Effect of the local wall cooling/heating on the hypersonic boundary layer stability and transition

Andrey Sidorenko, Pavel Polivanov, Yury Gromyko, Dmitry Bountin and Anatoly Maslov

Khristianovich Institute of Theoretical and Applied Mechanics (ITAM)
RUSSIA 630090, Novosibirsk, Institutskaya str. 4/1.

The development of secure and re-usable re-entry vehicle requires the complete control of the heat distribution on its thermal protection system (TPS). During the most critical re-entry phase, the hypersonic flow along the vehicle initiates a laminar boundary layer inside of which most of the transfer phenomena take place (heat, momentum and mass transfer). If at one position of the vehicle, this boundary layer experiences a transition from the laminar to the turbulent regime then at the corresponding position the TPS will receive a sharp increase of the incoming heat flux (minimum 3 times higher). If the vehicle aims to be re-usable, it is mandatory to protect it adequately against this overheat. Therefore aerospace designer needs to receive the proper information and tools allowing a better prediction and ultimately a better control of the transition in hypersonic regime.

For configurations having aerodynamically smooth surfaces, transition is associated with excitation in the boundary layer and downstream amplification of unstable modes, namely, the first and second modes. Although features of these instabilities and opportunities of their control have been studied by the research community for more than fifty years, they have been focused on boundary layers having fairly uniform distributions of the wall temperature and heat fluxes. However, actual TPS may have elements of different heat conductivity and/or emissivity. Junctures between these elements lead to jumps of the heat-transfer boundary conditions. Furthermore, active TPS may produce regions of localized relative heating or cooling of the aerodynamic surface. These thermal non-uniformities may significantly affect the boundary-layer mean flow, excitation and evolution of unstable modes and, ultimately, transition locus. Investigation of physical mechanisms associated with the foregoing thermal effects will help us to design advanced thermal protection systems providing capabilities of transition control.

An effect of local cooling / heating on the development of the boundary layer disturbances was studied numerically and experimentally in framework of FP7 project TransHyberiAN for the test case of the hypersonic flow formed above the 7° cone under zero angle of attack (**Ошибка! Источник ссылки не найден.**). The model was equipped with the surface temperature control section which was able to provide the temperature in the range -200÷200°C by means of electric heater and liquid N_2 cooler. The model body was made from PEEK for IR surface temperature measurements. The model was equipped by PCB unsteady pressure sensors flush mounted in the surface.

The experimental study was performed in wind tunnel Tranzit-M (ITAM SB RAS). Tranzit-M is an impulse type aerodynamic facility equipped with fast opening valve. The experiments were conducted for the following flow conditions: M=6, $Re_1 = 5 \div 30 \cdot 10^6\, m^{-1}$ and $T_0 = 400K$. Priory to the stability/transition experiments the free flow noise characterization tests were performed to provide the background for the data comparison.

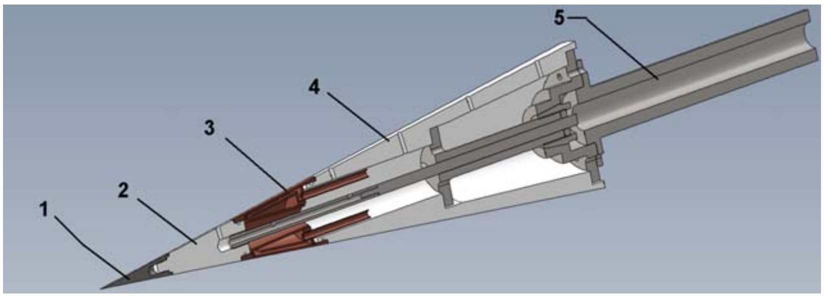

Fig.1 Cone model (450mm)

1 – nose (steel),
2 – nose section (PEEK),
3 – heater/cooler (copper),
4 – tail section (PEEK),
5 – model holder

The numerical simulation was performed for principal design of the cone model and analysis of the experimental data. The reliable modeling of laminar\turbulent transition is possible only by DNS and involves considerable computational power therefore it can not be used for the parametrical study. The current investigation deals only with linear stage of the disturbance development so the computations may be considerably simplified. The boundary layer stability was numerically studied in two ways: 1) LST analysis; 2) 2D DNS simulation. The first approach allows to estimate an effect of the local surface cooling/heating on the development of the first and second modes in parallel approximation. The second approach takes into account the flow non-parallelism but allows to simulate only development of the most unstable 2D waves.

Generation of disturbances in DNS simulation was carried out by specifying of slow acoustic wave at the boundary of the computational domain or small synthetic jet on the model surface. For 2D DNS sequential analysis of many frequencies is not efficient because the growth of perturbations occurs in a wide range of frequencies. A separate review of a large number of discrete frequencies requires a substantial amount of computation time. Therefore it was decided to use the linear combination of several harmonic waves of equal amplitude as the initial perturbation. The preliminary calculations have shown a good agreement between the level of perturbation obtained in batch mode and reconstructed as sum of the individual frequencies.

The parametric numerical study was performed before designing of the experimental model. It was found that: 1) the effect of the wall temperature is cumulative and depends on the length of the heated/cooled region; 2) the space gradient of the temperature on the cooler/heater edges does not affect the disturbance development; 3) the local wall temperature effect is different for the first and second modes of disturbances.

The DNS numerical simulation on the conical model was performed for the conditions of the experiment The combined analysis of the experimental and CFD data allowed to study the effect of the space gradients of the wall temperature on the hypersonic boundary layer stability and transition.