Experimental Investigation of 2-D Turning Diffuser Performance by Varying Inflow Reynolds Number

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ABSTRACT

A turning diffuser is a kind of adapter used in the fluid flow system to recover surplus energy by converting kinetic energy to pressure energy. Nevertheless, minimal energy is commonly recovered as the flow within turning diffuser is often disrupted due to the nature of its geometry, leading to excessive losses. This paper aims to investigate the performance of 2-D turning diffuser by varying inflow Reynolds number (Re_{in}). The outlet pressure recovery (C_p) and flow uniformity (σ_u) of 2-D turning diffuser with an area ratio of AR=2.16, operated at inflow Reynolds number of Re_{in}= 5.786E+04-1.775E+05 have been experimentally tested. The experimental rig was developed incorporated with several features of low subsonic wind tunnel. This was mainly to produce a perfect fully developed and uniform flow entering diffuser. Particle image velocimetry (PIV) was used to examine the flow quality, and a digital manometer provided the average static pressure at the inlet and outlet of turning diffuser. The best produced pressure recovery of C_p=0.239 was recorded when the system was operated at maximum Re_{in}=1.775E+05. However, the flow uniformity was considerably distorted, σ_u=6.12 with the increase of Re_{in} mainly due to secondary flow separation. A compromise between the maximum permissible pressure recovery and flow uniformity needs to be sought. The results obtained from this study will be in future used to validate the CFD codes. Several other configurations will be tested numerically in order to establish mathematical models.

Keywords- turning diffuser; flow uniformity; pressure recovery; particle image velocimetry (PIV)

1. INTRODUCTION

There are various types of diffusers which are commonly classified by their geometries and applications. Study of the geometric and operating parameters that affect on the diffuser performance has been of fundamental interest to researchers in the area of fluid mechanics since decades and it continues to grow [1]-[14]. The performance of diffuser is evaluated in terms of its 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.

In the present work, the effects of varying inflow Reynolds number (Re_{in}) on 2-D turning diffuser performance are investigated experimentally. A 2-D turning diffuser with 90° angle of turn that expands at z-y direction with an area ratio of AR=2.16 and outlet-inlet configurations of W_2/W_1=2.16 and X_2/X_1=1 is considered (see Fig. 1). The operating condition represented by Re_{in} is varied from 5.786E+04 to 1.775E+05.

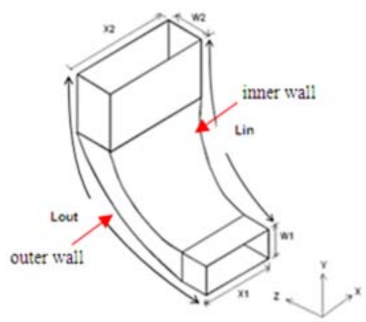


Fig. 1. A geometric layout of 2-D turning turning diffuser with configuration of 90° turning angle, AR=2.16, W_2/W_1=2.16 and X_2/X_1=1

In order to produce a fully developed and uniform flow entering diffuser, the experimental rig is developed to be incorporated with several wind tunnel features. Particle image velocimetry (PIV) is used to examine the flow quality, whereas a digital manometer with resolution of 1Pa provides the inlet and outlet average static pressures.

2. EXPERIMENTAL AND MEASUREMENT SETUP

2.1. Rig Development and Operating Conditions

Fig. 2 shows the experimental rig that was developed incorporated with several features of a low subsonic wind tunnel system such as settling chamber with multiple screens arrangement and contraction cone of 1:6 ratio [10]. As depicted in Fig. 3, the flows entering diffuser at different Re_{in} have been proven to be steady, uniform and perfectly developed.

The mean inlet air velocity (V_{inlet}) was calculated using $V_{inlet}=0.9V_{max}$, with the maximum inlet air velocity (V_{max}) for a fully developed flow occurred at the center diffuser inlet. Average static pressure was measured using a digital manometer with resolution of 1 Pa. Four tappings were made at each side of the outlet and inlet diffuser walls and joined to the Triple-T design piezometer. Table 1 shows the results of V_{inlet}, P_{inlet} and P_{outlet} obtained by varying Re_{in}= 5.786E+04-1.775E+05.

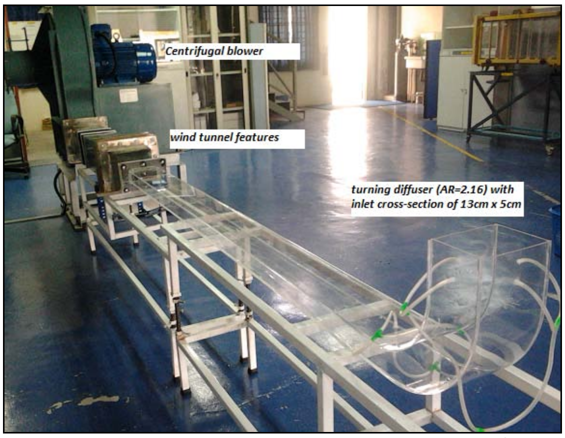


Fig. 2. Experimental rig incorporated with several wind tunnel features, *i.e.* settling chamber with multiple screens arrangement and contraction cone of 1:6 [10]

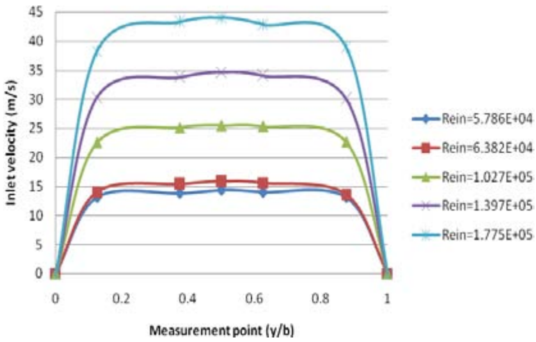


Fig. 3. Flow entering diffuser at different Re_{in} is perfectly developed, uniform and steady [10]

Table 1. Maximum inlet air velocity (V_{max}), mean inlet air velocity (V_{inlet}), inlet (P_{inlet}) and outlet (P_{outlet}) average static pressure

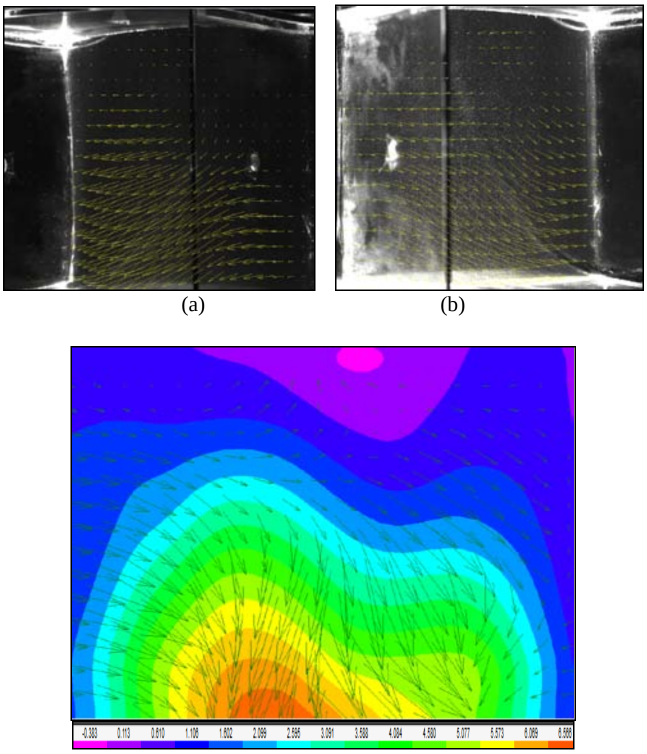
Re_{in}	V_{max} (m/s)	V_{inlet} (m/s)	P_{inlet} (E+05Pa)	P_{outlet} (E+05Pa)
5.786E+04	14.36	12.92	1.013049	1.013235
6.382E+04	15.84	14.25	1.012978	1.013225
1.027E+05	25.48	22.94	1.012429	1.013090
1.397E+05	34.68	31.21	1.011471	1.012725
1.775E+05	44.06	39.66	1.010255	1.012440

2.2. Particle Image Velocimetry (PIV) Setup

The flow quality within turning diffuser was examined using PIV by capturing several planes at the outlet and side of turning diffuser. 3-D stereoscopic PIV was used to obtain the local and mean outlet air velocity, whereas 2-D PIV was applied to visualize the flow structures.

3-D PIV allows the third velocity component, *i.e.* w-component to be determined by correlating the 2-D PIV data obtained by camera 1 and 2, as shown in Fig. 4. Two CCD cameras were mounted according to Scheimpflug rules at 30^{o} angle. The standard calibration target board of 200 mm x 200 mm was used, with the pinhole model adopted. Eurolite smoke fluid with average diameter of 1 µm was used as seeding particles. The laser light was set to be at the thickness of about 20 mm and maximum intensity of 10. The time between pulses (Δt) within the range of 20-90 µs was applied, with 86 numbers of images captured.

The flow structure within turning diffuser, such in Fig. 5 was visualized by applying 2-D PIV setup. Calibration was done by adopting direct linear transform (DLT) model. A CCD camera mounted perpendicular to laser light sheet was used to capture the flow structure images. Images captured were masked in order to get the best covered flow structures within diffuser.



(a) (b) (c)

Fig. 4. The 2-D vectors obtained from (a) camera 1 and (b) camera 2 are used to correlate (c) the third velocity component

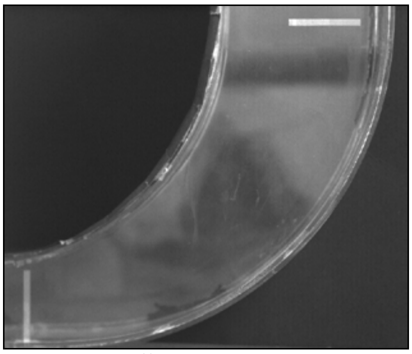


Fig. 5. Flow structure within diffuser was captured by applying 2-D PIV setup

2.3. Performance Parameters

The performance of turning diffuser is evaluated in terms of outlet pressure recovery coefficient (C_p) and flow uniformity index (σ_u). C_p represents the kinetic energy that is converted into pressure energy due to diffusing action,

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

where,

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

The flow uniformity is evaluated by calculating standard deviations (σ_u) of outlet velocity. The least of absolute deviation corresponds to the greatest uniformity of flow. Standard deviation (σ_u) can be expressed as,

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

where,

N= number of measurement points
V_i = local outlet air velocity (m/s)
V_{outlet} = mean outlet air velocity (m/s)

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

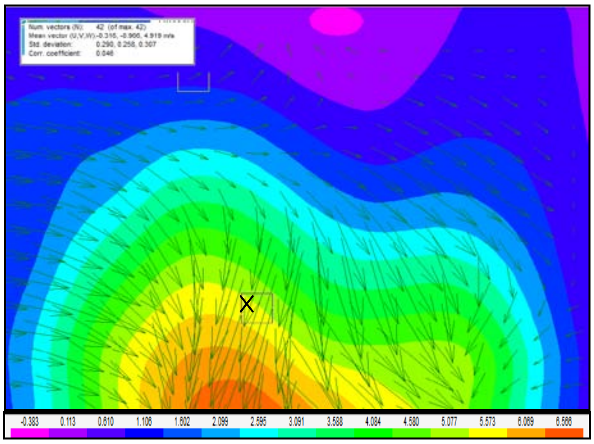
$$K = 1 - Cp \quad (3)$$

3. RESULTS ANALYSIS AND DISCUSSION

3.1. Verification of PIV Results

The results obtained from PIV have to be verified in terms of their accuracy [12]. Velocity magnitudes obtained basically vary to the set value of time between pulses (Δt). In this study, the time between pulses was set in the range of 20-90µs. As illustrated in Fig. 6, the velocity measured using Pitot static probe at one particular point as been marked was compared with the velocity measured using 3-D PIV.

The most appropriate time between pulses should give the least percentage of deviation between PIV and Pitot static probe results as depicted in Table 2.



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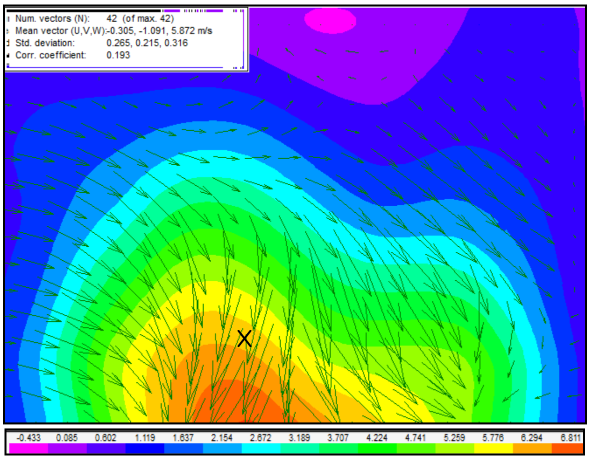

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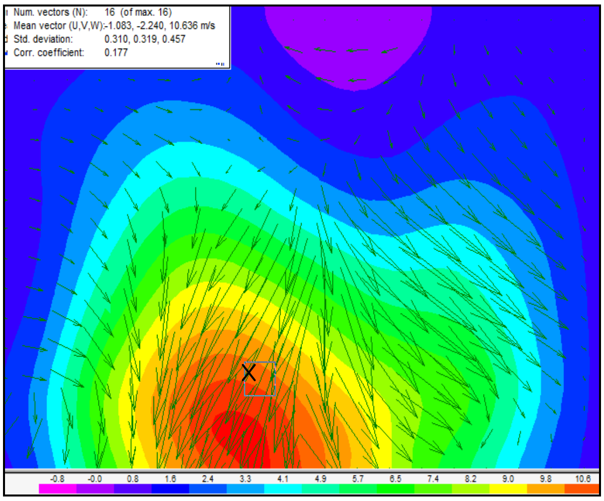

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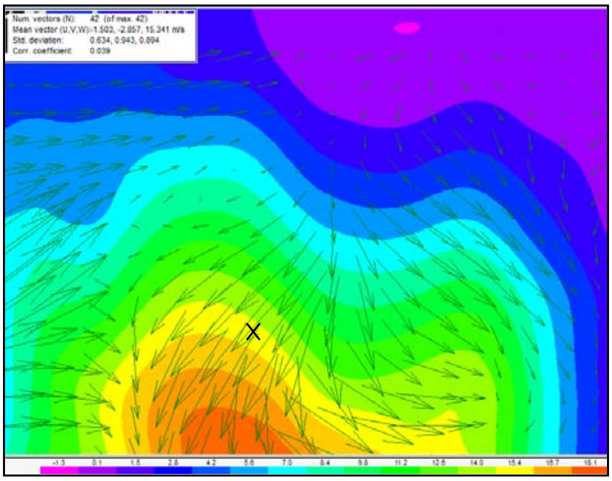

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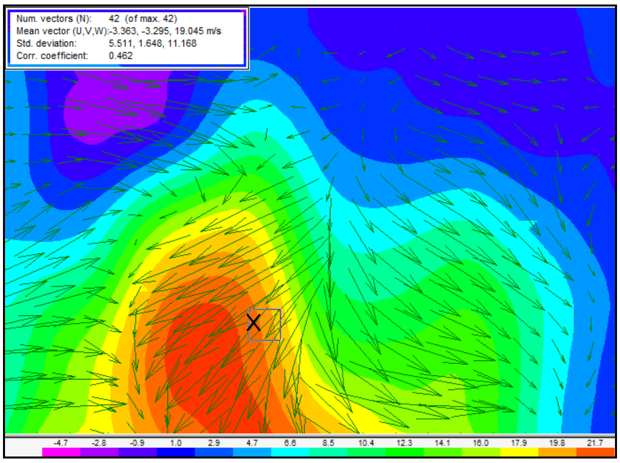

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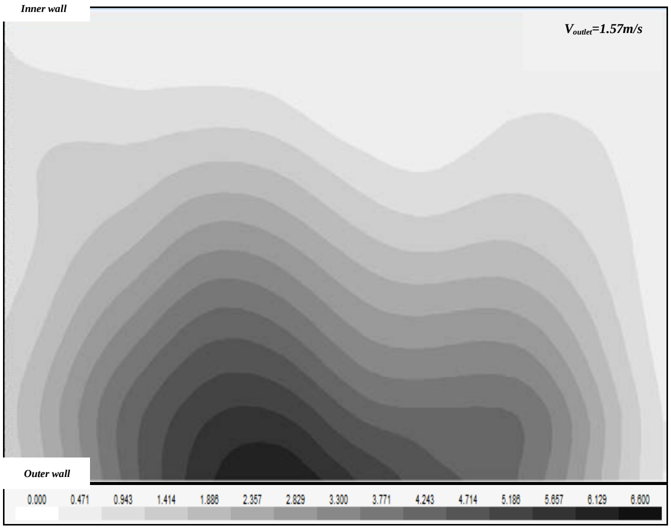
Fig. 6. The third velocity component, w obtained by PIV was compared with the velocity measured using Pitot static probe at one particular point as been marked (a) Re_{in}= 5.786E+04 (b) Re_{in}=6.382E+04 (c) Re_{in}=1.027E+05 (d) Re_{in}= 1.397E+05 (e) Re_{in}=1.775E+05

Table 2. Verification of PIV results

Re_{in}	$w_{pitot\ static}$	w_{piv}	*Deviation (%)*	*The best Δt (μs)*
5.786E+04	4.98	4.92	1.2	70
6.382E+04	5.92	5.87	0.8	70
1.027E+05	11.05	10.64	3.7	50
1.397E+05	15.45	15.34	0.7	30
1.775E+05	19.75	19.05	3.5	20

3.2. Effect of Varying Inflow Reynolds Number on Flow Uniformity

Fig. 7 shows the outlet velocity planes captured by 3-D PIV at different Re_{in}. The mean outlet velocity obtained is within the range of 1.57-5.75 m/s, *i.e.* a reduction of approximately 88% of mean inlet velocity. Rapid flow mostly occurs within the outer wall region. The flow uniformity gets distorted, maximum up to σ_u=6.12 with the increase of Re_{in}.



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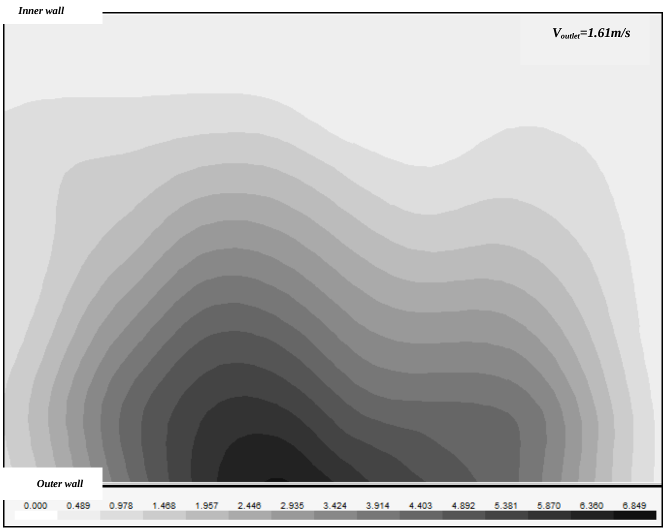

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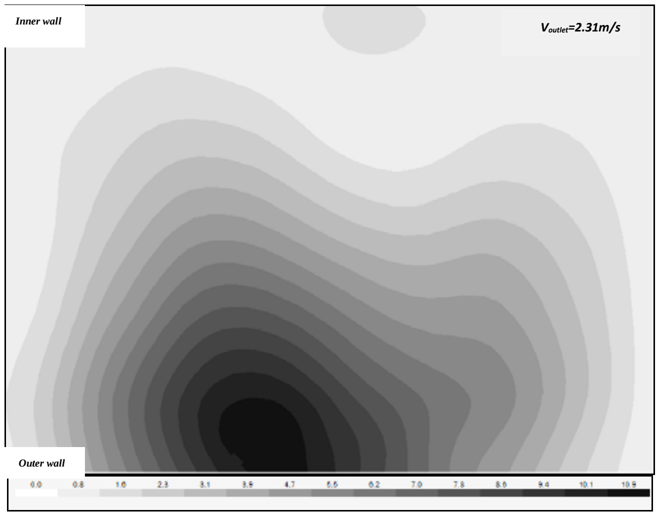

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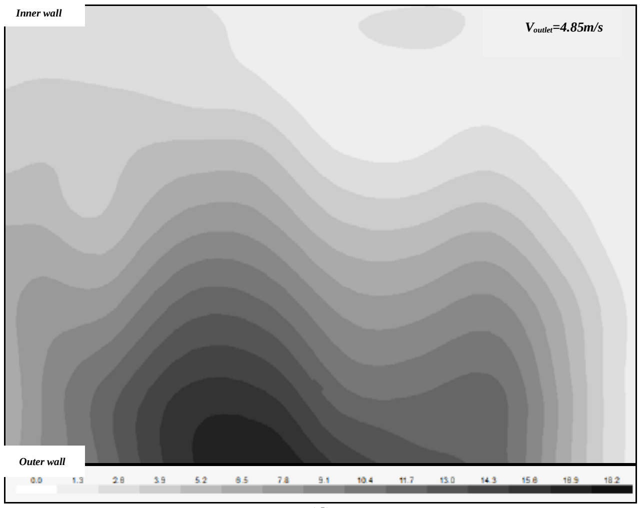

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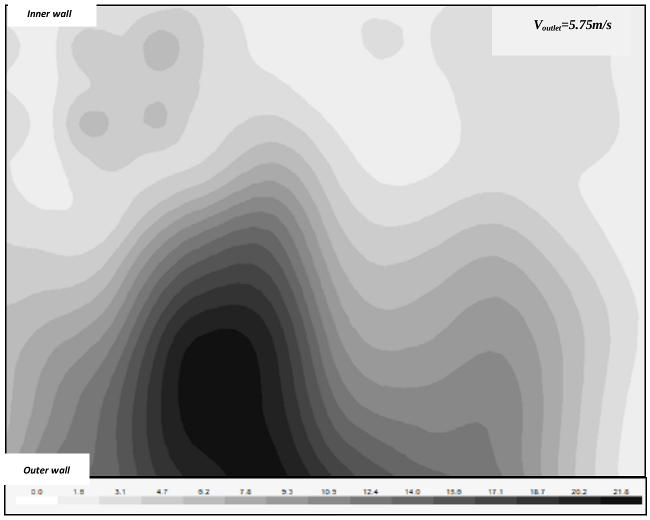

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Fig. 7. The outlet air velocity plane of turning diffuser operated at (a) Re_{in}= 5.786E+04 (b) Re_{in}=6.382E+04 (c) Re_{in}=1.027E+05 (d) Re_{in}= 1.397E+05 (e) Re_{in}=1.775E+05

3.3. Flow Structures within Turning Diffusers

Fig. 8 shows the effect of varying Re_{in} on outlet velocity profiles. The inner wall is subjected to the curvature induced effects, where under a strong adverse pressure gradient, the boundary layer on the inner wall is likely to separate, and the core flow tends to deflect to the outer wall. This eventually leads to the formation of pressure-driven secondary flows that thicken the inner wall boundary layer and makes it susceptible to flow separation as illustrated in Fig. 9.

The flow separation is basically undesirable in many fluid systems as it would increase the pressure drag, decrease the core flow area, reduce the handling stability, generate noise and enhance the structural vibration [7].

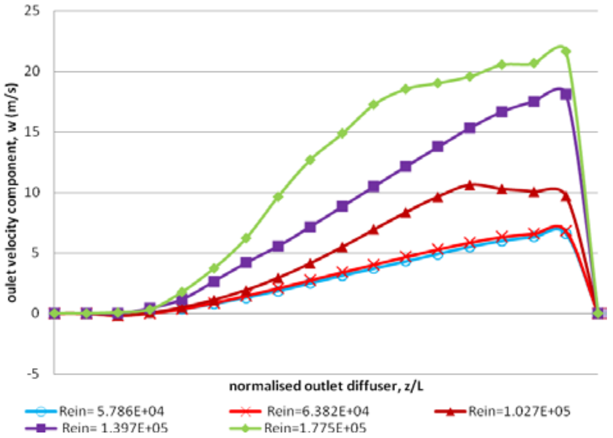
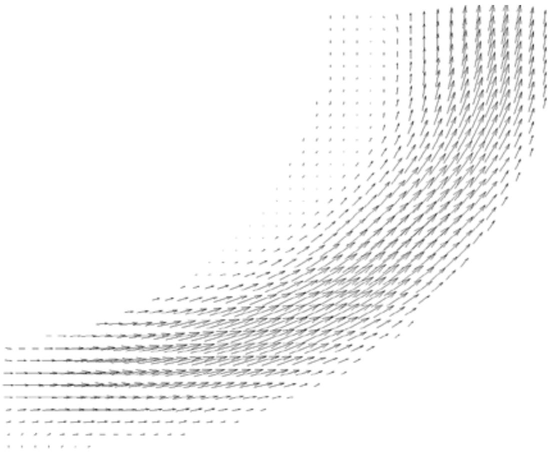


Fig. 8. The effect of varying Re_{in} on outlet velocity profiles



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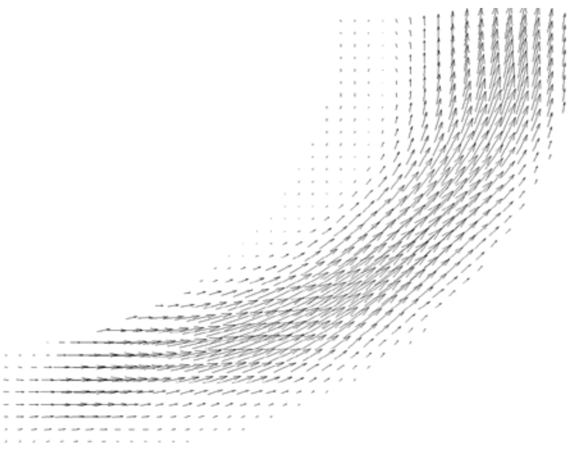

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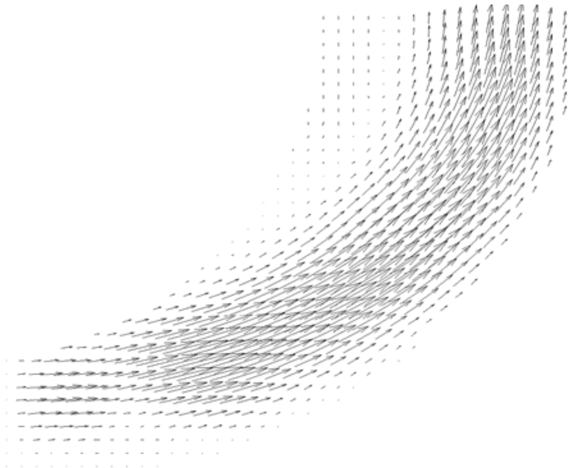

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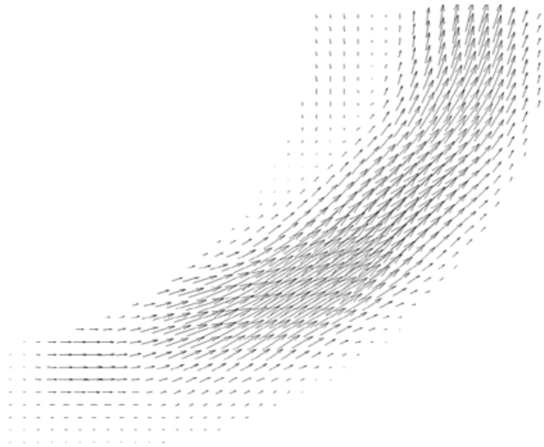

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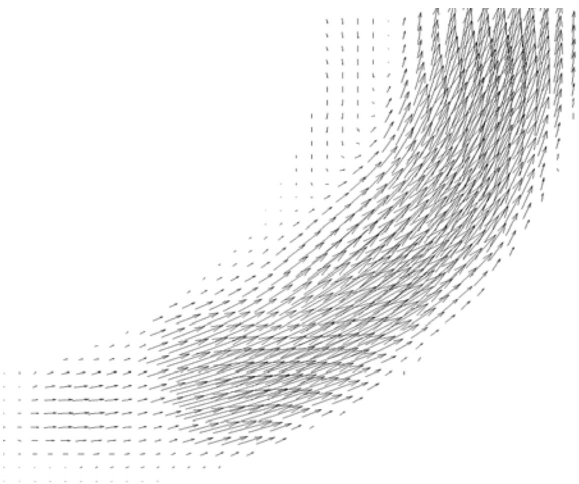

(e)

Fig. 9. Flow structures within turning diffuser operated at (a) Re_{in}= 5.786E+04 (b) Re_{in}=6.382E+04 (c) Re_{in}=1.027E+05 (d) Re_{in}= 1.397E+05 (e) Re_{in}=1.775E+05

3.4. Effect of Varying Inflow Reynolds Number on Outlet Pressure Recovery

Table 3 presents the effect of varying Re_{in} on outlet pressure recovery (C_p). C_p only improves of approximately 25% with the increase of Re_{in} to maximum, 1.775E+05. This is due to the AR that has been introduced rather large for a kind of turning diffuser with 90^o angle of turn. Fox and Kline [1] have suggested that the AR should be introduced within the range of 1.3-2.0 for a turning diffuser with 90^o angle of turn in order to avoid severe flow separation.

However, in certain circumstances due to design constraint the less efficient turning diffuser is still be in use. A compromise between the best produced pressure recovery and the maximum possible flow uniformity has to be sought and this basically answered by the customer needs.

Several other configurations have to be tested in order to equip the data to establish the mathematical model that can be represented as guidance for choosing the optimum turning diffuser performance.

Table 3. The effect of varying Re_{in} on C_p and K

Re_{in}	C_p	K
5.786E+04	0.191	0.809
6.382E+04	0.209	0.791
1.027E+05	0.216	0.784
1.397E+05	0.221	0.779
1.775E+05	0.239	0.761

4.0. Conclusion and Future Directions

In conclusion, the best produced pressure recovery of C_p=0.239 is recorded when the system operated at maximum Re_{in}=1.775E+05. However, the flow uniformity is considerably distorted, σ_u=6.12 with the increase of Re_{in} mainly due to secondary flow separation. Hence, a compromise between the maximum permissible pressure recovery and flow uniformity has to be sought. The results obtained from this study will be in future used to validate the CFD codes. Several other configurations will be tested numerically in order to establish mathematical models.

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