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Effect of leading edge bluntness on the interaction of ramp induced shock wave with laminar boundary layer at hypersonic speed

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ABSTRACT

Present investigations deal with ramp induced shock wave and boundary layer interaction (R-SWBLI) in the presence of leading edge bluntness. A second order accurate finite-volume compressible flow solver is employed to assess the effectiveness of leading edge bluntness in reducing the separation bubble size. Boundary layer edge Mach number and temperature, sonic height, boundary layer thicknesses, skin friction coefficient and pressure difference are considered for this assessment. Present studies reveal the existence of two critical radii of leading edge bluntness associated with R-SWBLI. Increase in separation bubble size has been observed with increase in leading edge radius until the first critical radius called as 'inversion radius' which corresponds to maximum extent of separation. Swallowing of the entropy layer by the boundary layer is seen to increase the separation zone size while the separation bubble length decreases when the boundary layer is immersed within the entropy layer. The inversion radius is shown to be associated with equal thicknesses of the entropy and boundary layers. Increase in leading edge radius beyond the second critical radius, called as 'equivalent radius', is found to decrease the size of separation zone in comparison with that of the sharp leading edge case. This reduction is attributed mainly to the existence of a wide over pressure region. Physics-driven predictive strategies, to determine the critical radii for given geometry and freestream conditions, are derived successfully from the present numerical simulations. Current studies on a 50 mm long plate with 15° compression ramp for Mach number 6 and wall temperature of 300 K show that the inversion radius lies between 0.3 and 0. 6 mm while the equivalent radius lies between 1 and 1.2 mm.

1. Introduction

Viscous-inviscid interaction is one of the characteristic features of supersonic or hypersonic flow regimes. Ramp induced shock wave and boundary layer interaction (R-SWBLI) is the prominent example of the same for laminar as well as turbulent flows. Internal and external flow aerodynamics face the design challenges in the presence of this interaction. Engine inlet, wing-body junctions, control surfaces, etc. are the most prevalent components where such interaction can be encountered. Sudden turning of the flow around such compression corners forms an oblique shock which offers an adverse pressure gradient to the approaching boundary layer. Minimum flow deflection angle required to separate this boundary layer is called as incipient separation angle. This critical angle depends on viscous interaction parameter, freestream Mach number and freestream Reynolds number [1]. The impending boundary layer experiences substantial changes, for certain distance upstream of the ramp foot, even for the ramp angles smaller than the incipient separation angle. The most upstream station from the ramp foot which experiences such alterations is termed as upstream influence starting location. Distance of this vital location from the ramp foot is defined as extent of upstream influence (L_{ui}). Thus, the effectiveness of a control surface and efficiency of the engine depend upon state of the boundary layer beyond the upstream influence location. Nevertheless, possibility of flow separation at the ramp foot limits the performance of these components. Therefore R-SWBLI has been investigated by various researchers [1–9] to evaluate and understand the dependence of its distinctive features like upstream influence, separation bubble length and separation zone pressure on ramp angle and freestream conditions. Apart from the experimental studies, this problem has received considerable attention for computational studies through development of compressible flow solvers [10–12] and understanding of interaction dynamics [13,14]. Development of

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Nomenclature

C	Chapman–Rubesin parameter
C_f	skin friction coefficient
C_p	pressure coefficient
E	total energy per unit mass
E_I, F_I	convective flux vectors in x and y-directions respectively
E_V, F_V	viscous flux vectors in x and y-directions respectively
H	total enthalpy per unit mass
L	length of forward flat plate section of the model
L_{ui}	upstream influence extent
L_b	separation bubble size
M	Mach number
M_0	Mach number at the edge of boundary layer just ahead of interaction zone
P	pressure
P_{incp}	incipient pressure
P_1	pressure at upstream influence start location
P_3	pressure behind the reattachment
q	heatflux
Re	Reynolds number
R_n	leading edge radius
S	Sutherland's constant
St	Stanton number
t	time
T	temperature
x_0	distance from leading edge to upstream influence starting location
x, y	x and y coordinates
u, v	velocity components in x and y directions respectively
U	conservative variable vector
δ_0	boundary layer thickness at x_0
δ_0^*	displacement thickness at x_0
μ	coefficient of dynamic viscosity
ρ	density
τ	stress

Subscripts

∞	free stream conditions
0	total or stagnation values/parameters at x_0
ref	reference values
w	wall properties
e	boundary layer edge value

correlations to predict the interaction parameters has been the outcome of some of the literature reported findings [1–3,8,14–16]. Recently Marini [17] and Dolling [18] have reviewed the various investigations related to shock wave and boundary layer interaction studies.

Boundary layer separation, possibility of turbulent transition and enhanced surface heating are the possible causes for under performance of associated components in the presence of R-SWBLI. Therefore, various control mechanisms are reported in the open literature to reduce the intensity of this interaction by delaying separation [7,19–22]. Provision of leading edge bluntness is the most widely considered separation control technique for R-SWBLI and incident shock based interaction. Schematic of the flowfield for R-SWBLI with leading edge bluntness is as shown in Fig. 1. Dynamics of shock wave and boundary layer interaction completely changes in the presence of leading edge bluntness. Primary reason for this change is the replacement of attached shock by a stronger detached bow shock. Formation of strong entropy layer in the presence of bow shock and interaction of the same with the boundary layer adds to the complexity for understanding this interaction. Apart from detachment of the shock, leading edge bluntness induces a favorable pressure gradient which accelerates the flow passing over the object of interest. Therefore a high speed shear flow comprised of boundary layer and entropy layer approaches the ramp for sudden turning. Hence, the upstream influence location, separation location, separation bubble size, incipient separation angle and the re-attachment station change with respect to the corresponding reference values of sharp leading edge case. In view of this, it is inevitable to understand the effect of leading edge bluntness on these fundamental interaction parameters before implementing it for separation control.

Coet and Chanetz [7] conducted experiments to study the effect of leading edge bluntness for Mach 10 flow over 15° ramp attached with flat plates having different leading edge curvatures. The pressure and heat transfer measurements revealed that the separation bubble size decreases with increase in leading edge radius. Apart from this, reduction in peak pressure and heat flux in post re-attachment zone has also been noticed. Holden [19,20] conducted theoretical and experimental investigations for wide range of hypersonic Mach numbers, leading edge radii and freestream Reynolds numbers to study the R-SWBLI. It was observed that the increase in leading edge bluntness initially increases the separation zone size till a critical radius, beyond which decrease in the separation bubble size was noticed. The later was referred to as the bluntness dominated zone while the former was called as the displacement dominated zone. Decrease in boundary layer edge Mach number has been accounted for the initial separation zone widening. Bluntness induced favorable pressure gradient has been attributed for onwards decrease in separation zone size. Among the limited investigations in laminar region, shock tunnel based studies of Neuenhahn and Olivier [23] on R-SWBLI for scramjet intake flow with leading edge bluntness portrayed that relative thickness of boundary layer and entropy layer is responsible for variation in separation bubble size.

It is evident from the reported findings that the leading edge bluntness has been believed as the effective technique for separation control. However, very few findings provide a cautious remark about the proposed control technique since it does not always decrease the separation bubble length. Among those limited studies as well, diversity has been noticed for reasoning the anomaly of this control technique. It has also been noticed that, all those findings focus on relative change in separation bubble size with increase in leading edge radius. Therefore emphasis of their studies has been limited to only one critical radius after which separation bubble size decreases. However, such relative decrement should not just be accounted since decrease in separation bubble size in comparison with the sharp leading edge case is essential for implementation of this technique as the separation control technique. Hence, this fact portrays the existence of second critical radius beyond which separation control can be guaranteed. Therefore computational investigations are carried out using an in-house higher resolution compressible laminar flow solver to understand the R-SWBLI for leading edge radii ranging from 0.1 mm to 2 mm. Investigations of two critical radii, understanding the physics of flow around those radii and their qualitative predictions are the major motives behind present studies. These simulations are performed for the base geometry and freestream conditions considered by Marini [9] during their experimentation. Efforts