Thermodynamic Scaling of Supersonic Retropropulsion Flowfields

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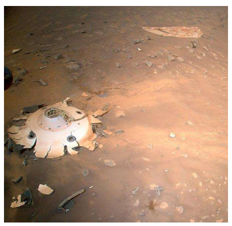
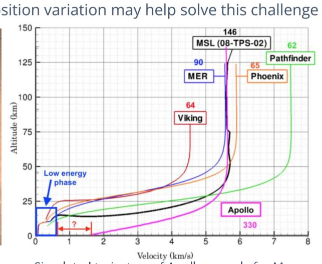
Problem Statement and Motivation

- SRP needed to safely land high ballistic coefficient payloads on Mars
- Flight relevant conditions are hard to simulate in a wind tunnel making existing SRP datasets unreliable (all cold gas Air-Air interactions)
- Modern CFD analysis lacks multi-gas validation dataset
- Existing similarity parameters have questionable ability to account for thermodynamic effects of rocket plume
- Temperature and gas composition variation may help solve this challenge



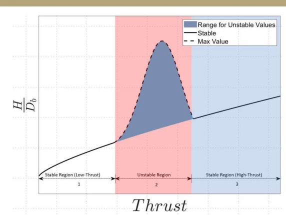
Destroyed back shell of Mars 2020 [4]



Simulated trajectory of Apollo capsule for Mars EDL compared with exiting robotic missions [1]

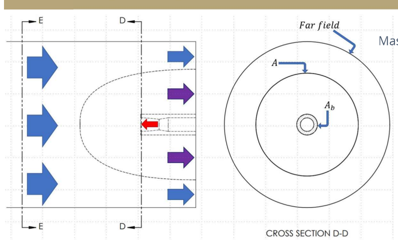
Flow Topology and Trends

- Most important features include bow shock standoff distance and curvature
- Standoff distance measured from the retronozzle exit plane to bow shock leading edge
- Stability profile shows the high thrust regime (shown in light blue) where test conditions occur and where flow is hypothesized to be self similar



Stability profile highlighting different flow regimes

Mass Conservation Control Volume Analysis



Control volume (CV) used to analyze fluid interaction. Dashed E-E and D-D lines represent flux boundaries for CV. Blue denotes freestream fluid, red is jet, and purple is mixed fluid. Dotted parabola represents the bow shockwave.

Mass Balance: $\frac{A}{A_b} = \frac{\rho_j v_j A_e}{\rho_\infty v_\infty A_b} + \int_{S_R}^{S} mixing\ region$

Suggested variables from mass conservation

$$\Psi = \frac{MW_\infty}{MW_j}\frac{T_{0,j}}{T_{0,\infty}}$$

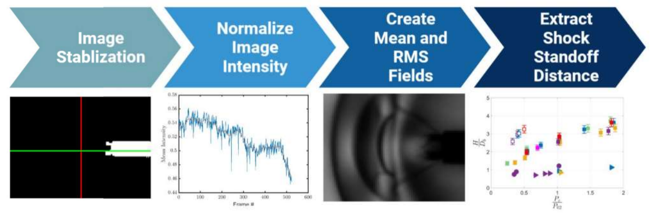
Molecular weight Stagnation temperature

$$\Gamma = \frac{\gamma_j}{\gamma_\infty}$$

Ratio of specific heat

	Ψ	Γ
Earth EDL	1-5	0.8-1
Mars EDL	1-35	1-1.3
Test Range	1-17	1-1.3

Workflow

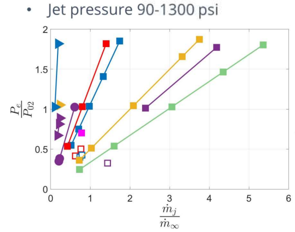


Parameter Space

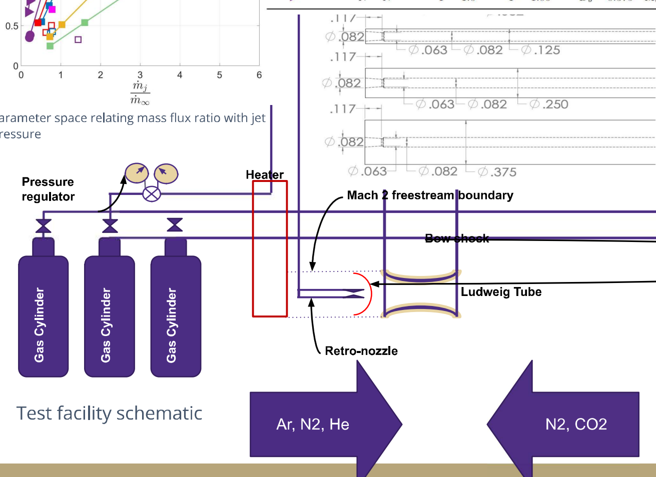
Varied Parameters

- M_e ranged between 2-3 with $M_\infty = 2$
- Jet and freestream gas composition
- Jet temperature (20-200 deg C)
- Nozzle outer diameter (1/8" – 3/8")
- Jet pressure 90-1300 psi

Symbol	Freestream-Retro	Condition			
■ (green)	$CO_2 - Ar$	$\Gamma = 1.29$	$\Psi = 1.15$	$D_b = 0.125$	$M_e = 2$
■ (blue)	$CO_2 - He$	$\Gamma = 1.29$	$\Psi = 11.43$	$D_b = 0.125$	$M_e = 2$
■ (red)	$CO_2 - He$	$\Gamma = 1.29$	$\Psi = 16.3 - 17.1$	$D_b = 0.125$	$M_e = 2$
▶ (blue)	$CO_2 - He$	$\Gamma = 1.29$	$\Psi = 11.43$	$D_b = 0.375$	$M_e = 2$
□ (blue)	$CO_2 - He$	$\Gamma = 1.29$	$\Psi = 11.43$	$D_b = 0.125$	$M_e = 3$
□ (red)	$CO_2 - He$	$\Gamma = 1.29$	$\Psi = 16.3 - 17.1$	$D_b = 0.125$	$M_e = 3$
■ (orange)	$CO_2 - N_2$	$\Gamma = 1.09$	$\Psi = 1.58$	$D_b = 0.125$	$M_e = 2$
▶ (orange)	$CO_2 - N$	$\Gamma = 1.09$	$\Psi = 1.58$	$D_b = 0.375$	$M_e = 2$
■ (magenta)	$N - He$	$\Gamma = 1.19$	$\Psi = 7.40$	$D_b = 0.125$	$M_e = 2$
■ (purple)	$N_2 - N_2$	$\Gamma = 1.0$	$\Psi = 1.06$	$D_b = 0.125$	$M_e = 2$
□ (purple)	$N_2 - N_2$	$\Gamma = 1.0$	$\Psi = 1.06$	$D_b = 0.125$	$M_e = 3$
● (purple)	$N_2 - N_2$	$\Gamma = 1.0$	$\Psi = 1.06$	$D_b = 0.25$	$M_e = 2$
▶ (purple)	$N - N$	$\Gamma = 1.0$	$\Psi = 1.06$	$D_b = 0.375$	$M_e = 2$

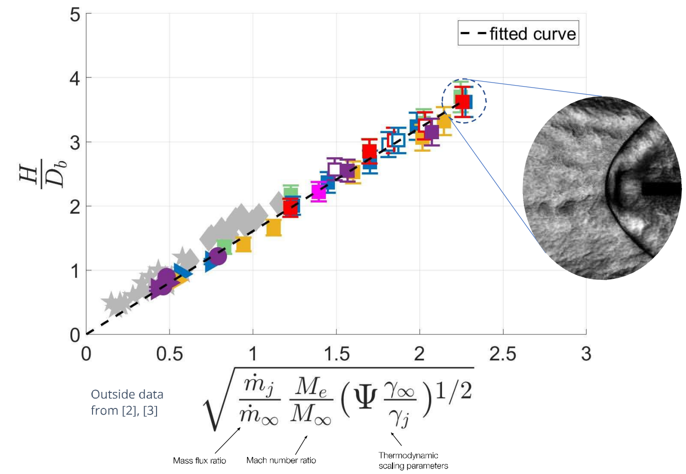


Parameter space relating mass flux ratio with jet pressure

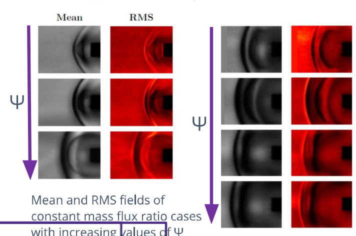


Test facility schematic

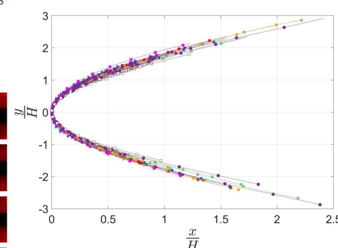
Scaling Results



- Data points in grey from outside sources
- Conditions include freestream Mach numbers 1-7, jet Mach numbers 1-3, Air-Air interactions, unheated



Mean and RMS fields of constant mass flux ratio cases with increasing values of Ψ



Shock shape extraction analysis

Conclusions

- Linear fit of standoff distance and scaled mass flux ratio independent of varied parameters
- Scaling is consistent with conservation of mass derivation
- Shock shape shown to be self similar

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[1] Fagin, M. H., PAYLOAD MASS IMPROVEMENTS OF SUPERSONIC RETRO-PROPULSIVE FLIGHT FOR HUMAN CLASS MISSIONS TO MARS, Master's thesis, Purdue University, West Lafayette, Indiana, December 2015.
[2]Romeo, D. J. and Sterrett, J. R., Exploratory investigation of the effectof a forward-facing jet on the bow shock of a blunt body in a Mach number 6 free stream, National Aeronautics and Space Administration, 1963
[3] Gutsche, K., Marwege, A., and G¨ulhan, A., "Similarity and Key Parameters of Retro-propulsion Assisted Deceleration in Hypersonic Wind Tunnels," Journal of Spacecraft and Rockets, 2021, pp. 1–13.
[4] NASA, JPL/CalTech

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