

REVIEW

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# Survey of control techniques to alleviate repercussions of shock-wave and boundary-layer interactions

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## Abstract

The primary focus of the present survey is to categorize the results of various investigations on the Shock/Boundary-Layer Interactions (SBLIs), their repercussions, and the effective ways to control them. The interactions of shock waves with the boundary layer are an important area of research due to their ubiquity in several applications ranging from transonic to hypersonic flows. Therefore, there is a need for a detailed inspection to understand the phenomena to predict its characteristics with certain accuracy. Considering this in mind, this article presents some key features of the physical nature of SBLIs, their consequences, and the control techniques in a sequential manner; in particular, the passive control techniques for the supersonic and hypersonic intakes are reviewed in detail.

## Highlights

1. Shock/Boundary-Layer Interactions (SBLIs) and their consequences in high-speed aircraft are reviewed.
2. Various active and passive control strategies that have been used to mitigate the effects of SBLI are addressed.
3. The efficacy of Porous Cavity and Micro-Vortex Generators in controlling SBLI is described in detail.

**Keywords:** Oblique shock, Boundary layer, Separation bubble, Surface bump, Porous cavity, Micro-vortex generator (MVG), Plasma jet

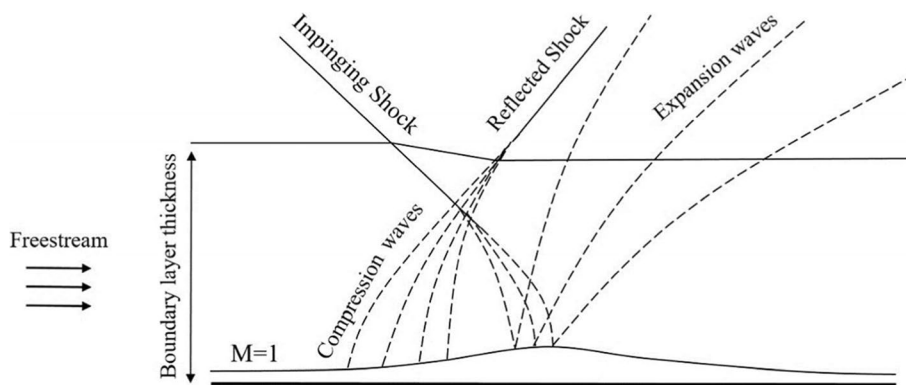
## 1 Introduction

The interaction of a shock wave with the boundary layer is a kind of fluid dynamic phenomenon that exists in all supersonic, hypersonic, and even transonic vehicles. The presence of SBLIs can be referred to several practical flow situations that include airfoils, the tip of the turbo-machinery blades in transonic flow, supersonic and hypersonic intakes. However, the undesired consequences of SBLIs severely affect engine performance. The shock wave offers high wave drag into the supersonic flow, and the interaction of the shock wave with the boundary layer often results in flow separation, eventually leading

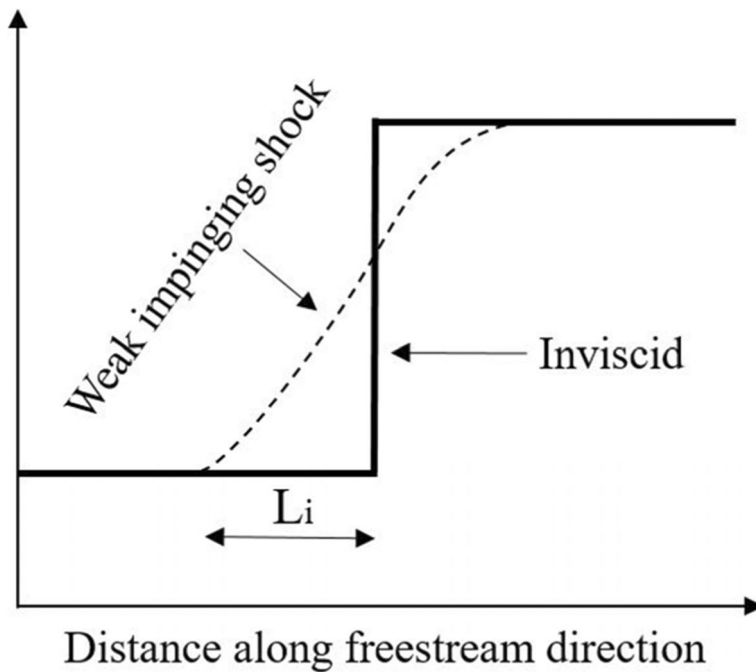
to viscous drag. Also, the unsteadiness in the flow field associated with the flow separation causes high fluctuating pressure loads, which often results in the buffeting of wing or intake buzz. Due to the unsteady nature, the regions of the SBLIs are the region of fluctuating high thermal load. The combinations of these phenomena are very much responsible for the degraded engine performance of a high-speed aircraft. The detrimental impacts of SBLIs are even more severe due to the viscous and the vorticity interactions, and high temperature in the shear layer. Because of this, SBLIs have been the subject of special attention, which has motivated several researchers in the last few decades. Nevertheless, it should be noted that, despite having several decades of research and the incredible development of theoretical, computational, and experimental fluid dynamics, the complete flow physics of SBLIs and their controlling mechanisms are still unclear due to inherent complexities. Hence, it is necessary to understand the physical mechanism of SBLIs to control the undesired consequences.

This interaction is often called Shock/Boundary-Layer Interaction (SBLI). As the pressure changes abruptly across the shock wave, the boundary layer thickens at the shock impingement location. Subsequently, the transmission of the pressure signal from the downstream side through the subsonic portion of the boundary layer results in retardation or thickening/separation of the boundary layer upstream of the shock location. Subsequently, the boundary layer thickening/separation deflects the flow towards the bulk flow, which results in a series of compression waves. These waves merge to form the separation shock outside the boundary layer. Similarly, a reattachment shock will be created when the separated flow re-attaches the body again. Besides, the impinging shock is reflected as the expansion waves from the sonic line of the boundary layer. The consequences of SBLIs are total pressure loss, flow separation, increased drag, unsteady shock oscillations, etc., which sometimes may lead to engine failure. Further, SBLI enhances turbulent intensity, which leads to considerable viscous dissipation.

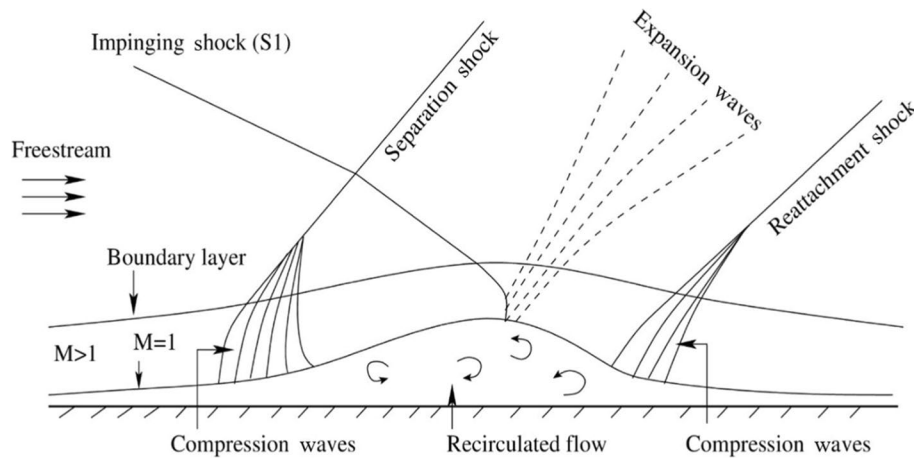
The interaction pattern of a shock wave with the boundary layer in a two-dimensional domain is shown in Fig. 1, where the impinging shock is relatively weak. Inside the boundary layer, the shock gradually curls as the local flow speed decreases towards the inner part of the boundary layer. Besides, the strength of the impinging shock diminishes gradually as it penetrates the boundary layer and eventually ceases at the sonic line. In the subsonic part of the boundary layer, the shock-induced pressure rise can be felt both



**Fig. 1** Schematic diagram of a typical SBLI over a flat surface due to a weak impinging shock



**Fig. 2** Wall static pressure distribution for a weak SBLI



**Fig. 3** Schematic diagram of a typical SBLI over a flat surface due to a strong impinging shock

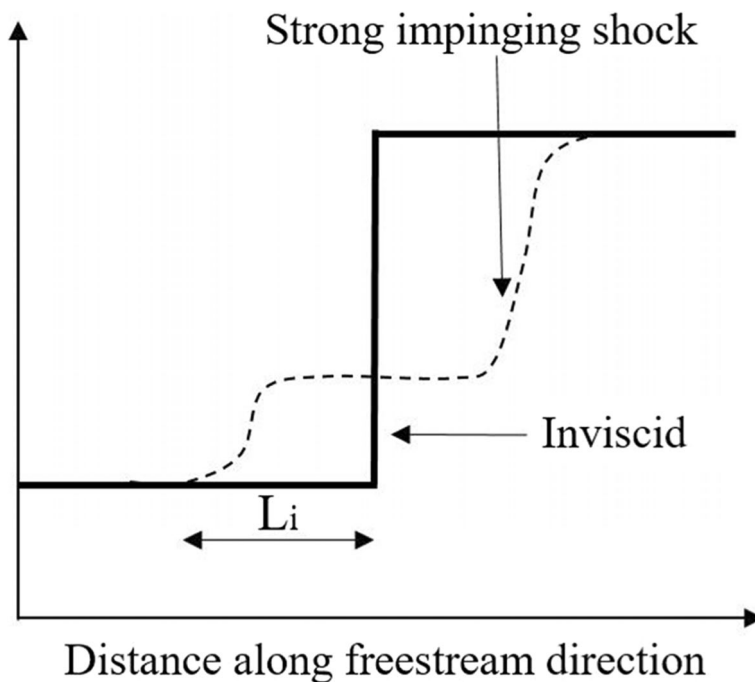
in upstream and downstream directions, as seen in Fig. 2. The figure reveals the smooth pressure rise in both the upstream and the downstream directions. Thus, the subsonic part of the boundary layer is thickened over a finite region. Moreover, the deflection of outer supersonic flow results in a series of compression waves. Outside the boundary, these compression waves coalesce to form a reflected shock. This interaction process is termed the weak interaction as the physical phenomena involved in this process are not very different from the inviscid flow situation.

In a different flow situation, where the impinging shock is strong, the adverse pressure gradient is sufficient enough to cause the flow reversal in the subsonic part of the boundary layer. As shown in Fig. 3, the incident shock S1 impinges over the subsonic part of

the boundary layer, leading to its separation. The compression waves are formed at the onset of the distorted thick boundary layer, whose feet fall at the sonic line. These compression waves merge together outside the boundary layer to form the separation shock. Further, the impinging shock S1 slightly changes its direction while interacting with the separation shock and gets reflected from the separated layer as expansion waves. This causes a deflection of the separated layer which subsequently reattaches after a certain downstream distance due to strong mixing action between the fluid inside and outside the separated shear layer. This reattachment process is accomplished by the generation of a series of compression waves that further merge together above the boundary layer to form the reattachment shock. This type of interaction process is termed as the ‘strong viscous-inviscid interaction’ as the strong viscous effects dominate the interaction process. The flow phenomena, in this case, are markedly different from the pure inviscid flow situation.

The rise in wall static pressure due to the strong SBLIs is shown in Fig. 4. Notice that, unlike the weak interaction process, in the strong SBLIs, the wall static pressure increases in two different stages, separated by a pressure plateau. The first and second peaks in pressure are primarily associated with the separation and the reattachment process. Essentially, the rise in pressure at the separation point is dependent on the upstream flow properties and the viscous-inviscid interaction process.

For a complex geometry like intake, the shock waves generated from the compression ramp and cowl lip interact with the boundary layer, resulting in SBLIs. The degraded boundary layer due to these interactions is susceptible to boundary layer separation, which may lead to a reduced mass flow rate through the intake [1]. The flow separation causes a drastic change in the overall flow and shock pattern. Most often, the separated



**Fig. 4** Wall static pressure distribution for a strong SBLI

flow is the source of the entire flow field unsteadiness and high thermal load, which thereby results in the “engine-unstart” and worst-case engine failure [2, 3]. Also, the unsteadiness in the flow field is the origin of highly fluctuating pressure load. In some cases, the frequency of the pressure fluctuations is nearly the same as the resonant frequencies of the vehicle structures. This situation may lead to a large fluctuating pressure load [4]. These interactions are frequently observed in several aerospace applications, particularly in internal aerodynamics. Essentially, the intake geometries of a high-speed aircraft are such types of configurations that are directly affected by SBLIs. The air-breathing engine efficiency of a supersonic or hypersonic aircraft is greatly dependent on the effectiveness of the intake. Therefore, to improve engine performance, a thorough understanding of the SBLIs phenomena in the supersonic and hypersonic intake and their control is necessary. Though the computation power has been increased substantially in recent times, the inadequacy in the turbulent models, particularly, in the separated flow region makes them less effective in accurately predicting the SBLIs. Moreover, for complex geometries like aircraft intakes, the computation techniques are inadequate in capturing the interaction and their control mechanisms. On the other hand, the experimentally obtained values are the most reliable and widely accepted. Therefore, it is essential to carry out an experimental observation to have a proper understanding of the flow physics behind the SBLI inside the uncontrolled and controlled intakes. So far, significant advancements have been made in experimental investigations such as in-wall pressure measurements, particle image velocimetry measurements, etc. to analyze the laminar and turbulent interactions [5–7]. These methods help in identifying some of the key parameters that influence the interactions.

As the interactions are very severe and detrimental, the control techniques are employed to make a substantial change in the flow or/and the shock structure so that the shock/boundary-layer interactions can be manipulated. This may lead to reduced shock strength, suppressed separation bubble, stable flow field, reduced thermal load, etc., which essentially improves the overall engine performance. Most often, passive or active means of control are utilized by several researchers in the last few decades. The main objective of this study is to provide an overview of the various passive control techniques and their advantages in controlling SBLIs, especially in high-speed intakes. Since different control techniques have different purposes in interaction control, the following reviews also characterize different shock and boundary layer controls depending on their specific advantages in controlling the interactions.

## **2 SBLIs and their consequences**

### **2.1 Boundary-layer thickening and/or separation**

More than 70 years of research have been dedicated to the fascinating field of shock/boundary-layer interactions due to their inherent complexities and pervasiveness in high-speed flow regimes. In aviation, the most common situations where the shock/boundary-layer interactions have been encountered are the flow over the transonic airfoils or flow in the supersonic or hypersonic intakes. Since the mid-1940s, several works have been carried out to understand the basic physical mechanism of the SBLIs in transonic and supersonic flows over curved or flat surfaces [8–14]. Generally, the interactions for both cases, where the boundary layer is attached or separated, have been talked

about. It was mentioned that the nature of the incoming boundary layer greatly influences the SBLI characteristics. Besides, the upstream influence of the interactions was found to be dependent on the laminar or the turbulent nature of the boundary layer. More importantly, the boundary layer often stays attached for a normal shock having strength up to 1.3. In these investigations, some were conducted over the curved surfaces in transonic flow [9, 10]. However, in such situations, the supersonic flow is established over a small region in the flow domain. Also, the curvature of a surface inevitably yields a streamwise pressure gradient. To eliminate these complexities, special attention has been given to producing the shock wave externally over the flat plate or the compression corner. The work of Barry et al. (1951) and Liepmann et al. (1951) can be referred to in that respect. Essentially, the investigations are conducted for both laminar and turbulent SBLIs [12, 13]. The nature of laminar interaction was exclusively described by Ackeret et al. (1947), where a near-normal shock formed over a convex corner terminates the locally obtained supersonic flow region [10]. They found that the laminar interactions at Mach 1.23 cause the flow separation and give rise to the lambda-shock structure. The investigations further extended at Mach 1.1 and 1.3, where similar flow and shock structures have been observed. Liepmann et al. (1951) have investigated SBLIs with both the laminar and turbulent boundary layer over a flat plate [12]. It was observed that the upstream influence length is substantially lesser for the turbulent boundary layer than the laminar one. The separation region, formed at the near upstream location of the shock wave, is due to the presence of an adverse pressure gradient. The frequent separation was observed in the case of a laminar boundary layer compared to the turbulent boundary layer. The laminar separation process was investigated in detail by Messiter [15]. They concluded that the minimum pressure jump of 10% is necessary to separate the laminar boundary layer for the Reynolds number of  $10^5$  and more. The separation process was initiated with the formation of the leading edge of the lambda-shock. It was confirmed that the lambda-shock structure for a turbulent interaction is smaller than that in the laminar case. Since the subsonic part of the boundary layer is thicker for laminar interactions, the separation is more susceptible to causing the secondary lambda-shock [16]. However, in both laminar and turbulent interactions, the extent of the lambda structure was found to be larger than the thickness of the boundary layer [17].

So far, the studies were limited to the nature of SBLIs and their response to the incoming boundary layer. However, there are other factors, such as, Reynolds number, Mach number, and shock strength that directly impact the SBLIs [18–21]. Donaldson and Lange (1952) have provided an empirical relation for a rough estimation of the pressure rise across the shock [22]. In their experiments over a flat plate at Mach 3.03, it was concluded that the critical pressure rise is inversely proportional to the square root of the Reynolds number for a laminar flow, whereas, it is inversely proportional to the fifth root for a turbulent flow. They suggested that, due to the formation of the shock waves, the pressure rise results in separation and is proportional to the skin friction. Chapman et al. (1958), while introducing the concept of “Free interaction”, described that the interactions near the separation zone are influenced by the incoming Mach number of the flow as well as the boundary layer characteristics [23]. Later, the experimental studies of Seddon (1960), Kooi (1975) described the detailed mechanism of interactions, when a normal shock interacts with the boundary layer [24, 25]. It was observed that the transonic

SBLIs have some distinct features than that occurring at supersonic speeds. Seddon [24] explained many important aspects of the separated flows induced by a normal shock. It was observed that, due to flow separation, a strong normal shock is smeared to lambda-shock near the wall. The leading shock is dependent on the nature of the interaction of the boundary layer with the external inviscid flow. The flow is locally supersonic behind the rear shock up to a certain downstream distance. The wall pressure increased gradually across the interaction region. The nature of the wall pressure distribution was determined by the interaction between the viscous and the inviscid flows.

The dependency of the recirculation zone owing to SBLIs, particularly in hypersonic flow, is discussed by several researchers. Similar to supersonic flows, the separation length in a hypersonic flow is found to be dependent on many factors. For a compression corner, the separation length is found to be bigger at higher compression angles [26, 27]. Also, the separation length is always showing a growing trend with a decrease in Mach number irrespective of the state of the boundary layer [28–30]. However, the effect of Reynolds number on the separated length is not the same for laminar, turbulent, and transitional regions. For a laminar flow, the separation length increases with the increase in Reynolds number; however, for transitional flows, the trend is reversed [31, 32]. Whereas, in a turbulent flow, the impacts of the Reynolds number on separation length are still debatable. According to Coleman and Stollery (1972) and Holden (1972), separation length increases with Reynolds number, whereas, the observation of Settles and Bogdonoff (1982) and Roshko and Thomke (1976) concluded the opposite trend [21, 30, 33, 34]. Besides, it has been observed that the separation length increases with the wall temperature. Particularly, in laminar flows, the influence of the wall temperature on separation is higher than in turbulent flows [28, 30]. The direct impact of wall temperature on separation bubble size is also investigated by Zhu et al. (2017). They confirmed through their numerical investigation that an increase in wall temperature increases separation bubble size to a significant amount [35]. The aforementioned studies have investigated the various aspects of SBLIs considering the gas to be perfect. However, in the high-speed region, particularly, in the hypersonic flow regions, the situation may not be the same due to the dominance of the real-gas effects. It has been observed that, in a hypersonic flow regime, the real-gas effects have a significant impact on the separation bubble size [36].

Moreover, both the incident shocks and the wedge induced separation follow a similar trend of skin friction, wall pressure, and heat transfer distributions over a separated flow region, thus, from a qualitative understanding, the influence of the shock on the boundary layer or the separated shear layer is not very much different [33].

To summarize the works carried out on SBLIs phenomena, several review articles have been published. The excellent reviews of Green (1970), Delery (1985), and Viswanath (1988) are only a few of the several studies [37–39]. They included the excellent descriptions necessary for a good insight into the physical mechanism of attached and separated SBLIs along with their upstream influence. Besides, the influences of the state of the incoming boundary layer on SBLIs and their controls have been reviewed exclusively. Later, Délerly and Dussauge (2009) and Babinsky and Harvey (2011) beautifully described the key features of the physical nature of SBLIs for a detailed understanding of the interaction phenomena [40, 41]. Sriram et al. (2016) investigated the nature of



the separation bubble formed over a flat plate in a hypersonic flow [42]. They concluded that the separation bubble size is at the same length scale as the distance of the incident shock from the leading edge.

The latest investigations in supersonic flows are carried out by Davidson and Babinsky (2014, 2018) to find the impact of the incoming boundary layer on the normal shock/boundary-layer interaction [43, 44]. They stated that the boundary layer profile in the far downstream region is weakly dependent on the nature of the incoming boundary layer. However, at the near downstream location, the interaction is greatly influenced by the boundary layer properties. Interestingly, the turbulent nature of the incoming boundary layer has a higher impact on the interaction.

From the aforementioned study on SBLIs in transonic, supersonic, and hypersonic flows over different geometries, it is clear that the state of the incoming boundary layer has a huge impact on the shock structure. Indeed, the response of the boundary layer upon the shock impingement determines the structure of the interaction. Also, the laminar and turbulent interactions have distinct features and consequences on the flow structure. Therefore, it is necessary to have a good insight into the interaction to predict and control their undesired consequences.

## 2.2 High thermal loads

One of the major problems associated with supersonic and hypersonic aircraft is the aerothermal effect, which imposes serious challenges in designing the aircraft. Therefore, an efficient design with a better thermal protection system necessitates several investigations for an accurate prediction of the aerothermal effect, particularly at the interaction location of the hypersonic aircraft. Considering these aspects, Holloway et al. (1965) conducted systematic experimental investigations on the impact of SBLIs on heat transfer in all three regions of laminar, turbulent, and transitional flows [45]. They stated that, for a pure laminar separated region, the local heating rate is higher than that in the attached flow over a flat-plate, whereas, a reverse trend has been observed for a turbulent separation. However, the situation with transitional separation has more practical implications. Interestingly, for the case of transitional separation, within the transitional region, the heat transfer values fall below the values associated with the attached flow over a flat plate. Beyond this zone, the heat transfer values for separated flows rise rapidly compared to attached flows over the flat plate. In a subsequent investigation, Coleman and Stollery (1972) stated that, at the near downstream of the reattachment region, the heat transfer value rises rapidly and attains its peak [33]. They have identified some of the important features of turbulence and its effect on heat transfer distributions. The distribution of the heat transfer rate is found to be in close agreement with the nature of the pressure distribution.

It is seen that the interaction of the shock wave with the boundary layer is the source of high viscous dissipation and some part of the kinetic energy of the fluid is lost due to the dissipation. This lost energy reappears in the form of internal energy and thereby increases the temperature of the fluid. For this reason, the supersonic flow passed over the body increases the temperature of the body to a large extent. This situation is even more severe in hypersonic flow due to the viscous and the vorticity interaction, and high shear layer temperature [46–49]. This results in a tremendous amount of total



pressure loss, increase in separation bubble size, flow unsteadiness, high thermal load, etc. The most frequently observed aero-thermodynamic problems in hypersonic flows are reviewed by Holden [50]. He has described that the viscous-inviscid interactions in hypersonic laminar/turbulent flows are the source of the aerothermal problem. From the design point of view, the accurate prediction of the location and the extent of aerothermal problems is essential to have improved performance of the hypersonic vehicle. He stated that the interaction between the inviscid flow over the leading edge (or over the intake wall) with the laminar boundary layer can determine the extent of the aero-thermal effects. Besides, the viscous interaction has a great impact on the pressure and heat transfer distributions. The gradient of pressure and temperature is found to be higher near the separation and the reattachment locations, separated by a plateau which essentially represents the recirculation zone. The maximum gradient in heat transfer is obtained near the reattachment region. Besides, the estimation of the transition of a boundary layer is the most important concern as the hypersonic intake or the swept-wing experiences a tremendous amount of thermal load in turbulent flows. It is also observed that, for complex geometries like intake or control surfaces, the transition may occur in the region of adverse pressure gradients due to SBLIs. According to Scuderi (1978), unlike the attached flow where the pressure and the heat transfer rate increase gradually, in a separated flow, the rise in peak pressure and the heat transfer rate is separated by a plateau region [51]. Dolling (2001) mentioned that two main aspects of an SBLI induced aero-thermal heating are the location of its occurrence and the magnitude of the thermal load [52]. Also, in hypersonic flows, the peak heating due to shock/boundary-layer interaction and the shock/shock interaction can be up to a hundred times higher than the heating in the attached flows. The maximum heat transfer rate can be greatly dependent on the flow condition at the reattachment location; higher separation length implies increased heating at the reattachment point [53]. A recent study on Mach 5.8 flow over a flat plate confirmed the interaction of a shock with the boundary layer, which was found to be responsible for the boundary layer transition. Also, the initiation of the transitional state of the boundary layer results in higher peak heating [54].

The above observations yield an understanding of the thermal load due to SBLIs and their dependencies on the nature of the boundary layer, and the size of the separated region. It was seen that the thermal load has a severely detrimental effect, particularly in hypersonic flows, over different parts of an aircraft, such as intake, control surface, etc. Therefore, an accurate assessment of SBLIs and the prediction of the thermal loads are necessary to have an efficient engine design.

### 2.3 Unsteadiness associated with SBLIs

The interaction of a shock wave with the boundary layer often incurs large-scale unsteadiness in the flow field, which is essentially responsible for the fluctuating pressure and thermal loads [55]. Besides, it is seen that the fluctuating loads are amplified in the region of a higher heat transfer rate in a supersonic or hypersonic aircraft. Pozefsky et al. (1989) identified the regions in a hypersonic aircraft where the failure time is 1 min or sometimes even lesser than that [4]. These consequences are severe enough to result in the total failure of an aircraft [52]. Therefore, it is an utmost necessity to investigate the nature of the unsteadiness. Essentially, two primary sources are found to be

responsible for the fluctuations in SBLI. The first one is the interaction of shock waves with the turbulent boundary layer. The second one is due to the instabilities at the shock foot. The dominant frequencies are dependent on the characteristic dimensions and the incoming boundary layer properties. For example, when the characteristic dimension increases for a fixed boundary layer thickness, the dominant frequency decreases; on the other hand, for a fixed characteristic dimension, the dominant frequency reduces with an increase in the boundary layer thickness [56]. In the subsequent studies, Erenkil and Dolling (1991, 1993) provided a correlation between the fluctuating wall pressure in the upstream boundary layer and the velocity of the separation-shock foot [57, 58]. The contraction or expansion of a separation bubble changes the shock location either towards the upstream or towards the downstream sides. In the meantime, the passage of the turbulent fluctuations changes the shock oscillation. The combined effects of these phenomena result in “small-scale high-frequency” unsteadiness. Further, Brusniak and Dolling (1994) suggested that the frequency of oscillations in the flow field, related to the separation, is possibly dominated by the nature of the incoming flow [59]. They inferred that, in the separated region, due to the turbulence the primary vortices are highly unsteady. Since the leading edge of the primary vortex is essentially connected to the foot of the separation shock, the motion of the shock foot can directly be related to the expansion and contraction movement of the separation zone. The impact of this phenomenon is reflected in global pressure distributions. They also suggested that, since the low-frequency oscillation of the shock foot is very much affected by the primary vortex, necessary controls should be deployed to manipulate the scale of the vortices. At the same time, investigations were conducted to examine the upstream influence on the unsteady phenomenon. McClure (1992) and Ünalmiş and Dolling (1994) concluded that the large-scale shock motion is influenced by the incoming boundary layer thickness [60, 61]. Essentially, the low-frequency thinning and thickening motion of the boundary layer is the driving mechanism for the shock unsteadiness. Later, Wu and Miles (2000) confirmed that the motion of a shock is directly related to the structure of the boundary layer [62]. Beresh et al. (2002) and Hou et al. (2004) have observed that the velocity fluctuations inside the incoming boundary layer result in shock oscillations [63, 64]. Later, the governing mechanism of the unsteadiness in SBLIs, when formed over the compression corner, is described in detail by Ganapathisubramani et al. [65]. They concluded that the unsteadiness has its origin in the long vertical structure inside the incoming boundary layer. Nevertheless, it is a well-established fact that the shock oscillation is directly related to the flow separation and the oscillation frequency is significantly lesser than the frequency of the incoming boundary layer [66, 67]. Therefore, it can be said that the flow separation is not only responsible for the viscous drag, but also it accounts for the flow field unsteadiness.

Further, Clemens and Narayanaswamy (2014) extensively reviewed the investigations on low-frequency unsteadiness associated with a separated flow [68]. A debate on the cause of low-frequency unsteadiness due to the upstream boundary layer or the downstream instability is still prevalent among researchers. Nevertheless, not only the upstream influence, but also the downstream forcing mechanism have a strong impact on the interaction unsteadiness. However, the impact of the upstream boundary layer fluctuation is lesser for larger separated flows. Subsequently, in a Hypersonic Shock Tube

(HST) experiment, Sriram and Jagadeesh (2016) have investigated the flow field near the leading edge of a flat plate. They visualized the evolution of the flow field using high response sensors where the specific nature of unsteadiness of the separation bubble can be observed [69]. Following these studies, the recent review work of Ligrani et al. (2020) described the origin and the source of unsteadiness along with the impact of upstream and downstream forcing mechanisms on the SBLI induced unsteadiness [70]. They concluded that, depending on the size of the separated region, the relative importance of the upstream and the downstream mechanisms may appear.

The above-mentioned literature provides a fairly good insight into the unsteady nature of the interactions. Besides, the study of these characteristics inside the intake-isolator is equally important due to their vast practical applications. In a hypersonic intake, the behavior of shock-trains in the existence of background shock waves is studied by Tan et al. [71]. They discovered that the dominant frequency of shock-train oscillations is influenced by the upstream boundary layer's behavior. Furthermore, background wave interference with shock-trains increases the back-pressure ratio while reducing the shock-train length.

From the above discussions, it is evident that, though some physical mechanisms of mean properties of SBLIs are quite comprehensible; yet, the present understanding of the unsteady nature of SBLIs is not very clear. Even, for an accurate prediction of critical parameters of the mean properties of SBLIs, knowledge of the unsteady effect is essential. It is worth noting that, almost all the applications in high-speed aerodynamics are dominated by the fluctuating nature of SBLIs. Also, in supersonic and hypersonic aerospace vehicles, the severe heating associated with the inherent unsteadiness of SBLI has a great impact on the vehicle structure. The boundary layer, the separation characteristics, and the characteristic dimensions are the important parameters that affect the unsteady behavior. These aspects can never be ignored while designing a supersonic or hypersonic aircraft.

### 3 Computational studies

In the modern era, the advancement of space flights and aircrafts led to several new situations that demand a comprehensive study of the various aspects of SBLIs both experimentally and computationally. Along with the experimental investigations, the development in the computational methods with an enormous increase in computing power has enabled researchers to investigate the shock/boundary-layer interaction phenomena computationally. A validated computational code can effectively capture or resolve the complex characteristics of the interaction, particularly, in unsteady or transient flow situations [52]. Considering this, various computational models have been implemented in order to capture the interaction phenomenon. However, the DNS or LES are essentially high-fidelity time-resolved simulations, which are computationally expensive. Hence, the majority of studies have been conducted on RANS modeling. Gatski and Erlebacher (2002) and Gerolymos et al. (2004) reviewed several RANS studies to obtain a detailed insight into SBLIs characteristics [72, 73]. However, the vast majority of the work considers the linear dependencies between the Reynolds stress components and the strain rate tensor. This causes a large deviation in the computed values from the experimental results. Even in the non-linear eddy viscosity-controlled RANS

model, the unsteadiness in the flow field, the large fluctuating pressure, and the thermal load distributions cannot be captured. In order to exclude these shortcomings in RANS simulations, several computations have been carried out using LES and DNS simulation for both the compression corner and incident shock-induced SBLIs [74–80]. The efficacy of LES on predicting the SBLI characteristics was reviewed by Knight et al. [74]. Particularly, Loginov et al. (2006) and Teramoto (2005) perform the SBLIs studies over compression corners and the incident oblique shock, respectively [75, 76]. It is seen that these simulations are quite accurate in providing the intricate details of SBLIs. Li et al. (2010) and Tong et al. (2017) exclusively described the detailed flow structure containing the SBLI using DNS [81, 82]. The studies are concentrated on the SBLI phenomenon over the compression ramp at Mach 2.9. It is observed that transition is triggered for boundary layer suction and wall blowing [81]. Also, they claimed that the low-frequency oscillation is basically due to the unsteadiness of the separation bubble; not due to upstream turbulent disturbance. Tong et al. (2017) showed that the near-wall portion of the incoming boundary layer is characterized by elongated streamwise vortex formations [82]. The formations in the concave area, on the other hand, are dominated by large-scale hairpin-like vortices in the outer part of the boundary layer. Besides, the turbulent intensity is higher in the downstream side of the compression ramp. Recently, Direct Numerical Simulation has been carried out to understand the impact of incoming flow characteristics on SBLI. It was observed that the transitional boundary layer, which has a thicker subsonic part, shows lesser resistance than the turbulent boundary layer. As a result, the pressure jump due to shock exists over a smaller region, which thereby results in higher rms wall pressure peak for the turbulent boundary layer [83].

#### 4 SBLI control techniques

It is evident that the consequences associated with SBLIs are numerous and most often severe for both internal and external aerodynamics. Since the repercussions are primarily dependent on the shock strength, boundary layer, and separation characteristics, the manipulation of the shock structure and the flow field by some suitable control techniques are essential. In the course of our discussion so far, different types of geometries are investigated. However, in the following sections, the discussions will be mostly oriented to the SBLIs in aircraft intakes.

An intake is an essential part of an aircraft engine where the incoming flow is decelerated for an efficient combustion process. Specifically, in ramjets and scramjets, the incoming flow is slowed by the intentionally generated series of shock waves [41, 84, 85]. However, due to the interaction of shock waves with the boundary layer, the detrimental consequences are evident. The repercussions are high viscous dissipation, enormous pressure loss, unsteady shock oscillations, etc. [1, 86]. These undesired phenomena need to be controlled to alleviate or reduce the colossal losses and to increase the stability of the interaction. Considering these aspects into account, the control techniques address and mitigate the issues related to wave drag and viscous losses. Normally, the control techniques are employed to reduce either the wave drag or the viscous drag as the physical mechanisms involved with these control techniques (for reducing the wave drag or the viscous drag) are different from each other.

According to Delery (1985), control mechanisms can be classified into two groups depending on the location of their deployment [38]. First, the control can be employed to improve the nature of the incoming boundary layer (such as mass injectors, vortex generators). Second, a control can be at the interaction region itself (such as boundary layer bleed or deployment of the porous cavity).

The SBLI control techniques are classified as the shock controls (cavity covered with porous surfaces, surface bumps, etc.) and the boundary layer controls (vortex generators). Essentially, the shock control splits or smears shock a strong shock into multiple shocks to reduce the total pressure loss and the boundary layer control method reduces the loss related to viscosity.

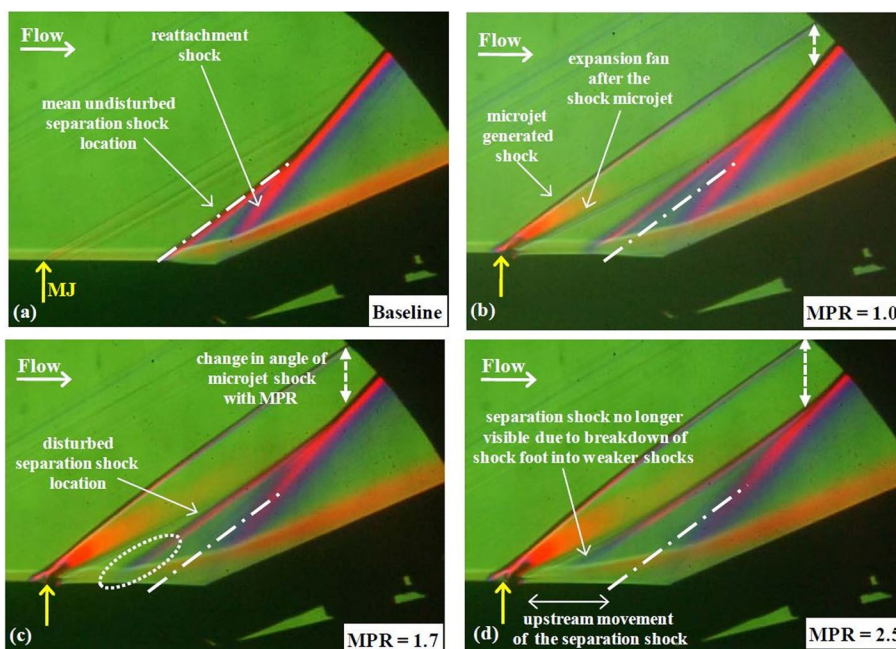
According to the energy requirement, the control technique may be classified into active control or passive control. In an active control, an additional source of energy is necessary, whereas, in a passive control, the control utilizes the energy from the main flow itself.

#### 4.1 Active control techniques

With the advancements of modern intricate techniques, the active controls nowadays are gaining prominence for improving aerodynamic performance. From the perspective of shock/boundary-layer interaction control in an intake, several works have been conducted on the tangential blowing or suction, as witnessed in the extensive review work of Delery [38] and Viswanath [39]. The tangential blowing inside the boundary layer increases the kinetic energy of the boundary layer fluids. Depending on the deployment of the tangential blowing upstream or at the interaction point, U-type or D-type mass injectors are utilized, respectively [87–89]. The deployment of an array of microjets, located upstream of the interaction region, significantly reduces the mean pressure across the separation and reduces the unsteadiness in the flow field [90, 91]. The reductions of separation bubble size with the increase in microjets pressure ratio are clearly shown in the study conducted by Ali et al. (2012) in Mach 2 flow, as shown in Fig. 5 [91]. It can be seen that the separation shock moves upstream and reduces its intensity with the increase in microjet strength. Besides, the air-jet vortex generator was also found to be effective in decreasing the separation length [92]. The experiment was conducted at flow Mach number 1.3. Essentially, the streamwise vortices generated by the air-jet vortex exchange the energy between the low and high momentum fluid and thereby energizes the fluid inside the boundary layer.

Another type of widely used active control (can be active or passive, depending on the energy requirement) is suction/surface bleed, where the low momentum fluid inside the boundary layer is sucked to improve the state of the incoming boundary layer [93, 94]. The deployment of the suction geometry relative to the interaction location governed the suction effectiveness. Fukuda et al. (1977) demonstrated that the suction location upstream or downstream of the interaction region is more effective than the interaction region itself at flow Mach number 2.5 [94]. However, this finding contradicts the assessment of Seebaugh and Childs (1970), where the suction geometry placed at the interaction location is found to be superior (at a freestream Mach number of 2.82 and 3.78). The discrepancies in these results may be due to the differences in the suction geometries [95]. Further, Weiss and Olivier (2014) investigated the influence of suction cavity





**Fig. 5** Schlieren flow visualization describing the effect of control with the variation of Microjet Pressure Ratio [91]

pressure at Mach range 1.45 to 1.85 by introducing the normal suction slot on all four walls of a rectangular nozzle [96]. It is interesting to observe that, when the suction slot is not choked, barrier shock is generated at the suction slot’s downstream corner at a cavity pressure level lesser than the static pressure upstream of the shock. However, the cavity pressure cannot influence the interaction if the suction slot is choked. The efficacy of suction and tangential blowing in reducing the recirculation bubble size was investigated and compared by Sriram and Jagadeesh (2014) at Mach 5.96 [97]. They observed that a suction or injection rate at one order lesser than the momentum deficit essentially reduces the separation bubble size, with a maximum reduction of 20% for tangential blowing. The physical mechanism behind the suction and the surface bleed techniques are quite similar with only the exception that suction utilizes an external pump to draw the low momentum fluids. Although the surface bleed techniques are quite simple (in most cases, it does not require additional power to drain low momentum fluid), additional actuation techniques to control the incoming airflow rate and bleed rate (specifically for active control) may require additional energy, which eventually makes them more complex.

Recently, the importance of the plasma jet has gained much more attention due to its superior effectiveness in stabilizing SBLIs. Normally, the plasma actuators are deployed upstream of the interaction to excite the instability in the recirculated zone. Narayanaswamy et al. (2012) utilized an array of pulsed plasma jets at Mach 3 flow to reduce the unsteadiness in the separated region [98]. Further, the localized arc filament plasma actuators were used at Mach 2.3 by Webb et al. (2013), where they noticed that the actuators are effective in reducing the low-frequency unsteadiness [99]. The actuators essentially induce additional heat inside the boundary layer to modify its nature. Greene

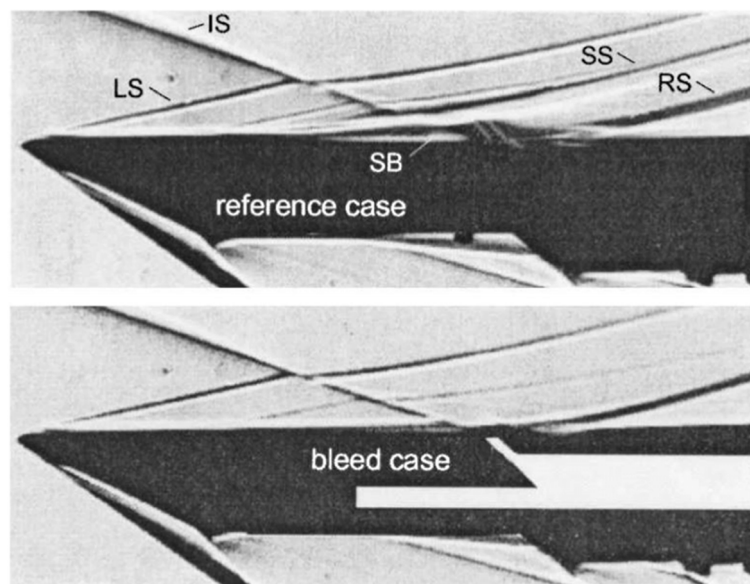
et al. (2015) demonstrated at Mach 3 flow condition that the implementation of the pulsed plasma jet suppressed the separation, particularly, the recirculation length from the separation point to the compression corner was reduced significantly [100]. Besides, magnetically driven surface discharge can effectively manipulate the boundary layer in controlling the SBLI at Mach 2.6 [101]. It was observed that the plasma actuation at a low current (below 80 mA) in the downstream side significantly alters the separation bubble structure, whereas, plasma actuation at a higher current (above 80 mA) in the downstream side significantly improves the separation bubble structure and wall pressure profile. When magnetic field strengths of more than 1 Tesla are applied, increasing the actuation current reduces the size and strength of the recirculation. Moreover, separation might be completely eliminated with magnetic field intensities of 3 Tesla and currents larger than 80 mA. The Magnetohydrodynamic (MHD) flow control technique also gained prominence in weakening the shock intensity by altering the boundary layer profile over the ramp surface. Essentially, MHD flow control can result in significant changes in flow behavior near the ramp, as well as there is a significant reduction in total pressure loss across the oblique shock [102]. It is also interesting to observe that the magnetic field causes the velocity of the plasma column to move at a much faster rate than that in the absence of the magnetic field.

Since, active control techniques involve complex mechanisms that sometimes become difficult to implement, particularly, in a hypersonic flight, where the temperature generated inside the intake is too high. This led the researchers to focus on passive control techniques more extensively.

#### 4.2 Passive control techniques

In high-speed aerodynamics, passive control techniques are widely used for their simplicity and effectiveness. As already discussed, depending on the nature of the operation, the control techniques can be classified as shock control or boundary layer control. A shock control extends the interaction regions to reduce the strength of the primary shock; boundary layer control energizes the boundary layer to offer more resistance to separation. Some of the well-established control methods used to manipulate the SBLIs are boundary layer bleed, vortex generators, streamwise slots, porous cavity, surface bump, splitter, etc. [103–111]. Boundary layer bleed is the widely used control technique (can be active or passive, depending on the energy requirement), where the low momentum fluids near the wall are bled and the high momentum fluids outside the boundary occupy their location. The high momentum fluids eventually impose more resistance to separation [103]. Schulte et al. (2001) investigated the efficacy of the boundary layer bleed in hypersonic flow [104]. It was seen that the boundary layer bleed dramatically reduces the separation bubble size up to 50%. Figure 6 describes a clear reduction in separation bubble size over the ramp controlled with surface bleed when compared with the uncontrolled case. They have described the optimum location of the bleed system, where the maximum pressure recovery can be achieved. It is seen that the streamwise slots are responsible for the bigger lambda-shock structures, which essentially improve the total pressure losses. Besides, the slots shed the streamwise vortices into the flow field, which may be effective in delaying the separation [107, 112]. Later, it was shown that the use of a surface bump on the ramp surface effectively controls the interaction by replacing a

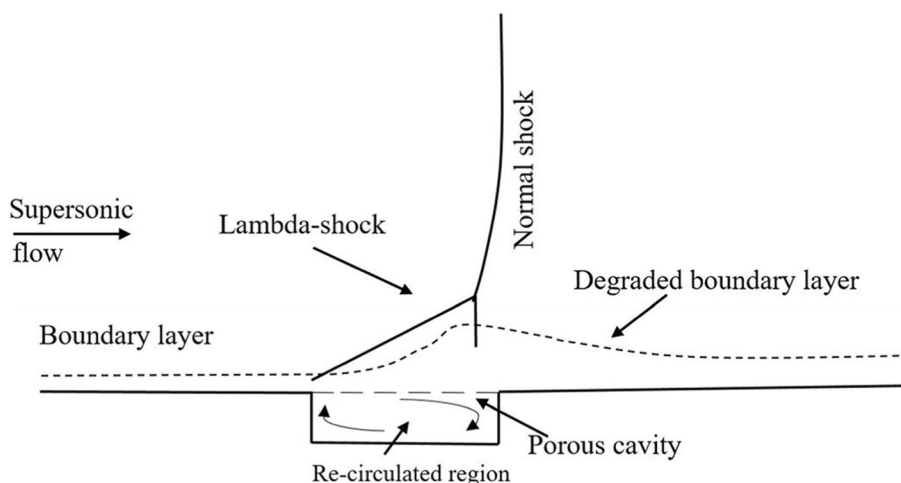




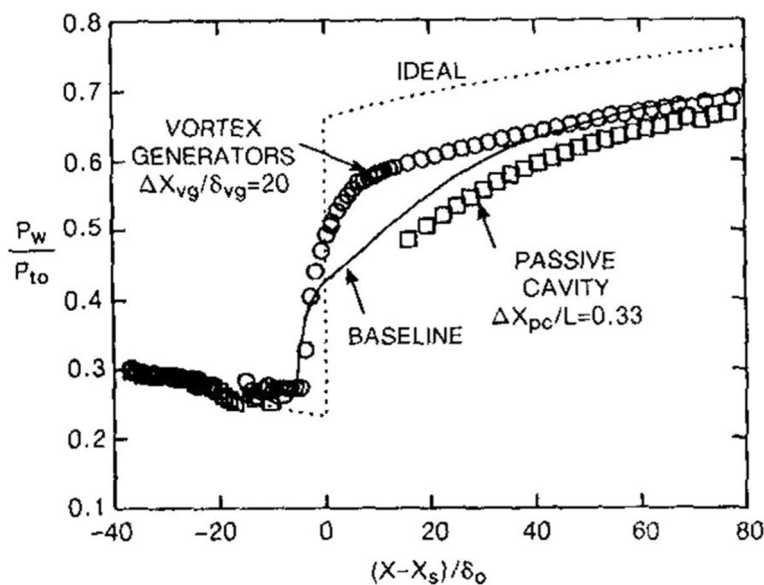
**Fig. 6** Schlieren flow visualizations for the uncontrolled ramp surface (reference case) and controlled ramp surface with surface bleed (bleed case) [104]

bigger separation bubble with two smaller bubbles [109, 113–115]. Further, the separation region induced by SBLI, at the Mach number range 4 to 6, was reduced with the introduction of splitters in the internal convergent portion of the inlet, which degenerates a single strong interaction into multiple weak interactions [110]. The modification of the cowl surface also has a prominent impact on SBLI. At Mach 4.03 flow, Senthilkumar and Murganandam (2020) through their numerical investigation found that concavity on the cowl surface significantly controls the SBLI [116]. Later, to lessen SBLI-induced separation, the combined effects of boundary layer bleed and boundary layer suction have recently been computationally explored. Essentially, a secondary recirculation jet is computationally investigated in order to control the flow. To limit the size of the separation bubble, the suction slot was found to be best when deployed on the upstream side of the flow separation zone in the supersonic flow [117].

Among the passive control techniques, few researchers have looked at the use of a porous surface over a shallow cavity as a shock control system. The primary goal of a passive cavity is to reduce the overall pressure loss caused by the extended interaction area due to the smeared shock system. Raghunathan (1988) studied the effects of SBLIs and their controls using passive control techniques at transonic flow [108]. The research looked at the benefits of using a porous surface deployed over a cavity at the shock impingement point for monitoring SBLIs. As a result, recirculation occurs spontaneously across the shock from the high-pressure zone (on the downstream side) to the low-pressure zone (on the upstream side), as shown in Fig. 7. Consequently, the strong shock is broken or smeared into lambda-shock. Later, a systematic analysis of passive control with a perforated plate supports its effectiveness over supercritical airfoils [119]. Rallo et al. (1992) described that the deployment of a porous cavity is responsible for the shock strength reduction which in turn weakens the strength of the interaction [120]. It is important to note that the comment on SBLIs strength reduction can directly be made



**Fig. 7** Control of SBLI using porous cavity [118]

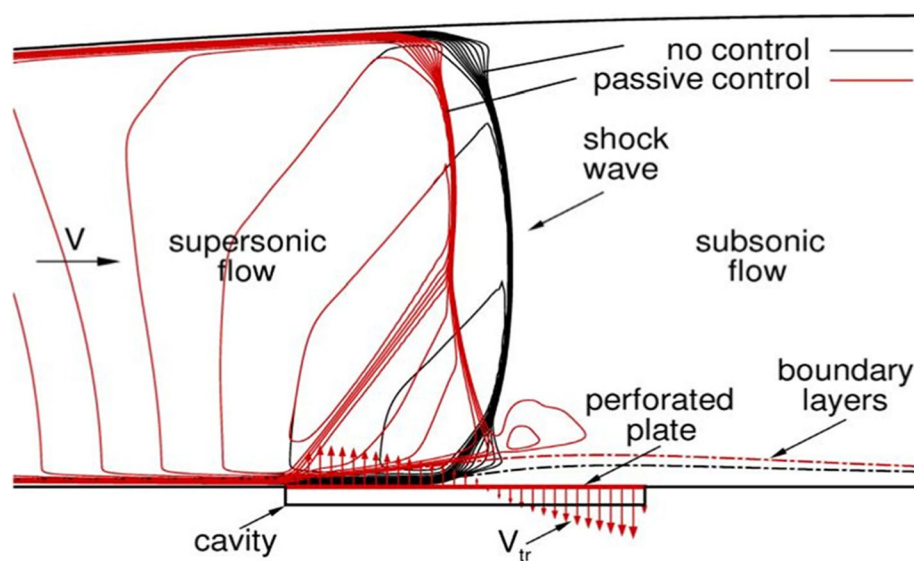


**Fig. 8** Wall static pressure distributions [121]

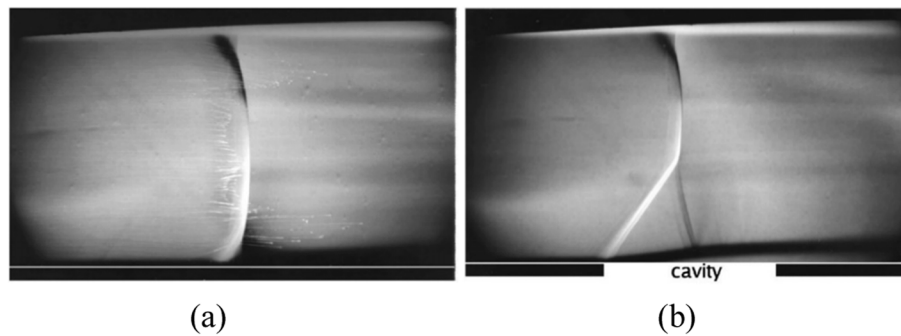
by observing a drop in the maximum wall static pressure at the interaction region. In addition, their investigation on the influences of surface porosity (introduced on a flat surface) on SBLIs at hypersonic flow indicated that the reattachment pressure decreases considerably when the surface porosity increases. Following that, in the experimental study, at Mach number range 1.56 to 1.65, McCormick [121] used both micro-vortex generators (MVGs) and a shallow cavity to manipulate the SBLIs. Due to the influence of a porous wall with a shallow cavity underneath (with evenly spaced pores) on a flat plate, the generated lambda-shock greatly decreased the shock intensity, as shown in Fig. 8 [121]. However, on the upstream side of the shock, degradation of the boundary layer (boundary layer thickening due to fluid injection) is observed.

Hanna (1995) investigated SBLI control in a hypersonic flow using a porous surface [122]. Because of upstream pressure transmission across the subsonic portion of the boundary layer, the interaction area for viscous flow is larger than for inviscid flow, according to the research. In addition, constant and variable porosity-controlled models were compared in the study. Surprisingly, the peak pressure comparably decreases in both cases. Bur et al. (1997) explored the effect of a porous cavity on a transonic airfoil when it is working in off-design conditions [123]. The porous cavity was shown to break a single shock into a lambda-shock system. The results showed a substantial decrease in wave drag; however, there was a significant increase in viscous drag. As a result, the net drag reduction was negligible. Nonetheless, under ideal flow conditions, a shallow cavity with a porous wall was proved to be very efficient in regulating SBLIs over a plain surface at a supersonic level of maximum Mach number of 1.35 [124]. The use of a porous surface effectively converts normal shock to lambda shock. As a result of this, the overall pressure loss is reduced, which decreases the typical shock strength. However, the boundary layer degrades downstream of the interaction region, as shown in Fig. 9. Therefore, the ultimate result is a balance of higher viscous losses and lower shock losses. The Schlieren view of the shock structure with and without the porous cavity is presented in Fig. 10. This clearly shows that the porous cavity effectively reduces the shock strength.

Notice that, these studies concentrated the SBLIs over a flat plate using the externally generated shock wave alone. However, in hypersonic intakes, the influence of expansion waves created at the convex corner of the ramp on the SBLIs cannot be neglected. Thus, Mahapatra and Jagadeesh (2008) investigated cowl and ram-induced multiple shocks inside a generic scramjet intake (Mach 8), where typical features of the shock structure at different contraction ratios were observed [125]. To numerically investigate the impact of throat area and incoming Mach number fluctuations, James and Kim [126] considered a hypersonic mixed compression intake at



**Fig. 9** Control of Shock/Boundary-Layer Interaction using porous cavity [124]



**Fig. 10** Schlieren flow visualization (a) without and (b) with the porous cavity [124]

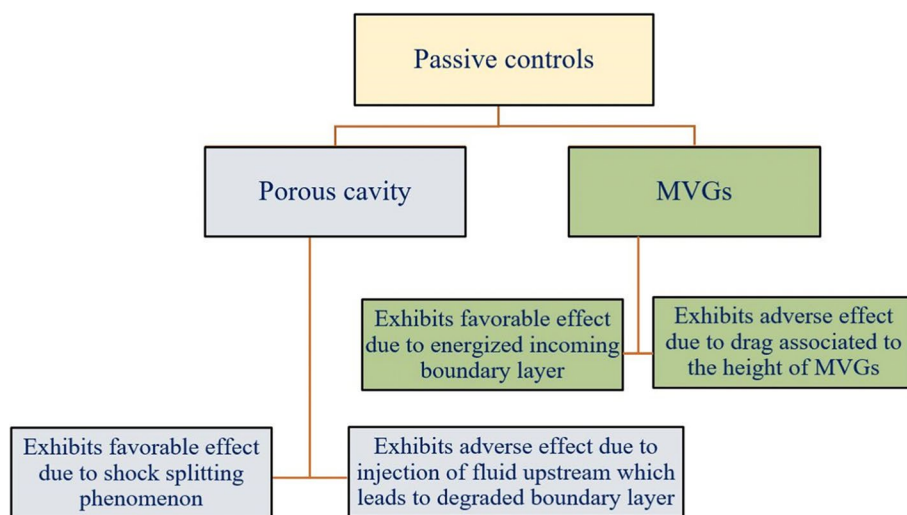
freestream Mach number 2, 3, and 5. They showed that an increase in the area ratio leads to a possible decrement in the mass flow rate. Besides, at higher Mach numbers, total pressure recovery is less [126]. Zhang et al. (2014) used a computational model to analyze the influence of expansion waves on SBLIs in a hypersonic intake with an upstream Mach number of 3.5 [127]. Expansion waves have both positive and negative effects. The shock-shock-expansion waves and shock-expansion wave-shock interactions are particularly beneficial in controlling the SBLI when the cowl shock occurs near the convex corner of the ramp. As a result, the separation bubble size is decreased. Recently, the influence of a porous cavity on SBLIs, mounted inside a Mach 2.2 supersonic intake, has been studied for various intake contraction ratios by Gunasekaran et al. [128]. The study revealed that the performance of a porous surface with a cavity is strongly dependent on the contraction ratio of a supersonic inlet. However, when the porous cavity is introduced, the boundary layer worsens, and the shape factor downstream of the interactions increases, as compared to the boundary layer in uncontrolled intake [121]. Therefore, to overcome the shortcomings of the shock control methods, the boundary layer control methods such as the micro-vortex generators (MVGs) were extensively studied.

The use of micro-vortex generators (MVGs) to reduce shock-induced separation has gained popularity in recent years due to their interesting result [105]. Furthermore, vortices of mixed size shed in a streamwise manner can effectively control the size of the recirculation field, according to the findings. These vortices can be shed by inserting traditional or sub-boundary layer vortex generators into the flow [129]. Through their research in transonic flow, Inger and Siebersma (1989) showed that placing vortex generators upstream of the contact point energizes the incoming boundary layer wave [130]. As a result, the pressure gradient around the contact zone rises, ultimately creating a strong shock. To suppress or delay the separation of the boundary layer, traditional vortex generators (VGs) of a height equal to the thickness of the undisturbed boundary layer have been used [131, 132]. However, sub-boundary layer vortex generators (SBVGs) with a height less than the undisturbed boundary layer thickness are more efficient in separation control than traditional vortex generators because they have less drag [133, 134]. MVGs are indeed very effective instruments for separation control; however, lowering the MVG's height below 10% of the boundary layer thickness is not effective in managing shear layer separation [135].

It was concluded that, micro-vortex generators (MVGs) shed adequate strength vortices in reducing separation time, unlike their conventional counterparts, where the vortex strength is too high and disrupts the flow [136]. MVGs’ distribution, in addition to their height, plays an important role in flow management. Due to their capacity to inhibit shock-induced separation, the array of MVGs has recently received a lot of research motivation [137, 138]. The flow control performance of the array of MVGs is also affected by their deployment position. The ability of the array of MVGs to monitor flow is also affected by the location where they are deployed. As the MVGs are deployed at or upstream of the interaction field, the boundary layer regains its momentum due to the augmented mixing, slowing the onset of flow separation and reducing the size of the separation bubble [138, 139]. It is easy to observe that, each control strategy has its advantages and disadvantages. For example, the favorable and adverse effects of two major passive control techniques, namely, shock control (using porous cavity) and boundary layer control (using MVGs) are shown in Fig. 11. Besides, the key technologies in regulating the SBLI with their benefits and drawbacks are summarized in Table 1.

Essentially, the SBLIs can be regulated by the shedding of the two counter-rotating vortices that originate from the MVGs, as shown in Fig. 12 for Mach 2.5 flow. These mixing-promoting vortices (Fig. 12) are extremely successful at transferring momentum between near-wall and outer boundary layer fluids, resulting in a better boundary layer [140]. Essentially, the low momentum region behind the vortex generator moves upward due to the vortex-induced upwash motion. At the same time, the higher momentum region is entrained towards the near-wall lower momentum region (Fig. 13). In this way, the transfer of momentum is happening between the high-speed freestream and the low-speed near-wall region fluid by the vortex-induced streamwise vortices.

The ramp-type MVGs are superior in the reduction of the recirculation region size since they generate counter-rotating micro-vortices with considerably higher intensity in the near-wall region [141]. Furthermore, highly swept micro ramps are very effective

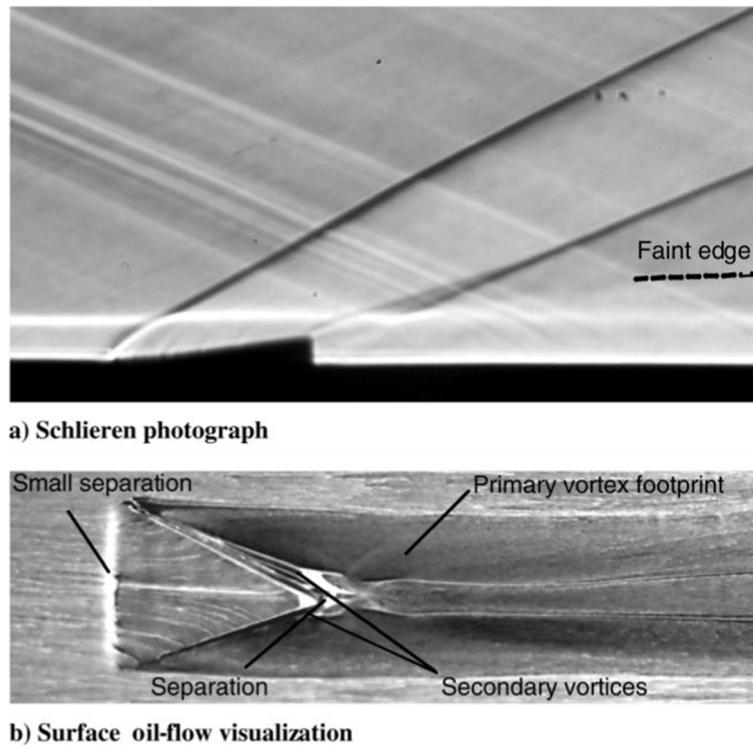


**Fig. 11** Benefits and drawbacks associated with major passive control techniques

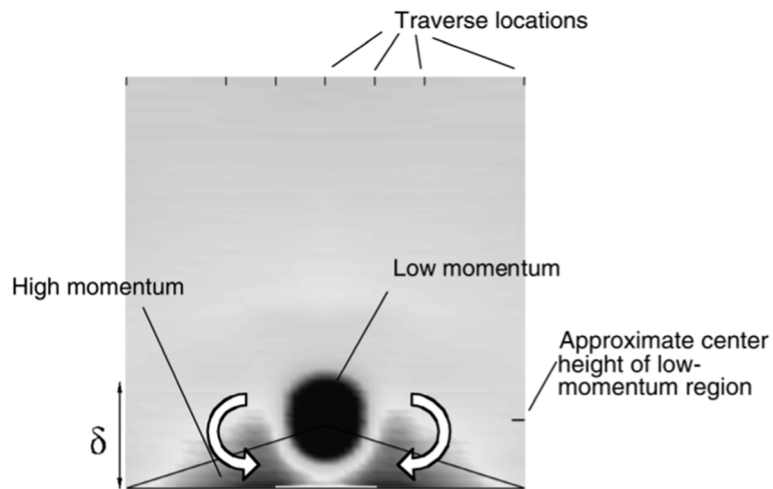
**Table 1** Key technologies in controlling SBLI with their benefits and drawbacks

Control Techniques	Benefits	Drawbacks
<b>Porous cavity</b> (Passive control) [118–122, 124, 128]	Very effective in splitting a single strong shock into several weaker shocks by recirculation of higher pressure fluid towards the lower pressure region through the cavity.	Promotes SBLI due to the thickening of the incoming boundary layer as a result of the injection of the fluid upstream of the shock.
<b>MVGs</b> (Passive control) [105, 121, 129–144]	Very efficient in suppressing the separated shear layer by energizing the incoming boundary layer through vortices.	Results additional drag due to the height of the MVGs.
<b>Surface bump</b> (Passive control) [109, 113–115]	Effectively suppress boundary layer separation by introducing a bump over a surface, where the separation region was observed for the uncontrolled case.	In off-design conditions, the shock impingement point changes its location. Thereby, for a wide range of Mach numbers, the bump is not very effective in controlling the flow.
<b>Slots and grooves</b> (Passive control) [107, 112]	Improve the total pressure recovery by smearing the strong shock into lambda shock.	This leads to the thickening of the boundary layer, which thereby results in an additional viscous penalty.
<b>Splitter plate</b> (Passive control) [110]	Effectively reduce the shock intensity and the boundary layer separation by splitting a single severe shock/ boundary-layer interaction into several weaker smaller interaction zones. Very efficient in a wide range of Mach numbers.	It exhibits additional drag to the flow.
<b>Boundary-layer bleed/suction</b> (Passive/Active control) [38, 39, 93–97, 103, 104]	Effectively suppress the boundary layer by sucking the low momentum fluid upstream of the interaction region. The level of actuation can be controlled according to the demand.	Due to lost mass through the bleed hole, ingested mass flow to the engine is reduced. In order to compensate for the mass flow, the intake area must be larger, which will increase drag and engine weight.
<b>Tangential blowing</b> (Active control) [38, 39, 87–89, 97]	Very effective in reducing the separation bubble size by energizing the boundary layer while injecting the fluid of high velocity. The level of actuation can be controlled according to the demand.	The injection of jets consumes a significant amount of pressurized air from the engine itself, which essentially decreases the efficiency of the engine.
<b>Micro jets</b> (Active control) [90, 91]	Effective in reducing the intensity of the shock wave since the compression is achieved gradually by micro jets generated shocks and separation shock. Besides, using micro jets, the unsteadiness in the interaction region can be suppressed.	An additional amount of energy is required for the micro jet to work, which essentially decreases the overall engine efficiency.
<b>Air-Jet Vortex Generator</b> (Active control) [92]	As effective as a vortex generator since the issuing jet, while interacting with cross-flow, creates stream-wise vortices. The air-jet vortex generator is very efficient since it has no parasitic drag.	Consumes extra energy, which thereby decreases engine efficiency.
<b>Plasma jets</b> (Active control) [98–102]	Improve pressure recovery, and suppress the separation since the voltage through the electrodes creates a certain region of heated flow that interacts with cross-flow, which results in the generation of stream-wise vortices. Besides, pulsed plasma jets effectively reduce the unsteadiness associated with SBLI.	Difficult to implement high frequency fully modulated pulsed jet in hypersonic flow situation.





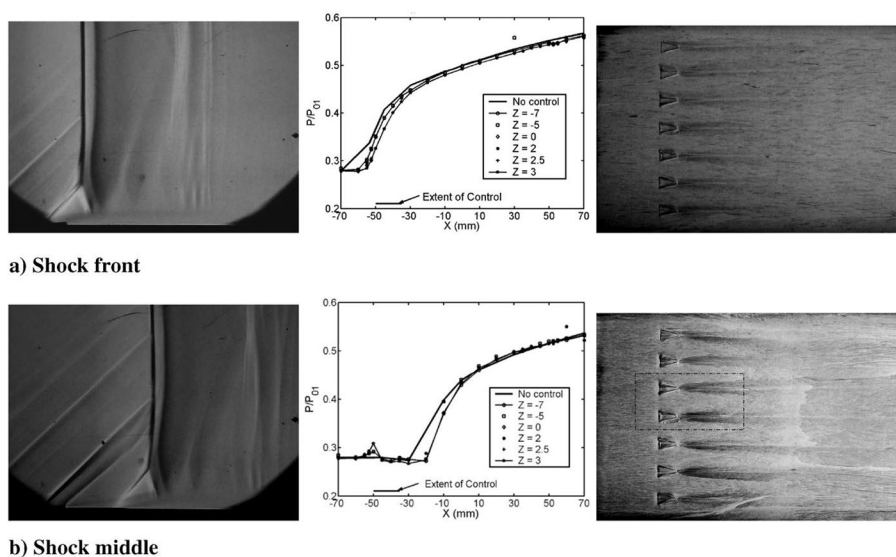
**Fig. 12** Flow visualization with the micramp of 4mm height [140]



**Fig. 13** The momentum variation between the baseline velocity profile and ramp flow [140]

as an SBLI control which induces the pre-compression via weak shock to escape swirling flow in the interaction location [142]. Although larger MVGs have higher control performance than shorter MVGs, they encounter the largest momentum shortage and much more drag. However, the separation delay can be overcome by putting smaller MVGs near areas with unfavorable pressure gradients, which decreases the drag due to viscosity [140–143]. Taking this into account, Saad et al. (2012) used MVGs to analyze



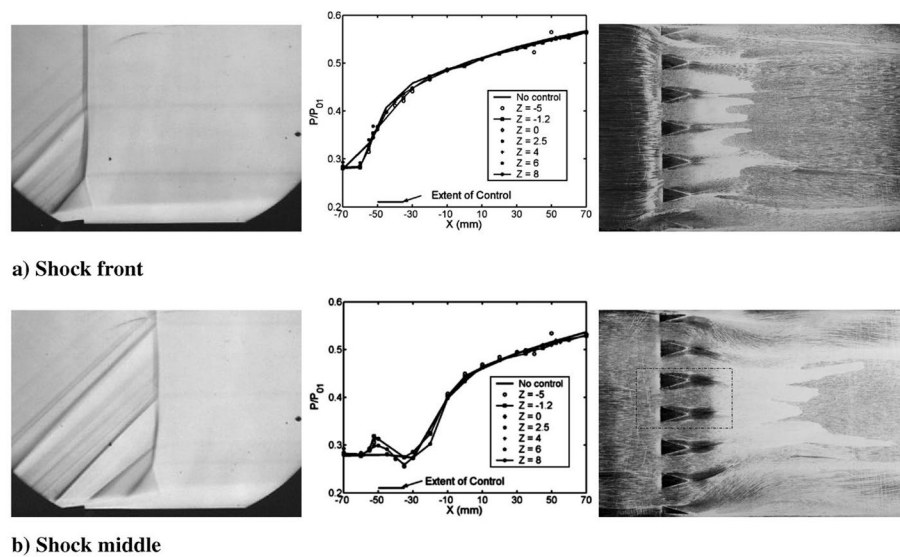


**Fig. 14** Schlieren flow visualizations, wall pressure measurements, and surface oil-flow visualizations for Vane-type Sub-Boundary Layer Vortex Generator [143]

the detailed flow structure in a hypersonic flow on a flat plate (Mach 5) [145]. They concluded that the MVGs induced mixed size vortices help to minimize the upstream interaction region, which in turn suppresses SBLIs. In the recent studies carried out by Kaushik [105] and Gunasekaran et al. [128], the efficacy of the MVGs as well as the porous surface, deployed over a shallow cavity mounted in a Mach 2.2 mixed compression intake, have been investigated experimentally. Since the effects of passive controls in a hypersonic intake may not be the same as in the supersonic intake, therefore, an investigation into the hypersonic intake controlled with passive techniques is essential to identify their effectiveness.

Huang et al. (2020) recently published a systematic review that demonstrated the supremacy of MVGs in the reduction of shock-induced separation for both external and internal flows [146]. Interestingly, the micro-vanes (Fig. 14) were found to be more effective at removing the separation bubble. Micro-vanes, on the other hand, are unstable at high Mach numbers due to their slender design [143], while wedge-shaped micro-vortex (Fig. 15) have a more stable configuration. Furthermore, smaller wedge and vane-shaped MVGs are effective and vigorous in regulating the SBLIs. On the other hand, a triangular-shaped micro-vortex generator can efficiently shed mixed-size vortices, which is desirable from the perspective of improved mixing, according to the literature.

It can be seen from the literature that most of the studies are carried out over the simplified model, i.e., over the flat plate or curved surfaces, where the combined effect of multiple shocks and expansion waves is absent. Since their effects on the boundary layer are non-linear, the investigation of their combined effects is essential for a complete understanding. Considering this in mind, Jana et al. (2020) investigated the effect of a porous cavity in a mixed compression double ramp hypersonic intake (operating at Mach 5.7 and Mach 7.9 flow conditions) [118]. It is observed that the shallow cavity deployed over a porous surface can reduce the shock strength; the



**Fig. 15** Schlieren flow visualizations, wall pressure measurements, and surface oil-flow visualizations for Wedge-type Sub-Boundary Layer Vortex Generator [143]

shock strength is decreased with the increase in surface porosity. However, the separation bubble size is decreased up to 17% surface porosity, and beyond that limit, the bubble size starts increasing again. They concluded that the higher injection of fluid into the incoming boundary layer promotes the SBLI to such an extent which cannot be reduced by the favorable effect of shock strength reduction. In a subsequent study, Jana et al. (2021) examined the effect of an array of Micro Vortex Generators (MVGs) of varied heights separately deployed at two different locations at Mach 5.7 [144]. The MVGs of height 0.7 mm deployed upstream of the interaction region are the most effective in reducing the separation bubble size. However, shock strength reduction is achieved when the MVGs of 1 mm are placed at the interaction region. They have concluded that, though the passive control is very effective in reducing the SBLI, there is an optimum limit of each passive control technique (porous cavity, MVGs), beyond which the control may promote SBLI.

It is observed from the earlier discussions that SBLI has several detrimental consequences in transonic, supersonic, and hypersonic flow regimes. In a transonic flow situation, the subsonic flow behind the shock wave influences the intensity, shape, and location of the shock and thereby, alters the upstream interaction significantly. In these flow regimes, SBLI can be exclusively observed over transonic aircraft wings and transonic turbine- and compressor-blade cascades. The major control strategies in transonic flow, which can be effectively implemented, are cavity-covered porous surface and surface bump deployed over the surface. In the supersonic regime, SBLI is a common occurrence over supersonic aircraft and in the intake isolator section of ramjet/scramjet engines. There are several passive and active control strategies, such as boundary layer suction and blowing, air-jet vortex generators, micro jets, plasma jet actuators, surface grooves, splitter plate, surface bump, porous cavity, MVGs to improve the interactions, which are discussed in detail. Finally, the hypersonic flow

region is characterized by severe interaction of shock wave with boundary layer which leads to very high-temperature rise, higher total pressure loss, huge separation bubble, flow unsteadiness, etc. In these flow situations, surface bumps, porous cavities, splitter plates, and MVGs like passive control techniques are mainly implemented in order to control SBLI in the scramjet inlet and isolator section. Boundary layer bleed is also an important choice in controlling hypersonic interactions. Moreover, the recent investigation on low wavelength wavy patches, placed in the interaction region, has gained prominence in effectively controlling the SBLI in hypersonic flow (Mach 8.5) [147].

## 5 Further development

Several investigations have been conducted in order to understand the physical mechanism of SBLI. Besides, various control techniques are implemented to regulate the SBLI while extracting the maximum favorable effect from the shock wave in compressing the flow. Although significant progress has been achieved in SBLI research, numerous features of SBLI in the hypersonic flow domain remain unknown. Estimation of the transition of a boundary layer in hypersonic flow is a vital aspect that needs to be investigated further. It can be noted that most investigations on the influence of control strategies on SBLI regulation are carried over a basic model. Further research should be conducted on the complex geometries which are employed in actual scenarios. It can be seen that passive controls, such as porous cavities, and smaller wedge and vane-shaped MVGs have a significant impact on controlling SBLI by decreasing shock intensity and suppressing separation bubbles. Particularly, the impact of MVGs in controlling the separation bubble for supersonic and hypersonic intake is superior. The configuration, size, and location of MVGs with respect to the interaction region should be optimized as it has successfully proven its efficacy in several flow situations. Therefore, additional research on these passive techniques should be carried out in controlling the supersonic and hypersonic intakes to improve the combustion characteristics of ramjet/scramjet engines. Besides, the recent investigation on low wavelength wavy patches placed in the interaction region demands further research on the wavy patches in controlling the SBLI in hypersonic flow. Most of the existing literature separately investigated the effects of different control strategies. However, their effect on the boundary layer is non-linear. Therefore, investigations need to be carried out to find their cumulative impact on the boundary layer. According to Dolling (2001), in recent times, a validated computational code can efficiently capture or resolve the complex nature of SBLIs, especially in unsteady or transient flow situations [52]. Considering this, Direct Numerical Simulation (DNS), Large Eddy Simulation (LES), and even several Reynolds-averaged Navier-Stokes (RANS) models can be carried out along with the experimental study in order to capture the interaction phenomenon in detail. In addition, the hypersonic boundary layer transition control technique should be carefully looked into in order to develop future hypersonic aircraft [148].

## 6 Conclusions

This review essentially presents an overview of the several important features of SBLIs and the control techniques to effectively manipulate them. It is evident that the response of the boundary layer upon the shock impingement determines the structure of the

interaction. In addition, the laminar and turbulent interactions have distinct features and consequences on the flow structure. Besides, the thermal loads are dependent on the nature of the boundary layer, and the size of the separated region. Almost all the applications in high-speed aerodynamics are dominated by the fluctuating nature of SBLIs. Also, in supersonic and hypersonic aerospace vehicles, the severe heating associated with the inherent unsteadiness of SBLI has a great impact on the vehicle structure. The boundary layer, the separation characteristics, and the characteristic dimensions are the important parameters that affect unsteady behavior. Though the active control techniques are utilized in regulating the interactions, they involve complex mechanisms that sometimes become difficult to implement, particularly, in a hypersonic flight, where the temperature generated inside the intake is too high. On the other hand, passive controls such as the porous cavity, and micro-vortex generators are very efficient in controlling the SBLIs depending on the type of control requirement. As observed from the vast quantity of literature, in the last eight decades, though remarkable achievements have been made in SBLI research, several aspects of SBLI in the hypersonic flow domain are yet to be revealed. As seen in the literature, most of the investigations are conducted with oversimplified models. However, for a complete understanding, the investigations should be conducted on complex models where the effect of multiple shock and expansion waves is present. These issues are yet to be resolved for a proper understanding to control them. This makes SBLIs a subject of current interest and there is nothing wrong to say that it will continue to be a topic of research in the future as well.

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**Authors' contributions**

TJ performed the literature survey and wrote the first draft. MK supervised the study and edited the manuscript. The authors read and approved the final manuscript.

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**Availability of data and materials**

All the supporting data is included in the manuscript itself. No separate data file is required.

**Declarations****Competing interests**

The authors declare that they have no competing interests.

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