Atmospheric Entry

Technology, Mathematical Model and Simulation

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RWTH Aachen, August 26th 2016
Outline

1. Introduction to Atmospheric Reentry

2. Rarefied Gases: From Science Fiction to Simulation

3. PhD Topic

Atmospheric Entry Talk
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Introduction to Atmospheric Reentry
Atmospheric reentry

Atmospheric entry is the movement of human-made objects as they enter the atmosphere of a celestial body from outer space.

Object can be:

- Spacecraft
  - Space capsule
  - Space ship
- Satellite
- Intercontinental ballistic missile
Main objectives:

1. search for trace atmospheric gases
2. test critical technology for future missions

- Trace gas orbiter
- Entry, decent and landing demonstrator module
Mars EDL

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Atmospheric reentry made in Hollywood
Some hard facts about reentry

- Reentry starts at Karman line
  - Earth 100km
  - Mars 80km
- Velocity of reentry vehicle
  - Low Earth orbit 7.8 km/s
  - Lunar return 11 km/s
  - Mars return 14 km/s
- Surface temperature more than 1000K
- Energy exchange between kinetic energy and thermal energy
- Mars landing is not possible above 2km ground level

Further Mars missions require advanced technologies
- Reentry vehicle and Heat shield
Mars landings

Pathfinder 1997
Beagle 2 2003
Curiosity 2012
Spiral 2004
Opportunity 2004
Phoenix 2008

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Reentry path and velocity curve

- Narrow corridor
- Velocity curve and range
- Reentry time
Reentry vehicle design

Low ballistic coefficient for fast deceleration

Heat protection by design

Apollo capsule
Heat shield technologies

Heat sinks
• Spread out and store the heat
• Increase in mass of object

Ablation
• Melt vehicle’s outer shell, taking heat away
• Not reusable

Radiative cooling
• radiates a large percentage of the heat away before the vehicle can absorb it
• Combine with thermal isolation
• Space Shuttle uses ceramic tiles

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Flow field around vehicle

- Fast cold flow in front of vehicle
- Bow shock around leading edge
- Strong shock at nose
- Subsonic layer
- Highest temperature around shock
- Dissociation and ionization
- Heat transported to the sides
- Vortices in recirculation region
- Relatively narrow wake
Rarefied Gases: From Science Fiction to Simulation
Hypersonic wind tunnel:
Flow between high and low pressure chamber

Problems:
- Temperatures not high enough
- Velocity to slow
- Pressure ratios too low
- Measurement time very, very short
Numerical simulations

1. Develop mathematical model and implement numerical solution method

2. Set up test case and run computer program on big machines

3. Get simulation results
Why simulations?

Development and optimization needs testing

1. Real-world experiments
2. Wind tunnel experiments
3. Simulations

Problems of experiments:
- Small parameter range
- Limited measurement capabilities
- Expensive

Benefits of simulations:
- Variable conditions
- Detailed measurements possible
- Repeatable
What to simulate?

- Edge of space: vacuum plus molecules, particle model

- High altitude: rarefied gas, new model

- Ground level: dense gas, continuum model

Rarefied flow characterized by large Knudsen number:

$$\text{Kn} = \frac{\text{mean free path}}{\text{characteristic length}} = \frac{\lambda}{L}$$
Mathematical models for rarefied gases

Rarefied flow characterized by large Knudsen number: \( Kn = \frac{\lambda}{L} \)

- \( \lambda \): mean free path length of molecules
- \( L \): characteristic length of system

Applications for large Knudsen numbers:

- **Large** \( \lambda \): reentry flights, hypersonic flows
- **Small** \( L \): microchannels, microelectromechanical systems
Standard Solution methods

Stochastic particle method: Direct Simulation Monte-Carlo
- Single particles that move through space and collide
- Needs many particles
- Stochastic noise in results

Continuum models
- Derive equations from conservation of mass, momentum and energy
- Example: Euler or Navier-Stokes equations

\[
\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{u}) = 0 \\
\frac{\partial (\rho \mathbf{u})}{\partial t} + \nabla \cdot (\mathbf{u} \otimes (\rho \mathbf{u})) + \nabla p = 0 \\
\frac{\partial E}{\partial t} + \nabla \cdot (\mathbf{u}(E + p)) = 0
\]
PhD Topic
Moment model

Rarefied gases:

- Continuum models too inaccurate
- Particle models too expensive

Extension of standard continuum model: additional equations and variables

Prediction of new effects:

- Heat flux from cold to warm
- Knudsen paradox
Mathematical Modelling

Boltzmann Transport Equation:

\[ \frac{\partial f}{\partial t} + c_i \frac{\partial f}{\partial x_i} = S(f) \]

PDE for particles' probability density function \( f(t, x, c) \)
- \( f(t, x, c) \) probability of finding a particle at time \( t \) and position \( x \) with velocity \( c \)
- Boltzmann equation describes change of \( f \) due to transport and collisions

Relation to macroscopic quantities:
- Density \( \rho = \int f \, dc \)
- Momentum \( \rho v_i = \int c_i f \, dc \)
- ...
Mathematical Modelling II

Aim: Derivation of a hyperbolic PDE system

\[
\frac{\partial u}{\partial t} + A_i \frac{\partial u}{\partial x_i} = S(u)
\]

Hyperbolicity is important for:
• Physical solutions with bounded propagation speeds
• Well-posedness and stability of the solution

Drawbacks:
• Numerical solution of new model is more difficult
• Accuracy of the model compared to experiments is unclear
Thank you for your attention!