International Journal of Heat and Mass Transfer 121 (2018) 986–998

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

journal homepage: www.elsevier.com/locate/ijhmt

# Numerical simulation of local wall heating and cooling effect on the stability of a hypersonic boundary layer ☆

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ARTICLE INFO

*Article history:*
Received 3 August 2017
Received in revised form 28 November 2017
Accepted 13 January 2018

*Keywords:*
Hypersonic boundary layer
Boundary layer transition
Laminar flow control
Temperature strip

ABSTRACT

In this study, a numerical investigation of the perturbation evolution in a Mach 6 flat-plate boundary layer with a local heating or cooling strip is presented. The position of the temperature strip is varied while the strip length is constant and approximated to the boundary-layer thickness. Simulations are based on a time-accurate integration of the compressible Navier-Stokes equations, with a small disturbance of fixed frequency triggered via periodic suction-blowing at the plate leading edge. The stability characteristics of the hypersonic boundary layer are interpreted by spatial linear stability theory (LST). The results indicate that the relative location of a local heating/cooling strip and the synchronization point significantly affect Mode *S*. With respect to the heating-strip cases, the unstable mode is amplified when a heating strip is located upstream of the synchronization point, and the effect is reversed if the heating strip is placed downstream. In a manner opposite to the local heating effect, placing a narrow cooling strip upstream of the synchronization point stabilizes mode *S*, while the effect is reversed if the cooling strip is put downstream of the synchronization point. Different from previous stability studies on roughness and porous wall, the location of the synchronization point is not fixed, and this is mainly caused by the change to the phase speed of Mode *F*. The results suggest that an efficient way to stabilize the boundary layer is to put a narrow cooling strip further upstream of the synchronization point, or put a narrow heating strip downstream of the synchronization point.

## 1. Introduction

Laminar-to-turbulent transition generates significant increases in viscous drag and heat flux, leading to severe restrictions on the performance and thermal protection system of hypersonic vehicles. Estimates for the National Aerospace Plane (NASP) show that the payload-to-gross-weight ratio would nearly double if the vehicle boundary layer is fully laminar when compared to the fully turbulent scenario [1]. Moreover, early transition causes higher heating, and this requires an increased performance thermal protection system (TPS), active cooling, or trajectory modification, leading to higher cost and weight of hypersonic vehicles [2]. In order to control boundary-layer transition and maintain the laminar flow as long as possible, extensive works have been focused on the transition mechanisms [3–6]. It has been acknowledged that the transition is a manifold process, which strongly depends on the mean flow and external disturbance. Even for relatively simple two-dimensional or axisymmetric boundary layers on a flat plate or a sharp cone at zero angle of attack, there are several paths for transition [7]. If freestream disturbances are small, transition to turbulence along a smooth vehicle surface occurs due to amplification of the unstable boundary layer mode (path A in [7]) [8]. This path is typical for high-altitude flights in a low disturbance environment. The small environmental disturbances enter the boundary layer and excite the boundary-layer wave modes, through the receptivity process. Subsequently, the unstable wave modes develop linearly, which could be predicted by stability theory [3]. Finally, the unstable modes reach certain amplitudes, and non-linear and three-dimensional effects begin to dominate, leading to the final transition [10]. The current study only considers small amplitude blowing-suction perturbations, which undergo the particular Path A.

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☆ This study was supported by the Research Grants Council, Hong Kong under Contract No. C5010-14E and the National Natural Science Foundation of China under Grant No. 11402024, 11502267. We would like to show the honest appreciation to Prof. Li Xinliang for his generosity of providing the DNS codes.

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https://doi.org/10.1016/j.ijheatmasstransfer.2018.01.054
0017-9310/

## Nomenclature

| | |
|---|---|
| $x$,$y$ | Cartesian coordinates |
| $\xi$, $\eta$ | curvilinear coordinate |
| $u$, $v$ | velocity components |
| $\rho$ | density |
| $p$ | pressure |
| $T$ | temperature |
| $e$ | total energy |
| $\tau_{ij}$ | stress tensor |
| $q_j$ | heat flux |
| $\mu$ | molecular viscosity |
| $\gamma$ | specific heat ratio |
| $Pr$ | Prandtl number |
| $Re$ | Reynolds number |
| $Ma$ | Mach number |
| $L$ | reference length scale |
| $E$ | integral kinetic energy |
| $\delta$ | boundary-layer thickness |
| $\delta_s$ | relative sonic line thickness |
| $a$ | phase speed |
| $\alpha_i$ | growth rate |
| $\alpha_r$ | streamwise wavenumber |
| $f$ | suction-blowing frequency |

*Subscripts*

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|---|---|
| $'$ | fluctuating parameters |
| $*$ | dimensional variables |

*Subscripts*

| | |
|---|---|
| $\infty$ | freestream parameters |
| $w$ | parameters at the wall |
| strip | parameters at the strip |
| $r$ | recovery variables |

In hypersonic boundary layers, modes $F$ and $S$ originate from fast and slow acoustic waves, respectively, in the leading-edge vicinity through the receptivity process. Mode $S$ constitutes both Mack first mode and second mode. The first mode is an inviscid instability wave, associated with the generalized inflection point in the boundary-layer mean profile where $\partial(\rho\partial u/\partial y)/\partial y = 0$. Here $\rho$ and $u$ denote density and streamwise velocity, respectively, and $y$ denotes the axis normal to the wall. This mode is strongly stabilized by wall cooling. On the other side, Mack second mode belongs to the family of trapped acoustic waves. Once the second mode sets in, it becomes the dominant instability with a growth rate that tends to exceed that of the first mode. For insulated surfaces, this occurs for Mach numbers $Ma > 4$. With respect to cooled surfaces, the second mode can dominate at even lower Mach numbers [6,11]. According to the transition procedure, stabilizations of Mack first mode and second mode are critical to transition control at high Mach number conditions [10].

Transition control techniques are roughly divided into the following two categories: passive control and active control. Passive control aims to modify the mean flowfield to inhibit the growth of unstable waves. Such methods include roughness [12–16], wavy wall [17,18], porous coating [9,10,19–23], etc. Active control attempts to suppress the environmental disturbance, such as retuned blow-suction [24], $CO_2$ injection [25,26] and plasma actuators [27]. Because of the severe heat fluxes and high temperatures around the hypersonic vehicle surface, it is difficult to utilize active control techniques. Therefore, passive techniques are of primary interest [9]. Whereas the shape parameters of roughness (height, width and spacing) and porous wall (porosity, depth, and pore radius) directly affect the stabilization performance, the location of the above passive techniques seems critical to the control efficiency. Fong et al. [14,15] numerically studied the effect of 2-D roughness of finite height on the development of second mode instability. They found the synchronization point at which the phase speed of mode $F$ synchronizes with that of mode $S$ at a particular frequency of disturbance plays an important role in the stabilization. Perturbations could be damped only if the roughness element was placed downstream of the synchronization point. Otherwise, perturbations are amplified by the roughness. Fedorov et al. [21] investigated the effect of an ultrasonically absorptive coating (UAC) on hypersonic boundary-layer stability by both experimental and numerical analyses. The results show that the porous coating strongly stabilized the second mode and marginally destabilized the first mode. Mack second mode instabilities develops initially at lower Reynolds numbers as first mode instabilities, and thus destabilization of the first mode actually decreases the efficiency of the second mode stabilization [28,29]. Wang et al. [10,29] denoted that the most efficient way to stabilize laminar boundary layer is to put porous coating downstream of the synchronization point, through a series of numerical simulations.

In connection with this, the effect of local surface heating and cooling on the evolution of unstable modes have been investigated recently [30–34], with the background that TPS of hypersonic vehicles may possess elements of different heat conductivity and/or emissivity, and also future active TPS design. Polivanov et al. [30,31] performed numerical and experimental research on the hypersonic boundary layer stability perturbed by a local heating/cooling wall element. They found that heating of the surface section accelerates the transition downstream of the section, while cooling significantly delays the transition. This behavior is completely different from the known effect of uniform heating of surface that stabilizes the second mode and of uniform cooling that destabilizes the second mode [3,31]. Soudakov et al. [32,33] numerically and experimentally investigated the effect of local heating or cooling on stability and transition of the boundary layer flow on a sharp cone at Mach number 6, and drew a similar conclusion that the hot strip leads to increasing of the instability amplitude, while, the cold strip produces an opposite effect. However, the above claims might be worth deliberating, since a heating strip generates compression and expansion waves as the roughness element. The location of the temperature strip, especially the relative position to the synchronization point, should be critical to the stabilization efficiency, as documented in [15]. Nevertheless, to the best of the knowledge of the authors, no existing studies examined the role of synchronization point on boundary layer stabilization using temperature strips. As a result, a comprehensive understanding of the local heating or cooling transition control technique is still lacking.

In the present study, the stabilization effect of local heating or cooling strip is investigated by a combination of direct numerical simulation (DNS) and linear stability theory (LST). The role of synchronization point is identified based on the analyses of a Mach 6 flat-plate boundary layer with a narrow temperature strip located at different positions. Moreover, the possible stabilization or excitation mechanisms are preliminarily discussed.