Numerical Investigation of Suction Effects on Interaction and Transition of Laminar/Transitional SWBLI in a Hypersonic Double Wedge

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ABSTRACT This study numerically investigates the effect of suction on laminar/transitional shock-wave/boundary-layer interaction (SWBLI) and the transition of the boundary layer in a double wedge configuration. Compression ramp-induced laminar SWBLI occurring on hypersonic vehicles' engine inlets increases the drag due to separation and may damage the control surface due to severe thermal loads at the transition location. Thus, control methods to mitigate the effects of SWBLI on hypersonic vehicles gained attention. The control strategies in the literature focussed mainly on the turbulent SWBLI to reduce the interaction region size, and very few studies are available on the laminar/transitional SWBLI. This work studies the effects of the active suction control technique on laminar/transitional SWBLI of a double wedge geometry using the modified γ-model. Various suction parameters, such as slot width, location, and suction pressure on the double wedge for various wall temperatures and deflection angles, are numerically investigated to understand their effect on the interaction region and transition.

1 INTRODUCTION

Shock-wave/boundary-layer interactions are complex phenomena often seen in hypersonic air-breathing vehicles. The adverse pressure gradient across the shock wave interacts with the low momentum boundary layer and separates it from the surface. When the free shear layer gains enough momentum to counteract the adverse pressure gradient, the shear layer re-attaches to the wall, forming a separation bubble. One of the canonical configurations used to study the SWBLI is the compression ramp, which usually occurs on the engine inlet and external control surfaces. Compression ramp SWBLI with separated flows are classified as laminar, transitional, and turbulent SWBLI based on boundary layer state. Turbulent SWBLI is straightforward since the boundary layer is fully turbulent throughout the interaction region. However, laminar/transitional compression ramp SWBLI sometimes results in the transition of the boundary layer at the reattachment region, which induces high thermal load, resulting in surface damage to the external control surface. Further, laminar SWBLI reduces the mass flow to the engine due to a larger separation bubble than turbulent SWBLI for the same adverse pressure gradient, resulting in reduced engine efficiency, especially on the scramjet engine inlet (Threadgill et al. (2021)).

Laminar/transitional SWBLI thus changes the pressure distribution, flow stability, transition, and separation, affecting the aerothermodynamics of hypersonic vehicles. In order to reduce the adverse effects of SWBLI, many control strategies have been studied in recent decades. Some control strategies, such as microjets, plasma actuators, and tangential blowing, involve transitioning the boundary layer before the interaction to increase the momentum of the boundary layer (Ligrani et al. (2020)). However, the control of the entire laminar/transitional SWBLI has not been explored much in the literature. This study focuses on the steady and distributed boundary layer suction (BLS) and its effects on the interaction and transition of the laminar/transitional SWBLI. BLS is one of the most promising active control methods for transition in subsonic airfoils, as well as supersonic and hypersonic flat plates. Moreover, a small amount of suction significantly reduces the separation size for laminar boundary layers. The main advantage of BLS is its control application in both laminar and turbulent boundary layers. Further, the size of the interaction region and the transition of laminar/transitional SBLI depends on wall temperature, deflection angle, Mach number, and Reynolds number. Hence, this work numerically investigates the effect of various parameters, such as suction slot location, suction width, and suction pressure, on the laminar/transitional double wedge configuration using a modified γ-transition model (Divia et al. (2022)). This work also explores how the optimized suction parameters change for various wall temperatures and deflection angles.

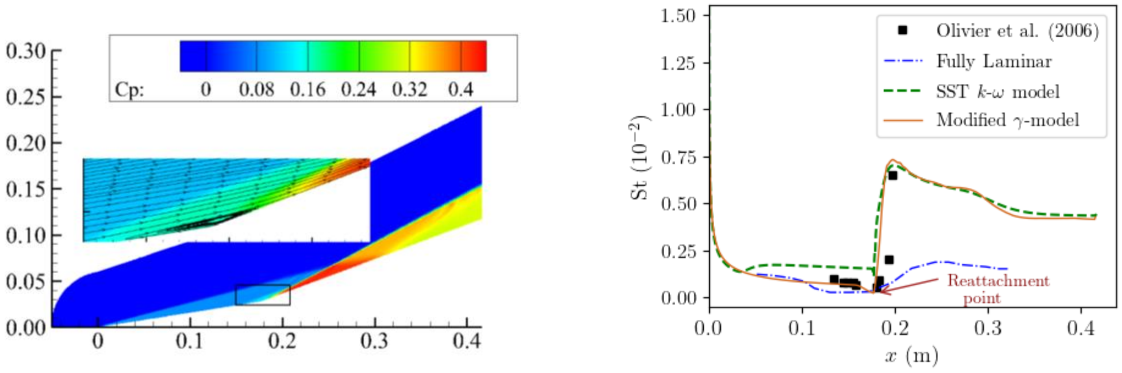
2 METHODOLOGY

All the computational studies are simulated using an in-house 2D/axisymmetric, compressible, finite volume-based Navier-Stokes solver in Cartesian coordinate with SST k-ω turbulence model and modified γ-model for transition prediction. The modified γ-model is an all-speed flow transition model that can predict separation and transition. The solver is OPEN-MP parallelized with the flux reconstruction using the second-order HLLC (Harten-Lax-van Leer Contact) scheme with Venkatakrishnan limiter and the time marching using the fourth-order explicit Runge-Kutta method. The least square method is used to determine the gradients (Olivier et al. (2006)). The baseline double wedge configuration consists of 180 mm and 255 mm wedges with a sharp leading edge and wedge angle of 9° and 20.5°, respectively. Table 1 shows the freestream conditions for the baseline configuration. Figure 1(a) shows the pressure coefficient (C_p) contours calculated from the modified γ-model.

The C_p contours clearly show the separation shock, separation bubble, and boundary layer reattachment. Figure 1(b) shows the verification of the modified γ-model for baseline double wedge configuration with the experimental data. This is a typical case of interaction-transitional SWBLI since the flow becomes turbulent after the reattachment of the boundary layer.

Table 1. Freestream conditions of a baseline double wedge configuration [Olivier et al. (2006)]

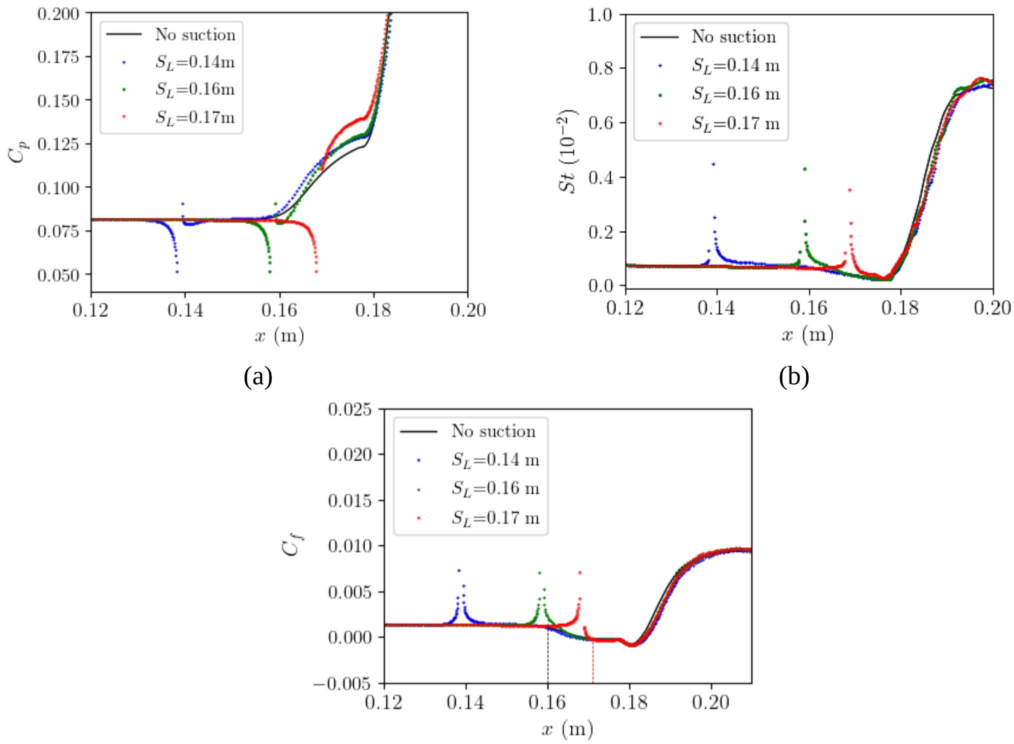
M_∞	T_0 (K)	T_∞ (K)	T_w (K)	P_∞ (N/m^2)	TI (%)	Fluid
8.1	1430	106	600	520	0.5	Dry air



(a)

(b)

Figure 2. (a) Surface pressure coefficient contours of baseline configuration (b) Stanton number distribution using various models for baseline configuration.



(a)

(b)

(c)

Figure 2. (a) Surface pressure coefficient distribution (b) Stanton number distribution (c) Skin friction coefficient distribution on double wedge surface with 1mm suction slot at various locations.

3 RESULTS AND DISCUSSION

The preliminary results of suction on compression ramp SWBLI are shown in Figure 2. Here, three different locations (0.14 m, 0.16 m, and 0.17 m) are chosen to study the effect of suction on the interaction and transition of laminar/transitional SWBLI in a double wedge configuration. All the configurations have a slot width of one mm (0.7δ at the onset of interaction in baseline configuration), and a suction pressure of $0.7p_\infty$ is applied in all the cases. The C_p results (Figure 2(a)) show that the suction slot located increases the pressure in the interaction of the laminar/transitional SWBLI. Stanton number distribution (Figure 2(b)) shows that suction with considered parameters does not affect the heat transfer rate and transition. However, the bubble size is reduced for $S_L = 0.17$ m configuration.

The skin friction coefficient distribution (Figure 2(c)) clearly shows the reduction in the interaction region for $S_L = 0.17$ m configuration (marked with a red line) compared to the baseline configuration (marked with a black line). The other two slots, i.e., those placed ahead of the interaction onset region of baseline configuration, do not have any significant effect. The full paper will study the parametric effects of slot width, number of suction slots, suction pressure, and their combinations with the slot locations for baseline configuration, various deflection angles, and wall temperatures.

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