Passive Control of a Hypersonic Non-Equilibrium Boundary Layer using Regular Porous Coating

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Abstract: For hypersonic transportation vehicles and reentry capsules, control of boundary layer transition to maintain laminar flows or delay transition can result in lower drag, lower heat flux to surface, and higher fuel efficiency. In the past decade, passive control of hypersonic boundary layer using porous coatings has been studied by theoretical analyses, experiments, and numerical simulations. Previous studies indicated the thermo-chemically non-equilibrium of hypersonic flows may affect the efficiency of passive control using porous coatings. However, no previous work has been done in this area. In this paper, we carried out numerical simulations on the passive control of a hypersonic non-equilibrium boundary layer using regular porous coating. The simulation of non-equilibrium steady flow and unsteady simulations of passive control using regular porous coating are ongoing. Theoretical analysis based on the linear stability theory for perfect gas flow will also be included in the final paper.

Keywords: Passive Control, Transition, Non-Equilibrium, Porous Coating.

1 Introduction

The performance of hypersonic transportation vehicles and reentry capsules and the design of their thermal protection systems are significantly affected by the laminar-turbulent transition of boundary-layer flows over vehicle surfaces. Transition can have a first-order impact on the lift and drag, stability and control, and heat transfer properties of the vehicles [1]. Transition control to maintain laminar boundary-layer flows or delay transition can result in lower drag, lower heat flux to surface, and higher fuel efficiency.

In the past decade, passive control of transition using porous coating to stabilize hypersonic boundary layers over flat plates and cones has been studied by theoretical analyses [2], experiments [3], and numerical simulations [4]. Fedorov et al. [2] theoretically analyzed the second-mode stability of a hypersonic boundary layer over a flat plate covered by an ultrasonically absorptive coating (UAC). They found that the second mode growth was massively reduced. Rasheed et al. [3] studied the stability of a Mach 5 boundary layer on a sharp 5.06-deg half-angle cone at zero angle of attack. The cone had a smooth surface around half the cone circumference and an UAC porous surface on the other half. Their experiments indicated that the porous surface was highly effective in stabilizing the second mode and delaying transition, when the pore size was significantly smaller than the disturbance wavelength. Egorov et al. [4] studied the effect of porous coating on stability and receptivity of a Mach 6 flat-plate boundary layer by two-dimensional numerical simulation using a second-order TVD scheme. They found that a porous coating of regular porosity effectively diminishes the second mode growth rate, while weakly affecting acoustic waves.

Recently, Wang and Zhong [5] analyzed the porous coating admittance and noticed it was the phase angle of admittance that induces the phase discrepancy between the velocity and pressure perturbations on the wall. The effect of the admittance phase angle on Mack's first mode destabilization and Mack's second mode stabilization is then studied by series of numerical simulations for artificial porous coatings. The results showed that the destabilization effect decreases with the phase angle of admittance decreasing. It is also noticed that thermo-chemically non-equilibrium of hypersonic flows may affect the phase angle of porous coating admittance.

2 Problem Statement

For perfect gas flow, the governing equations are the three-dimensional Navier–Stokes equations. For non-equilibrium and chemically reactive flows, the governing equations for 5-species air are Navier-Stokes equation with source terms (no radiation). Details of the governing equations will be included in the final paper. In the simulation of a Mach 12.56 boundary layer over a blunt wedge with 20-degree half angle, the effects of thermo-chemically non-equilibrium of hypersonic flows are studied by comparing numerical results of perfect gas flow and non-equilibrium flow. Figure 1 compares pressure contours of the steady base flows for perfect gas and non-equilibrium gas. It is noticed that non-equilibrium gas leads to a smaller shock standoff distance and a bow shock closer to the wedge, which causes the significant difference in pressure contours.

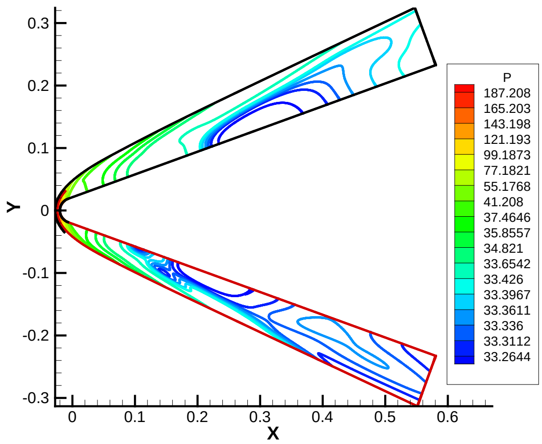

Fig. 1. Pressure contours of of the steady base flows for perfect gas (upper half with black boundary) and non-equilibrium gas (lower half with red boundary).

3 Conclusion and Future Work

In this paper, we carried out numerical simulations on the passive control of a hypersonic boundary layer using regular porous coating. The effects of thermo-chemically non-equilibrium of hypersonic flows are investigated by comparing numerical results of perfect gas flow and thermally non-equilibrium and chemically reactive flow. The preliminary results of steady flow simulation show non-equilibrium of hypersonic flows has a strong effect on the boundary layer structure.

References

[1] Report of the Defense Science Board Task Force on National Aero-Space Plane (NASP) Program. 1992, Defense Science Board.

[2] Fedorov, A.V., Malmuth, N. D., Rasheed, A., and Hornung, H. G., Stabilization of hypersonic boundary layers by porous coatings. AIAA Journal, 2001. 39(4): p. 605-610.

[3] Rasheed, A., Hornung, H. G., Fedorov, A. V., and Malmuth, N. D., Experiments on passive hypervelocity boundary-layer control using an ultrasonically absorptive surface. AIAA Journal, 2002. 40(3): p. 481-489.

[4] Egorov, I.V., Fedorov, A. V., and Soudakov, V. G., Receptivity of a hypersonic boundary layer over a flat plate with a porous coating. Journal of Fluid Mechanics, 2008. 601: p. 165-187.

[5] Wang, X., and Zhong, X., Phase angle of porous coating admittance and its effect on boundary-layer stabilization. AIAA Paper 2011-3080, 2011.