Atmospheric Reentry Analysis: Heat Flux, Trajectory, and Ablation Modeling

A Comprehensive Study of Ballistic and Lifting Reentry Profiles

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Abstract

This research paper presents a comprehensive analysis of atmospheric reentry dynamics for spacecraft vehicles. We develop and compare ballistic and lifting reentry trajectories, computing time histories of altitude, velocity, deceleration, and stagnation-point heat flux. The analysis includes an exponential atmospheric model, Sutton-Graves heat flux correlation, and a simplified ablation model for thermal protection system sizing. Multiple entry angles and ballistic coefficients are evaluated to determine optimal reentry profiles for human-rated and cargo vehicles.

1 Introduction

Atmospheric reentry is one of the most challenging phases of space flight, subjecting vehicles to extreme thermal and mechanical loads. The kinetic energy of an orbiting spacecraft must be dissipated through aerodynamic drag and converted to heat, much of which is transferred to the vehicle surface. Understanding the physics of reentry is essential for thermal protection system (TPS) design and crew safety.

Definition 1 (Ballistic Coefficient) *The ballistic coefficient characterizes a vehicle's resistance to atmospheric drag:*

$$\beta = \frac{m}{C_D A} \tag{1}$$

where m is vehicle mass, C_D is drag coefficient, and A is reference area. Higher β results in faster descent and higher heating rates.

2 Mathematical Framework

2.1 Equations of Motion

For planar reentry, the equations of motion in a rotating frame are:

$$\frac{dV}{dt} = -\frac{\rho V^2}{2\beta} - g \sin \gamma \tag{2}$$

$$\frac{d\gamma}{dt} = \frac{1}{V}\left[\left(\frac{V^2}{r} - g\right)\cos\gamma + \frac{L}{m}\right] \tag{3}$$

$$\frac{dh}{dt} = V \sin \gamma \tag{4}$$

$$\frac{dr_d}{dt} = \frac{V \cos\gamma \cdot R_E}{R_E + h} \tag{5}$$

where V is velocity, γ is flight path angle (negative for descent), h is altitude, and r_d is downrange distance.

2.2 Atmospheric Model

We employ an exponential atmosphere:

$$\rho(h) = \rho_0 \exp\left(-\frac{h}{H}\right) \tag{6}$$

with scale height $H \approx 8.5$ km for Earth's lower atmosphere.

2.3 Heating Relations

Theorem 1 (Sutton-Graves Correlation) *The convective heat flux at the stagnation point of a blunt body is:*

$$\dot{q}_s = C\sqrt{\frac{\rho}{r_n}}V^3 \tag{7}$$

where $C = 1.83 \times 10^{-4}\ W{\cdot}m^{-1.5}/(kg^{0.5}m^{-3}s^{-3})$ *and* r_n *is the nose radius.*

The total heat load is the integral over the trajectory:

$$Q = \int_0^{t_f} \dot{q}_s\, dt \tag{8}$$

2.4 Ablation Model

For ablative TPS, the surface recession rate is:

$$\dot{s} = \frac{\dot{q}_s - \sigma T_w^4}{H_{eff}} \tag{9}$$

where H_{eff} is the effective heat of ablation and T_w is the wall temperature.

3 Computational Analysis

4 Computational Algorithm

```
Input: Initial state [V_0, γ_0, h_0], vehicle parameters β, r_n, L/D
Output: Time histories of V(t), h(t), q̇(t), peak values
Initialize state vector;
for each time step do
    Compute atmospheric density ρ(h);
    Compute gravity g(h);
    /* Aerodynamic accelerations                              */
    D/m ← ρV^2/(2β);
    L/m ← (D/m) · (L/D);
    /* Equations of motion                                    */
    Integrate equations (2)-(5);
    /* Heat flux                                              */
    q̇_s ← C sqrt(ρ/r_n) V^3;
    Store results;
end
Compute peak deceleration and heat flux;
Compute total heat load Q = ∫ q̇ dt;
return Trajectory data, thermal loads
```

Algorithm 1: Atmospheric Reentry Simulation

5 Results and Discussion

5.1 Vehicle Comparison

5.2 Key Observations

Remark 1 (Vehicle Configuration Trade-offs) *The Shuttle configuration experiences the longest reentry duration due to its high L/D ratio, which reduces peak heating but increases total heat load. The capsule configuration experiences the highest peak deceleration but shortest heating duration.*

The **??** configuration achieves the lowest peak deceleration of **??** g, making it most suitable for human-rated missions (typically requiring < 10 g).

5.3 Entry Angle Sensitivity

Remark 2 (Entry Corridor) *Shallow entry angles reduce peak heating but extend the heating duration and increase total heat load. Steep entry angles cause excessive deceleration. The entry corridor is bounded by skip-out (too shallow) and structural limits (too steep).*

5.4 Thermal Protection Implications

For the capsule with $\gamma_0 = -2°$:

- Peak heat flux: **??** MW/m^2
- Peak heating occurs at $t =$ **??** s
- Altitude at peak heating: **??** km
- Total heat load: **??** MJ/m^2

6 Ablation Analysis

For an ablative heat shield with $H_{eff} = 30$ MJ/kg and density $\rho_{TPS} = 1500$ kg/m^3:

$$\text{Minimum TPS thickness} = \frac{Q}{\rho_{TPS} \cdot H_{eff}} \tag{10}$$

For the capsule configuration:

- Minimum ablator thickness: **??** mm
- Design thickness (SF = 2.0): **??** mm

7 Limitations and Extensions

7.1 Model Limitations

1. **2D trajectory**: Neglects out-of-plane maneuvers and Earth rotation
2. **Exponential atmosphere**: Does not capture density variations with latitude/season
3. **Constant aerodynamics**: C_D and L/D vary with Mach and Reynolds numbers
4. **Simplified heating**: Neglects radiative heating and real-gas effects
5. **No ablation coupling**: Surface recession not coupled back to aerodynamics

7.2 Possible Extensions

- 6-DOF simulation with attitude dynamics
- Knudsen number effects in rarefied upper atmosphere
- Real-gas thermochemistry for shock layer

- Coupled ablation-aerothermal analysis
- Monte Carlo trajectory dispersion analysis

8 Conclusion

This analysis demonstrates the critical trade-offs in atmospheric reentry vehicle design:

- Higher L/D ratios reduce peak g-loads but extend heating duration
- Larger nose radii reduce peak heat flux (spreading over larger area)
- Entry angle selection is constrained by the entry corridor
- The **??** configuration with peak deceleration of **??** g is most suitable for crew return

The computational methods provide a foundation for preliminary TPS sizing and mission design.

Further Reading

- Anderson, J. D. (2006). *Hypersonic and High-Temperature Gas Dynamics*. AIAA.
- Sutton, K., & Graves, R. A. (1971). A general stagnation-point convective-heating equation for arbitrary gas mixtures. NASA TR R-376.
- Tauber, M. E., & Sutton, K. (1991). Stagnation-point radiative heating relations for Earth and Mars entries. Journal of Spacecraft and Rockets.