International Journal of Heat and Mass Transfer 70 (2014) 81–90

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

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

# Shock wave boundary layer interactions in hypersonic flows

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ARTICLE INFO

*Article history:*
Received 11 July 2013
Received in revised form 23 October 2013
Accepted 27 October 2013

*Keywords:*
Shock boundary layer interaction
Hypersonics
Separation
Laminar hypersonic flow

ABSTRACT

Shock-wave boundary layer interaction (SWBLI) and associated changes in wall properties for ramp induced flow breakdown have been considered in the present studies. A two dimensional finite volume based CFD solver has been developed and implemented successfully to study the SWBLI. Pressure measurements are invariantly considered in the literature for qualitative prediction of various SWBLI parameters. Hence efforts are made herewith to understand the laminar boundary layer separation in the presence of ramp induced shock wave through surface heat transfer rates, wall skin friction coefficient and wall pressure distributions. Effect of variation of freestream and wall properties along with geometric changes is considered in present studies. It has been observed from present limited investigations that ratio of wall temperature to freestream stagnation temperature is the governing parameter for SWBLI instead of the individual temperatures. Increase in Mach number is found to suppress the upstream influence which results in decrease in extent of separation. Efforts are also made to study the effect of leading edge bluntness on the SWBLI. These studies are found useful to confirm the earlier reported experimental observations regarding turbulent re-attachment.

## 1. Introduction

Research in the field of high-speed aerodynamics is centred on shocks and their interactions that alter the flowfield. These alterations affect the forces and heat loads on bodies under consideration [1–3]. A topic of great importance and interest in this regard is shock wave boundary layer interaction (SWBLI), which essentially deals with inviscid-viscous interaction [4]. The presence of SWBLI may lead to boundary layer separation [5,6], enhanced heating loads [7] or even turbulent re-attachment [8]. Internal as well as external flow aerodynamics gets affected by this interaction. Various components or subsystems like wing body junctions, engine inlet, nozzle, control surfaces etc., experience such shock wave boundary layer interactions. Therefore conscious efforts must be undertaken in the design of several subsystems of a space vehicle or a missile to account for the effect of these interactions. Numerous experimental and computational findings along with the allied development of various flow control techniques are reported in the open literature as an outcome of the research investigations on this topic [9,10].

A typical schematic diagram representing the ramp induced SWBLI is shown in Fig. 1. The abrupt deflection of flow, in the presence of ramp, leads to generation of shock wave emanating from the compression corner, which interacts with the boundary layer over the wall. Hence, the boundary layer experiences adverse pressure gradient near the region of flow deceleration or oblique shock. Separation of the flow in the presence of adverse pressure gradient depends on many parameters. Separation of laminar boundary layer depends on several factors including Mach number, Reynolds number, ramp angle, wall temperature and boundary layer stability. Amongst which the incipient separation angle of a particular case can be identified from the relation given by Needham and Stollery [11].

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

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

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

If the deflection angle is higher than the incipient separation angle, then boundary layer separation takes place. The separation of the flow occurs at station ‘S’ (shown in Fig. 1), well ahead of the compression corner, depending on the viscous interaction parameter. In such a case, separation shock forms ahead of the separation region due to the coalescence of compression waves induced by the separation process [12]. The nearly constant pressure region downstream of the separation point is invariantly considered as the indicator to identify the separation bubble during pressure measurement experiments. This recirculation zone extends up to the reattachment point R (Fig. 1), where the flow reattaches on the ramp surface. Distance between the point of separation and

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0017-9310/$ - see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.ijheatmasstransfer.2013.10.072

## Nomenclature

| | |
|---|---|
| $\bar{X}_L$ | viscous interaction parameter |
| $\rho$ | density |
| $\theta$ | ramp angle |
| $\theta_{is}$ | incipient separation angle |
| $\mu$ | coefficient of dynamic viscosity |
| $\tau$ | shear stress |
| C | Chapman–Rubesin constant |
| $C_f$ | skin friction coefficient |
| $C_p$ | pressure coefficient |
| E | total energy |
| $E_I$ | *x*-component of convective flux vector |
| $F_I$ | *y*-component of convective flux vector |
| $E_v$ | *x*-component of viscous flux vector |
| $F_v$ | *y*-component of viscous flux vector |
| H | total enthalpy |
| $L_{ref}$ | reference length (forward flat plate length in present studies) |
| M | Mach number |
| $P$ | pressure |
| $Pr$ | Prandtl number |
| $q$ | heatflux |
| $r$ | leading edge radius |
| $\mathrm{Re}_\infty$ | Reynolds number/meter ($\rho_\infty\ U_\infty/\mu_\infty$) |
| $\mathrm{Re}_{L_{ref}}$ | Reynolds number ($\mathrm{Re}_\infty\ L_{ref}$) |
| $St$ | Stanton number |
| $T$ | temperature |
| $T_r$ | reference temperature |
| U | conservative variable vector |
| u | velocity in *x*-direction |
| v | velocity in *y*-direction |
| $\tau$ | stress |

*Subscripts*

| | |
|---|---|
| $\infty$ | free stream conditions |
| 0 | total or stagnation values |
| r | reference values |
| w | wall properties |
| CR | critical |

the reattachment point is called as the length of separation bubble. A ramp angle smaller than the incipient separation angle, can lead to significant alteration in the basic flat plate laminar boundary layer profile ahead of the ramp-foot, without separation. Such upstream flow alteration due to the presence of the ramp can be termed as upstream influence. The distance from the ramp-foot to the most upstream location, which experiences the influence, is generally defined as extent of upstream influence.

In the past, SWBLI has been investigated by several researchers owing to its growing significance. There are many reported investigations in this field for both high speed laminar and turbulent flows. The earliest literatures that give a physical understanding of SWBLI in supersonic and hypersonic flow regime are the investigations of Chapman et al. [5] and Needham and Stollery [11]. Through a series of experimental studies in both laminar and turbulent flow regimes, Chapman et al. [5] first developed the "free interaction concept" in the presence of various ramp angles. Holden [13,14] performed theoretical and experimental studies, to understand the influence of Mach number, Reynolds number, wedge angle and leading edge bluntness on SWBLI phenomena. Coet et al. [8], during their studies, focused on the effect of leading edge bluntness and associated entropy layer on the ramp induced shock wave boundary layer interaction. Rizzeta and Mach [15] conducted numerical investigation of ramp induced SWBLI in the laminar hypersonic ($M_\infty = 14.1$) flowfield by employing four different numerical algorithms. Marini [16] carried out experimental investigations to study the effect of geometrical parameters on the shock induced separation. Davis and Bradford [17] performed studies in high enthalpy non-equilibrium flow and computed the separation length both numerically and experimentally. SWBLI has also been computationally studied by Layland [18]. Recently Marini [19] has extensively studied and reviewed ramp induced SWBLI in the laminar hypersonic flow regime. In this review, numerical studies which reveal the influence of different flow parameters were presented along with discussion of former experimental studies. Numerical investigations of Reinartz et al. [20] is the latest reporting about the effect of wall temperature on ramp induced SWBLI. In this study, authors employed two different Reynolds Averaged Navier–Stokes solvers to analyse SWBLI in laminar as well as transitional flow regimes.

In spite of extensive numerical and experimental studies performed to understand SWBLI, there exist only a limited number of findings [14,16] that have noticed adverse effect of decrease in freestream Mach number and stagnation enthalpy on this viscous–inviscid interaction. Furthermore, the difficulties involved in measurement of wall shear stress in high-speed facilities necessitate the use of pressure and heat transfer measurements to understand the phenomenon of shock-induced separation. Results on separation length from pressure or heat transfer measurements must be interpreted qualitatively and quantifying these predictions is possible only through high-resolution computations. In line with this, effect of small leading edge bluntness radii on SWBLI has

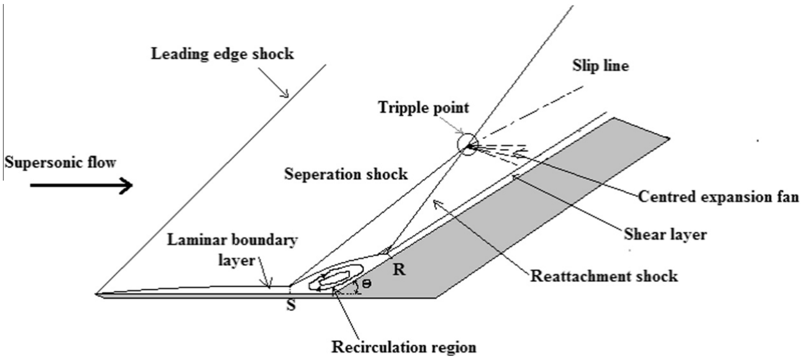

**Fig. 1.** Schematic diagram representing the two dimensional high speed flow over a compression corner with SWBLI.