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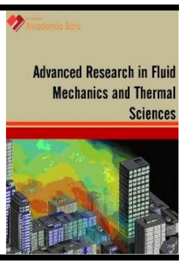

Base and Wall Pressure Control using Cavities and Ribs in Suddenly Expanded Flows - An Overview

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ABSTRACT

An understanding of fluid flow in sudden expansion has resulted in a great deal of research work in this area. Of particular interest is the study of base drag which influences the performance of automotive vehicles, aircraft and missiles. Problems of fuel mixing in combustion chambers and reduction of specific fuel consumption are also governed by the phenomenon of base drag. It is the aim of this study to present a brief review of the work carried out in the area of sudden expansion in a duct with particular accent on a few active and passive controls employed to modify the base drag. It is noteworthy that a reduction in base drag is of benefit in combustion mechanisms while an in-crease in base drag is preferred for net drag reduction of bodies moving through air. Suppression of flow oscillations that accompany the control of base drag also merits attention. A few suggestions by way of future work are also discussed.

1. Introduction

Fundamental challenges limiting the performance of automotive, aircraft and space applications can be attributed to the pressure at the external base region of the vehicles characterized by sudden expansion of the flow. Flow separation close to the base could cause a region of low-speed recirculation. Lower than atmospheric pressure exists in the base region. The total drag in the transonic region is attributable up to 50 – 60% of the base drag due to pressure differences. In supersonic region, similar differences in pressure could contribute as high as 30 % drag [1].

A host of problems are also caused on account of separated turbulent flows with undesirable base pressure fluctuations viz. base buffeting. In combustion chambers, an increased level of local turbulence due to sudden expansion of the fluid leads to improper fuel mixing conditions thereby, increasing specific fuel consumption (SFC) and higher operational costs. Fuel-efficiency is another key factor to obtain efficient and effective performance of any vehicle.

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In order to study the phenomenon of sudden expansion and pressure region development at the base, air flowing from a region of high pressure suddenly expanding into a duct with an area of larger cross-section is considered. A sketch of the sudden expansion occurring in an enlarged duct and its schematic is shown below in Figure 1 and Figure 2 respectively. Such a problem can be characterized by flow separation from the nozzle exit, shear layer separation, flow recirculation region below the shear layer, flow reattachment and new boundary layer formation past the reattachment point along the length of the duct [1–3].

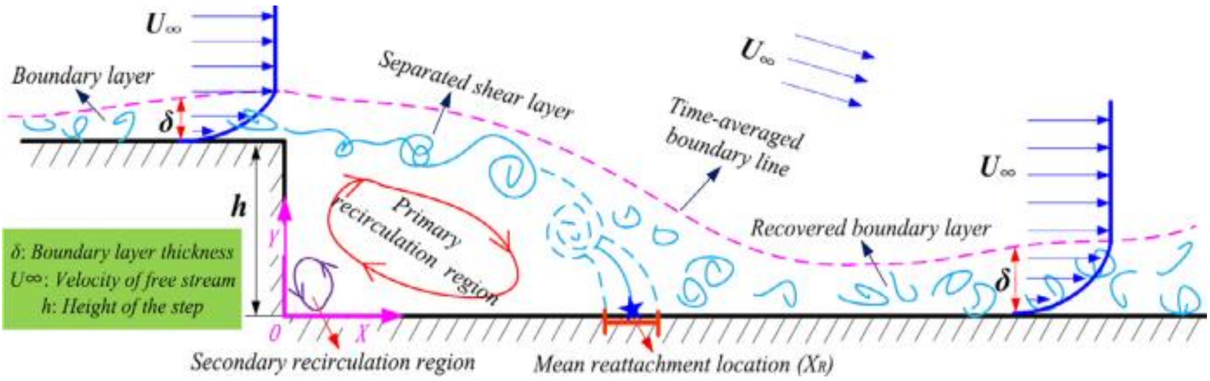


Fig. 1. Sudden expansion phenomenon [4]

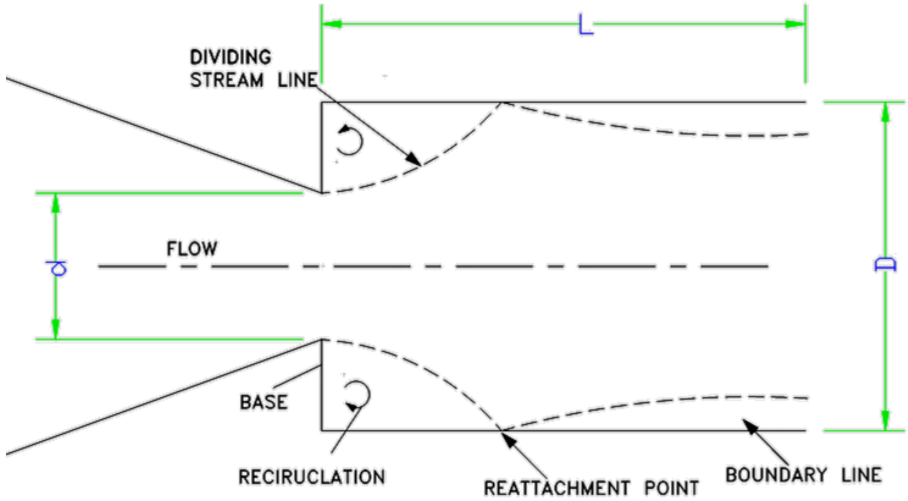
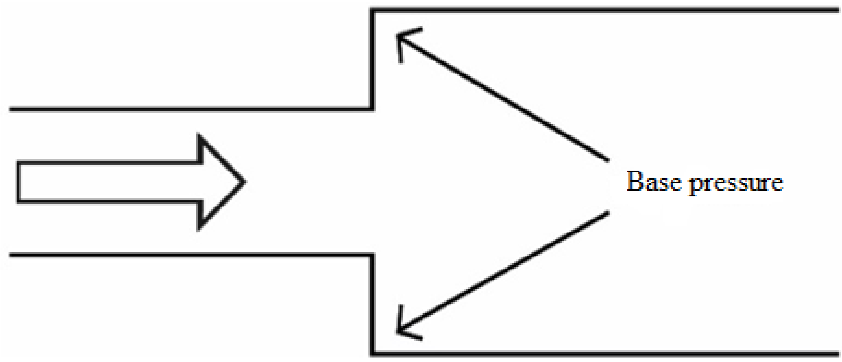


Fig. 2. Schematic sketch of sudden expansion phenomenon [2]

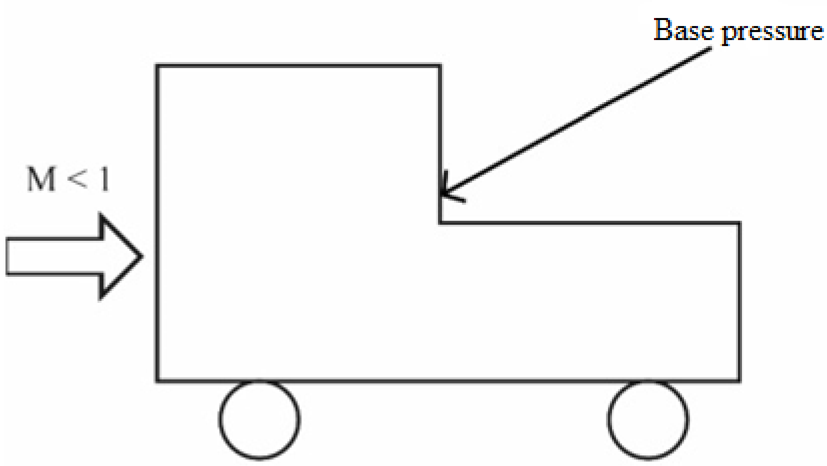
The air flow exits from the nozzle and a shear layer is formed. A recirculation region or separation bubble is a vacuum region that forms below the shear layer, leading to breaking down of large-scale vortices into smaller vortices [1–3]. The shear layer develops and reattaches downstream of the duct, post which a new boundary layer is generated along the duct.

The drag force resulting from the low pressure at base is essentially the product of base pressure (Pb) and base area (Pa) [2]. It is necessary to increase the base pressure viz. decrease the suction at the base in order to reduce this base drag. The suction base pressure is due to the vortex generated at the base. The base pressure can be increased when a control strategy can decrease the size of the vortex [1-2].

These problems of base drag can be illustrated as Figure 3. Base pressure and the flow downstream of the base are dictated by vortex dynamics, triggered by sudden expansion of the flow in the enlarged duct region. This is the general phenomenon occurring in normal fluid flows. Vortex dynamics plays an important role in the transport of mass, momentum, and energy in a flow field [2]. Thus, controlling of the vortex is the key to obtain better performance of any vehicle. The sudden expansion flow occurring in subsonic, sonic and supersonic regimes at different expansion levels are sketched below to provide a brief idea of the flow behavior.



(a)



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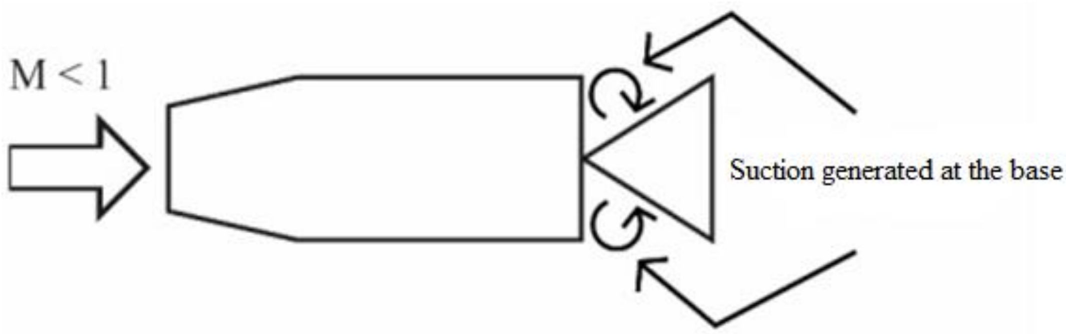

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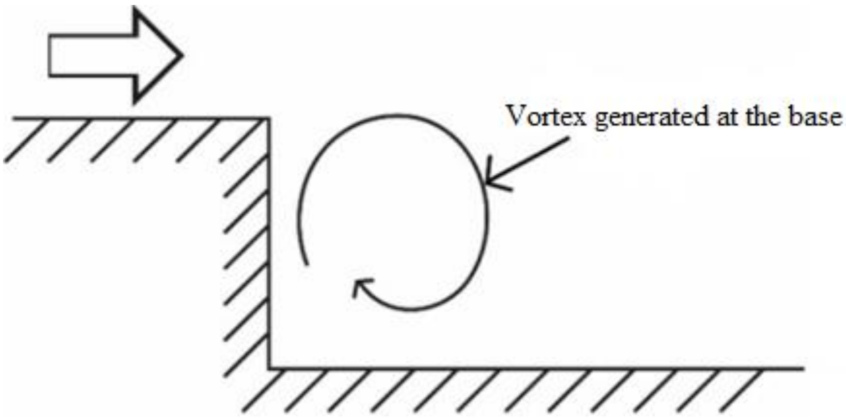

(d)

Fig. 3. Base drag in the downstream region of (a) an enlarged duct in the case of suddenly expanded flows, (b) rear portion of trucks, (c) rear portion of rockets and (d) vortex generated at the base

The Nozzle Pressure Ratio (NPR) which is the ratio of stagnation pressure in the settling chamber to the exit pressure, dictates the level of expansion at the nozzle exit [2]. As NPR is increased from a low value, the nozzle discharge progressively moves from over expanded to correctly expanded and underexpanded flow. Figure 4 shows the flow expansion phenomenon in subsonic flow, which is correctly expanded. Figure 5 and 6 are the cases of underexpanded sonic flow and correctly expanded sonic/supersonic flow, which have expansion fan and weak oblique shocks at the nozzle throat respectively.

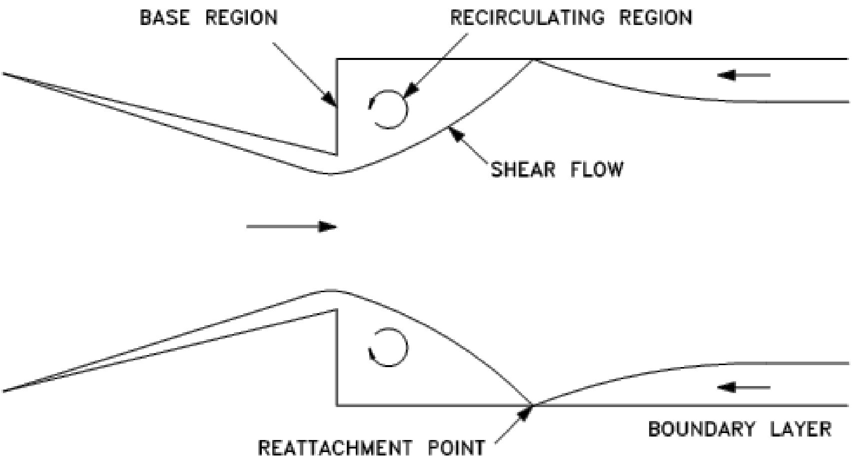

Fig. 4. Subsonic flow [2,5,6]

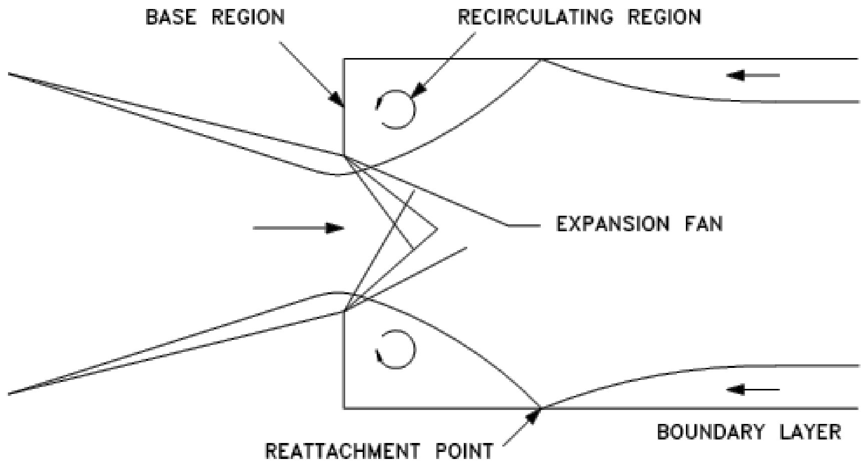

Fig. 5. Underexpanded sonic flow [2, 5]

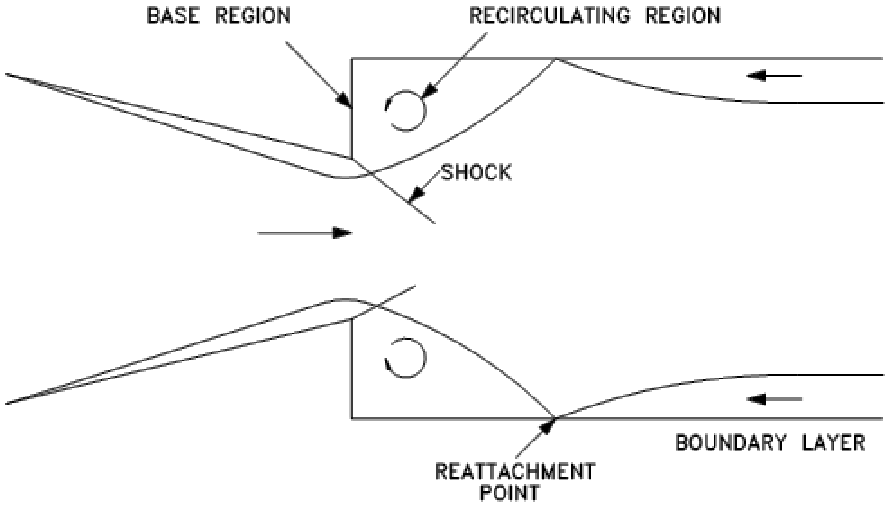

Fig. 6. Correctly expanded sonic/supersonic flow [2]

In the case of supersonic flows, under expansion of the jet leads to the generation of an expansion fan due to relaxation and underexpansion at the exit as shown in Figure 7. Expansion fans as well as weak shock waves are generated in the case of over expansion of the supersonic jet, as shown in Figure 8 [2].

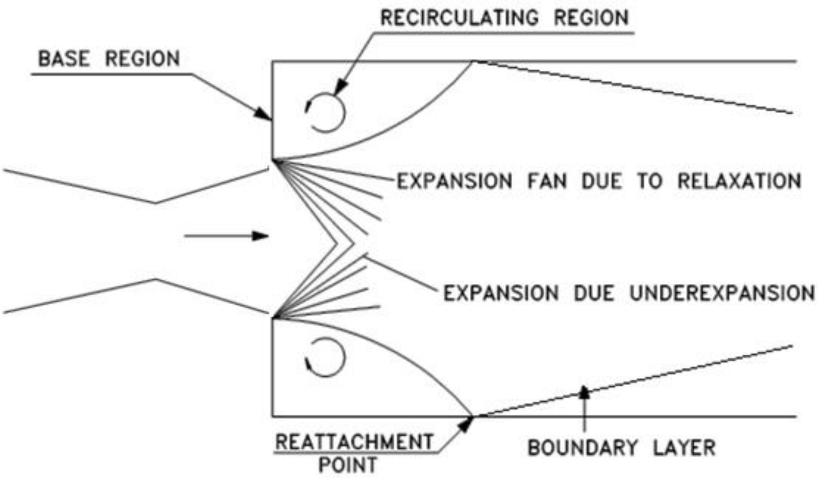

Fig. 7. Underexpanded supersonic flow [2, 5]

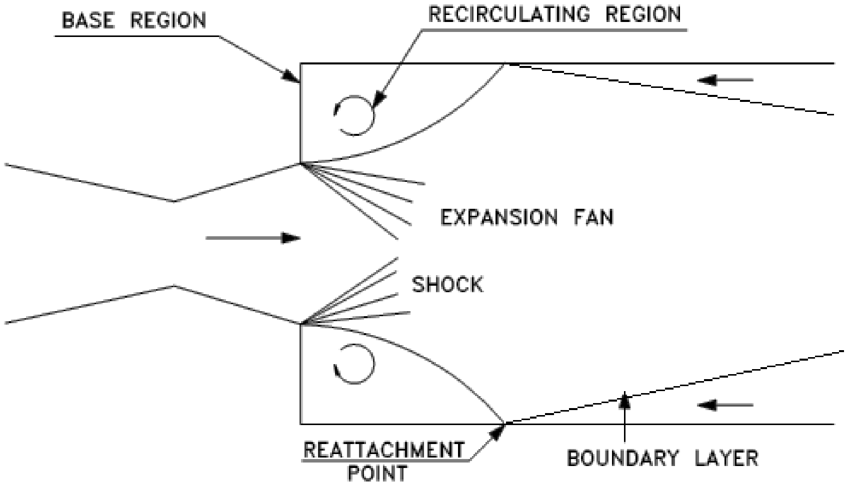

Fig. 8. Over expanded supersonic flow [6]

2. Oscillations in Flows

A system when in an oscillatory state means it has reached an unstable flow regime. Oscillations can be classified as oscillation due to (i) flow and (ii) acoustics. This section aims to present the oscillations caused due to the flow. Oscillations should have a source, for the phenomenon to occur. In the present case, the source of oscillation is the shear layer/re-circulation zone, which houses the oscillation in flow. The major input parameters contributing to the flow oscillations are flow Reynolds number, area ratio, duct length, surface smoothness. It should be understood that the operating parameters govern the nature of the solution. As the input parameters are varied, conditions of the system are bound to change. Any disturbance will cause the system to get into an oscillatory state [7].

The flow fields in abruptly expanding ducts contain separation regions, generating self-excited oscillations. They appear as regular periodic changes of the position of the reattachment point involving changes of the separation region volume and the shock wave pattern in transonic flows. Base pressure oscillation is controlled by the resonant frequency of longitudinal vibrations of the air column downstream of the sudden enlargement for all flow regimes [8]. Hill and Green [9] seem to be the first to have investigated intensive oscillations of the jet emerging from a duct having a short abrupt expansion. The pressure drops occurring due to the sudden expansion phenomenon causes flow oscillations. Mixing rates of the jet with the surrounding air increased considerably due to the high turbulence of the oscillating flow.

Szumowski and Piechna [8] report that for low Mach numbers of 0.3 on a relatively short abruptly expanding pipe of L/D < 6, the flow is not attached to the wall in every phase of the oscillation. A coherent structure with toroidal vortices is observed in the jets. These vortices are essential for the feedback loop mechanism of the oscillations. The type of oscillations inferred by these authors is an organ-pipe resonance triggered by the flow in abruptly expanding section.

Jungowski [10,11] discovered that the phenomenon of flow oscillation in the duct downstream of the nozzle is manifested by shock wave oscillation as well as by pressure oscillation in the dead-air region, in the region of the reattachment line dislocation, and in the further sector of the duct. This is applicable for sonic condition. Here, the frequency of shock and pressure oscillation is the same. The largest fluctuation of pressure appears near the nozzle in the region of the attachment line dislocation. The change of reattachment pattern is also cyclic, and therefore the wall is being touched in turn by supersonic and subsonic stream.

In addition, the self-induced oscillations exist because of the local shock boundary layer interaction involving the phenomena of scavenge and separation [10,11]. The oscillation is always associated with strong whistle or buzz, evoked probably by interaction of vortices with a shock wave, for underexpanded sonic and all supersonic flow regimes [10,11]. The physics is similar to what has been described by Williamson [7]. Besides, the noise from abruptly expanded jets has been studied by Anderson and Williams [12] found the detection of noise at three distinct tones under different conditions when measured both in terms of its overall sound pressure level and its frequency composition.

The oscillations can also be self-excited and a deeper understanding for the varied geometries and its effect on the flow conditions has yet to be established, for cases with passive controls. Flow oscillations is bound to happen in normal turbulent flow cases and at higher Reynolds numbers, it is more obvious due to turbulence effects. A study on effect of flow oscillations at subsonic, transonic and supersonic conditions is yet to be undertaken for different geometries to determine the flow physics behind flow oscillations.

Oscillations in suddenly expanded flows have been observed, but not quantified for cases with control mechanism in pipes [5,6,13–22]. In addition, the mechanics behind oscillations with flow control has not been fully explained. The oscillations can be altered by slight change of pressure in the dead-air region, which can be obtained by introduction of a control mechanism into the duct [10,11].

There are studies that looked at the sound levels and the physical processes that generate sound, noise and oscillations at the different flow regimes. There are also studies that look into base pressure and passive control. However, there has not been any study that links both domains. Passive controls influence both sound generation and wall/base pressures are the findings made by the previous researchers, yet how they influence/impact them and what the expected flow conditions will be, are still unknown.

3. Flow Control Strategies

Control strategies can be classified as active and passive controls. Active controls require an external source of power to perform their role as control devices. Many active jet control methods use energized actuators to dynamically manipulate the flow phenomenon by employing necessary algorithms. The design of an active flow control requires knowledge of the flow and selection of appropriate actuators, sensors and a control algorithm which makes it more complicated.

Active control strategy is used to achieve maximum receptivity for the specific medium considered. The flow can be excited by mechanical means such as acoustical perturbation, fluctuating flaps, piezoelectric surfaces, and modulating of the free stream. By choosing the proper frequency, the growth rate and entrainment characteristics of the shear layer can be controlled to either enhance or suppress them. Other methods of active control employed by researchers in the past include micro-jets, synthetic jets and actuators [23–29]. The need for external power source and other sophisticated devices proves to be expensive, and also a laborious process in the use of active controls.

Passive jet controls are preferred overactive controls as no external power source is required which makes them an alternative choice. Passive controls usually use geometrical modifications to the enlarged duct such as cavities and ribs, vary the jet control to change the shear layer stability characteristics and act as flow control. Both active and passive controls mainly aim to modify the flow characteristics, to get the desired flow condition by breaking down the large-scale vortices in the reattachment region to smaller vortices, making them better transporters of mass and momentum [2]. Hence, passive controls are potentially simpler and cost-effective.

3.1 Cavities

Cavities (Figure 9) were one of the most widely used flow control mechanisms for flow control in suddenly expanded flows which can increase (or) decrease base pressure depending upon application requirement [6,13,14,30–33]. A few studies on cavities are discussed here. A schematic sketch of the cavities in an enlarged duct is shown below.

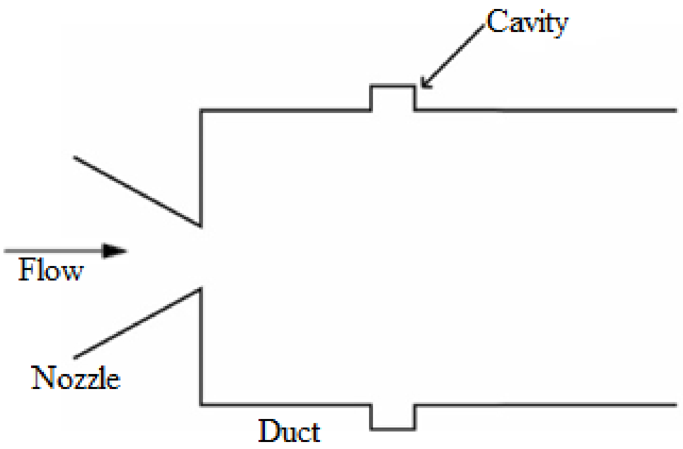

Fig. 9. Cavities in an enlarged duct [6]

The major parameters that are varied are area ratio, defined as the cross-sectional area of the duct to that of the nozzle exit [2], the length-to-diameter ratio of the enlarged duct, the aspect ratio of the cavities and the number of cavities, as well as the inlet Mach number into the sudden expansion. Base and wall pressures along the length of the enlarged duct and the static pressure at the cavities created by the flow are usually measured, while the entry Mach number and geometrical parameters are varied.

The effect of flow enlargement was studied by placing annular cavities positioned at fixed length interval in the enlarged duct by Anasu and Rathakrishnan [30]. The parameters that were varied included the stagnation pressure, length-to-diameter ratio of the enlarged section and area ratio at subsonic speeds. Mild oscillations (Figure 10) were noticed in enlarged duct with an introduction of a secondary circulation around cavities. This phenomenon caused a reduction in the flow oscillatory in the enlarged duct. The flow could thereafter develop (Figure 11) from the base pressure to the atmospheric pressure of jet discharge at the end of the enlarged duct. This leads to reduction in base pressure thereby, leading better performance similar to work carried by Rathakrishnan and Sreekanth [15].

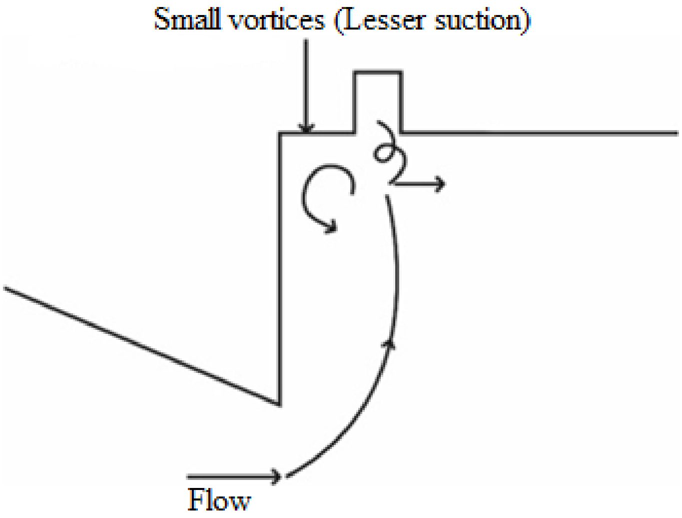

Fig. 10. Presence of smaller vortices generated during sudden expansion in the presence of cavities as control devices, leading to lower suction, reducing oscillatory nature of flow

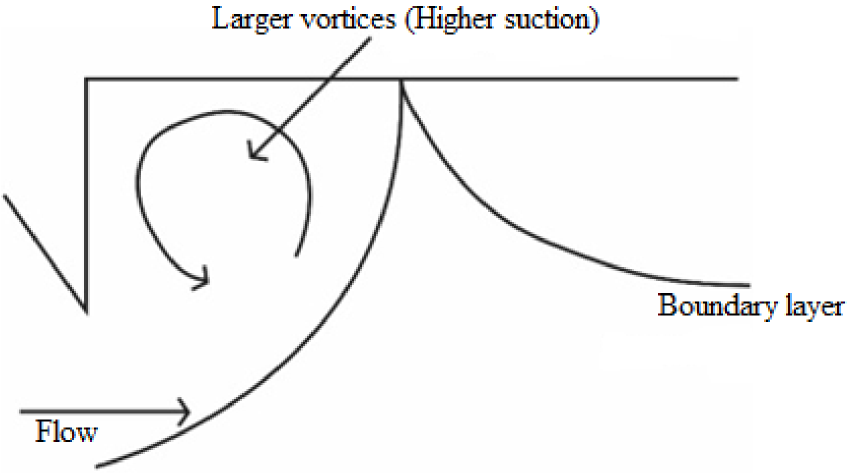

Fig. 11. Presence of larger vortices generated during sudden expansion without any cavities leading to higher suction and higher oscillations generated by the flow

Studies employing a range of cavity aspect ratios pointed out that the flow and the base pressure were influenced to a great extent by cavity aspect ratio and the secondary vortices due to cavities [14]. In certain range of flow parameters in subsonic Mach numbers and cavity geometry, the pulsations in the flow get increased. Instead of suppressing the pulsations, the cavities thus could lead to resonance at some combinations of cavity geometry and flow parameters. Under these conditions, a cavity maybe ineffective as a control device.

Since the cavities are extended surfaces projected in an outward manner and are not a solid boundary, the flow enters into the section, leading to three different cases of stagnation that commonly occur. At higher NPRs, the flow on entering the cavities gets trapped, causing recirculation within the cavities. This is due to the increased suction happening at the base at high NPRs, causing a second recirculation zone within the cavities. The sketches in Figure 12 shows closed-loop cavity, open-loop cavity and reverse open-loop cavity respectively.

The flow on entering the cavities gets trapped in the case of closed-loop cavity, causing re-circulation within the cavities. The flow is not completely trapped in the case of open-loop cavity and reverse open-loop cavity. There is partial recirculation happening within the cavities in both the cases and continues to take in fresh fluid and expel fluid that has been recirculating. This energizes the flow in the expanded region leading to higher suction at the base due to low base pressure, mainly because of the flow moving upstream towards the base.

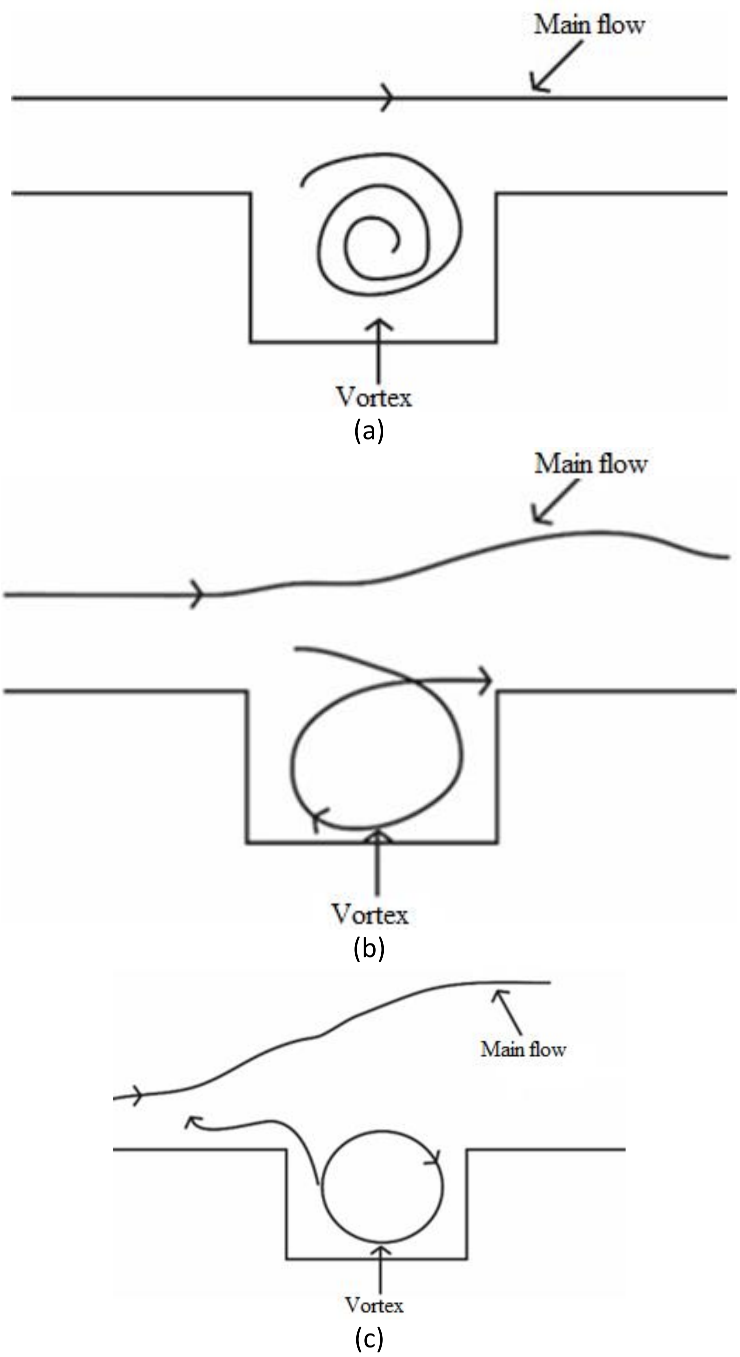

Fig. 12. (a) Closed-loop, (b) Open-loop and (c) Reverse open-loop cavity

The aspect of flow oscillations due to cavities was studied in detail by Gharib and Roshko [31], in conjunction with work of Anasu and Rathakrishan [30] and Rathakrishnan *et al.,* [14]. A low-cavity drag is possible with self-sustained periodic oscillations of the cavity shear layer in flows over an axisymmetric cavity. The stagnation point associated with the mean shear layer shifts to the downstream corner in the low cavity drag condition. 'Wake-mode' instability is possible with an abrupt increase of drag beyond a critical value of the width-to-depth ratio of the cavity. When the flow reattaches downstream it is analogous to a three-dimensional bluff body wake, with a deviation that the rear body interacts strongly with the wake of the front body. There were large differences between free shear layer and a cavity shear layer. The cavity shear layer controls the drag of the cavity with associated momentum transport. All these factors are responsible in amplifying the oscillations in the shear layer.

There were also radical differences in the oscillatory nature of the mean pressure field when the flow was expanded in a larger rectangular passage compared to similar expansion in a circular passage. The expansion in a circular passage had a fairly smooth mean pressure field as against the oscillatory field with a sudden expansion in a rectangular duct [14,16,30]. The effects of base cavity in subsonic Mach numbers up to high subsonic values were tested by Kruswyik and Dutton [32]. Their findings indicated that the vortex street structure remained practically unmodified even in the presence of base cavity. However, the vortex street appeared weakened by the base cavity. Thus, enhanced mixing could occur at the cavity entrance.

All the above-mentioned experiments were carried out only at subsonic levels. Among other researchers employing different control strategies and nozzles for sudden expansion, Rathakrishnan and Srikanth [33] whom studied the flow of air expanding into a short length cylindrical duct at sonic level. Some of the early experiments conducted by Viswanath [19] and Viswanath and Patil [17] were on passive control of drag in transonic flow. Different passive devices by way of base modifications to base drag and total after-body drag at transonic speeds were considered for their effectiveness. Modifications such as vortex suppression devices, base cavities and ventilated cavities formed the bulk of the modifications. It was reported that a 5 – 10% reduction of base drag was possible. But the loss associated with these configurations pointed to comparatively lower net drag reductions.

In addition, Viswanath and Patil [17] experimented using passive devices to reduce base pressure at a supersonic Mach number of 2 for axisymmetric flows. They used primary base cavities and ventilation cavities for their experiment. These devices were used on boat-tailed and flared bases. It was learnt that the base cavity and ventilation cavity did not have much effect on boat-tailing base in reducing the base drag and had limited benefit in the case of flared bases. Pandey and Rathakrishnan [6,13] employed cavities to test flow from nozzles expanding suddenly into circular pipes in high subsonic to supersonic Mach numbers. It was found that the secondary circulation due to cavities suppressed the oscillatory nature of the flow and this effect was prominent more in subsonic region than in supersonic ranges.

The area ratio of the enlarged duct strongly influences the base pressure as well as flow development [6,13–15, 30]. Cavity aspect ratio has a significant effect on the flow field as well as on the base pressure [34]. Cavities have no significant effect as far as the reduction of base pressure is concerned, especially for supersonic flow regimes. In the present range of flow parameters and cavity geometry, the presence of the cavities results in augmenting the oscillations. A smoothening effect on the flow field by the cavities was claimed but there is danger of the cavities themselves inducing resonance. Thus, instead of relieving pulsations, some combinations of flow parameters and cavity geometry could have enhanced pulsations.

3.2 Ribs

At certain flow conditions, the cavities used as passive control behave like closed surfaces. This nullifies their ability to control the flow, as explained previously in detail. Hence, ribs have been proposed as passive control of base and wall pressures in suddenly expanded flows. The ribs are projections as against cavities wherein the secondary vortices generated by the projections are expected to yield favourable base pressure values and better wall pressure distribution [5, 20]. A sketch of the enlarged duct with ribs positioned at equal intervals [20] and the secondary vortices generated by the ribs given in Figure 13 and 14 respectively.

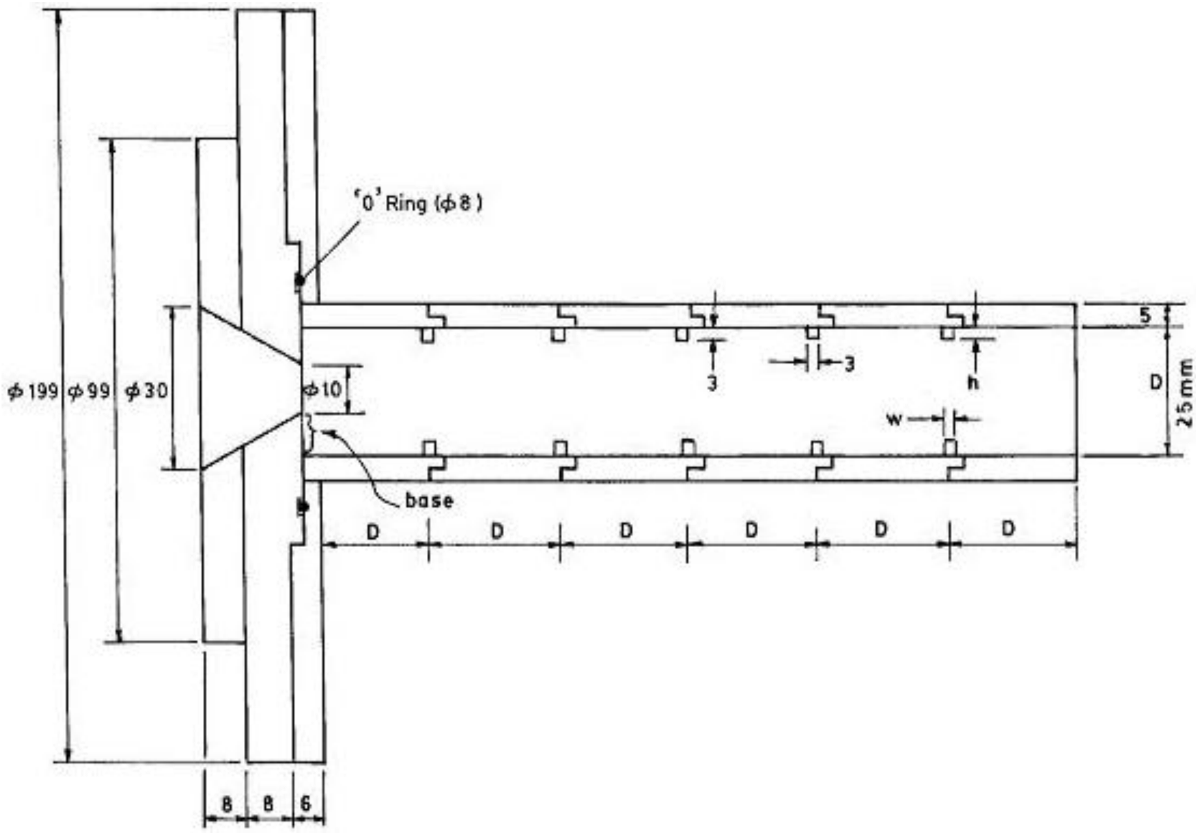

Fig. 13. Schematic sketch of enlarged duct with ribs positioned as projectiles at regular intervals [20]

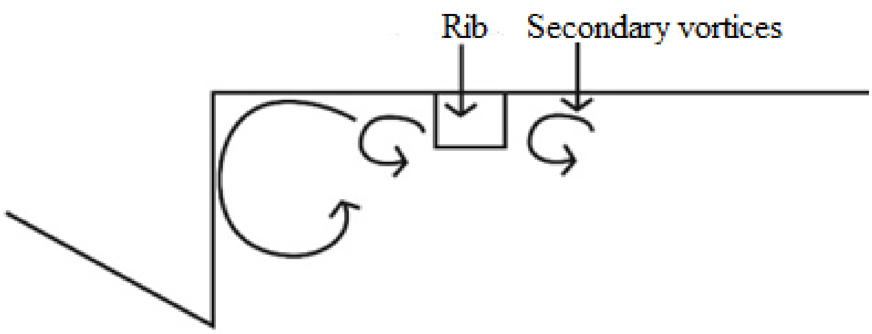

Fig. 14. Secondary vortices generated by ribs

The NPR which is Po/Pa is used as the controlling parameter to generate subsonic and sonic flow conditions at the nozzle exit for under expanded and correct states. As the NPR is increased from a low value, the subsonic Mach number finally reaches the sonic value. This slow increase of NPR provides a larger space for the boundary layer at the nozzle exit allowing the shear layer to expand. A vortex at the base region is thus established while the shear layer downstream of the base region gets attached to the enlarged duct wall. In this process, a low pressure is created at the base region on account of the recirculating flow. The flow then proceeds downstream in the enlarged duct. The low pressure at the base permits the boundary layer to grow downstream of the reattachment point.

In an under expanded sonic flow there is a reverse flow towards the base within the boundary layer from the reattachment point region. Sufficient length of the duct is required for the flow to reattach and the boundary layer to grow. Hence, the length-to-diameter ratio (L/D) of the duct is the deciding parameter for this reattachment and the boundary layer growth in the enlarged duct. A minimum value of 4 for the L/D is recommended [5] where less than this L/D value, the flow may not reattach at all.

The forgoing discussion was based on enlarged ducts without the presence of ribs as passive controls in the flow. When ribs are positioned in the enlarged duct, up to NPR 3 the base pressure does not register any appreciable change. This may be due to the reattachment of the expanding flow at the wall downstream. A reverse flow results as the flow meets the growing boundary layer downstream of the reattachment point. A rib placed downstream of the base region causes a disturbance to the whole process. For a rib located upstream of the reattachment point, the reverse flow in the recirculation zone is modified while the suction creating vortex is undisturbed when the rib is placed downstream of the reattachment point. The rib placed downstream of the reattachment point also blocks the reverse flow from the boundary layer growing after the reattachment point. Thus, the base pressure will be different with ribs as compared to the flow in the absence of ribs since the ribs may act as fences in preventing the reverse flow. Thus, greater suction at base with the presence of ribs in duct [5].

As a rule, the base pressure decreases as NPR is increased with or without ribs. But with increase of NPR, the flow will reattach past the rib and reverse flow is not likely to happen. As sonic jet is greatly underexpanded beyond NPR 4, the expansion fan at the exit of the nozzle becomes stronger and a Mach disk is formed. There is an increase of base pressure as he Mach disk and the expansion fan become stronger in underexpanded nozzle flows [5].

For supersonic flows the base pressure is influenced by the primary vortex which is dependent on the Mach number at the exit of the nozzle and the reattachment length of shear layer. The state of the boundary layer (laminar/turbulent) significantly controls the reattachment length and the level of low pressure at the base is dictated by the strength of primary vortex. This low pressure induces the flow towards the base region from the wall downstream of the reattachment point. Any extra mass entering the base region is ejected to the main flow through the shear layer. This phenomenon of ejection of mass is termed 'jet-pump' by Wick [35].

The flow of fluid into the base region causes the reduction in primary vortex strength and increase in the base pressure. The placement of rib prevents the flow from reattaching boundary layer entering into the base region. The ribs are thus effective form of passive controls in such flows. Care should be taken to limit the height of the ribs; otherwise they start behaving like forward-facing steps by introducing a secondary vortex into the flow. This will weaken the primary vortex and increase the base pressure.

The introduction of ribs as passive controls in sudden expansion makes the flow in the duct oscillatory as the length of the duct is increased. There is then a need to consider both the base and wall pressure variations along the duct, as functions of different geometrical and flow parameters [20]. The wall pressure fluctuations are influenced by the height of the rib, its position along the length of the duct and the inlet Mach number to the duct. For short lengths of the duct (L/D < 3) the flow does not have enough length for reattachment while in a long duct the wall pressure becomes almost equal to the back pressure. The wall pressure starting from the base pressure almost reaches the atmospheric value at the end of the duct. As the rib height is increased the point where the wall pressure reaches the atmospheric value also varies [20].

It is claimed that the location of rib in the enlarged duct has significant effect on the wall pressure oscillations. This claim has not been properly quantified and does not have any evidence on the method used to clarify the impact of ribs on the oscillations. Limited studies on ribs have shown them to be effective over a wider parameter range and perform better as jet control elements than cavities. Researchers in the past have studied ribs only for specific Mach numbers and fixed rib positions [5,20–22,36]. Therefore, the full potential of this control strategy is yet unknown.

4. Conclusions

The paper reveals that active controls that require external power sources for functioning are somewhat effective. As for the passive controls, the cavities lead to problems similar to closed surfaces and become ineffective after a stage. Ribs used as passive controls are fairy effective in modifying the base pressure. But the height of the rib has to be kept within limits to avoid oscillation of flow and a look at wall pressure is also necessary along with the control of base pressure. Flow visualization in supersonic flow regimes might provide greater insight into the effectiveness of flow control strategies in sudden expansion flows. This is one unexplored aspect of this interesting problem apart from detailed studies on the time-dependent pressure oscillations.

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References

[1] Sethuraman, Vigneshvaran, and Sher Afghan Khan. "Base pressure control using micro-jets in supersonic flow regimes." *International Journal of Aviation, Aeronautics, and Aerospace* 5, no. 1 (2018): 1.
[2] Sethuraman, Vigneshvaran, and Sher Afghan Khan. "Effect of sudden expansion for varied area ratios at subsonic and sonic flow regimes." *International Journal of Energy, Environment and Economics* 24, no. 1 (2016): 99.
[3] Chen, Lin, Keisuke Asai, Taku Nonomura, Guannan Xi, and Tianshu Liu. "A review of backward-facing step (BFS) flow mechanisms, heat transfer and control." *Thermal Science and Engineering Progress* 6 (2018): 194-216.
[4] Guo, Guang-ming, Hong Liu, and Bin Zhang. "Numerical study of active flow control over a hypersonic backward-facing step using supersonic jet in near space." *Acta Astronautica* 132 (2017): 256-267.
[5] Vijayaraja, K., C. Senthilkumar, S. Elangovan, and E. Rathakrishnan. "Base pressure control with annular ribs." *International Journal of Turbo & Jet-Engines* 31, no. 2 (2014): 111-118.
[6] Pandey, Krishna Murari, and E. Rathakrishnan. "Influence of cavities on flow development in sudden expansion." *International Journal of Turbo and Jet Engines* 23, no. 2 (2006): 97-112.
[7] Williamson, Charles HK. "Vortex dynamics in the cylinder wake." *Annual review of fluid mechanics* 28, no. 1 (1996): 477-539.
[8] Szumowski, A. P., W. C. Selerowicz, and G. E. A. Meier. "Oscillations of a subsonic flow in an abruptly expanding circular duct." In *Flow of Real Fluids*, pp. 28-40. Springer, Berlin, Heidelberg, 1985.
[9] Hill Jr, W. G., and P. R. Greene. "Increased turbulent jet mixing rates obtained by self-excited acoustic oscillations." (1977): 520-525.
[10] Jungowski, W. M. "On the flow in a sudden enlargement of a duct." *Fluid Dynamics Transactions* 4 (1969): 231-241.
[11] Jungowski, W. M. "Some self induced supersonic flow oscillations." *Progress in Aerospace Sciences* 18 (1979): 151-175.
[12] Anderson, J. S., and T. J. Williams. "Base pressure and noise produced by the abrupt expansion of air in a cylindrical duct." *Journal of Mechanical Engineering Science* 10, no. 3 (1968): 262-268.
[13] Pandey, K. M., and E. Rathakrishnan. "Annular cavities for Base flow control." *International Journal of Turbo and Jet Engines* 23, no. 2 (2006): 113-128.
[14] Rathakrishnan, E., O. V. Ramanaraju, and K. Padmanaban. "Influence of cavities on suddenly expanded flow field." *Mechanics research communications* 16, no. 3 (1989): 139-146.
[15] Rathakrishnan, E., and A. K. Sreekanth. "Flows in pipes with sudden enlargement." In *14th Space Technology and*

Science Symposium, pp. 491-496. 1984.
[16] Rathakrishnan, E., T. J. Ignatius, and Channa Raju. "An experimental study of suddenly expanded rectangular jet flow field." *Mechanics research communications* 18, no. 1 (1991): 1-9.
[17] Viswanath, P. R., and S. R. Patil. "Effectiveness of passive devices for axisymmetric base drag reduction at Mach 2." *Journal of Spacecraft and Rockets* 27, no. 3 (1990): 234-237.
[18] Viswanath, P. R. "Flow management techniques for base and afterbody drag reduction." *Progress in Aerospace Sciences* 32, no. 2-3 (1996): 79-129.
[19] Viswanath, P. R. "Passive devices for axisymmetric base drag reduction at transonic speeds." *Journal of aircraft* 25, no. 3 (1988): 258-262.
[20] Rathakrishnan, E. "Effect of ribs on suddenly expanded flows." *AIAA journal* 39, no. 7 (2001): 1402-1404.
[21] Vijayaraja K, Elangovan S, and Rathakrishnan E. "Effect of Rib on Suddenly Expanded Supersonic Flow." *International Review of Aerospace Engineering* (2008): 196–199.
[22] Kahn, Sher A., and E. Rathakrishnan. "Active control of suddenly expanded flows." In *International Symposium on Space Technology and Science, 22 nd, Morioka, Japan*, pp. 961-967. 2000.
[23] Ashfaq, Syed, Sher Afghan Khan, and E. Rathakrishnan. "Active Control of Flow through the Nozzles at Sonic Mach Number." *International Journal of Emerging Trends in Engineering and Development* 2, no. 3 (2013): 73-82.
[24] Khan, Slier Afghan, and E. Rathakrishnan. "Active control of suddenly expanded flows from underexpanded nozzles-Part II." *International Journal of Turbo and Jet Engines* 22, no. 3 (2005): 163-184.
[25] Rehman, Shafiqur, and Sher Afghan Khan. "Control of base pressure with micro-jets: part I." *Aircraft Engineering and Aerospace Technology* (2008): 158–164.
[26] Khan, Sher Afghan, and E. Rathakrishnan. "Control of suddenly expanded flow." *Aircraft Engineering and Aerospace Technology* 78, no. 4 (2006):293–309.
[27] Smith, Barton L., and Ari Glezer. "Jet vectoring using synthetic jets." *Journal of Fluid Mechanics* 458 (2002): 1-34.
[28] Smith, Barton L., and Ari Glezer. "The formation and evolution of synthetic jets." *Physics of fluids* 10, no. 9 (1998): 2281-2297.
[29] Glezer, Ari, and Michael Amitay. "Synthetic jets." *Annual review of fluid mechanics* 34, no. 1 (2002): 503-529.
[30] Anasu, Rathakrishnan E. "Influence of Cavitation on Flow through Sudden Enlargement." In *14th Fluid Mechanics and Fluid Power Conference*, Kashmir, India, pp. 35–39. 1987.
[31] Gharib, M., and A. Roshko. "The effect of flow oscillations on cavity drag." *Journal of Fluid Mechanics* 177 (1987): 501-530.
[32] Kruiswyk, R. W., and J. Craig Dutton. "Effects of a base cavity on subsonic near-wake flow." *AIAA journal* 28, no. 11 (1990): 1885-1893.
[33] Srikanth, R., and E. Rathakrishnan. "Flow through pipes with sudden enlargement." *Mechanics research communications* 18, no. 4 (1991): 199-206.
[34] Sethuraman, Vigneshvaran, Parvathy Rajendran, and Sher Afghan Khan. "A Cost-effective Data Acquisition Instrumentation for Measurement of Base Pressure and Wall Pressure in Suddenly Expanded Flow Through Ducts." *Journal of Advanced Research in Fluid Mechanics and Thermal Sciences* 60, no. 1 (2019): 112-123.
[35] Wick, Robert S. "The effect of boundary layer on sonic flow through an abrupt cross-sectional area change." *Journal of the Aeronautical Sciences* 20, no. 10 (1953): 675-682.
[36] Bagabir, Ahmed M., Jabril A. Khamaj, and Ahmed S. Hassan. "Turbulent periodic flow and heat transfer in a square channel with different ribs." *CFD Letters* 5, no. 3 (2013): 67-80.