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Hypersonic Flows for Reentry Problems

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Problems for Analysis

In the perspective of European and American space projects, the knowledge of flows at high Mach numbers and large angles of attack, occurring during the atmospheric reentry of space vehicles, has regained recently considerable interest. The extreme physical conditions realized during this critical phase are at the limit of possible experimental measurements, because of the rarefied atmosphere and/or the very high temperatures. The experimentation is therefore very difficult (if available) and costly. In addition, safety requirements cannot be achieved by over-dimensioning the structures without compromising the operational performance. Hence, the numerical simulation is led to play a major role in the process of the project validation.

During reentry, three main types of flow are encountered:

- rarefied gas flow,
- reacting flow,
- non-reacting flow.

The governing equations to be solved are then respectively - the Boltzmann equations, - the Euler or Navier-Stokes equations combined with a chemistry model, - the Navier-Stokes equations possibly combined with a turbulence model.

The following eight critical problems have been proposed to the participants:

Problem 1: Flow over a Slender Cone

Problem 2: Base Flow

Problem 3: Flow over a 2D Ramp

Problem 4: Flow over a 3-D Obstacle

Problem 5: Corner Flow

Problem 6: Flow over a Double Ellipse/ Double Ellipsoid

Problem 7: Flow over a Delta Wing

Problem 8: Non-equilibrium Flow in an Arc Jet or a Shock Tube

Due to the interest or the difficulty of each test case, a level of gradation, ranging from no "star"(0) to four "star (****) has been attibuted. The mandatory condition for participation is to collect a sum of at least four stars, by any combination of test cases solved (for example four cases with one star (*), or two cases with two stars (**), etc...).

Fluid Characteristics and Notations

- **Fluid characteristics**

1. **Non-reactive flows**

• The fluid is a perfect gas with specific heats c_p, c_v with ratio

$$\gamma = \frac{c_p}{c_v} = 1.4$$

• If p is the static pressure, the pitot pressure p_t is defined by :

$$\frac{p_t}{p} = \left(\frac{(\gamma+1)M^2}{2}\right)^{\gamma/(\gamma-1)} \left(\frac{\gamma+1}{2\gamma M^2 - (\gamma-1)}\right)^{1/(\gamma-1)}$$

• The viscosity coefficients λ, μ verify the Stokes relation:

$$3\lambda + 2\mu = 0$$

• The Prandtl number is constant: $Pr = \mu c_p/\kappa = .72$ where κ is the thermal conductivity coefficient.
• The viscosity coefficient μ is a function of temperature T in Kelvin according to Sutherland's law:

– If $T_\infty \geq 120K$:

$$\mu(T) = \mu_\infty \left(\frac{T}{T_\infty}\right)^{1.5} \left(\frac{T_\infty + 110.}{T + 110.}\right) \quad \text{if } T \geq 120K$$

$$\mu(T) = \mu(120)\frac{T}{120} \quad \text{if } T \leq 120K$$

– If $T_\infty \leq 120K$:

$$\mu(T) = \mu_\infty \frac{T}{T_\infty} \quad \text{if } T \leq 120K$$

$$\mu(T) = \mu(120)\left(\frac{T}{120}\right)^{1.5} \left(\frac{120. + 110.}{T + 110.}\right) \quad \text{if } T \geq 120K$$

μ_∞ is obtained from the Reynolds number : $Re_\infty/m = u_\infty \rho_\infty/\mu_\infty$, a value of temperature in Kelvin is required to adjust the constant in Sutherland's law (T_∞ in Kelvin).
• When a turbulent simulation is required, the choice of the model is completely free.

2. **Non-equilibrium reactive flows**

• A computation with Park's model is required. This model is described in Appendix 1 where the unit for the rate constants is $cm^3/mole/s$. In addition, participants are encouraged to also use more accurate physical models to assess the influence of the model.
• The body surface is supposed to be fully non-catalytic in all test cases.

• Contributors should be aware that Sutherland's law is not physically relevent and alternate models should be used.

3. **Equilibrium reactive flows**

• Similar models as for non-equilibrium reactive flows but with the assumption of local equilibrium.

4. **Rarefied gases**

• The internal energy model to be considered is the Larsen - Borgnakke model. Calculations should be performed for a monoatomic gas for comparison or if the participants have not implemented the Larsen - Borgnakke model.

• The fluid is characterized by the mean free path at infinity λ_∞.

• **Notations**

The following non dimensional coefficients are defined:

• Pressure coefficient: $C_p = \frac{p - p_\infty}{0.5\rho_\infty u_\infty^2}$ where ρ_∞ and u_∞ are the density and the velocity at infinity.

• Skin friction coefficient: $C_f = \frac{\tau_w}{0.5\rho_\infty u_\infty^2}$ (τ_w: wall shear stress)

• Heat flux coefficient: $C_h = \frac{q}{0.5\rho_\infty u_\infty^3}$ where q is the heat flux; in the continuum regime: $q = -\kappa \nabla T \cdot n$ where n is the outward normal to the wall.

• Stanton number : $St = \frac{q}{\rho_\infty \; u_\infty \; c_{p\infty}(T_{0_\infty} - T_w)}$ where $c_{p\infty}$ is the free stream specific heat at constant pressure, T_{0_∞} is the reservoir isentropic stagnation temperature and T_w is the wall temperature.

• All dimensions are given in the meter, kilogram, second (MKS) system.

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