American Journal of Engineering Research (AJER)
e-ISSN: 2320-0847 p-ISSN : 2320-0936
Volume-11, Issue-05, pp-104-111
www.ajer.org
Review Paper Open Access

A comparative pressure characteristic study of two modified sudden expansion configurations

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Abstract— *In this paper, a numerical study on pressure characteristics in configurations of sudden expansion with central restriction only (Model-1) and sudden expansion with central restriction and blowing (Model-2) has been carried out. The two dimensional steady differential equations for conservation of mass and momentum are solved for Reynolds number ranging from 50 to 200, percentage of central restriction (CR) from 10% to 40% and for an aspect ratio (AR) from 1.5 to 6 for both the sudden expansion configurations. In addition, a blowing at the top corner with a fixed slot size of 0.01 (non dimensional distance) on side wall with percentage of blowing (B) from 0% to 10% of inlet mass flow is considered for Model-2. The effect of each variable on average static pressure distribution and average stagnation pressure drop at a section has been studied in detail. From the average static pressure distribution, it is observed that maximum average static pressure rise increases with increase in Reynolds number and percentage of central restriction for both the configurations. Maximum magnitude of average static pressure rise is achieved at lower aspect ratio. The maximum average static pressure rise is always less in case of blowing configuration (Model-2) compared to without blowing configuration (Model-1) when all other conditions remain same. The average stagnation pressure drop at a section decreases with increase in Reynolds number and also increase in percentage of central restriction for both the cases. This pressure drop at a section is less at lower aspect ratio. The average stagnation pressure drop at a section is always more in case of blowing configuration compared to without blowing configuration.*

Keywords - *average static pressure, blowing, central restriction, Reynolds number, sudden expansion*

Date of Submission: 05-05-2022 Date of acceptance: 19-05-2022

I. Introduction

A plain dump configuration in a device creates a separation of the boundary layer from the wall which results positive and negative pressure zone at the post throat region. This post throat region greatly influence the static pressure which is considered an important parameter in assessing the performance of various components of gas turbine engine such as diffuser, combustor etc. In this research activity, we have become interested to study the pressure characteristics of fluid passing through two modified sudden expansion configurations. First modification is considered by incorporating some central restriction in the inlet zone of sudden expansion configuration (Model-1). After incorporating central restriction in the inlet zone blowing has been considered at the top corner on side wall of sudden expansion configuration (Model-2).

In order to understand the effect of fluid flow through plain or modified dump configuration, different researchers have performed theoretical and experimental investigation. Among them, Durst et al. [1] have experimentally studied the flow characteristics of air downstream of a plane symmetric sudden expansion at low Reynolds number flow. They have considered a 3:1 symmetric expansion in a duct with an aspect ratio of 9.2:1. During their experiment, they have considered three different flow conditions and corresponding Reynolds numbers are 56, 114 and 252, based on upstream channel height and peak upstream velocity. Truskey et al. [2] have experimentally and numerically studied the flow characteristics through asymmetric sudden expansion configuration to examine the effect of complex flows upon endothelial cells in vitro. They have used flow visualization technique to observe recirculation flow pattern. Vradis and Otugen [3] have numerically studied the flow of a non Newtonian viscoplastic Bingham fluid over an axisymmetric sudden expansion. They have used Reynolds number in the range between 2 and 100. They have seen that reattachment length increases with increase in Reynolds number for a fixed value of yield number. They have observed that the reattachment length and size of the recirculating flow region decreases with increase in yield numbers for a fixed value of Reynolds number. Haidekker et al. [4] have performed a two dimensional numerical simulation of the onset phase of flow through sudden expansion configuration. They have studied fluid shear stress to see the effect of endothelial cells in blood vessels. Chakrabarti et al. [5] have numerically carried out the performance simulation of a vortex controlled diffuser in low Reynolds number regime. They have considered a sudden expansion configuration with suction slot on different position of vertical and horizontal walls. They have used Reynolds number ranging from 20 to 100, aspect ratio for 2 and 4, and bleed fraction for 2 per cent, 5 per cent and 10 per cent. They have established that the position of the bleed slot should be located preferably at the vertical wall top corner of the vortex controlled diffuser for the best performance. Behrens et al. [6] have experimentally studied the combustion characteristics in a modified backward-facing step combustor using countercurrent shear to enhance the turbulent burning velocities. In modified configuration, they have considered a suction slot of 0.25 times of channel inlet height located immediately below the trailing edge. A secondary flow is pulled from the combustor via a suction pump. Abu-Nada et al. [7] have carried out numerical investigation of heat transfer and fluid flow over a backward facing step configuration under the effect of suction and blowing. In their configuration, part of the channel's bottom wall, adjacent to the step, is considered permeable and constant uniform velocity is allowed to bleed through it. They have used Reynolds number in the range of 200 to 800 and bleed coefficient ranging from -0.005 to 0.005 for an expansion ratio of 2. They have observed that the reattachment length of the primary recirculating bubble increases by increase in blowing bleed coefficient and decreases by increase in suction bleed rate. They have also observed that suction increase the size of the secondary bubble and blowing reduces it. Layek et al [8] have carried out numerical simulation to study the effects of suction and blowing on flow separation in a symmetric sudden expansion channel. They have considered uniform blowing or suction at the lower and upper porous step walls. They have used expansion ratio of 1:2 and non-dimensional inlet channel length of 4. They have observed that the blowing through the channel wall makes the asymmetric nature of flow to the symmetric by diminishing the region of separation. Ali-Baig and Khan [9] have experimentally studied the effect of different levels of over expansion on base pressure in a suddenly expanded axisymmetric duct. Tuncer et al. [10] have experimentally investigated the stability and structure of lean premixed methane air flames in a swirl stabilized premixed dump combustor at atmospheric pressure. At the inlet of the dump plane, they have considered a 45^0 angled eight blades swirl vane which is installed on a 20 mm diameter centre body. They have observed two elliptically shaped counter rotating recirculation vortices behind the dump plane and a central recirculation zone just downstream of dump plane.

As per brief review of literature, it is noted that a number of researchers have studied the flow through sudden expansion geometry or sudden expansion with some modification. However, it is realized that comparative study on pressure characteristics in case of sudden expansion configurations with central restriction and sudden expansion configurations with central restriction and blowing is not addressed. Therefore it has motivated authors to study systematically the effect of Reynolds number, percentage of central restriction, aspect ratio and blowing variation on average static and average stagnation pressure of fluid passing through sudden expansion configurations with central restriction and sudden expansion configuration with central restriction and blowing.

II. Mathematical formulation

A. Governing equations

A schematic diagram of the computational domain for flow through sudden expansion with central restriction only (Model-1) and sudden expansion with central restriction and blowing (Model-2) is illustrated in Fig.1. (a) and (b) respectively. The flow under consideration is assumed to be steady, two-dimensional and laminar. The fluid is considered to be Newtonian and incompressible. The following dimensionless variables are defined to obtain the governing conservation equations in the non-dimensional form;

Lengths: $x^* = x/W_1$, $y^* = y/W_1$, $W^* = W/W_1$, $L_i^* = L_i/W_1$, $L_{ex}^* = L_{ex}/W_1$, $L_R^* = L_R/W_1$, $L_f^* = L_f/W_1$

Velocities: $u^* = u/U$, $v^* = v/U$.

Pressure: $p^* = p/\rho U^2$

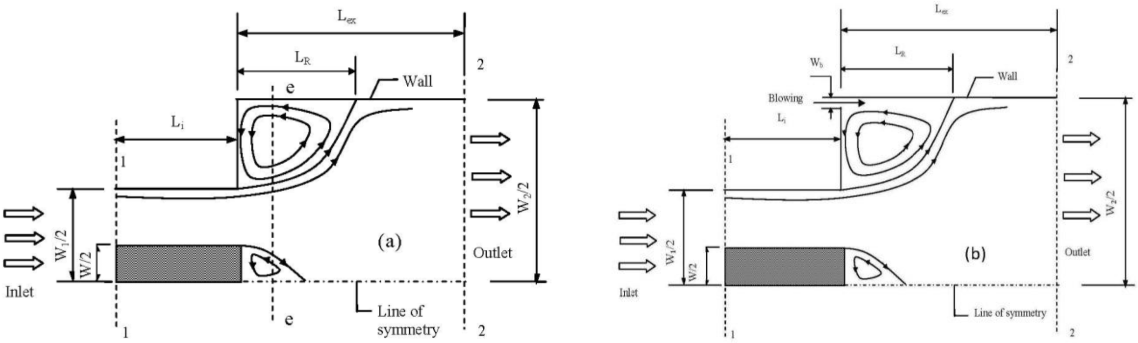

Fig. 1. Schematic diagram of the computational domain (a) Model-1 (b) Model-2

With the help of these variables, the mass and momentum conservation equations are written as follows,

$$\frac{\partial u^*}{\partial x^*}+\frac{\partial v^*}{\partial y^*}=0 \qquad \text{--------------} \quad (1)$$

$$u^*\frac{\partial u^*}{\partial x^*}+v^*\frac{\partial u^*}{\partial y^*}=-\frac{\partial p^*}{\partial x^*}+\frac{1}{Re}\left[\frac{\partial}{\partial x^*}\left(\frac{\partial u^*}{\partial x^*}\right)+\frac{\partial}{\partial y^*}\left(\frac{\partial u^*}{\partial y^*}\right)\right] \qquad \text{--------------} \quad (2)$$

$$u^*\frac{\partial v^*}{\partial x^*}+v^*\frac{\partial v^*}{\partial y^*}=-\frac{\partial p^*}{\partial y^*}+\frac{1}{Re}\left[\frac{\partial}{\partial x^*}\left(\frac{\partial v^*}{\partial x^*}\right)+\frac{\partial}{\partial y^*}\left(\frac{\partial v^*}{\partial y^*}\right)\right] \qquad \text{--------------} \quad (3)$$

Where, the flow Reynolds number, $Re = \rho U W / \mu$.

B. Boundary Conditions

Four different types of boundary conditions are applied to the present problem. They are as follows,

1. At the walls: No slip condition is used, i.e., $u^* = 0$, $v^* = 0$.
2. At the inlet: Axial velocity is specified and the transverse velocity is set to zero, i.e., $u^* = \text{specified}$, $v^* = 0$. Fully developed flow condition is specified at the inlet, i.e., $u^* = 1.5\left[1-(2y^*)^2\right]$.
3. At the exit: Fully developed condition is assumed and hence gradients are set to zero, i.e., $\partial u^*/\partial x^* = 0$, $\partial v^*/\partial x^* = 0$.
4. At the line of symmetry: The normal gradient of the axial velocity and the transverse velocity are set to zero, i.e., $\partial u^*/\partial y^* = 0$, $v^* = 0$.

C. Numerical Procedure

The partial differentials equations (1), (2) and (3) are discretised by a control volume based finite difference method. Power law scheme is used to discretise the convective terms [11]. The discretised equations are solved iteratively by SIMPLE algorithm, using line-by-line ADI (Alternating directional implicit) method. The convergence of the iterative scheme is achieved when the normalised residuals for mass and momentum equations summed over the entire calculation domain fall below 10^{-8}.

In the computation, flow is assumed fully developed at the inlet and exit and therefore, exit is chosen far away from the throat. The distribution of grid nodes is non-uniform and staggered in both coordinate direction allowing higher grid node concentrations in the region close to the step and walls.

III. Results and Discussion

The important results of the present study are reported in this section. The parameters those affect the flow characteristics are identified as,

(1) Reynolds number, $50 \le Re \le 200$
(2) Aspect ratio, AR = 1.5 to 6
(3) Central restriction from 10% to 40%
(4) Blowing, B=0% to 10% of inlet mass flow

3.1 Average static pressure distribution along the axial distance

In the present work, the average static pressure at any cross section is determined by the following expression:

$$P_{av} = \frac{\int p\, dA}{\int dA} \qquad \text{------------} \qquad (4)$$

The average static pressure distribution along the axial distance has been computed in this section considering the effect of blowing variation, percentage of central restriction, Reynolds number and aspect ratio. The average static pressure distribution curves along the axial distance for the configuration of sudden expansion with 20% central restriction and 0% (i.e. without blowing), 2%, 4%, 6%, 8% and 10% blowing are shown in fig. 2. For all the cases, a fixed Reynolds number of 100 with a constant aspect ratio of 2 are considered. The general characteristics of all the curves are that the steep fall of average static pressure takes place at the throat. Then, at the post throat region, at a given section there are zones of positive pressure and negative pressure. So the numerator of the equation is greatly influenced by negative pressure zone. Accordingly, the average static pressure rise at this post throat region nearer to throat is small. After reaching the maximum value, the average static pressure gradually droops due to dominating frictional effect for the rest of the region. From the figure, it is noted that the maximum magnitude of average static pressure rise from throat decreases with increase in percentage of blowing. Again, at a particular value of Reynolds number and aspect ratio, the magnitude of average static pressure rise at a section is less in case of Model-2 (blowing configuration) compared to the case of without blowing (i.e., Model-1). The probable reason may be that, when blowing is considered the recirculating bubble size decreases. Because of that, the effect of diffusion also decreases compared to without blowing configuration. This reduced diffusion decreases the magnitude of average static pressure at any section.

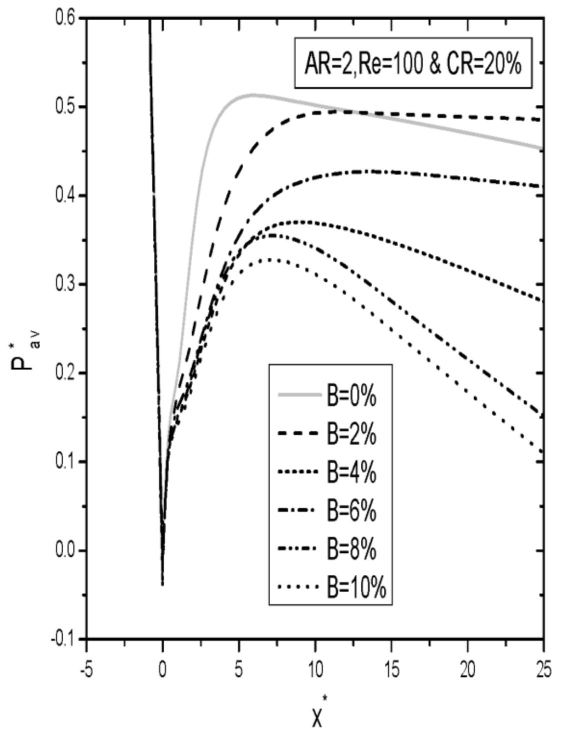

Fig. 2 Effect of blowing on average static pressure distribution

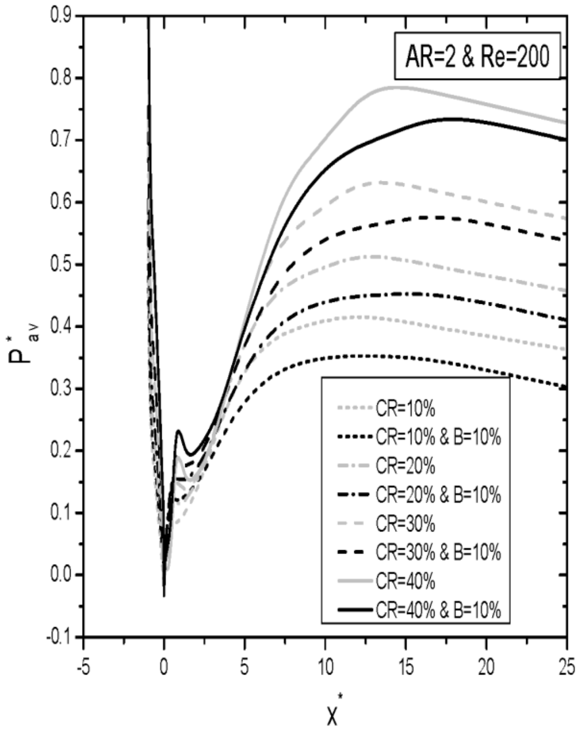

Fig. 3 Effect of central restriction on average static pressure distribution

The effect of central restriction on average static pressure distribution along the axial distance for Model-2 with 10% blowing and Model-1 (without blowing) is illustrated in fig. 3. In each case, different central restrictions are considered as 10%, 20%, 30% and 40% for a fixed Reynolds number of 200 with a constant aspect ratio of 2. It is noted that the maximum magnitude of average static pressure rise from throat increases with increase in percentage of central restriction for both the configurations of Model-1 and Model-2. It is also observed that, at any section the magnitude of average static pressure rise is less for the case of Model-2 compared to without blowing configuration (Model-1). Fig. 4 represents the average static pressure distribution along the axial distance for Model-1 with typically 40% central restriction and Model-2 with typically 40% central restriction and 10% blowing for typical Reynolds numbers of 50, 100, and 200 to investigate the effect of Reynolds number on average static pressure rise for stated configurations. In each case, a fixed aspect ratio of

2 is considered. It is seen that the maximum average static pressure rise from throat increases with increase in Reynolds number for both the configurations. Like earlier observation, for this case also, maximum magnitude of average static pressure rise from throat is always less in case of blowing configuration compared to without blowing configuration for a fixed value of Reynolds number.

The effect of aspect ratio on average static pressure distribution with axial distance for Model-1 with typically 40% central restriction and Model-2 with typically 40% central restriction and 10% blowing is presented in fig. 5. For all the cases, different aspect ratios of 1.5, 2, 4, and 6 are considered with a fixed Reynolds number of 100. At this higher percentage of central restriction (i.e., CR=40%), it is noted that the maximum magnitude of average static pressure rise from throat gradually decreases with increase in aspect ratio in case of Model-1. But, for the case of Model-2, this maximum magnitude of average static pressure rise from throat initially increases with increase in aspect ratio, and then it gradually decreases. In this case, peak value of maximum average static pressure rise is achieved at aspect ratio of 2. From the figure, it is also observed that at a particular value of aspect ratio the maximum magnitude of average static pressure rise is less in case of blowing configuration compared to without blowing.

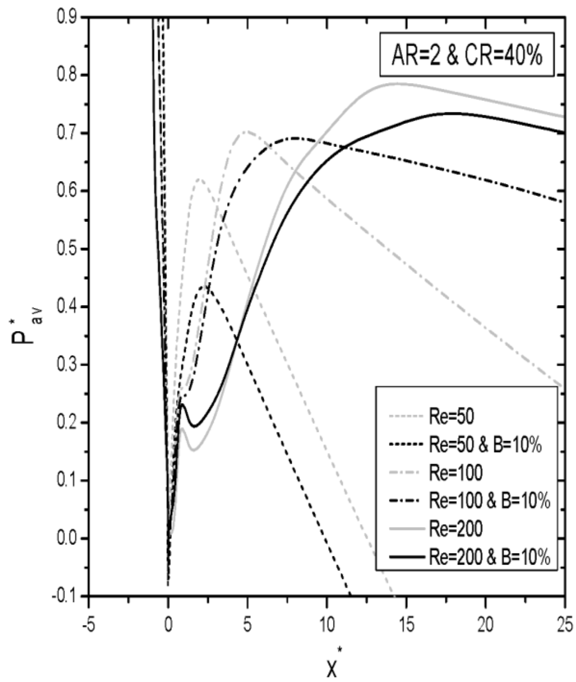

Fig. 4 Effect of Reynolds number on average static pressure distribution

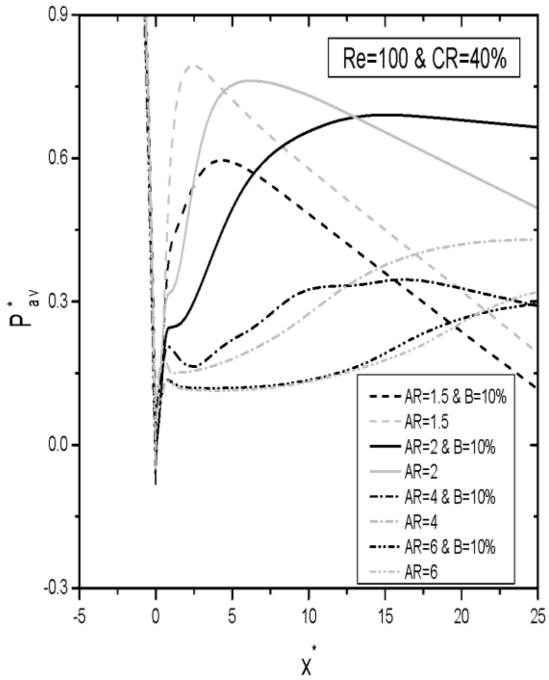

Fig. 5 Effect of aspect ratio on average static pressure distribution

3.2 Average stagnation pressure distribution along the axial distance

Stagnation pressure is very important parameter on which the overall cycle performance of gas turbine engine depends. Stagnation pressure is constant in a stream flowing without heat or work transfer only if friction is absent i.e., the stagnation pressure drop can be used as a measure of fluid friction. The computation of average stagnation pressure at any section should take into considerations of the direction of the velocity vector particularly in a flow situation, like the present case where the flow is the recirculating type. An attempt has been made to compute the average stagnation pressure at any section by the following expression:

$$P_{sav} = \frac{\int_{A_e} \left(p_e + \frac{1}{2} \rho \overline{V_e}^2 \right) u_e \, dA_e}{\int_{A_e} u_e \, dA_e} \quad \text{-----------} \quad (5)$$

Where the subscript 'e' refers to the plane of measurement.

The average stagnation pressure distribution curves along the axial distance for Model – 2 with typically 20% central restriction and different percentages of blowing for a fixed Reynolds number of 100 and an aspect ratio of 2 are shown in fig. 6. Different percentages of blowing are considered as 0% (without blowing), 2%, 4%, 6%, 8% and 10% of inlet mass flow. The general behaviour of all the curves is drooping characteristics for both the configurations (with and without blowing). From the figure, it is noted that the average stagnation pressure drop increases at any section with increase in percentage of blowing. The probable reason may be that, with increase in blowing, the static pressure at any section decreases which has been observed in the earlier subsection 3.1. As Reynolds number is fixed for the considered cases, kinetic energy diffusion may increase slightly or remains more or less same because of increase in blowing. Blowing may decrease the viscous dissipative effect slightly. Finally, the viscous dissipative effect dominates the effect of diffusion as blowing percentage increases and this leads to increase in average stagnation pressure drop at any section.

The average stagnation pressure distribution with axial distance has been computed for Model – 1 with 10, 20, 30 and 40 percent central restrictions and Model – 2 with 10, 20, 30 and 40 percent central restrictions with blowing of 10% of inlet mass flow for a typical Reynolds number of 200 and an aspect ratio of 2. The outcome of the exercise has been depicted in fig. 7. From the study, it is seen that, for a fixed value of Reynolds number, the average stagnation pressure drop at any section increases with increase in percentage of central restriction for both the models. It is also noted that, at a particular value of Reynolds number and central restriction, more stagnation pressure drop occurs at a section when blowing configuration (Model – 2) is considered compared to without blowing configuration (Model – 1). The reason is explained earlier in this subsection. The effect of Reynolds number on average stagnation pressure distribution along the axis for Model – 1 with typically 40% central restriction and Model – 2 with typically 40% central restriction and 10% blowing has been investigated and illustrated in fig. 8.

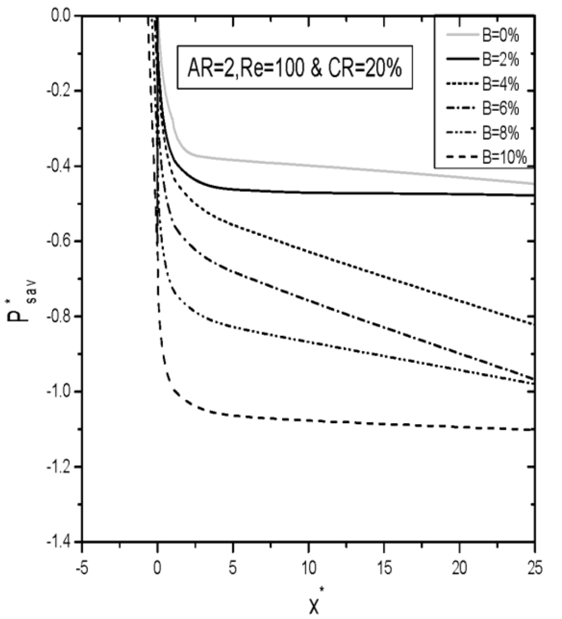

Fig. 6 Effect of blowing on average stagnation pressure distribution

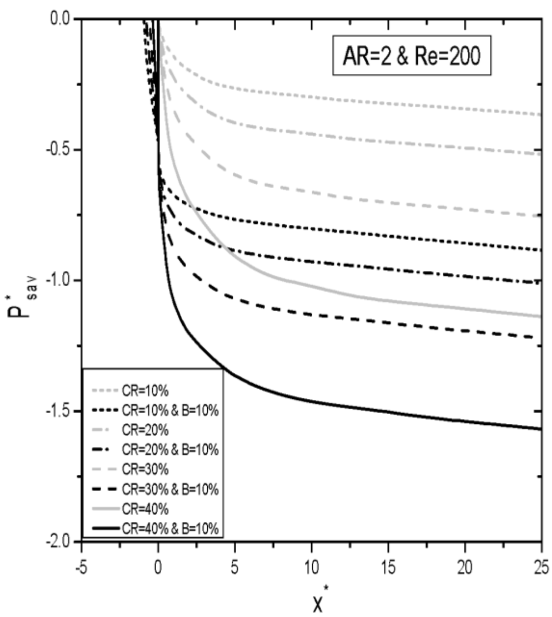

Fig. 7 Effect of central restriction on average stagnation pressure distribution

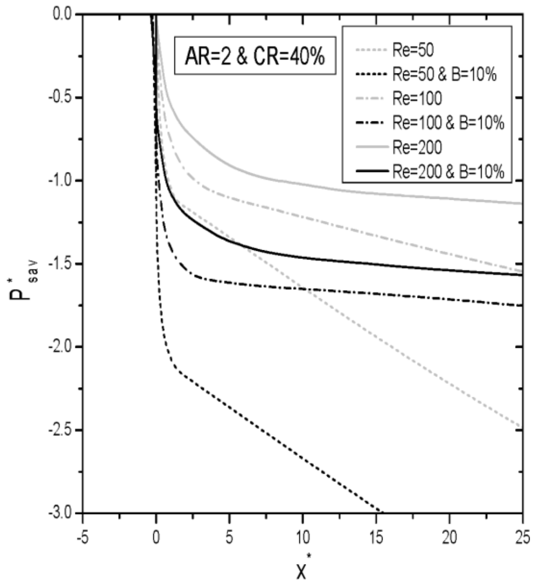

Fig. 8 Effect of Reynolds number on average stagnation pressure distribution

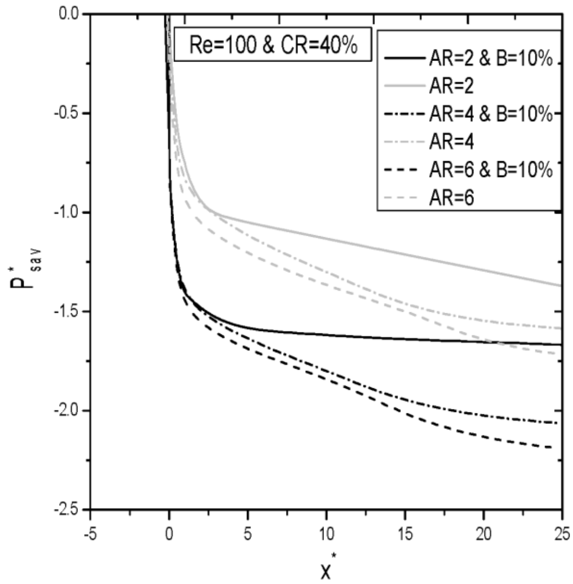

Fig. 9 Effect of aspect ratio on average stagnation pressure distribution

The different Reynolds numbers are considered as 50, 100 and 200 for a particular aspect ratio of 2. The general characteristics of all the curves in case of with and without blowing configurations are similar in nature. Form the figure; it is found that the average stagnation pressure drop at a section is more in case of Model – 2 compared to the case of Model – 1, like earlier observation.

The variation of average stagnation pressure distribution along the axial distance for different aspect ratio of 2, 4 and 6 for Model – 1 with 40% central restriction and Model – 2 with 40% central restriction and 10% blowing is shown in fig. 9. In each case, a typical Reynolds number of 100 are used. It is noted that the average stagnation pressure drop at a section increases with increase in aspect ratio for both the considered models. Like earlier observation, it is again noted that the average stagnation pressure drop at a section is more in case of Model – 2 (with blowing) compared to the Model – 1 (without blowing).

IV. Conclusion

The effect of Reynolds number, central restriction and aspect ratio on average static pressure distribution and average stagnation pressure drop at a section has been investigated for both the configurations of Model-1 and Model-2. Also, the effect of blowing variation has been investigated for Model-2. This leads to the following important observations;

i) At a particular value of Reynolds number, percentage of central restriction and aspect ratio, the maximum magnitude of average static pressure rise is less in case of Model-2 compared to Model-1, and this maximum magnitude decreases gradually with increase in percentage of blowing variation.

ii) Maximum magnitude of average static pressure rise from throat increases with increase in percentage of central restriction and flow Reynolds number for both Model-1 and Model-2.

iii) Maximum magnitude of average static pressure rise from throat gradually decreases with increase in aspect ratio in case of Model-1. But, for the case of Model-2, this maximum magnitude of average static pressure rise from throat initially increases with increase in aspect ratio, and then it gradually decreases. In this case, peak value of maximum average static pressure rise is achieved at an optimum aspect ratio of 2.

iv) The average stagnation pressure drop at a section decreases with increase in Reynolds number and also increase in percentage of central restriction for both the cases. For a fixed percentage of central restriction and Reynolds number, average stagnation pressure drop at a section increases with increase aspect ratio. When other parameters remain constant the average stagnation pressure drop across a section is always more in case of blowing configuration compared to without blowing configuration.

Therefore, from the study, it may be concluded that Model – 2 may give less benefit in terms of maximum magnitude of average static pressure rise and average stagnation pressure drop across a section compared to Model – 1 for all the considered parameters.

Nomenclature

L_i Inlet length (i.e., length between inlet and throat sections), m

L_{ex} Exit length (i.e., length between throat and exit sections), m

L_R Reattachment length, m
P or p Static pressure, [N/m^2]
P^*_{av} Dimensionless average static pressure
P^*_{sav} Dimensionless average stagnation pressure
Re Reynolds Number
u Velocity in x-direction, ms^{-1}
U Average velocity, ms^{-1}
v Velocity in y-direction, ms^{-1}
$\overline{V_e}$ Velocity vector at section e-e, ms^{-1}
W width of central restriction, m
W_1 Width of inlet duct, m
W_2 Width of exit duct, m
AR Aspect ratio = W_2/W_1
B Percentage of Blowing
CR Percentage of central restriction = W/W_1
x, y Cartesian co-ordinates
ρ Density, kg m^{-3}
μ Dynamic viscosity, kg $m^{-1}s^{-1}$

Subscripts
* Dimensionless terms
1-1 Inlet
2-2 Exit
e pertaining to section e-e

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