Transition in hypersonic flows including high-temperature gas effects

By Christian Stemmer †

1. Motivation and Objective

Hypersonic transition poses a special challenge for direct numerical simulations. Comparable data from Wind-tunnel tests or free-flight testing are not available or not accurate enough for comparison. The wind-tunnel testing does not allow for the exact match to the free-flight conditions at such high Mach-numbers.

Flat-plate boundary-layer transition at high Mach-numbers is investigated in this work. A simulation case was chosen where chemical non-equilibrium plays an important role but ionization can be neglected. The chosen case at an altitude of H=50Km lies close to one point on the descent path of the Space Shuttle. The failure of the Space Shuttle has shown that an improved vehicle for space transportation is imperative in the close future. Transition research for an improved space-transportation vehicle is crucial in order to estimate the heat load during re-entry.

2. Numerical Method

A sixth-order accurate numerical method (Adams & Shariff 1996; Adams 1998, 2000) is extended to incorporate chemical source terms and a conservation equation for the vibrational temperature (Stemmer & Mansour 2001). This is necessary for the simulation of chemical non-equilibrium which is present in the investigated regime.

Compact finite differences are employed and the grid is stretched in the wall-normal direction. Periodic conditions in the spanwise direction are enforced. A third-order accurate Runge-Kutta method is used for the advancement in time. Shocks can be treated separately through a hybrid ENO method, which is applied only in the areas where shocks are present.

For the presented simulation, a resolution of $1500 \times 240 \times 6$ points in x, y and z-direction was used. This yields a resolution of $\Delta x = 0.066$, $\Delta y_{min} = 7.717 \cdot 10^{-3}$ and $\Delta z = 0.146$, where the lengths are made dimensionless with the boundary-layer thickness $\delta_1 = 0.2197$m.

3. Results

A comparison for the steady base-flow results for three different cases is presented. Firstly, the **ideal-gas** case is considered. The second case considers **chemical equilibrium** and at last, the **chemical non-equilibrium** case is calculated.

The most notable difference for the three steady flows is in the temperature which is shown in the following graphs. The wall-normal profiles of the five chemical species are also shown.

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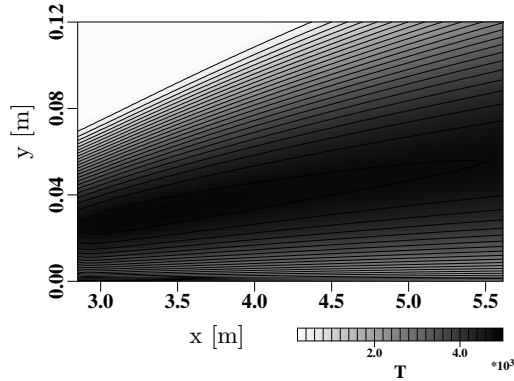
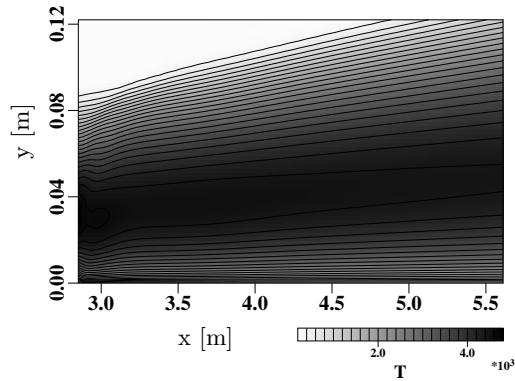FIGURE 1. Ideal gas case; temperature in the M=20 boundary layer; contours in intervals of 200K from 200-5000K

FIGURE 2. Chemical equilibrium case: temperature in the M=20 boundary layer; contours in intervals of 200K from 200-5000K
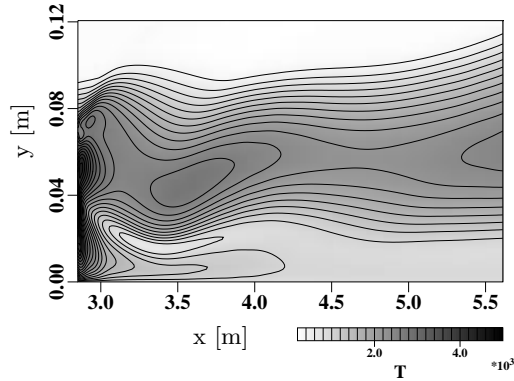
FIGURE 3. Chemical non-equilibrium case; temperature in the M=20 boundary layer; contours in intervals of 200K from 200-5000K
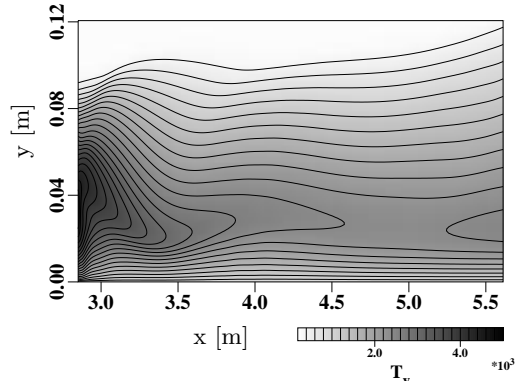
FIGURE 4. Chemical non-equilibrium case: vibrational temperature in the M=20 boundary layer; contours in intervals of 200K from 200-5000K

For the ideal-gas case (Fig.1), the similarity solution given at the inflow (Re=1.13 × 10^6) exhibits a maximum temperature of T=4773.2K at y=0.033m away from the wall. This temperature is approximately retained in the growing boundary layer.

For the chemical equilibrium case (Fig.2), after a short accommodation effect downstream of the similarity solution inflow, shows a maximum temperature of T=4478K for a given downstream location of x=5.0m at a wall-normal distance of y=0.047m. This constitutes a decrease in temperature of Δt=6.2%.

For the chemical non-equilibrium case (Fig.3), the development of the non-equilibrium conditions takes somewhat longer and the maximum temperature drops to T=2028K at y=0.066m at the same downstream location. The vibrational temperature in this case is shown in Fig.4. The vibrational temperature at T=2100K is close to the level of the translational temperature, but the maximum is observable closer to the wall at y=0.042m for the same downstream location.

The wall-normal profiles of the species concentrations for the chemical equilibrium case are shown in Fig.5 and for the non-equilibrium case in Fig.6. In both cases, the concentrations of the species N and NO are multiplied by a factor in order to make them
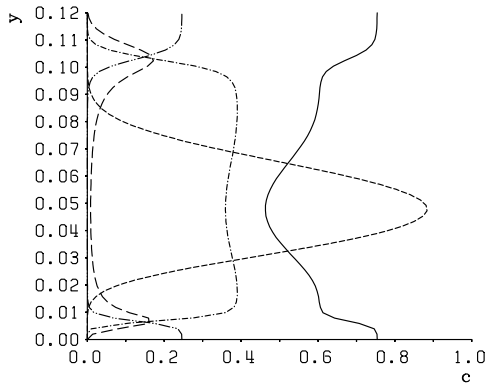
FIGURE 5. Chemical equilibrium case: concentration of chemical species ($c_N \times 5$ ---- ; c_{N2} —— ; c_O —·— ; c_{O2} —··— ; $c_{NO} \times 10$ ---)
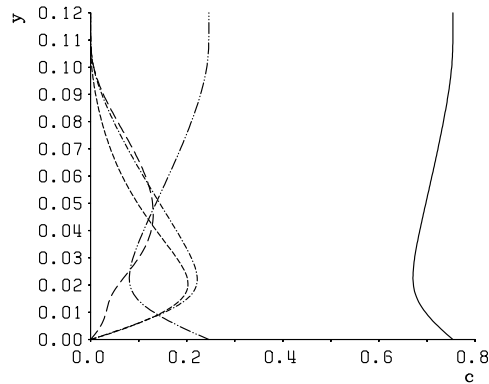
FIGURE 6. Chemical non-equilibrium case: concentration of chemical species ($c_N \times 10$ ---- ; c_{N2} —— ; c_O —·— ; c_{O2} —··— ; $c_{NO} \times 10$ ---)

visible in the chosen graph range. In the equilibrium case, the concentrations are a direct function of the temperature distribution as shown in Fig.2. The temperatures are high enough to almost entirely dissociate molecular oxygen inside the boundary layer. Nitrogen is dissociated to a lesser extent and the molecular level remains at almost 50% for the maximum temperature of T=4478K. For the non-equilibrium case, the deviation from the equilibrium state is most noticeable closer to the wall. The maximum dissociation levels are attained at y=0.02m and the maximum level of NO is reached a little further away from the wall at y=0.045m for the same downstream location x=5.0m.

4. Future Work

Normal and oblique mode transition studies for the described Ma=20 flow will be performed. Simulations will be undertaken to provide for chemical and thermal non-equilibrium conditions.

To mimic closer the introduction of disturbances in an experimental environment, a point source disturbance, Stemmer (2001), will be introduced. Therewith, a single frequency but all possible spanwise wave numbers can be excited simultaneously leaving it to the flow to amplify the unstable components of the disturbance.

Laminar-turbulent transition scenarios under varying disturbance conditions will be investigated to understand more about the physical behavior of chemically reacting flows in transition on a flat plate.

Qualitative comparison to the experiments by Mironov & Maslov (2000) will be conducted.

5. Acknowledgments

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