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Numerical assessment of correlations for shock wave boundary layer interaction

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ABSTRACT

Shock wave boundary layer interaction (SWBLI) is most attended research theme in the high speed flow regime for effective design of various parts of space vehicles. Hence, investigations in this field are invariantly carried out to estimate the extent of upstream influence, length of separation bubble, separation point pressure, plateau pressure and peak heatflux or Stanton number. Therefore, interaction of ramp induced shock and laminar boundary layer has been chosen as the test case for present studies. Literature reported correlations, for prediction of characteristic features of this interaction, are explored herewith using the in-house solver. However, results of present simulations for various freestream and wall conditions portrayed their inabilities to incorporate the variations of influencing parameters while retaining the linearity. In view of this, efforts are extended either to modify these widely appreciated correlations or to suggest a better among the reported ones to improve the estimates. The modifications suggested for prediction of extent of upstream influence, separation bubble size and peak Stanton number are seen to improve the applicability of the existing correlations.

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1. Introduction

The topic of shock wave boundary layer interaction (SWBLI) has gained inevitable significance in the area of high speed aerodynamics. Possibility of flow separation and intensive surface heating are the foremost motives for this ample attention. Sudden turning in the presence of ramp is very common event for occurrence of this phenomenon. Hence engine inlet, junctions, control surfaces, etc. are the most affected parts of the space vehicles which consequently need special concern at the design stage. Therefore the investigations for ramp induced SWBLI are extremely essential for successful design of associated systems or subsystems of the spacecraft.

A detailed schematic diagram representing the ramp induced SWBLI is shown in Fig. 1. The oblique shock, otherwise anchored at the ramp foot for inviscid flow, alters the flow over the upstream flat plate in the presence of SWBLI. These alterations might lead to flow separation, well before the ramp. Such separation relocates the shock position. Moreover, this laminar boundary layer separation depends on several parameters like Mach number, Reynolds number, wall temperature, ramp angle, etc. Amongst them incipient separation angle can be estimated using the relation given by Needham and Stollery [1].

$$M_\infty \theta_{i,s} = 80\sqrt{\overline{X}_L} \tag{1}$$

where $\overline{X}_L$ is the viscous interaction parameter at the flat plate-ramp junction, and is given by,

$$\overline{X}_L = M_\infty^3 \sqrt{C}/\sqrt{\mathrm{Re}_L} \quad \text{Where} \quad C = \frac{\mu_w}{\mu_\infty}\frac{T_\infty}{T_w} \tag{2}$$

Thus the laminar boundary layer separation is assured for the deflection angles higher than the incipient separation angle. Flow field for such a well separated flow, shown in Fig. 1, is comprised of a separation bubble bounded by the separation point 'S' and reattachment point 'R'. Distance between these two points is called as the length of separation bubble (L_b). Surface pressure distribution for the SWBLI with separation bubble, shown in Fig. 2, demonstrates this terminology. Constant pressure region or pressure plateau, which is a widely accepted pointer by the experimentalist to locate the separation bubble, is also shown in the same figure. Nevertheless, SWBLI for ramp angle smaller than the incipient separation angle leads to significant alteration in the flat plate laminar boundary layer profile ahead of the ramp-foot, without separation. The distance from the ramp-foot to the most upstream location, which experiences such alteration or upstream influence, is generally termed as extent/length of upstream influence (L_{ui}) and is shown in Fig. 2.

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Nomenclature

γ	specific heat ratio
β^*	temperature correction factor for upstream influence extent
β_{lb}	temperature correction factor for separation bubble size
$\overline{X}_L$	viscous interaction parameter
θ	ramp angle
θ_{is}	incipient separation angle
μ	coefficient of dynamic viscosity
C	Chapman–Rubesin constant
Cf	skin friction coefficient
Cp	pressure coefficient
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 ($\approx M_\infty$)
p	pressure
p_{inc}	incipient pressure
p_3	pressure behind the reattachment, approximated as pressure behind the inviscid attached shock
R_e	Reynolds number
x_0	distance from leading edge to upstream influence starting location
δ_0	boundary layer thickness at x_0
δ_0^*	displacement thickness at x_0
St	Stanton number
St_{peak}	peak Stanton number
T	temperature

Subscripts

1, 2 & 3	regions shown in Fig. 1
∞	free stream conditions
0	total or stagnation values/parameters at x_0
r	reference values
w	wall properties

Numerous experimental, theoretical and numerical investigations have been reported in the open literature about interaction of shock wave and laminar boundary layer. The studies of Chapman et al. [2] are the earliest in this field. Free-interaction theory proposed during these investigations describes independency of separation point location, plateau pressure and extent of first part of separation on downstream parameters. Needham [3] studied the effect of freestream Mach number on upstream influence and separation bubble size. Delay in separation and decrease in extent of separation with increase in Mach number were the observations of those findings which have also been reconfirmed later [4–6]. Contrary, separation zone widening with increase in local Reynolds number at most upstream influence location has also been reported [1,4,7]. In the overall conclusion, Needham and Stollery [1] and Holden [4,5] reported that the location of flow separation, separation bubble size and extent of upstream influence are very much dependent on local Reynolds number, freestream Mach number, ramp angle, freestream and wall temperature, specific heat ratio, etc. Amongst which adverse effect of increase in ramp angle on upstream influence and separation bubble size has been confirmed experimentally [4,8] and numerically [9,10] by few researchers. Coët and Chanetz [11] explored the influence of wall to interaction-zone upstream temperature ratio (T_w/T_1) on the intensity of SWBLI. Layland [12] reported the findings of computational analysis about the SWBLI at hypersonic speeds. Effect of high enthalpy non-equilibrium flow on SWBLI has also been accounted by Davis and Sturtevant [13]. Lately Marini [14] consolidated the ramp induced SWBLI interaction in the laminar hypersonic flow regime. Apart from this, very recently Di Clemente et al. [15,16] carried out SWBLI studies for reacting flows. The detailed numerical studies of shock induced separation of turbulent boundary layers can be credited to Sandham and Touber [17].

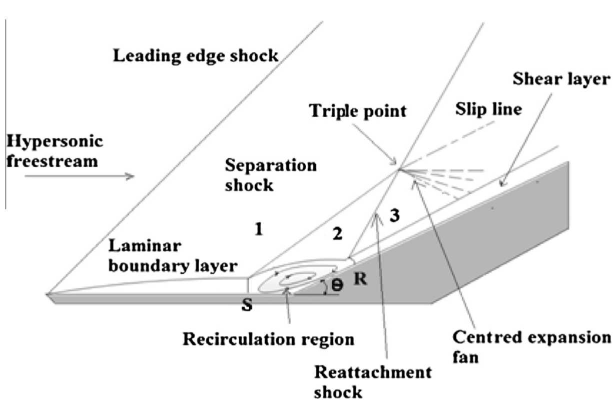

Fig. 1. Schematic diagram representing ramp based SWBLI.

In view of the literature reported studies about SWBLI, limited findings are available about the quantitative measure of separation bubble size and extent of upstream influence in terms of geometrical and freestream parameters. These selective results provide correlations to predict the characteristic features of the SWBLI for known geometry, freestream flow properties and surface conditions. The prime advantage of such simple correlations lies in the ease of their applicability in understanding the basics of ramp induced SWBLI, without costly experimental investigations or complex computational simulations. The correlations proposed by Needham and Stollery [1] and Katzer [6] are important in such aspects. Recently Davis and Sturtevant [13] have also proposed a new correlation for separation bubble size based on the classical triple-deck formulation of Stewartson and Williams [18]. However it has been observed that the scaling laws proposed by various researchers are not unique in nature. Hence the present investigations focus on assessment or suitability of literature reported and widely accepted correlations for quantitative prediction of SWBLI parameters. Efforts are also extended to modify these correlations to accommodate the available SWBLI data. Present studies are carried out using in-house compressible Navier–Stokes solver. Details of this solver, test cases and findings are discussed in the following sections.

2. Numerical methodology and validation

Numerical investigations of ramp-induced SWBLI phenomenon have been carried out using an in-house planer compressible laminar flow solver "USHAS" (Unstructured Solver for Hypersonic Aerothermodynamic Simulations). Finite volume formulation of this solver employs AUSM scheme [19] integrated with Venkatakrishnan's limiter function [20,21] for inviscid flux calculations. Viscous flux computations have been carried out using the approach

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