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EFFECT OF DOME SHAPE ON STATIC PRESSURE RECOVERY IN A DUMP DIFFUSER AT DIFFERENT INLET SWIRL

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ABSTRACT

Turbulent isothermal flow inside an axisymmetric dump diffuser and casing-liner annulus has been studied by using realizable k-ε model with and without swirl. Hemispherical, ellipsoidal and vertical ellipsoidal shapes of dome have been considered as liner heads in the simulation. The effects of different dome shapes on the flow pattern in the domain and pressure distributions along the casing and liner walls have been studied over a range of inlet swirl number. The static pressure recovery across the diffuser has been evaluated from the pressure distribution for each case. It is noticed that despite the variation in the size and intensity of the recirculating vortices, the pressure recovery remains nearly the same for all the three dome shapes for a particular swirl level in the inlet. However, swirl in the inlet flow considerably influences the pressure recovery. As the inlet swirl level increases, the size of the corner recirculation decreases, but a central reciculation is additionally formed. The static pressure recovery increases with the inlet swirl level in the range of swirl number considered. This indicates higher effectiveness in pressure recovery with swirl in flow.

Keywords: Gas turbine combustor, dump diffuser, swirl, dome shape, static pressure recovery.

1. INTRODUCTION

Diffuser is one important component of the gas turbine combustor following the compressor. It helps in slowing down the flow resulting in the recovery of static pressure following Bernoullian energy balance. Moreover, slower flow helps in reducing the frictional pressure loss in the combustor and stabilization of the flame. In case of aviation gas turbine, in order to minimize the size and weight of the engine, dump diffusers are often employed in the combustor.

In a dump diffuser flow separation from the outer wall occurs at the dump plane resulting in the formation of a recirculating vortex at the upper corner. Irrecoverable pressure loss occurs in the vortex due to flow irreversibilities and the amount of loss depends on the size and intensity of the vortex. The combustor liner (or flame tube), located centrally after the diffuser, turns the flow towards the outer wall and thereby influences the loss that occurs in the recirculation.

A lot of work has been done to study the flow behavior within the gas turbine combustor, under isothermal [1,2, 3, 4,5] and reactive [6,7,8,9,10] flow conditions. However, much less attention has been paid on the flow analysis in the dump plane and casing-liner annulus (i.e. the space between liner wall and outer casing).

Fishenden and Stevens [11] reported that a lower dump gap (gap between the dump plane and liner head) has a beneficial effect as it avoids flow separation in the pre-diffuser of the combustor. On the other hand, too little a dump gap rapidly increases the loss in the annulus, thus calling for an optimization. Karki et al. [12] computed the flow interaction in the diffuser-combustor geometry using an axi-symmetric simulation in the median plane of the combustor. Hestermann et al. [13] studied the flow in a combustor with pre-diffuser and dump diffuser, both experimentally and numerically. They investigated the maximum pre-diffuser opening angle with minimum dump gap to avoid flow separation inside the pre-diffuser. The importance of dump gap in pressure recovery in the diffuser was further investigated by Carrotte et al. [14] and Sanal Kumar et al. [15]. Walker et al. [16] optimized the integrated outlet guide vane (OGV)/pre-diffuser unit for better control of flow quality with improved performance parameters. The compressor outlet guide vane influences the swirl level in the flow approaching the diffuser which affects the size of the wall recirculation zone following the dump plane [17]. Rahim et al. [18] studied the effects of different liner dome shapes on the pressure distribution following the diffuser.

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The behaviour of the flow following the dump plane depends on the shape of the dome head and the swirl level in the flow. In the present work, a numerical model has been used to solve the flow in a dump diffuser with different dome shapes of the liner. Three different shapes, viz. hemispherical, ellipsoidal and vertical ellipsoidal, have been considered. Studies have been performed at different swirl levels at the inlet. The flow pattern and pressure recovery have been compared to illustrate the effects of different dome head.

2. MODEL DESCRIPTION

2.1 Physical model

The size and shape of the combustor (Figure 1a) considered in the present work are identical to those described in [18]. The length of the inlet pipe (L_i) and that of the casing (L_c) are 0.1m and 0.4572m, respectively. A swirler is considered at the inlet pipe to impart the necessary swirl to the flow simulating the condition of air flow from the compressor. Different vane angles of the swirler have been considered in order to vary the swirl level at the entry to the diffuser. Three different shapes of dome have been used for simulation (Figure 1b). The ratios of major to minor axes for the ellipsoidal and vertical ellipsoidal domes are 1.8:1 and 1:1.8 respectively. Diameter of hemispherical dome is same as the liner diameter. The outer diameter of swirler (D_s), swirler hub diameter (D_h), air casing diameter (D_c) and liner diameter (D_l) are 0.054m, 0.005m, 0.1524m and 0.0762m, respectively. The axi-symmetric computational domain for the analysis of flow in the annulus has been marked in the Figure 1a.

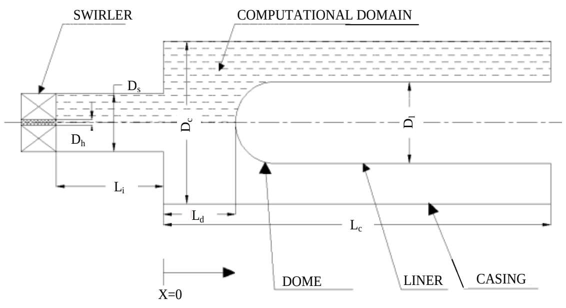

Figure 1.

Fig. 1a. Physical model of the combustor

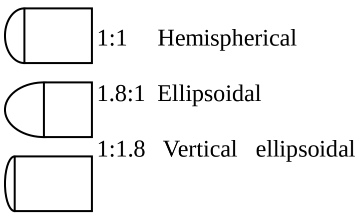

Fig.1b. Different liner dome shapes considered in the analysis

2.2 Numerical Model

The numerical solution has been performed in Ansys Fluent 13.0 software using SIMPLE algorithm. The Reynolds averaged form of conservation equations of mass and momentum have been considered in the model for solving the air flow under isothermal condition through the physical geometry shown in Figure 1a. The turbulent parameters are solved using the realizable k-ε model [19], which has been derived by satisfying the mathematical constraints on the normal stresses consistent with the physics of turbulent flow. A variable C_μ is considered in the eddy viscosity expression, which is expressed as a function of the mean strain, mean rate of rotation and turbulence quantities (k and ε). The ε-equation is expressed in a form that can better represent the spectral energy transfer in turbulent flow. The model constants are suitably considered.

The mass flow rate of air is so chosen that the Reynolds number (Re) based on the inlet axial velocity ($U_{x|in}$) and the diameter of the inlet pipe (D_s) is 1.2×10^5. The axial velocity at the inlet plane of the domain is considered to be uniform, while the tangential velocity resulting swirl there is also uniform over the plane. The degree of swirl is expressed by the swirl number, defined as,

$$SN = \frac{2}{3}\frac{\left(D_s^3 - D_h^3\right)}{\left(D_s^2 - D_h^2\right)\left(D_s - D_h\right)}\tan\theta$$

The turbulent intensity (I) and length scale (l) at the inlet plane are set using empirical relations as,

$$I = 0.16(\mathrm{Re})^{-0.125}$$
$$l = 0.07 D_s$$

At the outlet, the axial gradient of all the variables have been set to zero. No slip boundary condition with the standard law of wall has been considered on the solid walls, while the symmetric boundary condition is set on the axis.

3. RESULT AND DISCUSSION

The numerical predictions from the model are validated by comparing against the experimental data of Rahim et al. [18] for the same geometric and operating conditions. Accordingly, a swirl number (SN) = 0.38, $U_x|_{in}$=32.37 m/s, $U_\theta|_{in}$=18.68 m/s and a non-dimensional dump gap DG =(L_d/D_c)=1 with hemispherical dome at the liner head have been used in the computation. The validation has been made by comparing the radial distributions of axial velocity in the dump plane and casing liner annulus (Figs. 2a-d).

It is observed that the numerical predictions agree to the experiment quite closely, particularly within the annulus (Figs. 2c and 2d). Within the dump gap (Figs. 2a and 2b) some disagreement in the velocity magnitude is observed particularly on the axis, though the overall qualitative trend and the peak velocity remain the same.

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In the experiment, the reverse flow induced by the swirl was observed close to the dump plane. This has got a little delayed in the numerical results.

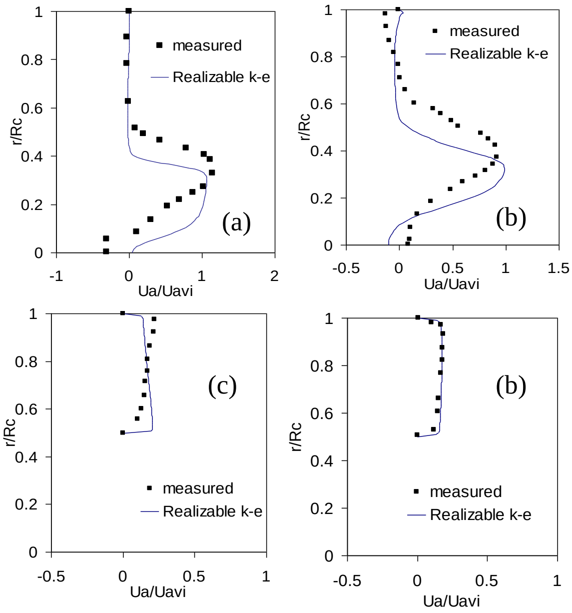

Fig. 2. Radial variation of Axial Velocity at different axial locations (a) X/Dc=0.1 (b) X/Dc=0.3 (c) X/Dc=1.5 (d) X/Dc=2.1.

3.1 Effect of different liner dome shapes on flow patterns

Figures 3a-c depict the flow distributions across the dump plane and in the casing-liner annulus for three different types of liner domes, i.e. hemispherical, ellipsoidal and vertical ellipsoidal. The inlet flow is purely axial without any tangential component in it. Corner recirculation zone is formed in each case as the flow separates from the outer wall at the dump plane, though the size of the vortex is different for different dome shapes. The largest vortex is formed with the hemispherical head, while the vertical ellipsoidal head produces the smallest recirulating vortex.

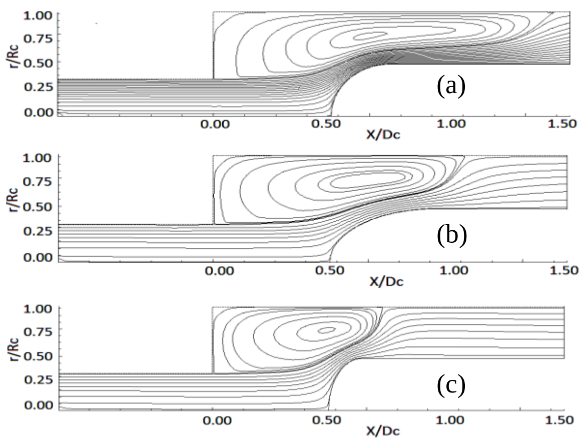

Fig.3. Stream function at no swirl with dome shape (a) Hemispherical (b) Ellipsoidal (c) Vertical ellipsoidal

The variation in the vortex size can be attributed to the interaction between the flow and the dome structure. The presence of the dome generates a restricted passage through which the flow gets accelerated. Moreover, the profile of the dome directs the flow through this passage in a way that influences the vortex structure. In case of the hemispherical dome the recirculating vortex is stretched to its largest size. In case of the ellipsoidal dome, the more gradual development of the dome profile does not favour such a long recirculation. While, in case of the vertical ellipsoidal dome, the head turns the flow much more abruptly towards the outer wall. The size of the corner recirculation is the minimum in this case.

Swirl in the inlet flow makes considerable changes in the flow profiles with the different dome shapes. Figs. 4a-c show the streamlines in the diffuser with three different liner heads, when the flow swirl number at the inlet plane is 0.38. The tangential velocity in the flow produces a central recirculation on the axis following the dump plane and adjacent to the liner dome. The central recirculation shifts the stagnation point away from the axis and facilitates in turning the flow more gradually and from an earlier location towards the outer wall. The passage available for the fluid past the dome widens and the flow get less accelerated. This reduces the size of the corner recirculation, particularly for the hemispherical dome. Moreover, the lower flow velocity past the liner weakens the vortex as well. The reverse flow cannot maintain itself up to the dump plane, and generates a small vortex at the corner of the dump plane which rotates in the opposite direction. This small vortex is also observed with the ellipsoidal dome head but not with the vertical ellipsoidal head. On the other hand, in case of the vertical ellipsoidal head, a small recirculation is observed on the liner wall induced by the tangential motion still sustained in the flow.

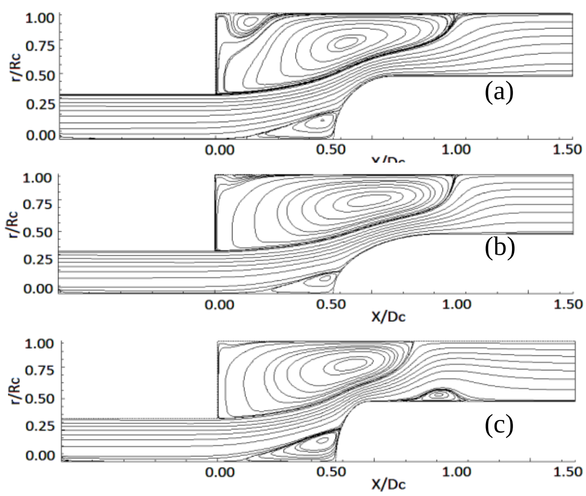

Fig.4. Stream function for SN=0.38 with dome shape (a) Hemispherical (b) Ellipsoidal (c) Vertical ellipsoidal

The pressure variation in the diffuser as a result of the flow pattern has considerable influence on the combustor performance and energy recovery. The variation in the outer casing wall pressure determines the size and intensity of the wall recirculation. A stronger and bigger recirculating vortex results in more pressure loss. The distribution of pressure on liner wall influences the distribution of dilution air in the combustor. A ore uniform pressure distribution is desired for uniform flow distribution giving better performance.

3.2 Effects on Casing Wall Pressure

Figure 5(a) shows the variation in casing wall pressure for different dome shapes without inlet swirl. In case of the hemispherical dome, the wall static pressure maintains nearly constant immediately following the dump plane. Thereafter, an adverse pressure gradient is observed resulting in the reverse flow within the corner recirculation adjacent to the casing wall. After the flow reattachment, the pressure remains almost constant up to the exit of the combustor.

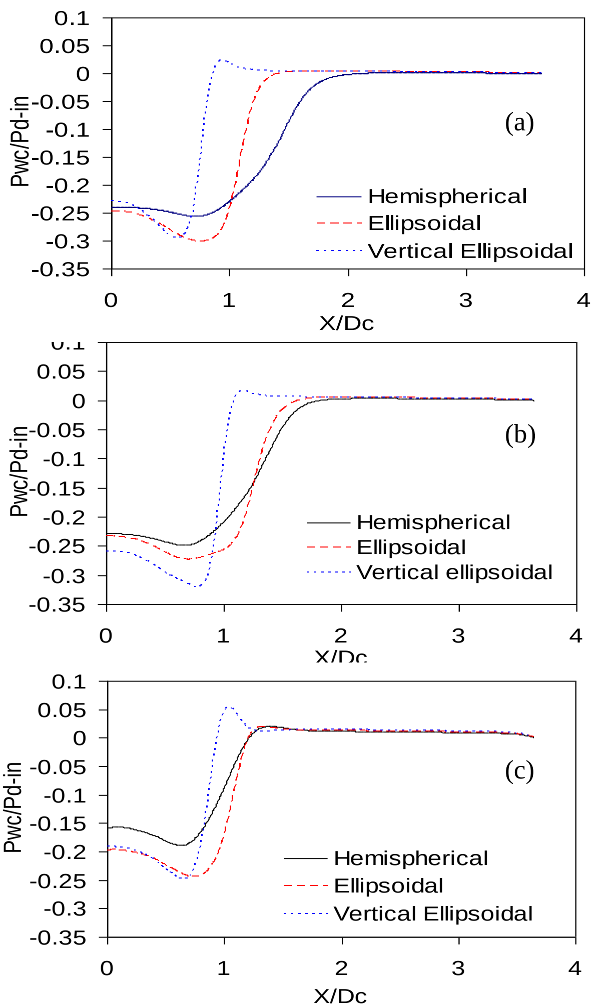

Fig.5. Casing wall pressure distribution with different dome for (a) SN=0.0 (b) SN=0.178 (c) SN=0.38

For the ellipsoidal and vertical ellipsoidal dome heads, a small initial pressure drop is observed following the dump inlet, which is succeeded by strong adverse pressure gradients. The reattachment occurs earlier along the casing wall depicting smaller recirculating vortices in these cases. However, stronger pressure gradients indicate towards higher intensity of eddies.

In figure 5 (b), the effect of dome shape on the casing wall pressure distribution is plotted for an inlet swirl number of 0.178. In this case of mild swirl, the hemispherical dome shows a similar casing wall pressure variation as in case of no swirl. However, it can be observed that because of the presence of swirl in flow, the reattachment occurs a little earlier. It indicates towards a shorter recirculation zone on the outer wall. With the ellipsoidal dome, the intensity of the corner recirculation is increased, which can be observed from the higher gradient in pressure variation. But the size of the circulating zone is smaller. As in Fig. 5(a), the blunt shape of the vertical ellipsoidal dome deflects the flow towards the casing wall and the same effect is enhanced by the presence of swirl, thereby reducing the vortex size. But the strength of the circulating zone is the highest for the present swirl number.

In figure 5 (c), the effect of stronger swirl (SN=0.38) is depicted with different dome shapes. The reattachment lengths for both hemispherical and ellipsoidal heads are almost the same and smaller than the reattachment lengths with zero and mild swirl. The strength of recirculation zone for hemispherical dome is the minimum at this swirl level reflected in the lowest pressure difference across the recirculation zone. Though the vertical ellipsoidal produces almost the same pressure drop as the ellipsoidal dome, the size of the vortex is smaller in case of the former. The pressure on the casing wall rises to a peak before dropping a little and then droop only a little due to friction.

3.3 Effect of swirl for different dome shape on liner wall pressure

Figure 6(a) shows the liner wall pressure variations for different dome shapes with no inlet swirl condition. Here for all the dome shapes, static pressure is the maximum at the tip of the dome due to stagnation of flow. The pressure decreases along the surface of the liner as the flow accelerates through the narrow passage between the liner and the corner recirculating vortex. The pressure further increases with the expansion of the flow and shrinking of the recirculation vortex. The liner wall pressure finally remains nearly constant up to the exit plane. Similar trends in liner pressure distributions are observed for all the three dome heads. However, the minimum pressure on the liner wall is observed with the vertical ellipsoidal head, which indicates towards the maximum flow velocity for this case. It can now be ascertained that high velocity directed towards the outer wall due to the head profile leads to the minimum size of the corner recirculation vortex in the case of vertical ellipsoidal dome.

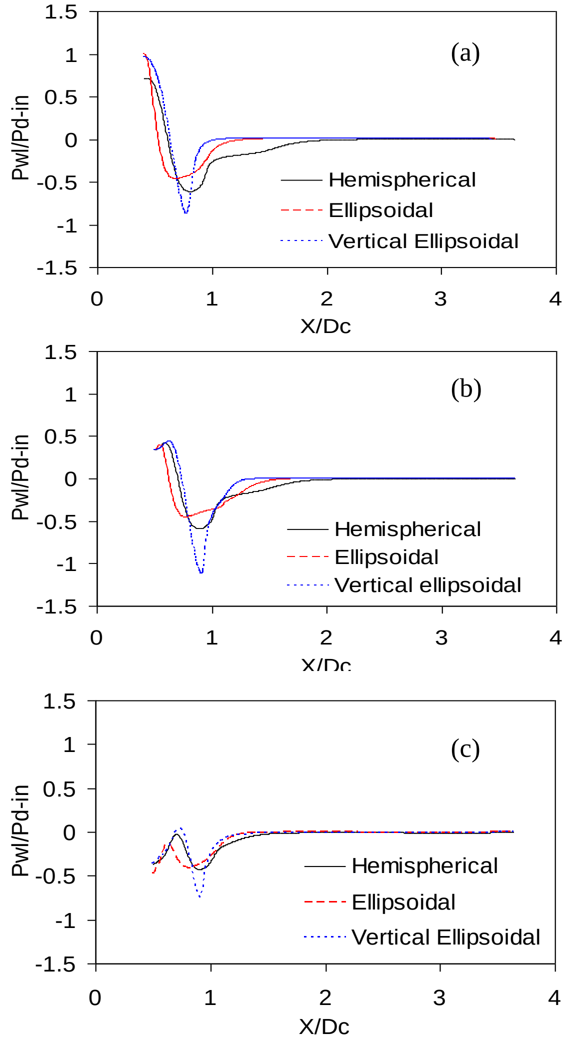

Fig.6. Liner wall pressure distribution with different dome for (a) SN=0.0 (b) SN=0.178 (c) SN=0.38

It is further observed from Fig. 6(a) that for the vertical ellipsoidal dome head the wall pressure on the liner flattens up at the earliest, while this flattening occurs at the furthest location in case of the hemispherical head. This is also an indication of the relative size of the recirculation in the three difference cases.

The variation of liner wall pressure follows nearly the same trend when a mild swirl (SN=0.178) is present in the inlet flow (Figure 6 (b)). However, a little difference is observed near the tip of the head, which shows that the peak pressure is reached a little away from the tip. This difference is further clearly evident when the swirl number in the inlet flow is raised to 0.38 (Fig. 6(c)). In this case the liner pressure first rises to a peak some distance away from the head tip and then decreases again. This happens due to the shift in the stagnation point as the central recirculation is formed adjacent to the dome head. The peak pressure is reached earlier for the ellipsoidal head as the size of the central recirculation is the smallest owing to the smoother profile of the head (Fig. 4).

It is now evident that the small peak with the mild swirl is because of a small central recirculation formed on the liner dome in this case.

3.4 Static pressure recovery

One important attribute of the performance of diffuser in the gas turbine combustor is the static pressure recovery achieved through it. Static pressure recovery coefficient (*Cp*) is defined as,

$$C_p = \frac{[\text{Avg. static pressure at exit}] - [\text{Avg. static pressure at dump inlet}]}{\text{Inlet dynamic pressure}}$$

The pressure recovery takes place following the expansion due to the Bernoullian conversion of kinetic energy. The ideal recovery coefficient considering ideal fluid and no loss of energy can be expressed as,

$$C_{Pideal} = \left[1 - \frac{1}{AR^2}\right], \text{ where, } AR = \frac{A_2}{A_1} = \frac{u_1}{u_2}$$

However, irreversible energy dissipation occurs within the recirculating eddies formed in the flow as well as due to loss in friction, which makes the actual recovery of pressure less than the ideal. An overall effectiveness (η) in recovery, expressed in percentage, may be defined as,

$$\eta = \frac{C_{P_{measured}}}{C_{P_{ideal}}} \times 100$$

The actual static pressure recovery is a function of the size and strength of the recirculation zones occurring in the flow. With the increase in swirl, the actual recovery in static pressure increases (refer Table 1) due to the quick reattachment of flow to the casing wall and reduced size and strength of CRZ. Though a central recirculation zone is present with the presence of swirl, which grows in strength with the inlet swirl level, yet the net energy loss is the minimum with swirl due to formation of smaller CRZ.

The variation in the shape of dome head does not produce much difference in the static pressure recovery and its overall effectiveness as observed in Tables 1 and 2. This is despite the differences observed in the flow features described in the earlier sections. It shows that the irreversible losses occurring in the flow remain nearly the same for all the three types of dome head when a particular swirl level is maintained at the inlet. For example, the size of the corner recirculation zone is the smallest in case of vertical ellipsoidal head with no swirl. However, the velocity of flow past the recirculating vortex is the highest and this induces more intensity to the recirculation. The increased intensity of recirculation compensates its reduced size to result in nearly the same loss in both the cases.

Table 1: Effect of Dome shape and Swirl number on Static Pressure Recovery Coefficient (C_p)

Dome Shape	**Static Pressure Recovery Coefficient**		
	SN=0.0	**SN=0.178**	**SN=0.38**
Hemispherical	23.036	35.527	57.528
Ellipsoidal	22.902	34.486	60.450
Vertical Hemispherical	21.176	37.076	54.428

Table 2: Effect of Dome shape and Swirl number on Overall effectiveness (η)

Dome Shape	**Overall effectiveness (%)**		
	SN=0.0	**SN=0.178**	**SN=0.38**
Hemispherical	23.702	36.554	59.191
Ellipsoidal	23.564	35.485	62.197
Vertical Hemispherical	21.788	38.147	56.001

4. CONCLUSION

The effect of different liner dome shapes on the flow structure and pressure distributions in a dump diffuser and casing-liner annulus has been studied numerically. Static pressure recovery coefficient and its overall effectiveness have been evaluated from the numerical predictions. The following major conclusions can be made:

1. A corner recirculation zone is formed at the dump diffuser, whose size and intensity is dependent on the shape of the dome.

2. However, for the three different domes considered (hemispherical, ellipsoidal and vertical ellipsoidal) the variations in size and intensity of the vortices are so adjusted that the static pressure recovery remains nearly the same.

3. The swirl level in the inlet flow, due to the design of the compressor outlet guide vane, influences the flow and pressure distributions considerably. A central recirculation zone is observed when the inlet swirl level is sufficiently strong. This recirculation directs the flow in a way to reduce the size and intensity of the corner recirculation.

4. The overall effect of the inlet swirl is to increase the recovery in static pressure in the flow. This is because of less irreversible loss in eddies formed in the flow. Higher recovery in static pressure helps in greater energy recovery in the turbine.

5. A nearly uniform pressure distribution is observed on the liner wall particularly with the vertical ellipsoidal dome. This ensures uniform flow distribution through the secondary and dilution hoes located on the wall of the liner.

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NOMENCLATURE

Symbol

A	Cross-sectional area
AR	Cross-sectional Area ratio
C_p	Pressure recovery coefficient
CRZ	corner recirculation zone
CTRZ	central toroidal recirculation zone
D_c	Casing diameter
DG	Non-dimensional dump gap (L_d/D_l)
D_h	Swirler hub diameter
D_l	Liner diameter
D_s	Outer diameter of swirler
L_c	Length of the air casing
L_i	Length of the inlet pipe
P	Static pressure
Pd-in	Dynamic pressure at inlet
Pwc	Casing wall static pressure
Pwl	Liner wall static pressure
Re	Reynolds number ($Uav_{in}\, D_s/\nu$)
SN	swirl number
Uav_{in}	Mass average axial velocity at inlet
X	Axial distance from dump inlet plane
ρ	Density
η	Overall efficiency of pressure recovery

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