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COMPATIBILITY OF 3-D TURNING DIFFUSERS BY MEANS OF VARYING AREA RATIOS AND OUTLET-INLET CONFIGURATIONS

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ABSTRACT

Combined turning and diffusing is often associated with detrimental flow phenomena that contribute to losses induced by the very nature of its geometry. This paper aims to investigate the compatibility of using 3-D turning diffusers in improving pressure recovery and flow uniformity by means of varying area ratios (AR) and outlet-inlet configurations (W_2/W_1, X_2/X_1). There were three cases considered; (i) Case-A (reference): 2-D turning diffuser (AR=2.0, W_2/W_1=2.0, X_2/X_1=1.0), (ii) Case-B: 3-D turning diffuser (AR=2.0, W_2/W_1=1.5, X_2/X_1=1.3) and (iii) Case-C: 3-D turning diffuser (AR=4.0 W_2/W_1=1.5 and X_2/X_1=2.7). Inflow Reynolds Number (Re) approximately of 20 was applied. The experimental rig was set up with the diffuser models fabricated using acrylic. Particle Image Velocimetry (PIV) was used to acquire the velocity profile and visualize the flow structure in the diffusers. Digital manometer with resolution of 0.1Pa provided pressure values. Results show pressure recovery (C_p) of respectively 0.3, 0.1 and 0.5 gained for Case A, B and C. In terms of flow uniformity, standard deviations (σ_u) of 2.04E-03, 3.14E-03 and 2.57E-03 were recorded, respectively. There was a reduction in terms of recovery and uniformity when a 3D turning diffuser with an AR=2.0 was introduced. Whereas, the compatibility of 3-D turning diffuser with an AR=4.0 seems more promising. The results obtained in this study will be used to validate the CFD codes. The intensive CFD simulation by means of varying other geometry configurations in the event of different inflow Reynolds number will be carried out in future.

Keywords: 3-D turning diffuser, flow uniformity, pressure recovery, particle image velocimetry.

INTRODUCTION

There are various types of diffusers which are commonly dictacted by their geometries. Study of the geometry effects to the diffuser performance has been of fundamental interest to researchers in the area of fluid mechanics since decades and it continues growth [1-4]. Basically, the performance of a diffuser is evaluated in terms of pressure recovery and flow uniformity. The main problem in achieving high recovery is the flow separation which results in non-uniform flow distribution and excessive losses.

The performance of a bend-diffuser with an area ratio (AR) of 7.2 that operates under inflow Reynolds number (R_e) less than 100 was investigated by Normayati *et al.*, [5]. To improve the performance of the existing system, turning baffles arrangement suggested by Macbain [6] was applied. There was a promising performance in terms of recovery which was up to 0.5 while having baffles. However, further efforts should be taken to improve the flow uniformity as by using baffles the standard deviation recorded, 2.95E-01, was still large. In addition, this system requires a huge space to be installed, as a bend-duct before diffuser should be introduced sufficiently long to ensure the flow is uniformly distributed [4].

As shown in Figure-1, turning diffusers are more compact to be used and offer massive configurations. This paper characterises a turning diffuser into two geometries, i.e., 2-D turning diffuser and 3-D turning diffuser. The geometeries basically differ in terms of expansion directions and outlet-inlet configurations offered. A 2-D turning diffuser expanses at x-y or z-y direction, whereas for a 3-D turning diffuser the expansion is in all directions. Table-1 shows outlet-inlet configurations samples for 2-D and 3-D turning diffuser of area ratios 2 and 4.

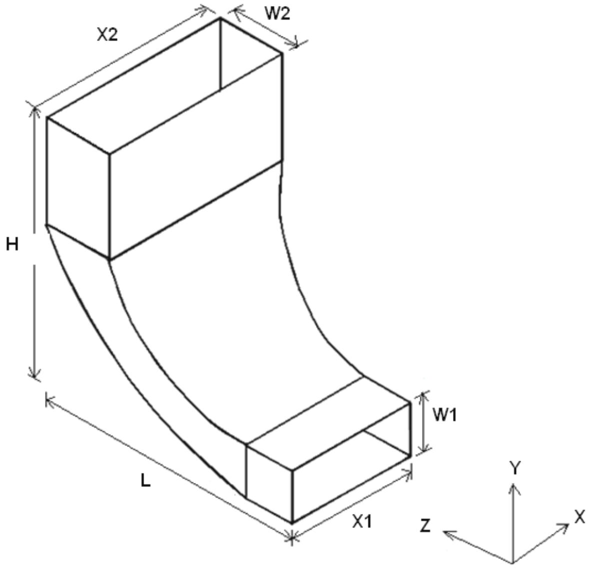


Figure-1. Schematic of the turning diffuser.

Table-1. A sample of outlet-inlet configurations for a 2-D and 3-D turning diffuser of AR=2.0 and AR=4.0.

Area ratio (AR)	Outlet-inlet configuration		Geometries/ expansion direction
	W_2/W_1	X_2/X_1	
2.0	2.000	1.000	2-D/ z-y
	1.800	1.111	3-D /x-y-z
	1.700	1.176	3-D / x-y-z
	1.500	1.333	3-D / x-y-z
	1.400	1.429	3-D / x-y-z
	1.200	1.667	3-D / x-y-z
	1.000	2.000	2-D / x-y
4.0	4.000	1.000	2-D /z-y
	3.700	1.081	3-D / x-y-z
	3.400	1.176	3-D / x-y-z
	2.700	1.481	3-D / x-y-z
	2.400	1.667	3-D / x-y-z
	1.900	2.105	3-D / x-y-z
	1.500	2.667	3-D / x-y-z
	1.000	4.000	2-D / x-y

There is often a compromise between the performance to be achieved and the geometries to be applied while selecting a turning diffuser. For example, due to the design constraint, a 2-D turning diffuser with x-y direction expansion had still been introduced by Nguyen *et al*., [7] for a wind tunnel circuit design application, despite its deficient performance. In fact, there are many applications which adopted not only a 2-D turning diffuser but also a 3-D turning diffuser.

Despite the wide use and promising potential of 3-D turning diffusers, no work has been reported so far focusing on the geometrical effects to the performance of 3-D turning diffusers.

This paper aims to experimentally investigate the compatibility of using 3-D turning diffuser with different configurations in improving pressure recovery and flow uniformity. **Case-A:** a 2-D turning diffuser (AR=2.0, W_2/W_1=2.000 and X_2/X_1=1.000) is to be a reference. Whereas, the performance of **Case-B:** 3-D turning diffusers (AR=2.000, W_2/W_1=1.500 and X_2/X_1=1.333) and **Case-C:** (AR=4.000, W_2/W_1=1.500 and X_2/X_1=2.667) are evaluated in terms of their compatibility to improve recovery (C_p) and uniformity (σ_u).

The system operates at low Reynolds number of approximately 20. The experimental results obtained in this current progress will be used to validate the CFD code before intensive numerical studies could be carried out.

REVIEW OF LITERATURE

Fox and Kline [8] have conducted a parametric study for a 2-D turning diffuser. As shown in Figure-2 the location of the first appreciable stall as a function of geometrical parameters were correlated. There are basically three geometrical parameters often considered for a 2-D turning diffuser namely the inner length to the width ratio (L_{in}/W_1), area ratio (AR) and turning angle (ϕ) [9].

The initial idea of introducing a turning diffuser is to provide flow uniformity and save pumping power requirement. However, this is not easy since the flow within a diffuser is complex and always initiates losses.

Tulapurkara *et al*., [10] have claimed that the flow within a turning diffuser was asymmetric due to the curvature effects. The flow separation often occurs within inner wall section and the core flow tends to deflect to the outer wall section.

The flow field at the turning diffuser outlet is generally not uniform, and pressure losses are usually high. Until recently, the efforts of improving the performance of turning diffusers are still on going and are being a subject for a further investigation [7], [11]. For instance, Chong *et al*., [11] have used passive flow control devices namely vortex generators, screens, honeycomb and guide vanes to improve the performance of 2-D turning diffuser with 90° angle of turn.

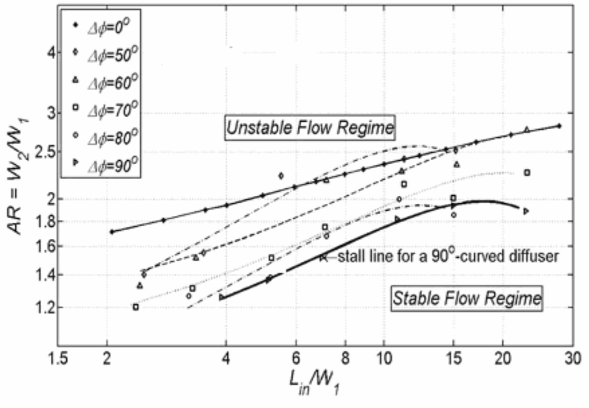


Figure-2. Location of the first appreciable stall (i.e. severe flow separation) as a function of $\Delta\phi$ for circular-arc centerline 2-D turning diffusers [8].

There are significant studies that have been conducted in the area of 2-D turning diffusers. However, there is a lack of work that has been reported so far in the area of 3-D diffusers. 3-D diffusers are often used since they can offer more in terms of design compatibility. Guihui and Saffa [3] for example have considered the 3-D straight diffuser to be used in an air-conditioning system. The study was conducted as to justify the lacking of reliable experimental data relating to 3-D straight diffusers.

El-Askary and Nasr [4] have considered the use of 3-D bend-straight diffuser. This system requires an optimum divergence angles and spacer length which depends on inflow Reynolds number as to ensure the flow is uniformly distributed. However, by doing all these, the energy will be lost due to the skin friction. Besides that, a large installation space is needed to install this system. Thus, a 3-D turning diffuser which is more compact seems to be a more viable option.

METHODOLOGY

The compatibility of turning diffusers in improving pressure recovery and flow uniformity was experimentally investigated. The experiments were conducted in the Aerodynamics Laboratory, Faculty of Mechanical and Manufacturing Engineering, Universiti Tun Hussein Onn Malaysia. Figure-3 shows a simple schematic view of the experimental set up.

The centrifugal blower is used to deliver the airflow of 0.117 m^3/h to the mainstream duct of hydraulic diameter (D_h) 7.2 cm. The duct introduced is of 3.60 m in length, which is sufficiently long to provide fully developed flow at the diffuser entrance. The inflow Reynolds number (Re) applied is approximately 20.

As presented in Table-2, there were three cases considered. Diffuser models were fabricated from acrylic as shown in Figure-4. Compatibility of each case is evaluated in terms of pressure recovery coefficient (C_p) and flow uniformity index (σ_u).

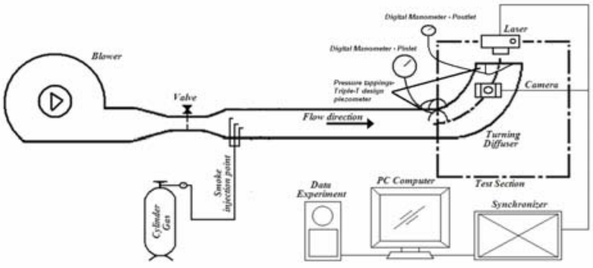


Figure-3. Experimental set up.

Table-2. Tested configurations.

Case	AR	W_2/W_1	X_2/X_1
A (ref)	2.0	2.000	1.000
B	2.0	1.500	1.333
C	4.0	1.500	2.667

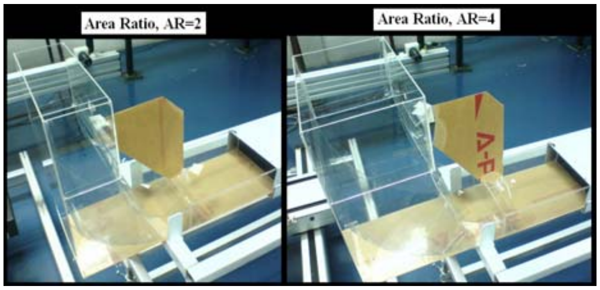


Figure-4. Fabricated turning diffuser from acrylic.

Pressure recovery coefficient (C_p) is given by:

$$Cp = \frac{2(P_{outlet} - P_{inlet})}{\rho V_{inlet}^{2}} \tag{1}$$

where,

P_{outlet} = average static pressure at diffuser outlet (Pa)
P_{inlet} = average static pressure at diffuser inlet (Pa)
ρ = density of air (kg/m^3)
V_{inlet} = inlet air velocity (m/s)

Average static pressures were measured by digital manometer with resolution of 0.1Pa. Four tappings were made at each side of the outlet and inlet diffuser walls and joined to the Triple-T design piezometer. Density taken was 1.176 kg/m^3 by considering the air temperature of 28^oC during the measurement.

In this study, PIV was used to acquire the velocity magnitudes and visualize the flow structure in the diffusers. Several planes were captured using PIV. The planes taken by PIV cannot cover the whole diffuser body, thus it should be captured part by part.

Figure-5 presents the location of planes taken by PIV. The important planes taken were an x-y plane at the inlet cross section to obtain inlet air velocity magnitude, five (5) y-z planes at the outlet control volume to evaluate the flow uniformity and three (3) y-z planes at the diffuser curve to visualize the flow structure.

The flow uniformity was evaluated by calculating standard deviations (σ_u) of outlet velocity. The least of absolute deviation proposes the greatest uniformity of flow. Standard deviation (σ_u) can be expressed as:

$$\sigma_u = \sqrt{\frac{1}{N-1}\sum_{i=1}^{N}(V_i - V_{ave})^{2}} \tag{2}$$

where,

N = number of outlet planes taken
Vi = average outlet velocity for each plane
V_{ave} = average outlet velocity

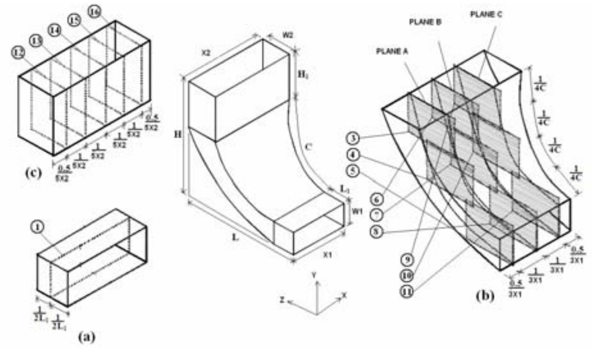


Figure-5. Location of planes taken by PIV (a) x-y plane at inlet cross-section (b) three y-z planes at diffuser curve (c) five y-z planes at the outlet control volume.

Besides that, the performance of turning diffuser can also be described by means the overall loss coefficient (K):

$$K = 1 - Cp \tag{3}$$

RESULTS AND DISCUSSIONS

The compatibility of using 2-D turning diffuser and 3-D turning diffuser in improving pressure recovery and flow uniformity is discussed. There are three cases considered in which each differs in terms of configuration offered (Table-2). The system operates at low Reynolds Number (Re) of approximately 20. There is a maximum expansion of 2.000 introduced at z-direction (W_2/W_1) for *Case A*, while none expansion introduced at x-direction. Having the same area ratio (AR) of 2.0, Case-B offers expansion at both x and z direction, X_2/X_1 = 1.500 and W_2/W_1=1.333, respectively. The effect of area ratio increment is investigated by considering Case-C having a 3-D turning diffuser with an area ratio of AR=4.0.

As shown in Figure-6, while having Case-B pressure recovery drops as much as 67% from 0.3 to 0.1. This is due to the expansion introduced at the inner curve of the diffuser, X_2/X_1 = 1.500. The expansion basically triggers severe separation to happen. Figure-7 (a)-(c) show that the flow structure at the middle plane of Case B diffuser is so deteriorated particularly at the inner wall. There are lots of back-flow and circulations which increase the form drag thus contributes to losses approximately 0.9.

As being expected that the losses increase when the expansion is introduced at the inner wall, i.e., x-direction. However, there is no such a guideline that can be referred proposing the optimum expansion at x-direction (X_2/X_1). Even Nguyen *et al*., [7] due to compatibility had to still install the most affected performance of 180^o turning diffuser with maximum expansion at the inner wall.

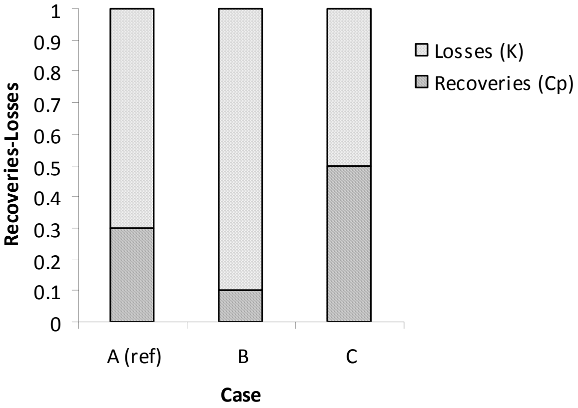
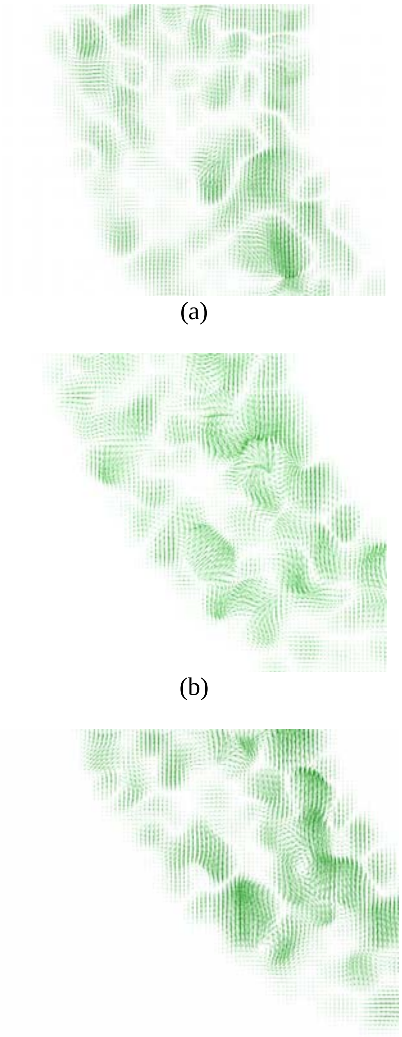


Figure-6. Pressure recovery coefficient (C_p) and losses coefficient (K) for case-A (ref), B and C.



(a)

(b)

(c)

Figure-7. Flow structure at the middle plane of Case-B diffuser (a) top part, (b) center part, (c) bottom part.

There is a significant increase in terms of recovery up to 0.5 while having a 3-D turning diffuser with an area ratio of 4.0, i.e., Case-C. However, the optimum area ratio could not yet be confirmed for a 3-D tuning diffuser until all the geometrical operating parameters are completely considered. Guihui and Saffa [3] have considered area ratios of 1.3 to 7.0 for a 3-D straight diffuser operated at high inflow Reynolds number of 2.1E+05. The area ratio of 1.95 has been suggested by Guihui and Saffa [3] to be an optimum producing recovery up to 0.48.

The flow uniformity is evaluated based on the outlet velocity profile. Standard deviation (σ_u) is calculated where the least of σ_u proposes the best uniformity of flow. As shown in Table-3, the flow uniformity is affected approximately of 3.14E-03 when the expansion is introduced at x-direction as much as $X_2/X_1=1.333$. The flow uniformity improved with 3-D turning diffuser of an area ratio of 4.0, i.e., Case-C. Figure-8 shows the outlet velocity profile for Case-A, B and C at the middle plane of turning diffuser outlet.

It is clear that for a 2-D turning diffuser the recovery and flow uniformity affected by flow separation which happens mainly at the inner wall. As shown in Figure-8, the flow at the diffuser outlet for Case-B and C seem more promising than Case-A. However, consideration of only one plane, i.e., y-z plane, is still not sufficient to judge the overall performance of 3-D turning diffuser. The x-z plane is the most appropriate plane to be captured for representing the flow uniformity at the diffuser outlet.

Table-3. Flow uniformity of each diffuser.

Case	Flow uniformity (σ_u)
A (ref)	2.04 E-03
B	3.14 E-03
C	2.57 E-03

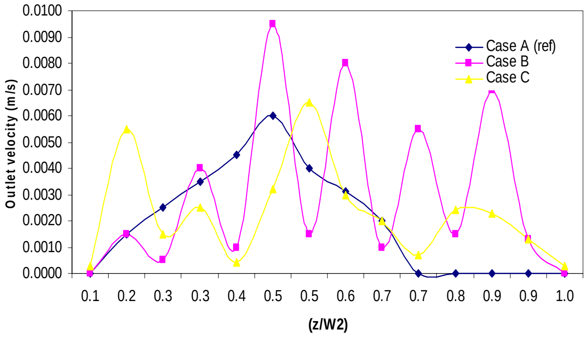
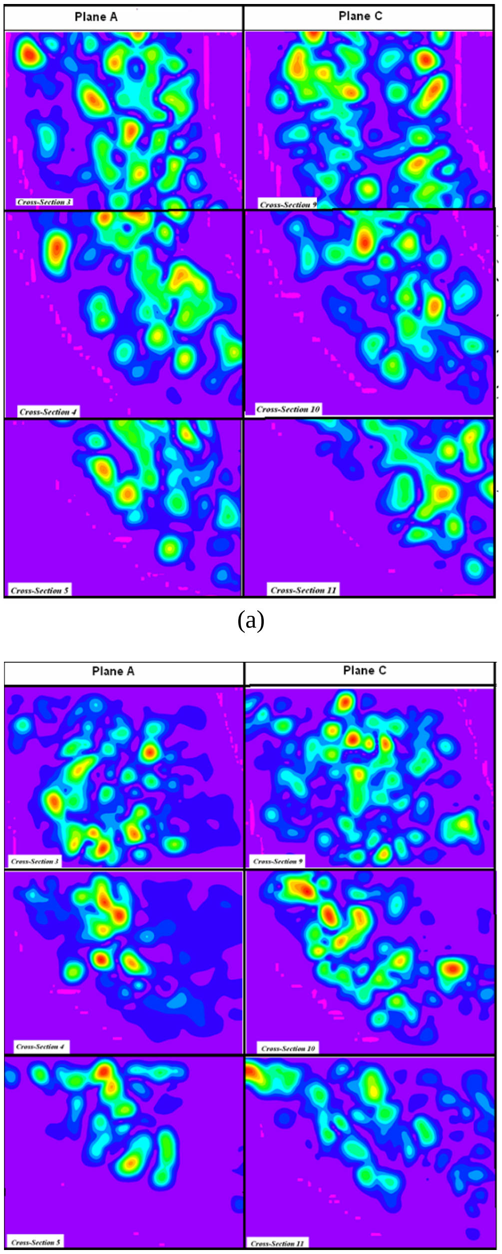


Figure-8. Outlet velocity profile at middle plane of case A, B and C.



(a)

(b)

Figure-9. Flow contour at plane a (left) and C (right) showing asymmetric flow behavior (a) case-B (b) Case-C.

Despite, the symmetrical geometries fabricated, the flow within 3-D turning diffusers is not necessarily symmetry. In fact, as shown in Figure-9, the flow at plane a (left) and C (right) for both Case-B and C is proven asymmetric. Basically, it is important to decide the appropriate planes to be taken by PIV as this can provide the right physical explanation of any results obtained. This is certainly true particularly when a 3-D turning diffuser is considered as the flow in it is much more complex to be judged.

Besides geometries, the operating condition applied also influences the performance of diffuser. Wang *et al*., [12] have focused more on varying inflow Reynolds Number, i.e., 100 to 1000, in order to enhance recovery for a straight diffuser. They proposed that recovery can be improved by means of increasing inflow Reynolds Number.

The future work is to validate the CFD codes using existing results and to vary the effect of other geometrical operating parameters such as AR=1.3 to 7.0, at least ten (10) sets of outlet-inlet configuration (W_2/W_1 and X_2/X_1) and high Reynolds Number (Re) to the recovery and flow uniformity. Several experimental works perhaps will be as well run to justify any inconsistency in the data.

CONCLUSIONS

Due to the advantages offered in terms of compactness and compatibility, a 3-D turning diffuser always becomes a main choice of being an adapter or an ejector in many fluid flow applications. However, there is no scientific or technical guideline so far available which can be referred particularly to choose the best optimum configuration of 3-D turning diffuser. The current work aims to investigate the compatibility of using 3-D turning diffusers in improving pressure recovery and flow uniformity by means of varying area ratios and outlet-inlet configurations in the event of low Reynolds Number.

Results show pressure recovery (C_p) of respectively 0.3, 0.1 and 0.5 gained for Case-A, B and C. In terms of flow uniformity, standard deviations (σ_u) of 2.04E-03, 3.14E-03 and 2.57E-03 were recorded, respectively. There was a reduction in terms of recovery and uniformity when a 3D turning diffuser with an AR=2.0 was introduced. Whereas, the compatibility of 3-D turning diffuser with an AR=4.0 seems more promising.

Results obtained from this study will be used to validate the CFD codes. The intensive CFD studies by means of varying other geometrical operating parameters will be carried out in future leading to more general findings.

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