Experimental Study on the Effect of Guide Vane Insertion and Reynolds Numbers on the Flow Pressure Drop in a 90º Rectangular Elbow

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Abstract: Flow features in circular elbows have been available in many literatures. These include flow pressure drop, secondary flow, as well as velocity distribution at a particular cross section. The availability of the information of flow characteristics in a rectangular elbow, however, is very limited. Pressure loss in an elbow is caused by friction as well as flow separation and secondary flow. One method to reduce pressure loss due to flow separation and secondary flow in a 90º elbow is by insertion of guide vanes. On the contrary, the insertion of the guide vanes increases the friction loss due to the augmentation of the solid surface contacts with the flow. Therefore, this study is intended to examine flow phenomenon in a 90º elbow and to investigate the effect of insertion of a guide vane on pressure loss.

Test section used in this study is a 90º elbow with rectangular cross section and radius ratio ($R_m/D_h$) equals to 1.875, with and without guide vanes. The geometry of cross section is 5 cm width and 10 cm height. The number of guide vanes are one, two, and three. Air is drawn into the test section using blowers after passed through honey comb and contraction area. Flow Reynolds numbers are set to be $Re_{D_h} \approx 2.1 \times 10^4$, $8.4 \times 10^4$ and $12 \times 10^4$ based on inlet freestream velocity ($U_\infty$) and test section hydraulic radius ($D_h$). Measured variables are stagnation and static pressures. The stagnation pressure was measured using a Pitot tube, while the static pressure was measured using wall static taps connected to inclined manometers.

The experimental results show a reduction in pressure drop for insertion one, two, or three guide vanes at $Re_{D_h} \approx 2.1 \times 10^4$. On the contrary, the insertion of guide vanes at $Re_{D_h} \approx 8.4 \times 10^4$ and $12 \times 10^4$ increases the pressure drop. Secondary flows (vortex flows) at the duct corners are clearly seen from smoke flow visualization.

Keywords: 90º Rectangular elbow, guide vane, pressure drop, secondary flow.

1. Introduction

Piping system plays an important role in industrial processes such as electrical power generation, marine system, and oil companies. 90º elbows are elements of piping system that contribute significantly in fluid pressure drop. The pressure drop in an elbow is larger than that in a straight pipe with equivalent in length. The pressure drop in the elbow is contributed by twofolds: frictional loss and separation loss. The increase in pressure drop is directly related to the pump, fan, blower, and compressor power consumption. Therefore, an effort for pressure drop reduction is a need for improving system efficiency.

Flow separation in an elbow contributes significantly in the increase in flow pressure drop. As the fluid flows through the 90º elbow, it separates at two regions: at the inner and the outer radius of the elbow. At the outer radius, the flow separation is due to inability of the flow to overcome an adverse pressure gradient developing at the outer radius of the elbow. At the same time, the flow separation also occurs at the near end of the inner radius of the 90º elbow. The concurrence of flow separation at the outer and the inner radius of the elbow results in the flow acceleration at the middle part of the elbow. This flow acceleration has an additional effect on the flow pressure drop.

As the fluid flows through an elbow, there will be a built-up of differential pressure between the outer and the inner radius due to the centrifugal effect. The higher fluid pressure at the outer radius than that at the inner radius pushes
the fluid particles from the outer to the inner radius. Simultaneously, the mainstream flow drag the fluid particles in the streamwise direction resulting in streamwise vortex flows in the elbow. This streamwise vortex flows result in such a blockage effect on the main flow. Finally, this blockage effect has a significant contribution to the total flow pressure drop in the 90° elbow. Kim and Patel [1], Cheng [2], and Marn and Primoz [3] have shown such as phenomena in their studies.

One method that can be used to reduce the pressure drop through an elbow is an insertion or addition of guide vanes. The insertion of guide vanes is intended to minimize the flow separation effect in the elbow walls. In addition, the presence of the guide vanes allows the fluid flows more smoothly follow the elbow walls. It is also expected that by the guide vanes insertion, the possibility of the formation of secondary flow in the elbow can be suppressed. It was shown in the study of Liou and Lee [4] that the addition of one guide vane in a 60° elbow can eliminate the back flow in the elbow. Next, Danbon and Soliec [5] reported that the velocity profiles are significantly distorted due to the presence of the elbow, and the velocity profiles relax back after approximately 8D downstream of the elbow. So far, there is no complete study of the effect of guide vanes insertion in a 90° rectangular elbow. Therefore, present study is focused on the effect of guide vanes insertion in a 90° rectangular elbow at various Reynolds numbers. Flow parameters that are studied include pressure drop, mean velocity profiles, and flow structure obtained from smoke visualization.

2. Experimental Details

Experiment was conducted in Fluid Mechanics Laboratory, Mechanical Engineering Department, ITS, Surabaya. Main component of this experimental set-up are 90° rectangular elbows without and with guide vanes. Air flow was driven by induced fans with flow capacity more than 15 m³/min, and the flow was passed through honey comb and contraction area before entering the test section. Figure 1 shows the main test sections and figure 2 shows the complete experimental set-up. The inner radius (Rᵢ) of the elbow is 100 mm, while the outer radius (Rₒ) is 150 mm. The elbow cross section is rectangular with 50 mm width and 100 mm height. Detail of elbow geometry are given in figure 3.

Pressure measurements were conducted using inclined manometers filled with red oil having the specific gravity (SG) of 0.804. The manometers were connected to wall pressure taps located at the test section walls and also connected to Pitot tube. A total pressure tube was used to measure total pressure at any location at a cross section. This total pressure together with static pressure at corresponding location are then used to obtain velocity profile at a particular test section.

![Figure 1. 90° rectangular elbow without guide vane](image1.png)

![Figure 2. Complete experimental set-up](image2.png)

Main parameters used in this study as shown in figure 3 include fluid density (ρ), fluid
viscosity ($\mu$), fluid freestream velocity at the elbow inlet $x_i^* = -1.5$ ($U_\infty$), elbow cross section width ($a$), elbow cross section height ($b$), inlet length ($L_1$), outlet length ($L_2$), inner radius ($R_i$), outer radius ($R_o$), and the number of guide vane ($n$). The elbow hydraulic diameter based on figure 3 is $D_h$. Figure 4 shows several locations to be investigated in this study. Table 1 shows main parameters of the elbow, while Table 2 shows detailed locations as shown in figure 4.

3. Results and Discussion

3.1 Wall Pressure Coefficient ($C_p$)

Wall pressure coefficient ($C_p$) is plotted as a function of Reynolds number ($Re_{Dh}$) and the number of guide vanes ($n$). Figure 5 shows the distribution of $C_p$ along the wall of the test section as a function of $Re_{Dh}$ for the elbow without guide vane, while figures 6, 7, and 8 show the distribution of $C_p$ for the elbow with one, two, and three guide vanes, respectively. In figure 5 it is shown that there is a significant different in static wall pressures between that is at the inner and the outer radius of elbow walls. This pressure difference allows the fluid particles move from the outer to the inner wall (radius) of the elbow as reported by Miller [6].

At this study, Reynolds numbers, based on the duct hydraulic diameter ($D_h$) and the inlet freestream velocity ($U_\infty$) are set to be $Re_{Dh} \approx 2.1 \times 10^4$, $8.4 \times 10^4$ and $12 \times 10^4$. Smoke flow visualization is done at lower fluid velocity of about 0.5 m/s, corresponds with $Re_{Dh} \approx 0.2 \times 10^4$. The smoke motion was then recorded using a high speed camera at approximately 125 frame per second (fps).
The insertion of one, two, or three guide vanes (figures 6 to 8) reduce significantly of the pressure difference between that is at the inner and the outer walls (radius) of the elbow. This phenomenon indicates that the cross flow of the fluid particles from the outer to the inner radius of the elbow should be suppressed. It is, therefore, conjectured that the pressure drop due to the secondary flow in the elbow can be reduced.

Although the insertion of guide vanes can suppress the formation of secondary flow, hence, the blockage effect on the main stream, it contributes to the increase in skin friction drag. The increase in skin friction drag is due to the augmentation of the solid-fluid surface area contact, and this effect is more pronounced at higher Reynolds numbers (see Table 3). The gross effect of the guide vane insertion is the increase in pressure drop at $Re_{Dh} = 8.4 \times 10^4$ and $12 \times 10^4$, and reduce the pressure drop at $Re_{Dh} = 2.1 \times 10^4$.

### Table 3. The effect of guide vane insertion on pressure drop.

<table>
<thead>
<tr>
<th>$Re_{Dh}$</th>
<th>Number of Guide Vanes</th>
<th>$\Delta p$ (N/m²)</th>
<th>$\Delta p$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>21000</td>
<td>0</td>
<td>4.01</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>2.67</td>
<td>-33.42%</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>2.73</td>
<td>-31.92%</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>2.71</td>
<td>-32.42%</td>
</tr>
<tr>
<td>84000</td>
<td>0</td>
<td>36.07</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>37.40</td>
<td>3.69%</td>
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<tr>
<td></td>
<td>2</td>
<td>51.12</td>
<td>41.72%</td>
</tr>
<tr>
<td></td>
<td>3</td>
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<td>106.79%</td>
</tr>
<tr>
<td>120000</td>
<td>0</td>
<td>79.11</td>
<td>-</td>
</tr>
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<td></td>
<td>1</td>
<td>88.66</td>
<td>12.07%</td>
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<td></td>
<td>2</td>
<td>118.22</td>
<td>49.44%</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

### 3.2 Mean Velocity Profiles

Mean velocity profiles at a downstream location of the elbow are shown in figures 9 to 12. The downstream location is $3D_h$ from the end of the guide vanes. In figure 9 it is shown the velocity profiles for elbow without guide vane at three different $Re_{Dh}$. For all elbow configuration, without and with one, two, or three guide vanes, the velocity profiles are affected by the value of $Re_{Dh}$. As it is expected, the profile is fuller at the higher value of $Re_{Dh}$, indicating that the flow is more turbulent.

A caution must be given, however, when evaluating the mean velocity profiles. Let us consider the mean velocity profiles for two guide vanes (figure 11). It seems that the velocity profile at the highest $Re_{Dh}$ is not as full as we expected. It is not true indeed. As we can see from figure 11, the slope of the velocity profile at the wall for the highest $Re_{Dh}$ is the largest among other profiles for different $Re_{Dh}$. The appearance of the structure...
of the profile at the core region, which is less uniform than others, is caused by the presence of the guide vanes. It is believed that at a location of $3D_h$ downstream of the guide vanes the profiles are far from relaxation. As it was stated in literature that the relaxation of the profiles is attained at approximately $8D_h$ downstream of the elbow with guide vanes [5].

Figure 10. Velocity profiles for elbow with one guide vane as a function of $Re_{Dh}$.

Figure 11. Velocity profiles for elbow with two guide vanes as a function of $Re_{Dh}$.

3.3 Smoke Flow Visualization

Figure 13 shows smoke flow visualization in the elbow without guide vane. Secondary flows are clearly seen in the figure. The existence of the secondary flows caused by either the difference in flow energy distribution between that in the outer radius and that in the inner radius or the corner effect contributes in negative sense to the flow. The secondary flow plays a significant role in the formation of the blockage effect on the main flow. As a result, the blockage effect reduces flow effective area, and thus increases the flow pressure drop. For instant, the smoke flow visualization for elbows with guide vanes cannot presented in this paper.

Figure 12. Velocity profiles for elbow with three guide vanes as a function of $Re_{Dh}$.

Figure 13. Secondary flow at a section $3D_h$ from the end of the elbow without guide vane at different instant of a reference time. a) $t=0.07s$; b) $0.13s$; c) $0.20s$; d) $0.27s$.

4. Conclusion

From present experimental study on the flow inside $90^\circ$ rectangular elbows with and without guide vanes can be drawn following conclusion:

1. Insertion of one, two, and three guide vanes contributes for the decrease in pressure drop up to approximately 33.42%, 31.92%, and 32.42%, respectively, at the lowest $Re_{Dh}$ ($Re_{Dh} = 21000$).
2. At the two higher $Re_{Dh}$ ($Re_{Dh} = 84000$ and 120000), the insertion of one, two, and three guide vanes contributes for the increase in pressure drop.
3. Velocity profiles show that at a location of $3D_h$ downstream of the elbow with guide vanes have not been relaxed back to the normal profiles.
4. Smoke flow visualization shows secondary flows (vortex flows) at a cross section of the rectangular duct.
References


