Trajectory Analysis of an Atmospheric Breathing Supersonic Retropropulsion (AB-SRP) Vehicle to Land Heavy Payloads on Mars

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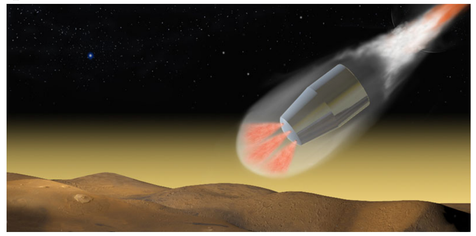
Abstract

Design and analysis of an atmospheric breathing supersonic retropropulsion system to land large-scale spacecraft (10+ MT) on Mars was performed. A simulation was developed to simulate the supersonic and subsonic phases of descent following hypersonic entry using a mid-lift-to-drag ratio elliptical sled. The ability of the atmospheric breathing retropropulsion system to land a 40 MT, human-scale payload on Mars was compared to that of a traditional supersonic retropropulsion system in order to evaluate their requisite propellant mass. The calculations confirmed that atmospheric breathing supersonic retropropulsion has the potential for significant mass savings relative to traditional architectures. Designs with higher oxidizer-to-fuel ratios were more mass efficient. The largest benefit was seen for small inlet area vehicles that leveraged deceleration from a terminal, instantaneous burn over higher thrust throughout the trajectory.

Introduction

- The exploration of Mars has progressed significantly over the last half century due to robotic landers and rovers
  - Landing capabilities of all mission have been based on incremental advances of Viking-heritage technology
  - Large-scale payloads (10+ MT) are beyond the capabilities of Viking-derived technology
- Supersonic retropropulsion (SRP) is a candidate to enable large mass missions
  - Use rocket engines directed in opposition to oncoming airflow to decelerate the entry vehicle
  - Attractive since performance can scale with payload size
  - However, drastically increases mass of vehicles since fuel is stored onboard

- Atmospheric breathing supersonic retropropulsion (AB-SRP) systems can reduce mass constraints on the entry architectures
  - Ingest oxidizer from the surrounding atmosphere and burn with onboard fuel
  - Martian atmosphere is CO_2 so traditional O_2-hydrocarbon combustion is not possible
    - Instead, can burn CO_2 with certain metals such as Mg
- Thrust profile and resulting trajectory are fundamentally changed due to airbreathing propulsion
  - Important to assess how propulsion differences correspond to overall propellant mass differences



Problem Statement

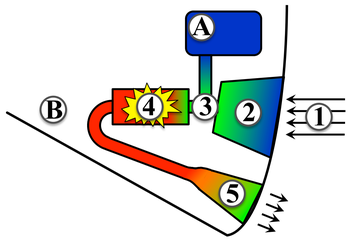
Can atmospheric breathing supersonic retropropulsion decrease entry vehicle mass by ingesting the oxidizer instead of carrying it onboard?

Propulsion System Overview

Propulsion System Diagram

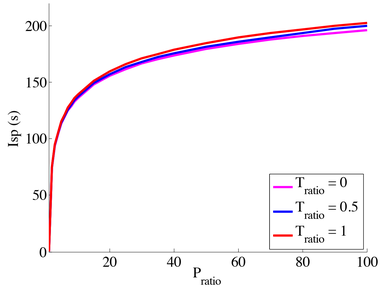
1) Oxidizer ingestion
2) Oxidizer compression
3) Fuel-oxidizer mixing
4) Combustion
5) Product expansion

A) Fuel tank
B) Vehicle outer mold line



Propulsion System Performance

- Isp = Thrust/(gravity*mass flowrate)
  - Measure of propulsive efficiency
- **Achieve I_{SP} = 140s**
- Airbreathing systems do not use onboard oxidizer
  - Scale I_{SP} by the specific fuel consumption to get $I_{SP,eff}$
  - Better metric to compare to rocket engines
  - **Achieve $I_{SP,eff}$ = 700s**
  - Compare to SRP: I_{SP} = 370s



Trajectory Simulation

- 3 DOF, point mass trajectory
- Numerically integrate equations of motion (1) – (4)
- Assumptions:
  - Inlets sweep out of column of atmosphere processing all CO_2 in that column
  - Engines in steady state (5)
  - Exponential atmosphere (6)
  - Constant aerodynamic coefficients, no lift
  - Constant OF = $\dot{m}_{ox}/\dot{m}_{fuel}$
- Vehicle parameters and initial conditions based on literature values of human-scale mission
  - M_{PL}= 40 MT, M_S = 10 MT
  - Start: h = 4600m, v = 555m/s, End: h = 0m, v = 0m/s
- AB-SRP unable to meet 0m/s condition with steady-state thrust
  - Remove final velocity with terminal impulsive burn
  - Oxidizer for terminal burn stored prior to thrust initiation
- Trajectories optimized to land with 0 propellant

$$\dot{v} = -g\sin(\gamma) - \frac{1}{m}\left(\frac{1}{2}\rho v^2 C_D A_{ref}\right) - \frac{T}{m}\cos(\theta) \quad (1)$$

$$\dot{\gamma} = -\frac{g}{v}\cos(\gamma) + \frac{1}{mv}\left(\frac{1}{2}\rho v^2 C_L A_{ref}\right) + \frac{T}{mv}\sin(\theta) \quad (2)$$

$$\dot{h} = v\sin(\gamma) \quad (3)$$

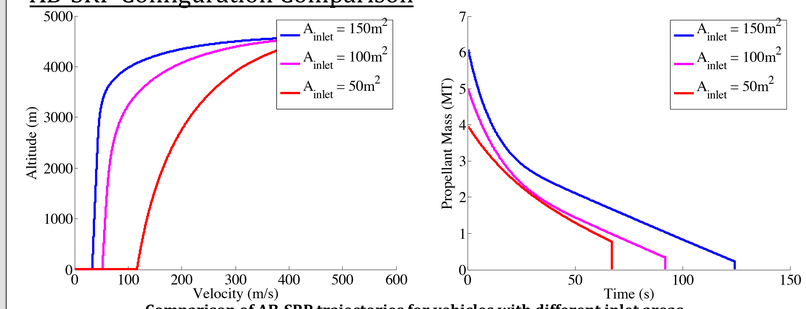
$$\dot{m}_f = \frac{-T}{gI_{SP}(OF+1)} \quad (4)$$

$$T = gI_{SP}\left(\frac{1}{OF}+1\right)\rho v A_{in} \quad (5)$$

$$\rho = \rho_0 e^{-h/H} \quad (6)$$

Results

AB-SRP Configuration Comparison

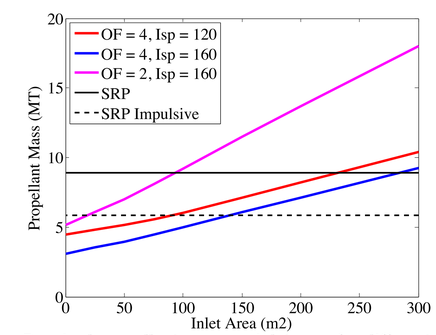


Comparison of AB-SRP trajectories for vehicles with different inlet areas

- AB-SRP vehicles reach pseudo-terminal velocity
  - Dependent on inlet area
- **Smaller inlet: lower total propellant**, larger terminal propellant
  - Vehicle preferences instantaneous burn over continual thrusting
  - Benefit from atmospheric drag and more efficient maneuver
  - Limited by amount of CO_2 capture and acceleration limits

AB-SRP and SRP Comparison

- **AB-SRP has potential to decrease propellant mass**
- Increased benefit for:
  - Large OF - leverage more atmospheric oxidizer
  - Larger I_{SP} – better mass efficiency
- Practical AB-SRP inlet sizes on order of the vehicle frontal area – 80m^2



Required propellant mass vs. inlet area for different AB-SRP configurations compared with SRP vehicles

Conclusion

- AB-SRP vehicles reduce propellant mass over SRP vehicles
- Highest benefits seen for large I_{SP} and large oxidizer-to-fuel ratios
- Vehicles with smaller inlets required less propellant – preference terminal burn over continual thrusting
  - Will be reassessed with more accurate estimates of CO_2 capture and acceleration limits
- Architectures exploiting innovative ways to increase oxidizer mass capture will have the most benefit since AB-SRP vehicles are limited by amount of CO_2 ingested

Acknowledgements

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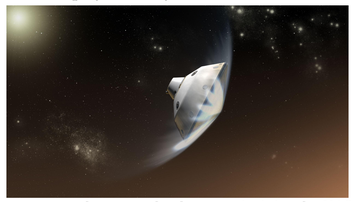

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