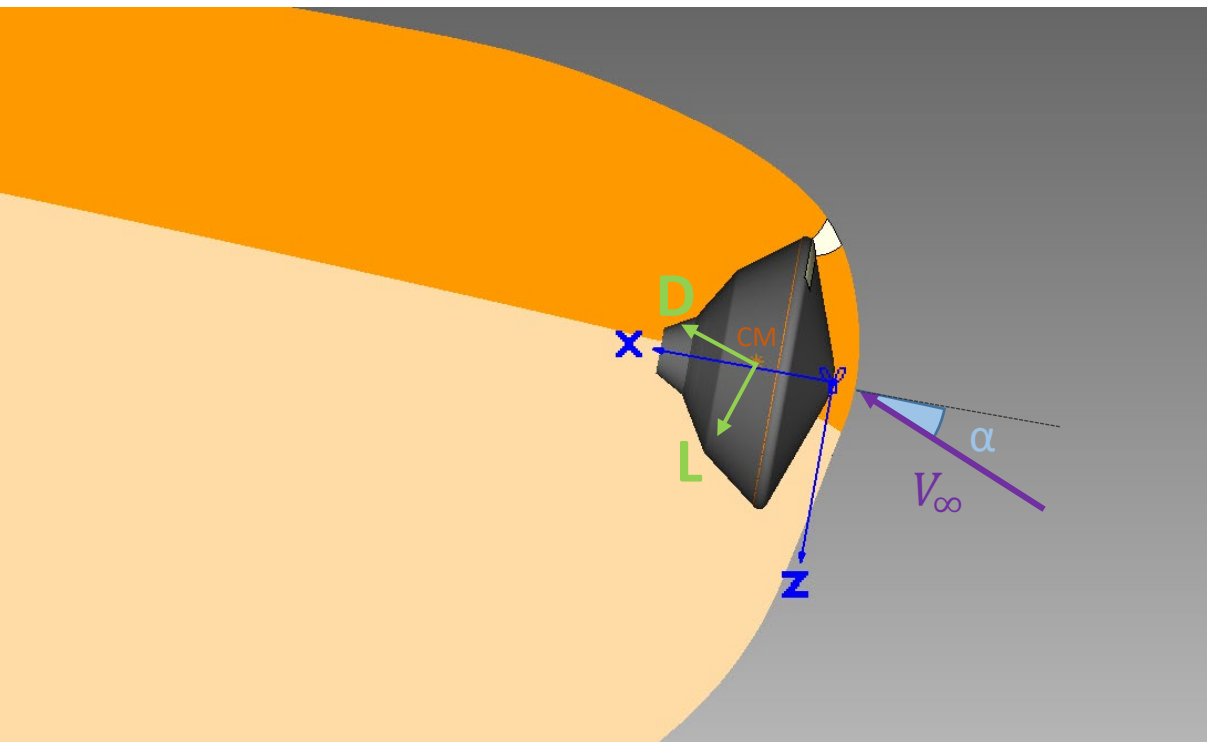
Cruden, B. A. (2023). *On the Fluid Dynamics Boundary Condition in Ablating or Blowing Flows*. June, 1–18. <https://doi.org/10.2514/6.2023-3614>



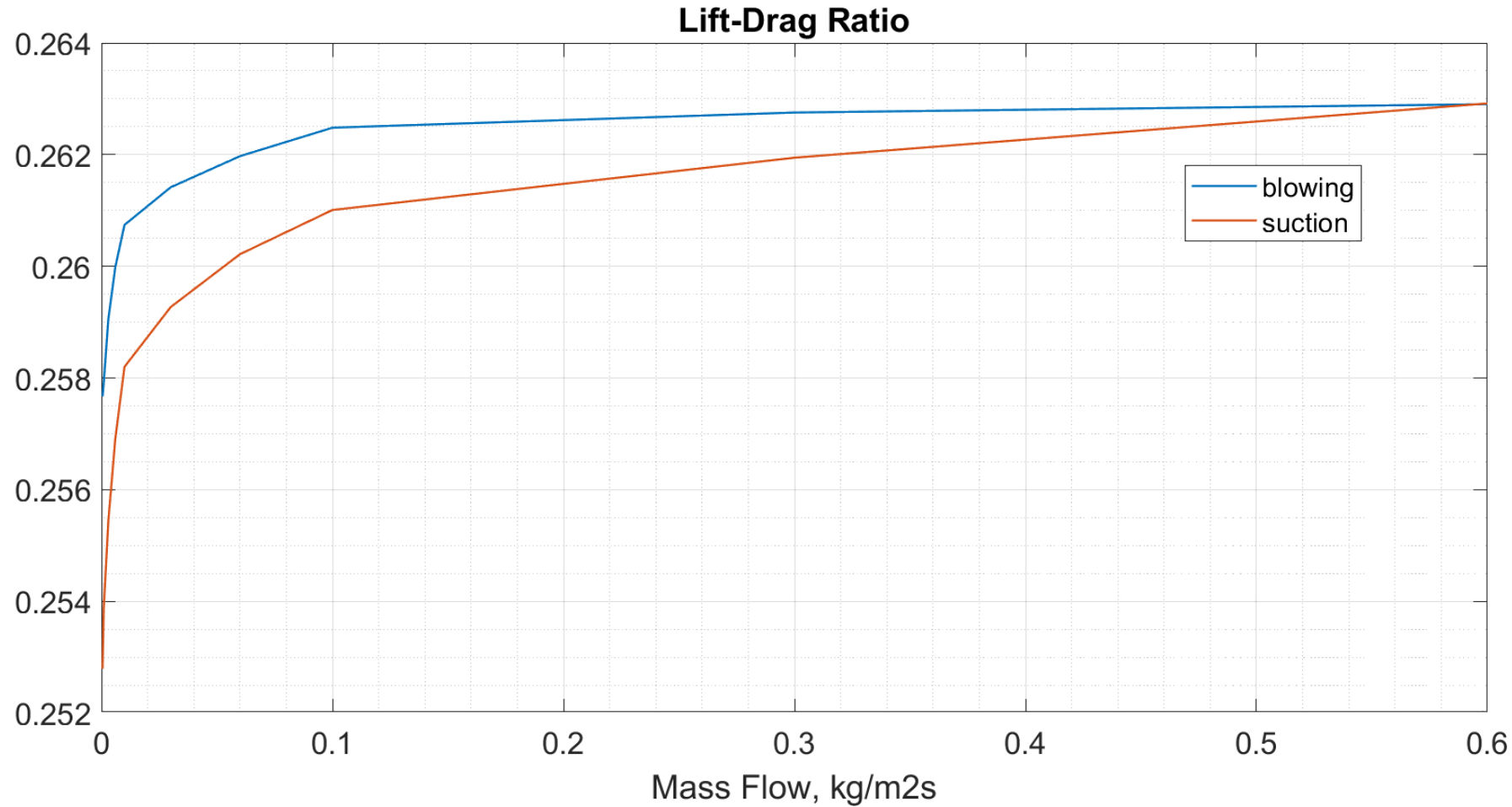
Results: Body Forces & Moments



Results: Lift & Drag Modulation



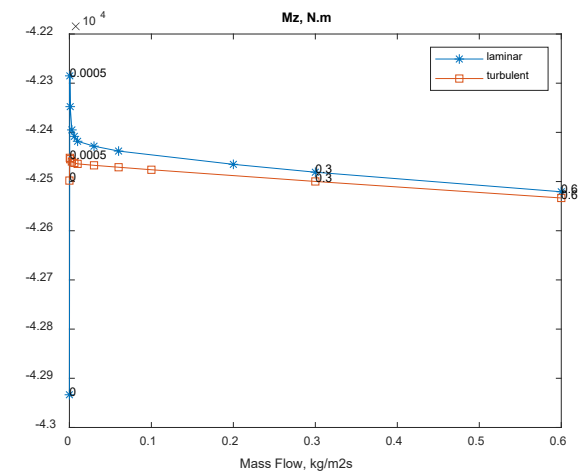
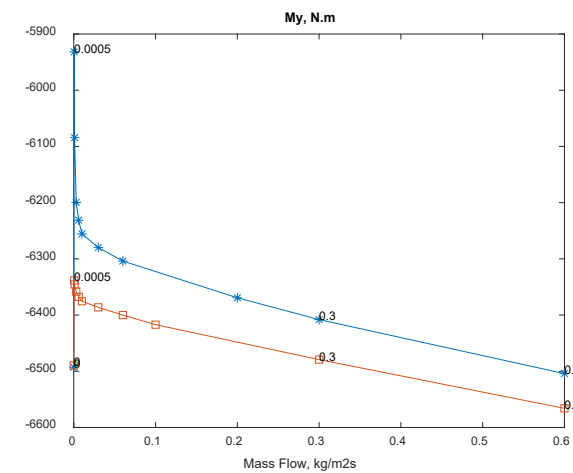
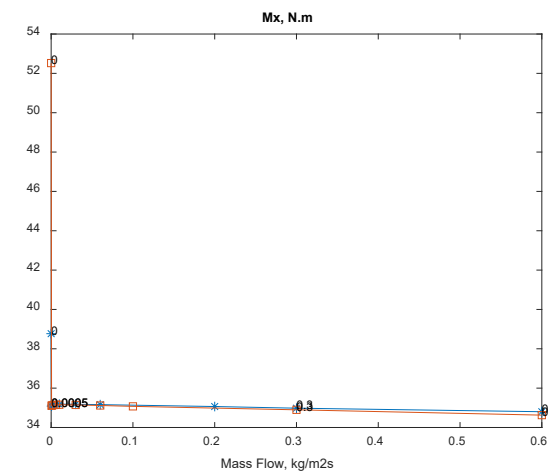
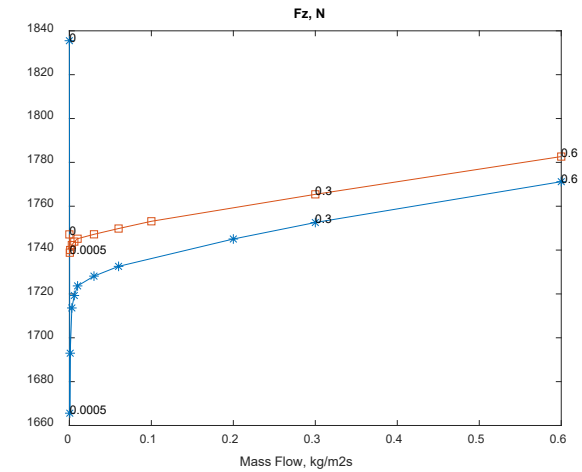
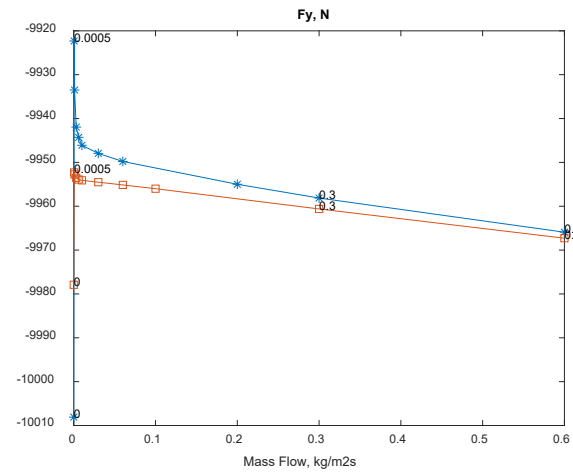
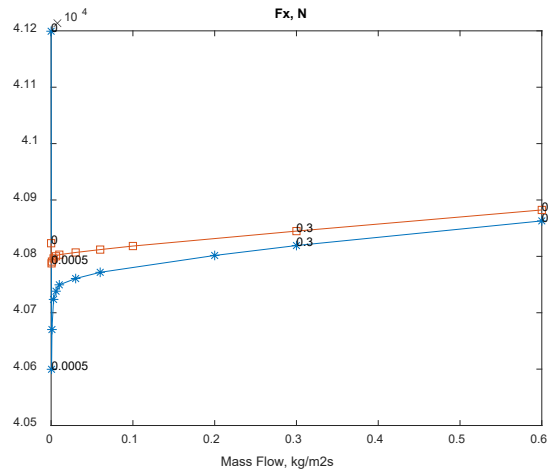
Results: Lift-Drag Ratio



NASA EDL
Goal: alter
L/D
acceleration
of $0.005\text{--}0.008\text{ s}^{-2}$



Results: Laminar vs Turbulent Body Forces & Moments



Future Work

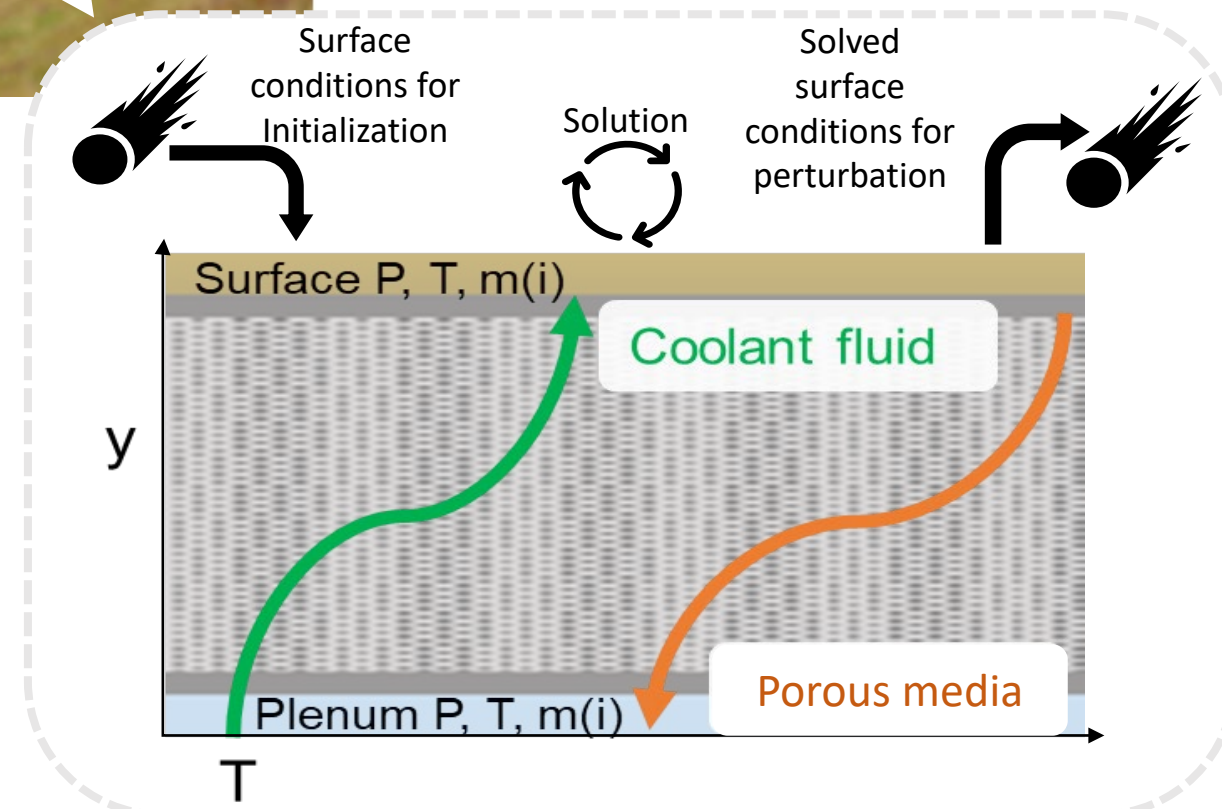
Where this is going:

- Material response solver
- 2-way coupling

Evaluation of dual system



Transpiration Cooling with Porous Ceramic Composites in Hypersonic Flow (2016, Bohrk, Hannah)





Thank you!

Any Questions?

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