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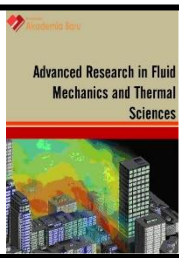

Analysis of Flow Through A Convergent Nozzle at Sonic Mach Number for Area Ratio 4

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ABSTRACT

The presence of a blunt base can be found in automobile industries as well as in the aerospace industry. The blunt base caused the lower base pressure than ambient pressure and resulted in significant value of the base drag. The present study addresses the effect of the base drag if the rectangular rib is located to the suddenly enlarged duct in which the flow from the convergent nozzle suddenly expands using CFD. The nozzle is operated at sonic Mach number, and the enlarged duct has a diameter of 20 mm. The height of the rib is varied from 1 mm to 3 mm while the width of the rib is maintained at 3 mm throughout the study. The rib is located at 1D (D = 20 mm), 2D, 3D, and 4D, and the nozzle pressure ratio is increased from 1.5 to 5 in the step of 0.5. The computational model is validated with experimental work, and then the pressure variations are analyzed. It is observed that the location of the rib is a prime factor in regulating the base pressure. As the rib is located downstream of reattachment point, the base pressure obtained is always higher than in duct without rib irrespective of any height.

Keywords:
Nozzle pressure ratio; base pressure; passive control; sudden expansion; the flow field

1. Introduction

Recirculation zone is formed due to the flow separation at the blunt base located behind the aerodynamic vehicles like missiles, unguided-rockets, projectiles, and bombs. The formation of the recirculation zone will result in a very low-pressure zone at the blunt base.

This low-pressure region behind these vehicles causes enormous drag, which can be more than 60 % of the total drag at sonic Mach number [1-3]. Sufficient methods and processes are defined by scientists to overcome such a complex flow separation phenomena and its after-effects. Base bleed, boat-tail, base burning, passive, and active control methods are few of the standard practices to reduce the drag. For active control method, microjets are placed at the base where the recirculation zone is disturbed by injecting the air through the control mechanism to break or weaken the powerful vortex located in the wake region. The tiny jets inject extra fluid which breaks the single vortex in

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many small vortices and causes an increase in the base pressure leading to reduced base drag. Ribs, cavities, spikes, splitter plate, step body, vortex locking mechanism, ventilated cavity, etc. are among passive techniques which can be adopted for the base pressure control and hence, the drag reduction. Suddenly expanded flows is one among the most investigated area in the field of external ballistics/aerodynamics. When the flow expands in the duct, the shear layer from the nozzle lip initially gets separated and then later attaches itself with the duct wall at some distance, as shown in Figure 1. This length from the nozzle exit to the reattachment point is famously known as reattachment length [4-11].

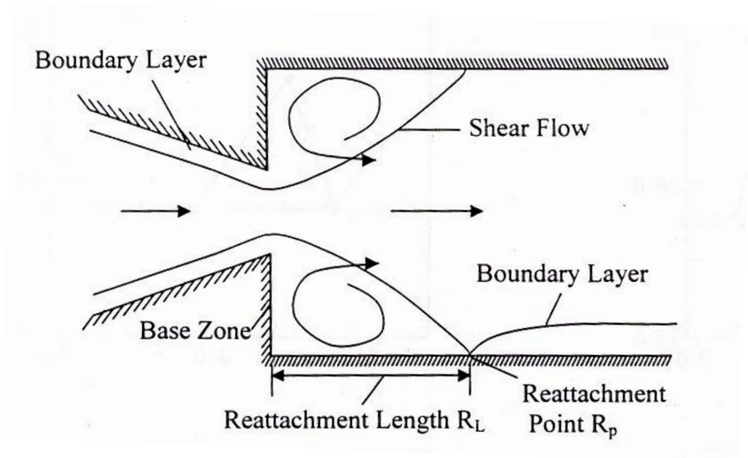

Fig. 1. The sudden expansion flow field [12]

Chaudhary *et al.*, [13] studied the consequence of the tests pertinent to control of pressure flow in the recirculation zone. An active control one-millimeter orifice diameter of micro-jets is located at ninety-degree intervals along a pitch circle diameter of 1.3 times the converging-diverging (CD) nozzle exit diameter in the base region. The Mach numbers of the abruptly expanded flows studied for the base pressure range from 1.1 to 3 and the obtained wall pressure distribution is depicted for Mach number 1.6 and 1.8 respectively. Axi-symmetric round brass tubes were used for jets, and cross-sectional area of ducts was 2.56 times the nozzle exit area. L/D ratio of the broadened circular pipe was varied from 10 to 1, and the NPR for which the tests were done, was in the range from 3 to 11. The study was carried out to assess the effectiveness of the flow regulations in the form of microjets to control the pressure in the base region of an abruptly expanded duct [14].

Microjets is not the only factor in controlling base pressure and wall pressure in a suddenly expanded axisymmetric duct. However, the experimental study on the use of micro-jets in an internal supersonic flow to control the base and wall pressure has been proved to be cost-effective as well as convenient [15].

Airflow from convergent-divergent axisymmetric nozzles expanded suddenly into the circular duct of the larger cross-sectional area than that of nozzle exit area is studied experimentally, focusing on the control of base pressure and the development of the flow in the enlarged duct. They found that the active control in the form of blowing through microjets is effective in controlling the base pressure field and the control mechanism do not augment the flow field in the duct adversely [16]. Khan *et al.*, [17-25] investigated the number of studies for base pressure control in a CD nozzle and the effectiveness of microjets as well as the wall pressure distribution through the duct length.

Rahman and Khan [15] experimentally investigated the information on internal supersonic flows in a CD nozzle with suddenly expanded axi-symmetric duct. The authors' found that the microjets controller does not adversely influence the results of wall pressure. Wind tunnel tests were conducted for Mach numbers for 1.25, 1.3, 1.48, 1.6, 1.8, 2.0, 2.5 and 3.0 and L/D (length to diameter ratio) varied from 10 to 1. The nozzles producing the above jet Mach numbers were operated with the level of expansion (NPR) in the range for 3, 5, 7, 9, and 11.

Chaudhary *et al*., [13, 26, 27] investigated the consequence of the examinations conducted to control the pressure in the base region of the CD nozzle with the suddenly expanded duct. Similarly, the effectiveness of the flow controllers to govern the pressure at the base in a suddenly expanded duct has been examined. Four microjets in number with one-mm diameters each, are positioned at the interval of 90-degrees at 13mm PCD (pitch circle diameter) experimentally were investigated to evaluate the effectiveness of the microjets under the influence of over, under, and correct expansion to control the base pressure in suddenly expanded axisymmetric ducts. They found that the maximum increase in base pressure is 152 percent for Mach number 2.58, and the microjets do not aggravate the flow field in the duct. In addition, results obtained show that microjets can serve as an active controller raising the base suction to almost zero levels for some combination for parameters [28].

Moreover, Rehman and Khan [15] performed an experimental work to investigate the base pressure control in a suddenly expanded axisymmetric duct. Results indicated that the wall pressure does not influence by the microjets and information on the internal supersonic flow [15]. Airflow from convergent-divergent axisymmetric nozzles expanded suddenly into a circular duct of the larger cross-sectional area than nozzle exit area are studied in Ahmed and Baig [16] who found that the active control in the form of blowing through microjets is effective in controlling the base pressure field [16].

Most of the studies mentioned above were performed experimentally. Thus, the use of numerical turbulence model for the simulation of high speed flows pertinent to suddenly expanded flows from a nozzle into the duct is crucial to understand intensively the variation of base pressure using a different type of control. This motivation has led to the development of a computational model of the converging nozzle and the enlarged duct whose cross-section is circular where the flow expands suddenly. The variation in base pressure with NPR, L/D ratio, and effectiveness of control in the form of annular ribs is studied numerically using k-ε turbulence model.

2. Numerical Methodology

The physical model of the converging nozzle and duct with rib is shown in Figure 2. The width, *W* of the ribs are 3 mm (fixed) and height, *H* (is varied from 1 to 3 mm). The diameter of the nozzle inlet is 30 mm, and the outlet diameter is 10 mm. Duct length is 120 mm, and the diameter of the duct outlet is 20 mm, with the ratio of nozzle exit area to duct area of the model 4. The flow from the nozzle expands in the duct and passes through the duct where it undergoes several stages of compression and expansion due to expansion fan/shock wave and finally reaches atmospheric pressure at the outlet.

The flow through the nozzle is considered to be turbulent in nature; hence, the k-ε standard model is applied for the compressible flow field. The continuity equation for the compressible flow (density ρ based) with steady state condition in the 2-dimensional cylindrical coordinate system

$$\frac{1}{r}\frac{\partial(\rho r u)}{\partial r}+\frac{\partial(\rho v)}{\partial z}=0 \qquad (1)$$

The time-averaged axial z-momentum equation representing u velocity of flow is given by

$$\frac{1}{r}\frac{\partial(\rho r u u)}{\partial z}+\frac{1}{r}\frac{\partial(\rho v u)}{\partial r}=-\frac{\partial p}{\partial r}+(\mu+\mu_t)\frac{\partial}{\partial z}\left[2\frac{\partial u}{\partial z}-\frac{2}{3}(\nabla.\vec{v})\right]+(\mu+\mu_t)\frac{\partial}{\partial r}\left[\frac{\partial u}{\partial r}+\frac{\partial v}{\partial z}\right] \quad (2)$$

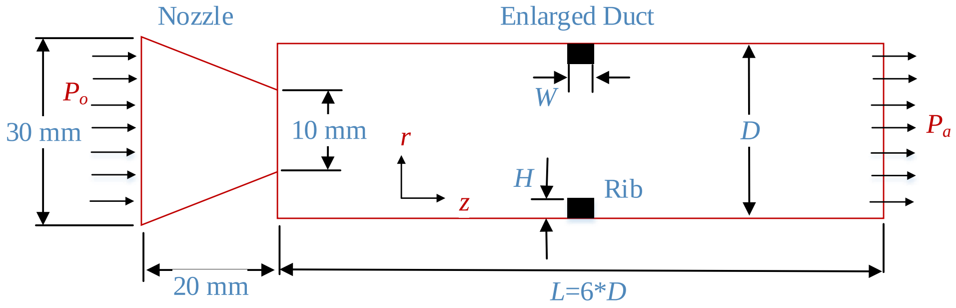

Fig. 2. Nozzle and duct arrangement with rib

The radial *r*-momentum equation for velocity, *v* is given by

$$\frac{1}{r}\frac{\partial(\rho r u v)}{\partial z}+\frac{1}{r}\frac{\partial(\rho v v)}{\partial r}=-\frac{\partial p}{\partial r}+(\mu+\mu_t)\frac{\partial}{\partial r}\left[\left(2\frac{\partial u}{\partial z}-\frac{2}{3}(\nabla.\vec{v})\right)\right]+(\mu+\mu_t)\frac{\partial}{\partial z}\left[\left(\frac{\partial u}{\partial r}+\frac{\partial v}{\partial z}\right)\right]-2\frac{(\mu+\mu_t)v}{r^2}+\frac{2}{3}\frac{1}{r}(\mu+\mu_t)(\nabla.\vec{v}) \quad (3)$$

The term $\vec{v}$ in Eq. (2) and (3) is given by

$$\nabla.\vec{v}=\frac{\partial u}{\partial z}+\frac{\partial v}{\partial r}+\frac{v}{r} \quad (4)$$

Here, μ is the viscosity, and μ_o is the reference viscosity (kg/m-s), *T* is static temperature, and T_o is the reference temperature (K). *S* is Sutherland constant depending upon sufficient temperature. The quantity $(k/C_p+\mu_t/Pr_t)$ represents the useful thermophysical property of fluid where k is the thermal conductivity (W/m^{2}k), C_p is specific heat capacity (kJ/kg-K), μ_t is turbulent viscosity in kg/m-s, and Pr_t is turbulent Prandtl number.

The K-ε turbulence model is one among the famously used model which provides economy, robustness, and sufficient accuracy for many kinds of flow situations. The k-ε turbulence model employed in this work is made available by the Ansys Fluent software. The turbulent kinetic energy, i.e., K-equation, is given by

$$\frac{\partial(\rho u \mathrm{K})}{\partial z}+\frac{1}{r}\frac{\partial(\rho v \mathrm{K})}{\partial r}=\frac{\partial}{\partial z}\left[\left(\mu+\frac{\mu_t}{\sigma_k}\right)\frac{\partial \mathrm{K}}{\partial z}\right]+\frac{1}{r}\frac{\partial}{\partial r}\left[r\left(\mu+\frac{\mu_t}{\sigma_k}\right)\frac{\partial \mathrm{K}}{\partial r}\right]-\rho\varepsilon+G \quad (5)$$

The term σ_k is the turbulent Prandtl number for K, and ε is turbulent kinetic energy dissipation rate, and *G* is turbulence generation term given by

$$G=\mu_t\left(\frac{\partial u_i}{\partial x_j}+\frac{\partial u_j}{\partial x_i}\right)\frac{\partial u_i}{\partial x_j}-\frac{2}{3}k\delta_{ij}\frac{\partial u_i}{\partial x_j} \quad (6)$$

The kinetic energy of turbulence dissipation, i.e., ε-equation is given by

$$\frac{\partial(\rho u \varepsilon)}{\partial z}+\frac{1}{r}\frac{\partial(\rho v \varepsilon)}{\partial r}=\frac{\partial}{\partial z}\left[\left(\mu+\frac{\mu_t}{\sigma_\varepsilon}\right)\frac{\partial \varepsilon}{\partial z}\right]+\frac{1}{r}\frac{\partial}{\partial r}\left[r\left(\mu+\frac{\mu_t}{\sigma_\varepsilon}\right)\frac{\partial \varepsilon}{\partial r}\right]-C_1 f_1\left(\frac{\varepsilon}{\mathrm{K}}\right)G-C_2 f_2\left(\frac{\varepsilon^2}{\mathrm{K}}\right) \quad (7)$$

The term $\mu_t = \rho f_\mu C_\mu k^2/\varepsilon$ represents turbulent viscosity, the value of C_μ, C_1, C_2, f_μ, σ_k, σ_ε are all arbitrary constants.

In ANSYS Fluent computational software, the above set of turbulent equations are solved simultaneously for the compressible flow. Working medium, in this study, is air is considered to be ideal, and the iterations are repeated until the residuals are within $10e^{-5}$. The unstructured mesh of rectangular type was refined appropriately to capture the velocity and pressure gradients of the flow. The grid sizes are change accordingly to achieve convergence and provide reliable accuracy. Grid size with nodes of about 48441 and element size of 47988 was decided for the domain after a grid independence study was performed using three different element sizes, as shown in Figure 3.

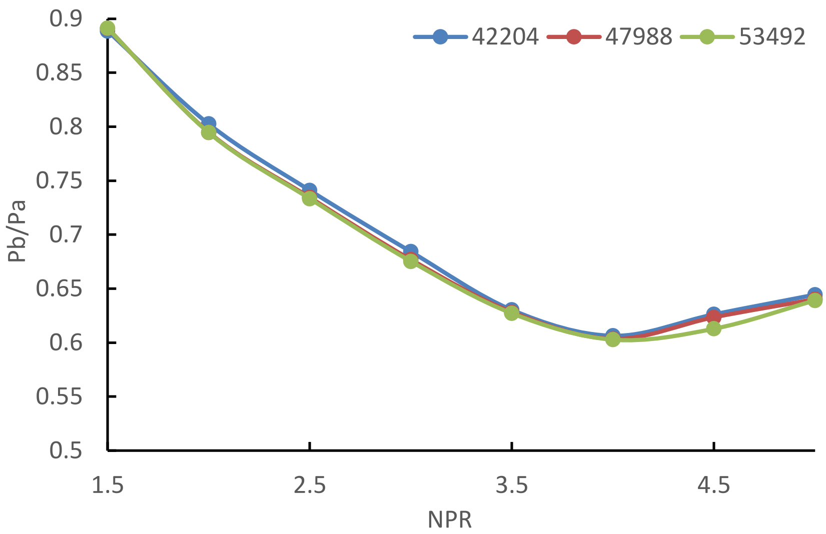

Fig. 3. Three different element size having converged values

In understanding the proper physics of flow inside the duct, this study firstly validated with the results of Rathakrishnan [29] who performed experimental work using 5 ribs placed at equidistant space in the duct, as shown in Figure 4. The results of base pressure variation with different NPR and L/D ratio, i.e., the ratio of length to the diameter of the duct, are plotted in Rathakrishnan [27]. This same work is initially repeated to validate the numerical results, having control with ribs and without ribs. The flow in duct without ribs is called as 'no control' flow. *Ambareen et al*., performed an experimental and numerical simulation of suddenly expanded square duct of 28 mm side for Mach numbers ranging from 1 to 2.5. It was found that with the increase in NPR there is a decrease in base pressure and this trend is found even when the jet is under-expanded [30].

Khan *et al*., studied the effect of area ratios in suddenly expanded duct and base pressure control with micro-jets of orifice diameter 1 mm for Mach 2.2, L/D ratio of 8 and NPR 9. It is observed that the area ratio plays a crucial role in base pressure control [31].

Mat et al., used CFD approach to optimize the dry ice blasting nozzle geometry in terms of divergent length on the effect of noise level and to study the noise development characteristic inside the nozzle geometry. Their results show that lowest value of the acoustic power level is responsible for producing lowest noise emission which is around 230 mm [32].

The base pressure variations obtained experimentally and numerically using k-ε turbulence model are compared in Figure 5. The nozzle operating at sonic Mach number and NPR = 2.458 were employed in the experimental study. The results show that the numerical results from this work and experimental values presented by Rathakrishnan [29] are in good agreement for duct having five ribs of aspect ratio 3:1 and 3:2. It is well known that flow will achieve sonic conditions at the exit of the nozzle for a primary pressure ratio of 1.89. This is possible with assumptions that the flow is isentropic, where the effects of viscosity and the boundary layer associated with it, are neglected. However, in the real flow, it does not happen; flow is neither isentropic nor inviscid. Hence, minor discrepancy obtained is quite apparent, and it can be considered to be within the acceptable limits. Another fact behind this is that the compressible flow nature of fluid at the sonic Mach number is always tedious to deal with as the flow field will be of shock waves and highly non-linear. Marginal variations in base pressure are also attributed to the effect of the backflow as well as the boundary layer effects at these L/Ds.

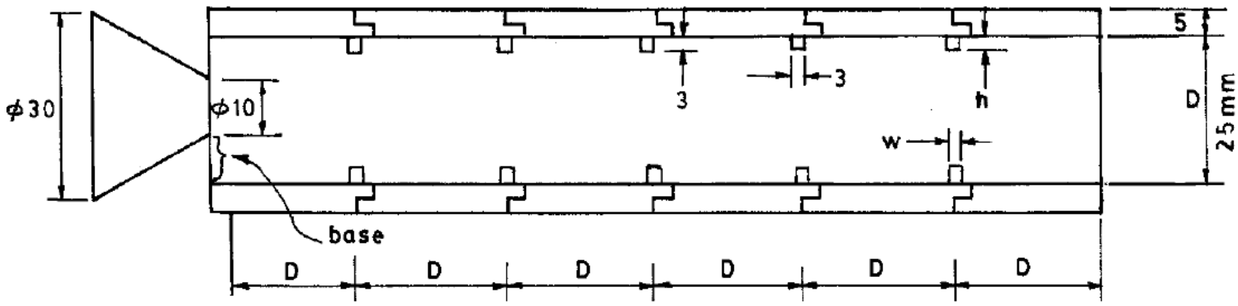

Fig. 4. Duct with 6 ribs used by Rathakrishnan [29] for experimental study

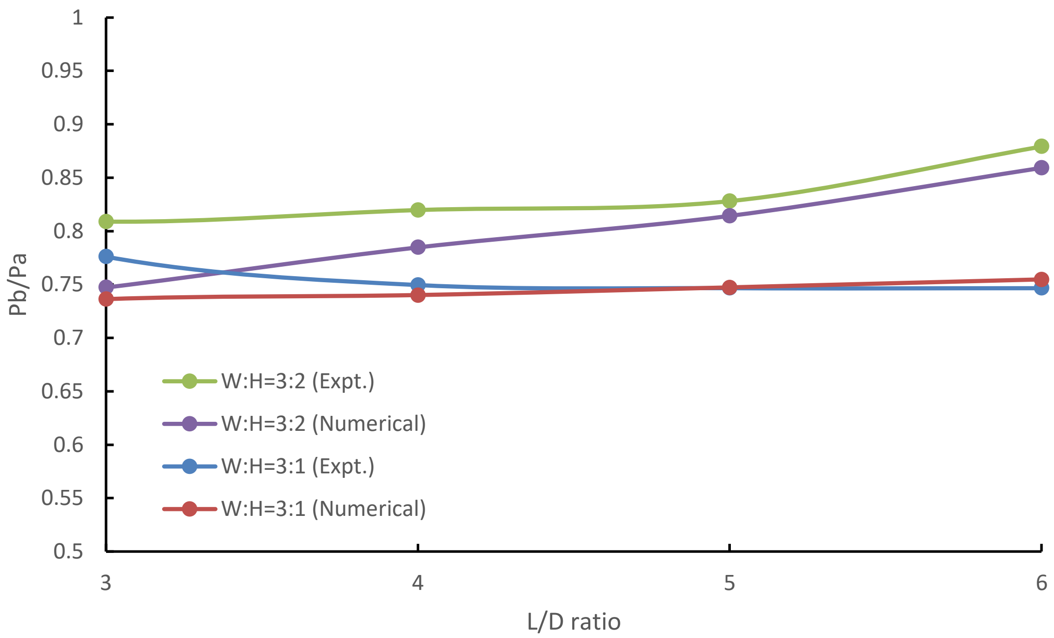

Fig. 5. Comparison of experimental and numerical results

3. Results

The numerical results of suddenly expanded flow through nozzle operating at sonic Mach number are discussed in this section. The diameter of the duct and the L/D ratio is fixed at 20 mm and 6, respectively. The base pressure variations for NPR from 1.5 to 5 and aspect ratio from 3:1 to 3:3 are discussed in detail. The pressure distribution for 1D, 2D, 3D, and 4D location of ribs are investigated in detail.

As the rib location is changed from 1D to 4D in the step of every ‘1D’ from the corner of the base in the downstream, the variation in base pressure can be seen in Figure. 6. The NPR is kept constant at 2.5 and simultaneously the rib aspect ratio, i.e., its height is increased from 1 mm to 3 mm. For each rib location, the height is changed, and the corresponding variations or reduction in base pressure is plotted in Figure 6. From the figure, it can be noted that the base pressure increases with shifting of rib position from 1D to 4D irrespective of its aspect ratio. It is interesting to note that the behavior of base pressure at different combinations of parameters is clearly demonstrated. At 1D location and for any aspect ratio of rib, i.e., when the rib is placed close to the base corner, the base pressure is almost the same. For other rib locations, the base pressure keeps slightly increasing when the aspect ratio is 3:1 and 3:2 while for 3:3 there is a significant jump in the base pressure at 3D and 4D. Such variations occur due to significant disturbances caused in the flow regime with the presence of rib where the flow aims to expand.

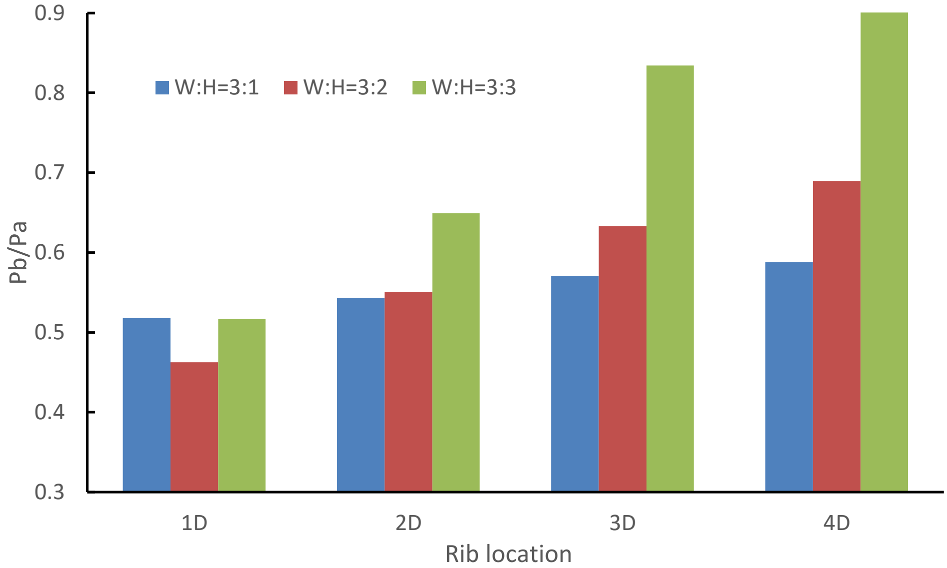

Fig. 6. Increase in base pressure with rib location and its aspect ratio

As mentioned in the introduction part about the jet pump action, the corner effects are dominant. When the flow from the nozzle exits at high velocity into the duct, the flow is either under expanded or correctly expanded, which depends upon the NPR value or level of expansion. In this case of sonic Mach converging nozzle with the dimensions described previously, the NPR required for correct expansion is 1.89. If NPR is lower than 1.89, the flow from the nozzle will not attain choked flow conditions, and for NPR greater than 1.89 the flow under-expanded and will be accompanied by the expansion waves and has to pass through these waves resulting in expansion of the flow.

In the case of over-expanded nozzles, there is an oblique shock at the exit of the nozzle, and when the jets are under-expanded, there is an expansion fan placed at the nozzle exit. Moreover, the reattachment point and the reattachment length gets affected by these flow behaviors. Another phenomenon which is coinciding with the flow recirculation zone occurring at the base corner of the duct is that the flow after getting expanded, the shear layer attaches itself with the duct wall in the downstream direction.

The fluid at the corner recirculates and dictates the level of suction or low base pressure level. Due to this low pressure in the wake region, the fluid from the reattachment point flows back into the base corner and gets thrown back into the mainstream flow via the shear layer entrainment. This phenomena of flow reversal and ejection continue in the steady-state. The base pressure with this cycle phenomena increases, and hence the presence of any barrier attached to the wall will cause either increase or decrease of fluid flow reversal affecting the primary vortex to a greater extent.

As explained above, the mass getting sucked into the dead zone at the corner is mainly disturbed, which also affects the reattachment point. The fluid reversal from the reattachment point is severely affected if the flow finds the rib height in its path. At the 1D position, the flow reattachment point is ahead of rib, and hence due to suction at the base, the fluid reverses but faces the barriers and hence the base pressure decreases compared to the smooth duct. If the height of the rib is further increased flow reversal ultimately reduces and reduction in base pressure is obtained. Furthermore, when the height of the rib is increased to 3 mm instead of again reduction in base pressure, the base pressure increases. The shear layer exiting from the nozzle is able to find the corner of rib even before reattaching itself with the duct wall. More amount of fluid mass is forced to flow into the corner region, which leads to the low strength of primary vortex and bigger size of the secondary vortex. A problem in placing the rib is vibration caused due to flow disturbances, and sometimes the disturbances could be severe. When the rib with these different aspect ratios is placed at 2D and higher positions in the downstream direction, the reattachment point lies well before them. This causes enough mass reversal and leads to improvement in base pressure.

The pressure distribution in the duct at different rib locations is shown in Figure 7. The NPR in these locations shown is familiar to 2.5. When the flow expands from the nozzle, the flows undergoes alternate compression and expansion due to the duct wall. Further, in the downstream of the nozzle, a compression zone can be seen which is similar to the diamond formed axially. Later they diminish as the flow travels longitudinally. As the rib location is shifted gradually from 1D to 4D, the distance between the successive compressed zones seem to be slightly reduced, showing the effect of rib. As the rib height increases, the strength of these zones increases showing the strong influence of the ribs.

Figure 8 depicts the contours of increases in pressure at the base corner in the enlarged duct. The aspect ratio of the rib is 3:2, and its location is varied from 1D to 4D with same NPR of 2.5 in each case. As explained earlier, the zone of compression ahead of nozzle lip is at quite some distance. 2D to 4D position find themselves at a shorter distance of compression zone occurring due to hitting of fluid to the wall. The more the compressed zones, the more significant is the base pressure, and the shorter the distance between them shows low velocity and higher corner pressure. The pressure distribution for a duct with rib having aspect ratio 3:3 is much clearer and explains its effect in Figure 9. It can be seen that the high-pressure zones are fewer for 1D position indicating lower base pressure. With increasing rib location from 2D to 4D, the pressure between the nozzle exit and rib corner is higher, indicating higher base pressure and lower velocity in that area. This is also evident by having more number of compressed zones and reduced distance between them.

The effect of NPR on base pressure in the duct where the flow expands from sonic Mach nozzle is depicted in Figure 10. The NPR is increased from 1.5 to 5 at a different aspect ratio of 3:1 to 3:3 and comparison is made between them and the duct having no rib. Figure 10 reveals that the base pressure decreases consistently for NPR ranging from 1.5 to 5 for no rib while for duct having ribs, the base pressure increases at different NPR. As for ribs having a 3:1 aspect ratio, although increment in base pressure unobservable, it is more than that in the smooth duct. For 3:2 and 3:3 aspect ratio, the base pressure increases after crossing NPR 2.5.

As the NPR increases the flow expands more rapidly with different level of expansion. The increases cause the shear layer to travel a longer distance before it attaches with the duct wall. Hence, the level of turbulence kinetic energy dissipation and viscous effects of the flow are low. As more length travelled by the viscous shear layer, the primary vortex size increases and a lesser amount of fluid reversal due to which base pressure reduces consistently. The region of the primary vortex is shown in Figure 10 where velocity (u) distribution is demonstrated. When a single rib having

1 mm height is placed, the flow gets affected, but instead of reduction, it remains nearly the same due to the occurrence of expansion fan at the nozzle exit.

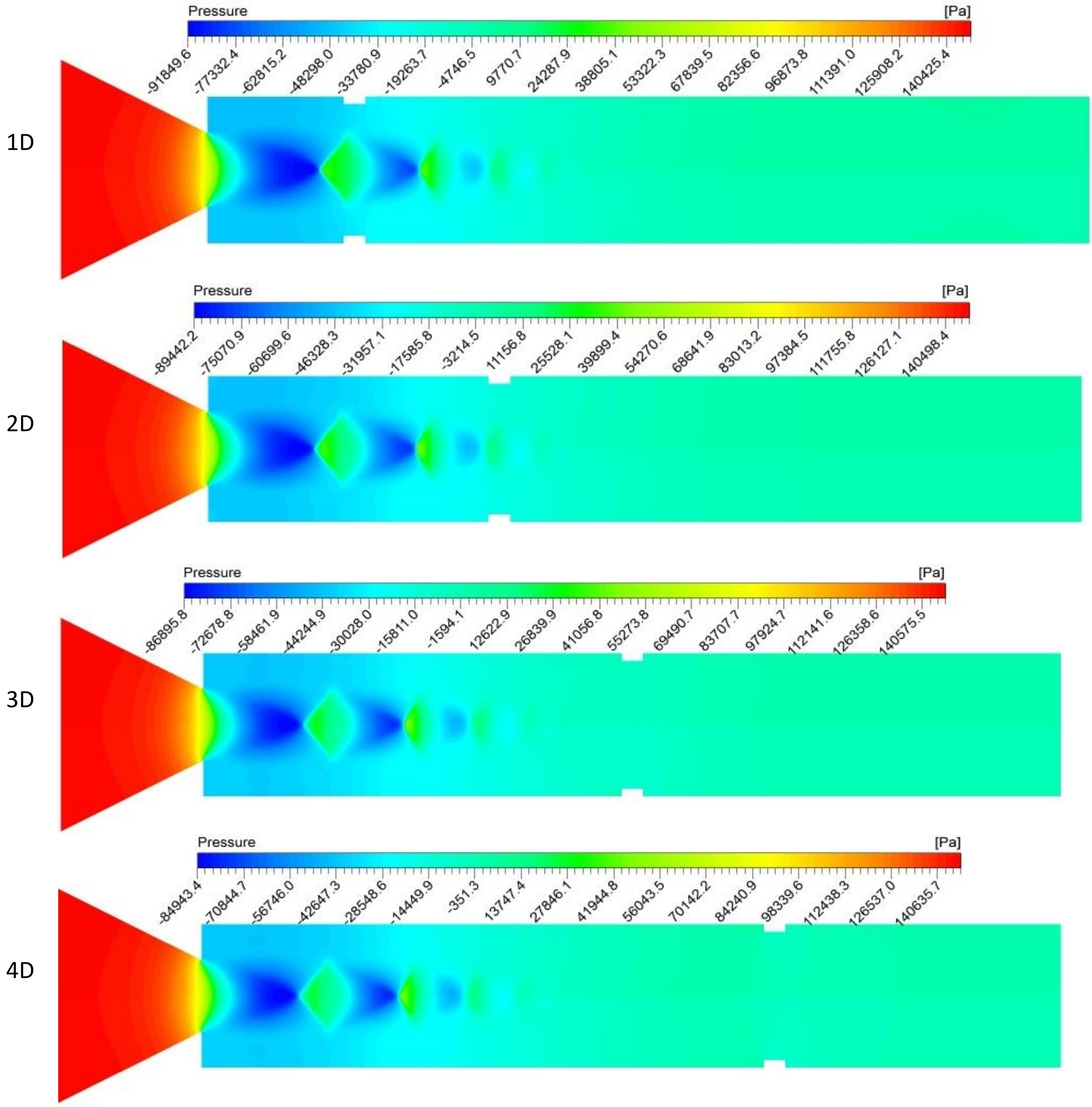

Fig. 7. Pressure distribution for different rib location of aspect ratio 3:1

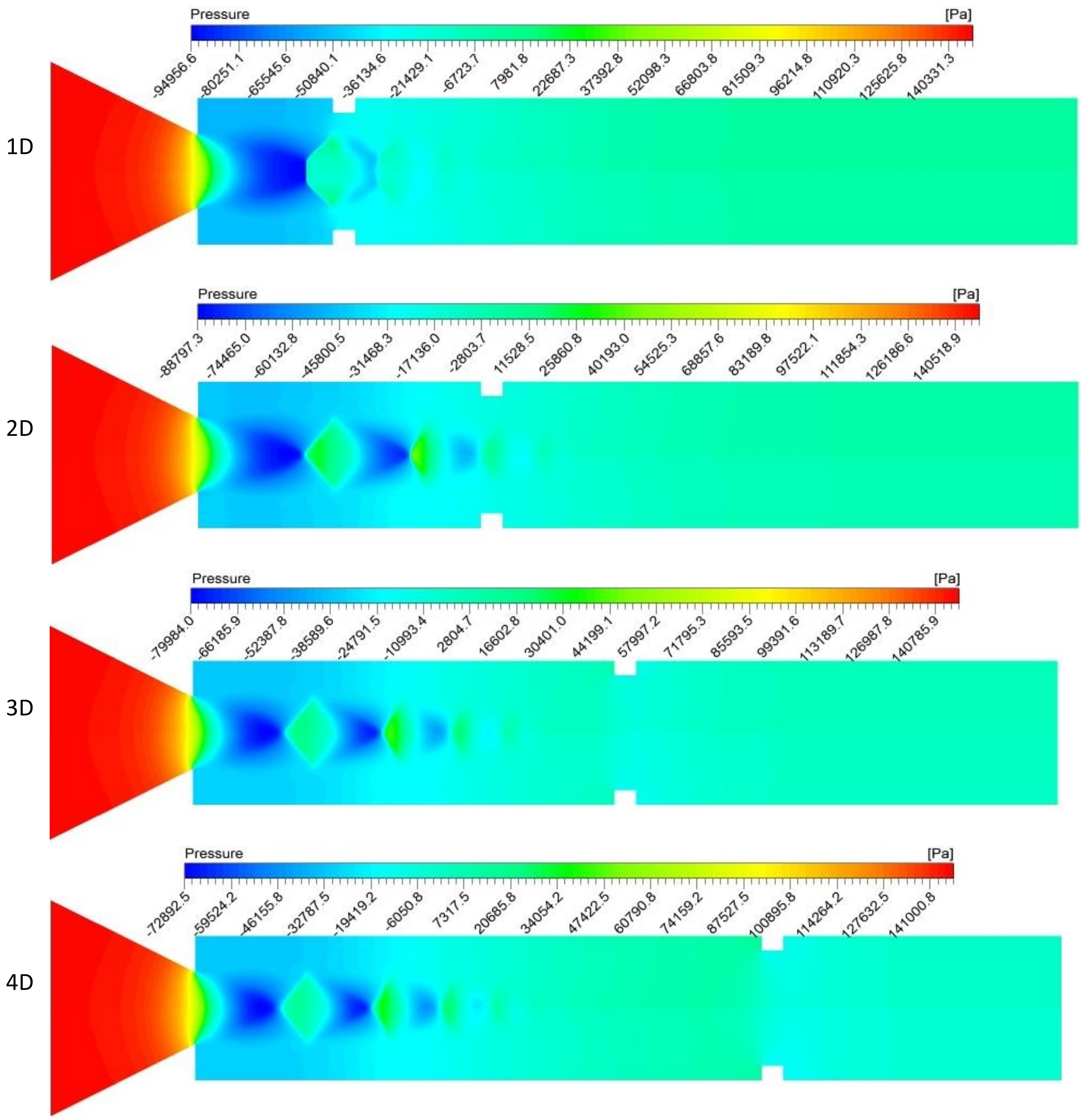

Fig. 8. Pressure distribution for different rib location of aspect ratio 3:2

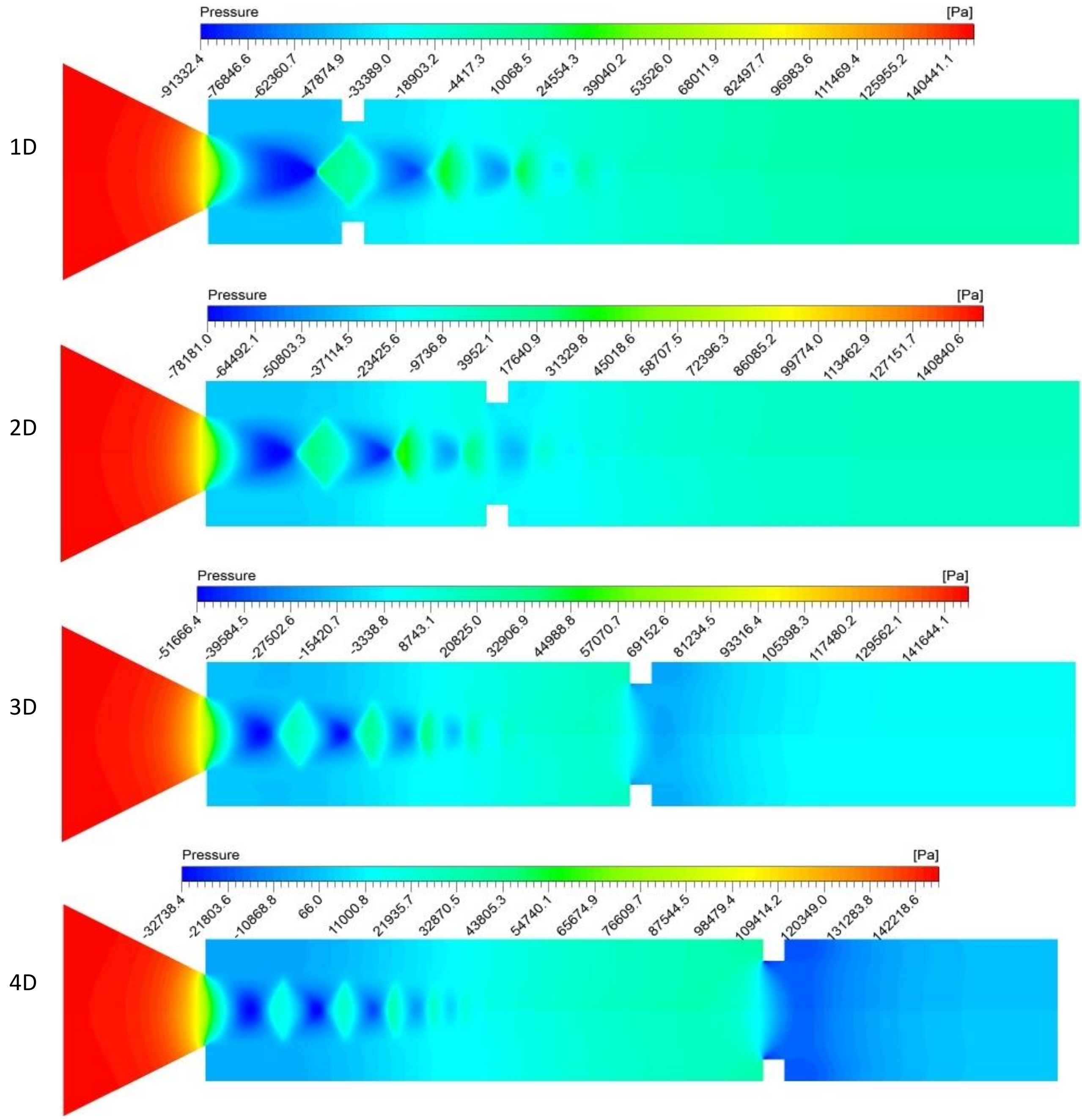

Fig. 9. Pressure distribution for different rib location of aspect ratio 3:3

With further increase in rib height, the level of flow expansion helps the rib to affect the reattachment point as shown in velocity iso-lines, as shown in Figure 11. In Figure 11, the occurrence of the primary and secondary vortex is shown where its size seems to become more significant with an increase in an aspect ratio of rib. This phenomenon has a significant influence on increasing the base pressure, where the percentage increase obtained in comparison with a smooth duct is massive.

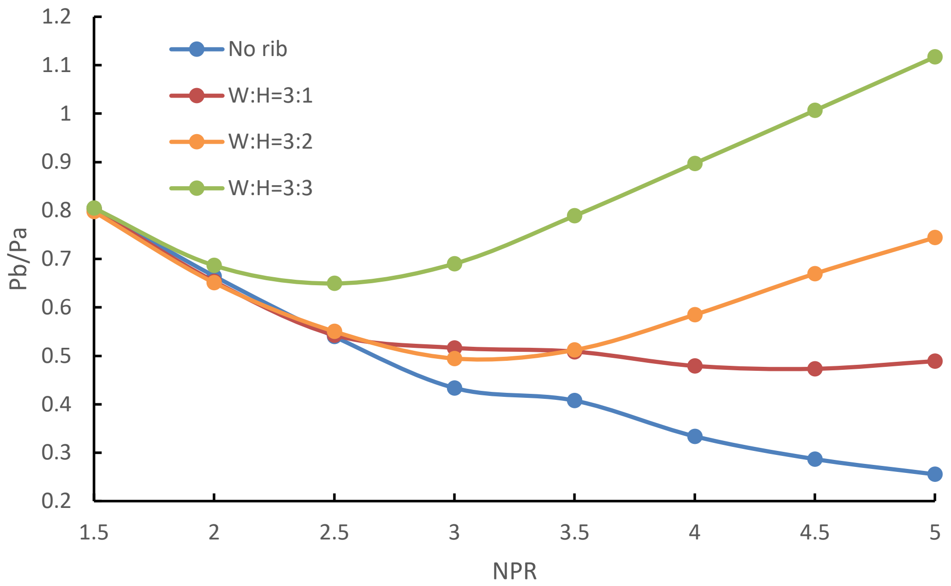

Fig. 10. Base pressure changes when NPR is increased from 1.5 to 5 and the aspect ratio is changed from 3:1 to 3:3

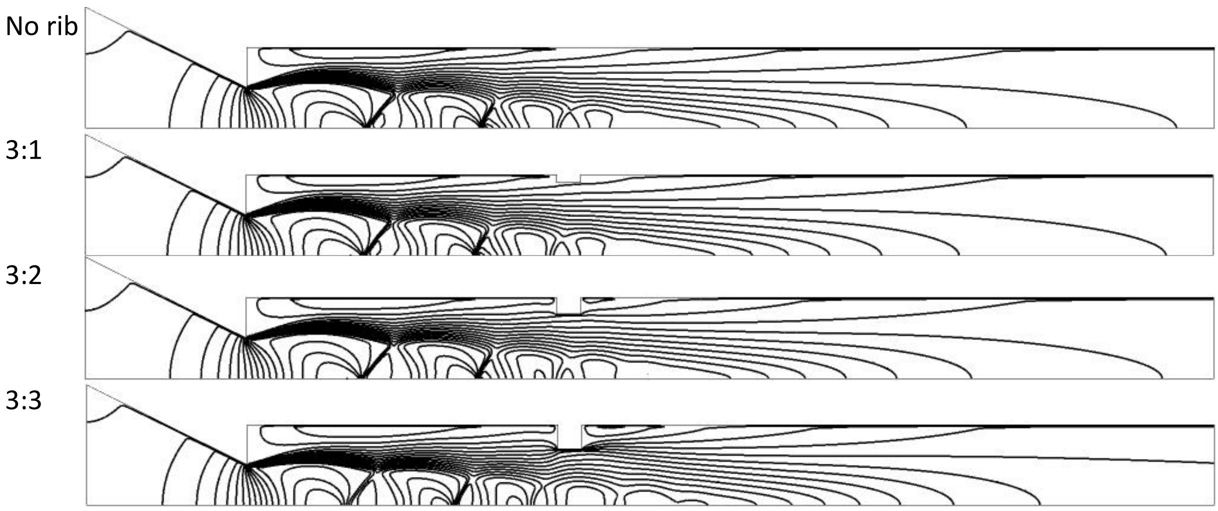

Fig. 11. Iso-lines of velocity (u) in the duct with no rib and rib having a different aspect ratio

4. Conclusions

The base pressure occurring at the corner recirculation zone in a duct contributes to a sufficient amount of total drag, which can be reduced using some control method. In this article, passive control using annular ribs are placed circumferentially in the duct where flow expands is analyzed numerically for changes in base pressure. Rib of different aspect ratio and their location are employed to increase the base pressure. The simulation of the computational model revealed exciting facts which can be concluded as follows: the height of the rib is the prime factor which affects the base pressure at the 1D location. Lower aspect ratio at nearer position reduced base pressure while higher aspect ratio ribs increase at the same location. For rib located ahead of reattachment length with any height tries to increase the base pressure. Higher aspect ratio located at farther position massively increase the base pressure compared to the smooth duct. The pressure in the duct comprises of expanded and compressed zones which are effected between the region of nozzle exit and rib location.

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