Pressure recovery performance of 2-D turning diffuser by varying area ratios and inflow Reynolds numbers

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Abstract. The paper aims to investigate the effects of varying area ratio, $AR = 1.2$ and $4.0$ and inflow Reynolds number, $Re_{in} = 5.478 \times 10^4 - 1.547 \times 10^5$ on the performance of $90^\circ$ two-dimensional turning diffuser. The optimum configuration area ratio and $Re_{in}$ to produce good pressure recovery is determined. The rig was developed to produce fully developed entrance flow by adopting arrangement of mesh net and sufficient hydrodynamic entrance length, $L_{h} a_{n} = 28 D_{o}$. Digital manometer was used to measure the inlet and outlet static pressures and Particle Image Velocimetry (PIV) to visualize the flow structure. The present results were compared with empirical solution of Asymptotic Computational Fluid Dynamics (ACFD) results to give acceptable deviation of $\pm 7.4\%$. The $AR=4.0$ produces pressure recovery $20\%$ more than $AR=1.2$ when applied low $Re_{in}<1.40 \times 10^5$. However, it is subjected to severe flow separation and circulation at $Re_{in}>1.40 \times 10^5$ that considerably disturbs the recovery. Therefore, turning diffuser of $AR=1.2$ is optimum applied for high $Re_{in}>1.40 \times 10^5$.

1. Introduction
Diffuser is a common engineering device which has the simplest design of an expanding area in the flow direction. It is applied widely in applications such as heating, ventilation and air conditioning (HVAC), wind-tunnel, gas turbine cycle and aircraft engine as an adapter to join the conduits of different cross-sectional areas or an ejector to decelerate the flow and raise the static pressure before discharging to the atmosphere. Diffuser is also be used to suck more water from a standard spigot which has a great impact in the overall performance of the system. There would be losses whenever a diffuser is interrupted by the inclusion of pipe fitting such as bend [1] and it is all dependent on the geometrical and operating parameters applied.

Fox and Kline [2] have suggested that the area ratio (AR) of a sharp $90^\circ$ turning diffuser should be within 1.2-2.0 in order to avoid severe stall. The stall is undesirable as it would decrease the core flow area, induce the presence of secondary flow vortices, increase the form drag and ultimately affect the pressure recovery [3 - 5]. Since early 1980s, the variation of operating conditions, $Re_{in}$ have been taken into consideration to affect the performance of diffusers such as $55^\circ$ 2-D turning diffuser ($Re_{in} = 7.8 \times 10^3 - 1.29 \times 10^6$) [6], annular diffuser ($Re_{in} = 6.0 \times 10^3 - 6.0 \times 10^5$) [7] and combined $90^\circ$ bend diffuser ($Re_{in} = 8.8 \times 10^4 - 1.94 \times 10^5$) [1]. Nordin [8] has recently established an empirical correlation integrating the effects of both geometrical and operating parameters on the performance of
90° 2-D turning diffusers using Asymptotic Computational Fluid Dynamics (ACFD) technique. This correlation will be used to verify the current work:

\[
C_{p_{ACFD}} = 0.200 + \left( \left( \frac{Re_{in}}{Re_{in\,ref}} \right)^2 - 1 \right) 0.0059 - \left( \left( \frac{L_{in}/W_1}{L_{in}/W_{1\,ref}} \right)^2 - 1 \right) 0.6569 - \left( \left( \frac{W_2/W_1}{W_2/W_{1\,ref}} \right)^3 - 1 \right) 0.0288
\]

where,

- \(C_{p_{ACFD}}\) = Outlet pressure recovery from ACFD
- \(Re_{in}\) = Inflow Reynold number
- \(L_{in}\) = Inner wall length (m)
- \(W_1\) = Inlet width (m)
- \(W_2\) = Outlet width (m)
- \(Re_{in\,ref}\) = 6.382 x 10^4
- \(L_{in}/W_{1\,ref} = 4.37\)
- \(W_2/W_{1\,ref} = 2.16\)

Upon verification, the effect of varying AR = 1.2 and 4.0 and \(Re_{in} = 5.478 \times 10^4\)-\(1.547 \times 10^5\) on the pressure recovery of 90° 2-D turning diffuser will be discussed and the optimum configuration to produce good pressure recovery will be decided.

2. Methodology

2.1. Design and development of rig

The experimental rig as shown in Figure 1 was designed to incorporate flow treatment consisting of an arrangement of mesh net and sufficient hydrodynamic entrance length, \(L_{h,turb} = 28D_h\) [9]. The turning diffusers of AR 1.2 and 4.0 with identical inlet dimension were designed to follow Chong et al. [5] procedures and fabricated from acrylic of 1.2 mm thickness (Figure 2). The rig was proven to produce fully developed entrance flow at specified \(Re_{in}\) as depicted in Figure 3.
Figure 2. 90° 2-D turning diffuser (a) AR=1.2 (b) AR=4.0

Figure 3. Fully developed entrance flow at specified Re_in = 5.478 x 10^4 - 1.547 x 10^5 (9 – 25 RPM)

2.2. Measurement parameters and setup
Pressure recovery coefficient, $C_p$ was used to evaluate the performance of turning diffusers. Equation (2) was applied in the present work to find the value of $C_p$. The outlet, $P_{out}$ and inlet, $P_{in}$ static pressures were measured using a digital manometer of resolution 0.1 Pa connected to pressure tappings as shown in Figure 4. In addition, the mean inlet velocity ($V_{inlet}$) was calculated using one-seventh power law velocity, with the maximum inlet velocity ($V_{max}$) measured using air flow meter at the center diffuser inlet [4].

$$C_p = \frac{2(P_{out} - P_{in})}{\rho V_{in}^2}$$

(2)

where,

$P_{out} = $ outlet average static pressure (Pa)
$P_{in} = $ inlet average static pressure (Pa)
$\rho = $ air density (kg/m$^3$)
$V_{in}$ = mean inlet air velocity (0.817$V_{max}$, m/s)
Figure 4. Average inlet ($P_{in}$) and outlet ($P_{out}$) static pressure measurement

Figure 5. PIV setup

Particle image velocimetry (PIV) was used to visualize the flow structure within centre longitudinal section of turning diffuser. Following is the PIV measurement procedures:

1. The camera was arranged to be perpendicular to the target plane as illustrated in Figure 5.
2. The calibration was performed by adopting IMF: DLT.
3. The laser was calibrated to get better aligned to the target plane with thickness of 2mm.
4. The blower was set to speed of 9 RPM. Seeding particle was then injected to the blower.
5. Measurements were taken after the seeding particle and air completely mixed.
6. The camera was in double frame mode and the optimum time between pulses was applied.
7. The images obtained were analyzed using cross correlation technique and the bad vectors were masked.
8. Steps 4 – 8 were repeated by increasing the blower speed to 10, 15, 20 and 25 RPM.

3. Results analysis and discussion
The results obtained by present work were compared with ACFD results calculated using Equation (1) [8]. As depicted in Table 1, there is relatively huge deviation in the case of AR=1.2 of average 19.1% as the ACFD correlation applied was not specifically developed to solve small AR of less than 2.16 [8]. On the other hand, the present and ACFD results for AR=4.0 satisfy each other well with deviation of 7.4%.
Table 1. Comparison of present work with ACFD solution

| \( Re_{in} \) | \( AR=1.2 \) | \( AR=4.0 \) |
|----------------|-----------------|-----------------|
|                | \( C_p \) present work | \( C_p \) ACFD | Dev (%) | \( C_p \) present work | \( C_p \) ACFD | Dev (%) |
| 5.478x10^4    | 0.295            | 0.296            | 0.3     | 0.354            | 0.321            | 9.3 |
| 6.072x10^4    | 0.298            | 0.306            | 2.6     | 0.359            | 0.322            | 10.3 |
| 8.974x10^4    | 0.296            | 0.369            | 19.8    | 0.357            | 0.328            | 8.1 |
| 1.174x10^5    | 0.305            | 0.453            | 32.7    | 0.351            | 0.337            | 3.9 |
| 1.547x10^5    | 0.360            | 0.599            | 39.9    | 0.332            | 0.351            | 5.4 |

Figure 6 shows the effects of varying AR and \( Re_{in} \) on \( C_p \). The \( C_p \) increases with the increase of \( Re_{in} \) for \( AR=1.2 \) to maximum recovery of 0.360 at \( Re_{in}=1.547 \times 10^5 \). Although producing higher recovery than \( AR=1.2 \), \( AR=4.0 \) shows an opposite trend of reducing \( C_p \) while increasing the \( Re_{in} \). In fact, the \( C_p \) of \( AR=4.0 \) is considerably affected to produce \( C_p \) less than \( AR=1.2 \) at maximum \( Re_{in} \). This is due to unstable flow happen within the turning diffuser as marked in Figure 7.

![Figure 6](image)

**Figure 6.** Effect of varying AR and \( Re_{in} \) on outlet pressure recovery

![Figure 7](image)

**Figure 7.** Flow structure of AR=4.0 at \( Re_{in}=1.547 \times 10^5 \)
The flow near to the inner wall (Region A) is subjected to curvature induced effect, where under a strong adverse pressure gradient the flow tend to detach from the wall and deflect towards the outer wall. Consequently, reverse backflow is formed to produce flow vortices as seen in Region B and C. The flow separation and vortices cause form drag that ultimately disturbs the £p.

Overall, it is promising to apply 90° 2-D turning diffuser of AR=4.0 when Re_in < 1.40 x 10^5 is applied, to give the optimum recovery 20% more than the AR=1.2. On the other hand, when Re_in > 1.40 x 10^5, the AR=1.2 should be opted as the AR=4.0 is subjected to highly distorted flow that inherently affects the overall performance of 90° 2-D turning diffuser.

4. Conclusion
In conclusion, the current work manages to investigate the effects of varying AR and Re_in on £p of 90° 2-D turning diffuser. The £p increases with the increase of Re_in for AR=1.2 while otherwise happens in the case of AR=4.0. In order to get optimum pressure recovery it is promising to apply 90° 2-D turning diffuser of AR=1.2 for high Re_in > 1.40 x 10^5 and AR=4.0 for low Re_in < 1.40 x 10^5.

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