Atmospheric Reentry
Introduction, Mathematical Model and Simulation

Julian Köllermeier
Theodor-Heuss Akademie, August 23rd 2014
A short history of human spaceflight

1944  V2 is first rocket in space
1957  Sputnik and start of Space Race, Sputnik crisis
1957  Laika is first living animal in space
1961  Yuri Gagarin first man in space, 108 minutes, single orbit
1965  first spacewalk by Alexei Leonov
1966  first Soyuz launch
1969  Neil Armstrong is first man on the moon
1981  first Space Shuttle flight
1986  start of Mir assembly
1998  start of ISS assembly
Atmospheric reentry

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

Objects can be:
- Spacecrafts
  - Space capsule
  - Space plane
- Satellites
- Intercontinental ballistic missile
Atmospheric reentry made in Hollywood
Some hard facts about reentry

• Reentry starts at Karman line
  – Earth 100km
  – Venus 250km
  – Mars 80km

• Velocity of reentry vehicle
  – Low Earth orbit 7.8 km/s
  – Lunar return 11km/s
  – Mars return 14km/s

• Mach number up to 25

• Peak temperature around velocity in m/s, surface temperature more than 1000K

• Energy exchange between kinetic energy and thermal energy
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

streamlined vehicle (high ballistic coefficient)

heat concentrated

attached shock wave

blunt vehicle (low ballistic coefficient)

heat spread over larger volume

detached shock wave
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
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
Experimental facilities and problems

Hypersonic wind tunnel:
Flow between high and low pressure chamber

Problems:
• Temperatures not high enough
• Velocity too 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

Benefits:
- Save money and time
- Repeatable
- Variable conditions

Atmospheric Reentry Talk
Julian Köllermeier
Theodor-Heuss Akademie, August 23rd 2014
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
Solution methods

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

Deterministic methods: Moment methods
- Derive equations for most important flow variables (density, velocity, temperature, heat flux)
- Extension of standard fluid dynamics

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

A New Approach for the Approximation of Kinetic Equations
- Stable Projections and High-Resolution Numerics of Real Applications

Milestones:

• Derivation of new hyperbolic equation systems for moments
• Investigation of analytical properties
• Development of dedicated numerical solution method
• Simulation of real application problems

Thank you for your attention!