Effect of Varying Inflow Reynolds Number on Pressure Recovery and Flow Uniformity of 3-D Turning Diffuser

Normayati Nordin[1, 2, a], Zainal Ambri Abdul Karim[2,b], Safiah Othman[1,c] and Vijay R. Raghavan[3, d]

[1]Faculty of Mechanical and Manufacturing Engineering, Universiti Tun Hussein Onn Malaysia, Parit Raja, 86400 Batu Pahat, Johor, Malaysia

[2]Department of Mechanical Engineering, Universiti Teknologi PETRONAS, Bandar Seri Iskandar, 31750 Tronoh, Perak, Malaysia

[3]OYL Research & Development Centre, Taman Perindustrian Bukit Rahman Putra, 47000 Sungai Buloh, Selangor, Malaysia

[a]mayati@uthm.edu.my, [b]ambri@petronas.com.my, [c]safiah@uthm.edu.my, [d]vijay@oyl.com.my

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Abstract. Various diffuser types characterized by the geometry are introduced in the flow line to recover the energy. A 3-D turning diffuser is a type of diffuser that its cross-section diffuses in all 3 directions of axes, i.e. x, y and z. In terms of applicability, a 3-D turning diffuser offers compactness and more outlet-inlet configurations over a 2-D turning diffuser. However, the flow within a 3-D turning diffuser is expected to be more complex which susceptible to excessive losses. As yet there is no established guideline that can be referred to choose a 3-D turning diffuser with an optimum performance. This paper aims to investigate the effects of varying inflow Reynolds number (Re_{in}) on the performance of 3-D turning diffuser with 90^o angle of turn. The outlet pressure recovery (C_p) and flow uniformity (σ_u) of 3-D turning diffuser with an area ratio (AR=2.16) and outlet-inlet configurations (W_2/W_1=1.44, X_2/X_1=1.5), 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 of the inlet and outlet of turning diffuser. There is a promising improvement in terms of flow uniformity when a 3-D turning diffuser is used instead of a 2-D turning diffuser with the same AR. An unexpected trend found with a drop of pressure recovery at maximum operating condition of Re_{in}=1.775E+05 shall require further investigations. The results obtained from this study will be in future used to validate the numerical codes. Upon successful validation, several other configurations will be numerically tested in order to establish the guidelines in the form of mathematical models.

Introduction

There are various types of diffusers which are commonly classified by their geometries and applications. In the circulating fluidised bed (CFB) system, a diffuser is installed to assemble the lower and upper part of riser which are at different cross-section. In the air conditioning system, a diffuser with free discharge is used as an outlet, discharging the conditioned air to the atmosphere. While, in the air craft application, diffusers are installed to convert kinetic energy into pressure energy. A turning diffuser is a kind of diffuser introduced as an adaptor or ejector in the flow line to recover the energy. It is characterised by its expansion direction into two, a 2-D and 3-D turning diffuser. A 3-D turning diffuser diffuses its cross-section in all axes directions, i.e. x, y and z. In terms of applicability, a 3-D turning diffuser offers compactness and more outlet-inlet configurations over a 2-D turning diffuser [1, 2].

Study the effect of geometric and operating parameters on the diffuser performance has been of fundamental interest to researchers in the area of fluid mechanics since decades and it continues to grow [1-15]. However, the guideline to choose the optimum 3-D turning diffuser has not yet been available reported. In the present work, the effects of varying inflow Reynolds number (Re_{in}) on 3-D turning diffuser performance are investigated experimentally. A 3-D turning diffuser with 90^o

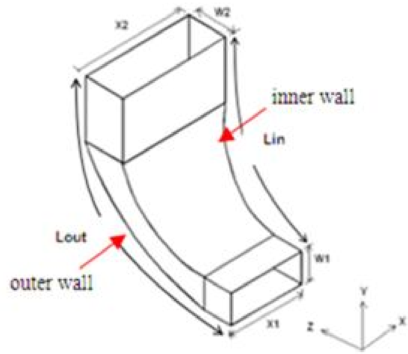

Fig. 1. A geometric layout of 3-D turning diffuser with configuration of 90^o turning angle, AR=2.16, W_2/W_1=1.44 and X_2/X_1=1.5

angle of turn, an area ratio of AR=2.16 and outlet-inlet configurations of W_2/W_1=1.44 and X_2/X_1=1.5 is considered (see Fig. 1). The operating condition represented by Re_{in} is varied from 5.786E+04 to 1.775E+05. 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.

Experimental and Measurement Setup

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 [12]. 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.

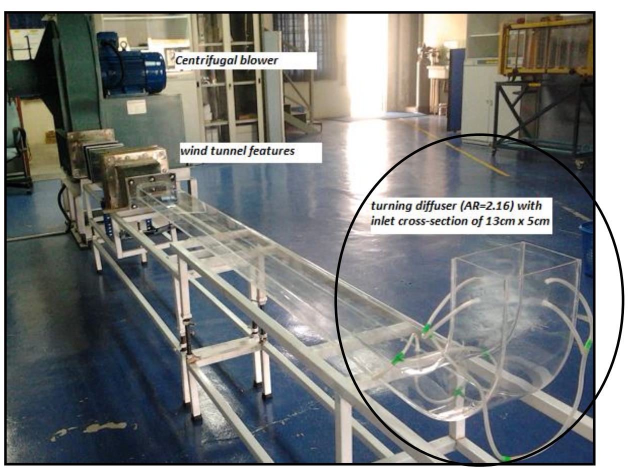

Fig. 2. Experimental rig incorporated with several wind tunnel features, *i.e.* settling chamber with multiple screens arrangement and contraction cone of 1:6 [12]

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	1.012916	1.013120
6.382E+04	15.84	14.25	1.012844	1.013101
1.027E+05	25.48	22.94	1.012431	1.013053
1.397E+05	34.68	31.21	1.011645	1.012886
1.775E+05	44.06	39.66	1.010955	1.012732

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. 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 30-90 µs was applied, with 86 numbers of images captured. The flow structure within turning diffuser, 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 the diffuser.

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,

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

where,

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

P_{inlet} = average static pressure at diffuser inlet (Pa) 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,

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

where,

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

V_i = local outlet air velocity (m/s)

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

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

Results Analysis and Discussion

Verification of PIV Results. The PIV results have to be verified in terms of their accuracy by comparing them with the results obtained using more reliable instrument, pitot static probe [14].Velocity magnitudes obtained by PIV basically vary to the set value of time between pulses (Δt). In this study, the time between pulses was set in the range of 30-90µs. 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.

Table 2. Verification of PIV results

Re_{in}	$w_{pitot\ static}$	w_{piv}	*Deviation (%)*	The best Δt (μs)
5.786E+04	4.13	4.02	2.7	90
6.382E+04	5.18	5.18	0.0	90
1.027E+05	9.38	8.76	6.6	70
1.397E+05	12.76	12.37	3.1	50
1.775E+05	15.90	15.36	3.4	30

Effect of Varying Inflow Reynolds Number on Flow Uniformity. Fig. 3 shows the outlet velocity planes captured by 3-D PIV at different Re_{in}. The mean outlet velocity obtained is within the range of 2.07-5.95 m/s. Rapid flow mostly occurs within the outer wall region. The flow uniformity gets distorted, maximum up to σ_u=5.05 with the increase of Re_{in}. The flow uniformity improves approximately of 17% when a 3-D turning diffuser is used instead of a 2-D turning diffuser with the same AR [2].

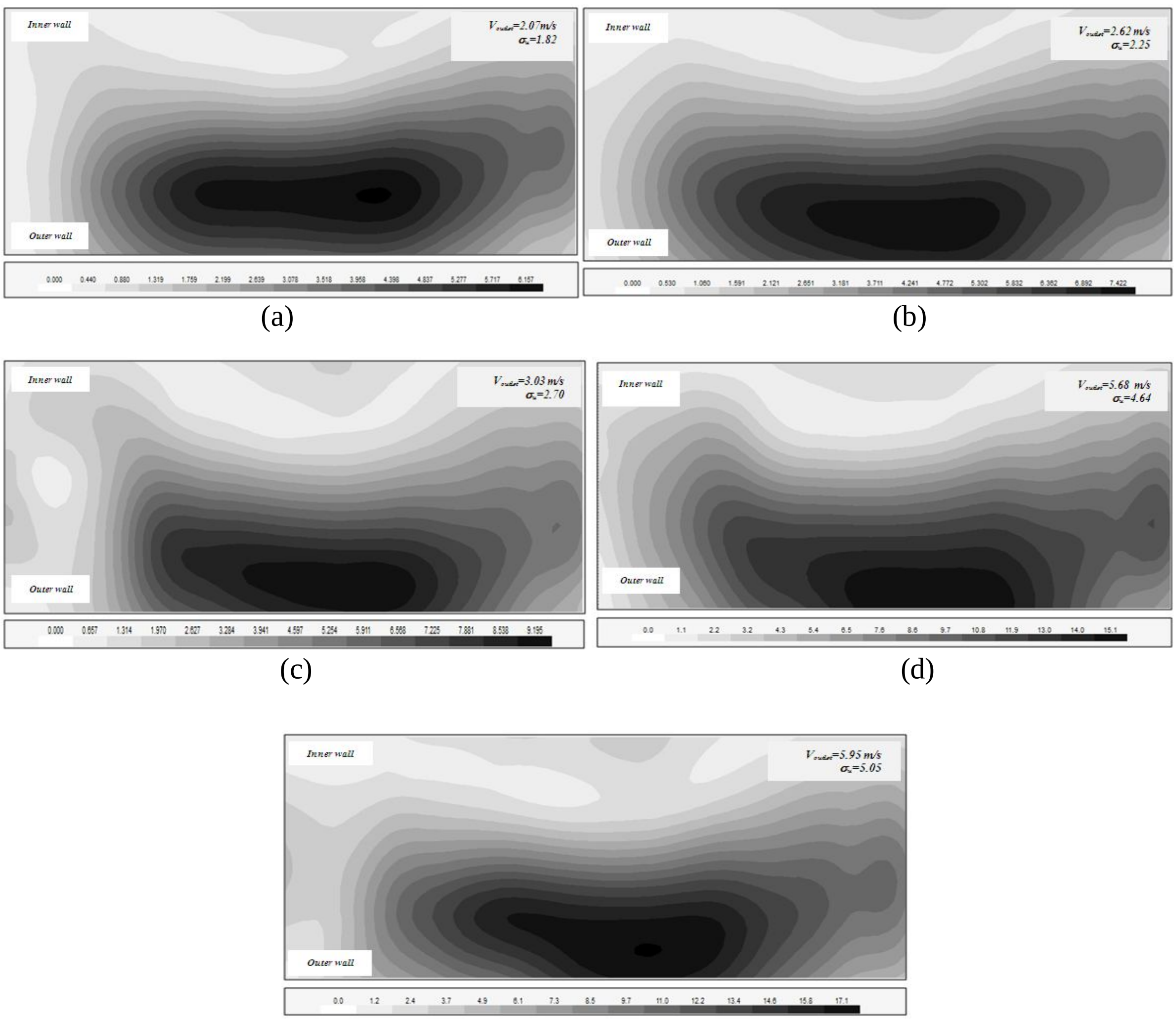

Fig. 3. The outlet air velocity plane of turning diffuser operated at (a) Re_{in}= 5.786E+04 (b) Re_{in}=6.382E+04 (c) Re_{in}=1.027E+05 (d) Re_{in}= 1.397E+05 (e) Re_{in}=1.775E+05

Flow Structures within Turning Diffuser. Fig. 4 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. 5.

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 [9].

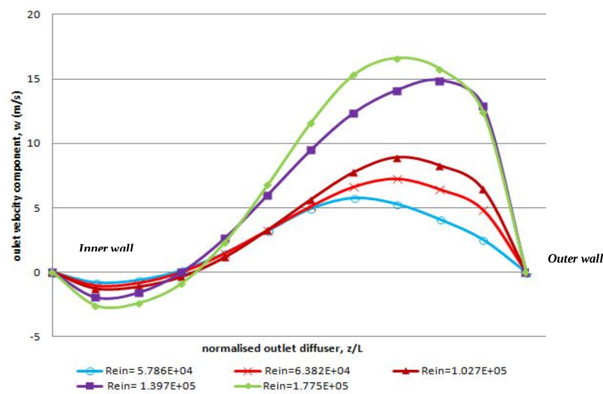

Fig. 4. The effect of varying Re_{in} on outlet velocity profiles

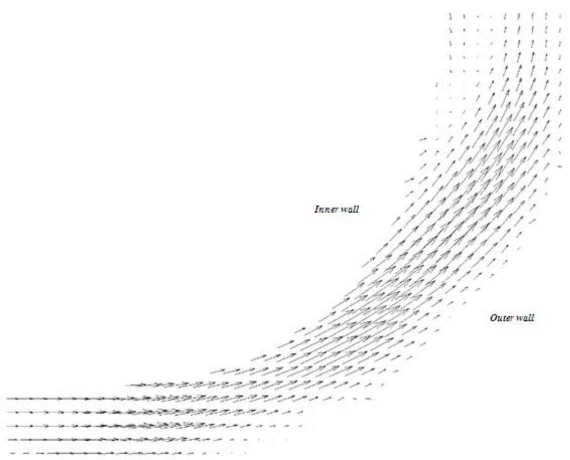

Fig. 5. Flow structures within turning diffuser operated at maximum Re_{in}=1.775E+05

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=0.219 is the maximum while diffuser operated at Re_{in}=1.397E+05. There is an unexpected trend where the recovery at maximum Re_{in} at sudden drops to 0.194. As the study of 3-D tuning diffuser is considered novel, further investigation should be carried out to really comprehend the trend.

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

Re_{in}	C_p	K
5.786E+04	0.210	0.790
6.382E+04	0.217	0.783
1.027E+05	0.203	0.797
1.397E+05	0.219	0.781
1.775E+05	0.194	0.806

Conclusion & Future Directions

In conclusion, there is a promising improvement in terms of flow uniformity when a 3-D turning diffuser is used instead of a 2-D turning diffuser with the same AR. An unexpected trend with a drop of pressure recovery at maximum operating condition of Re_{in}=1.775E+05 shall require further investigation, as the study of 3-D turning diffuser is considered novel. The results obtained from the experimentation will be in future used to validate the numerical codes. Upon successful validation, several other configurations will be tested numerically in order to establish mathematical models.

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