Effect of guide vane on Dean Vortex for single-phase turbulent flow through 90 degree pipe bend

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ABSTRACT

Development of Dean vortices on the downstream section of pipe bend are observed for flow through a 90 degree pipe bend. Due to the bend curvature, a centrifugal force developed within the fluid elements at bend portion. This causes different flow phenomena in the flow field like flow separation, secondary flow and dean vortices. In the present study effect of guide vane and its positions on dean vortices are carried out numerically. For that purpose, the study has been planned as a single phase flow through a 90 degree pipe bend with guide vane at different positions inside the bend. Total four different positions of guide vane have been considered inside the bend. Three different Reynolds number and a fixed value of curvature ratio ($R_c/D$) are taken into consideration for the present study. The position of the center of the Dean cells for all cases has been first recognized based on the cross-sectional streamlines and then presented. The study is extended to see how the position of dean vortices has been changed with the different positions of guide vanes for three different Reynolds number and fixed curvature ratio.

Keywords: Numerical study, 90 degree pipe bend, Guide vane, Dean Vortex, k-ω turbulence model

1. INTRODUCTION

Turbulent flows through 90 degree pipe bend are vital in many engineering and technical applications like internal combustion engines, nuclear reactors, heat exchanger, oil and gas pipelines etc. When the fluid passes through the 90 degree pipe bend generates a centrifugal force on the fluid particle and creates a pressure field to balance the forces. This adverse pressure gradient developed due to centrifugal force driving the high velocity fluid particle towards the outer wall and then replaced by the low velocity fluid particle along the wall towards the inner side of the bend and thereby forming two counter rotating cells, so-called Dean Vortices. These type of vortices and secondary motion was first theoretically introduced by W. R. Dean [1]. During the fluid flow in a curved pipe, the primary motion along the pipe is accompanied by the secondary motion in the plane of pipe cross section. This secondary motion decreases the rate of flow for a given pressure gradient. The behavior of Dean Vortices for laminar and turbulent flows has been visualized by some researchers [2] [3] [4]. This phenomena also known as swirl switching [5] [6] and may cause fatigue in piping system. Investigation regarding dean vortices in turbulent flow through pipe bend using direct numerical simulation (DNS) and Large eddy simulation (LES) has been carried out by [7] [8]. Performance evaluation, flow induced vibration
and noise has been studied by [9] [10]. In the present study, the effect of single guide vane at four different positions inside the 90° pipe bend has been studied numerically.

For that purpose, the study has been planned as a single phase flow through a 90 degree pipe bend with guide vane at four different positions inside the bend and considering the curvature ratio (Rc/D=1) fixed. Total four different positions of guide vane have been considered inside the bend and three different Reynolds number value ranging from $1 \times 10^5$ to $10 \times 10^5$ for the present study. The position of the center of the Dean cells for all guide vane positions has been first recognized based on the sectional streamlines and then presented. The study is extended to see how the position of dean vortices core changes along the downstream for the different position of guide vanes.

2. NUMERICAL METHODOLOGY AND VALIDATION

The present paper deals with the flow-through 90° Pipe bend with/without guide vane under high Reynolds Number condition. Water has been considered as the working fluid in present study. The problem becomes a turbulent, single-phase incompressible internal fluid flow through a 90° pipe bend with guide vane under high Reynolds number condition. RANS equation has been solved numerically using computational fluid dynamics solver ANSYS Fluent.

2.1 Turbulence Model

The present study has been carried out considering k-ω turbulence model. The equations, which govern incompressible fluid flow, are the conservation of mass and momentum with constant property are shown below.

$$\frac{\partial u_i}{\partial x_i} = 0$$ (1)

$$\frac{\partial u_i}{\partial t} + u_j \frac{\partial u_i}{\partial x_j} = f_i - \frac{1}{\rho} \frac{\partial p}{\partial x_i} + \nu \frac{\partial^2 u_i}{\partial x_j \partial x_j}$$ (2)

Equations (1) and (2) are the conservation of mass and momentum respectively,

The transport equation for k-omega in conservative form is given by the following and is also available in the well-known literature [15].

$$\frac{\partial (\rho k)}{\partial t} + \frac{\partial (\rho u_j k)}{\partial x_j} = \frac{\partial}{\partial x_j} \left[ \mu + \frac{\rho k}{\omega} \frac{\partial k}{\partial x_j} \right]$$ (3)

$$\frac{\partial (\rho \omega)}{\partial t} + \frac{\partial (\rho u_j \omega)}{\partial x_j} = \frac{\nu_k}{k} \rho \omega^2 + \frac{\partial}{\partial x_j} \left[ \left( \mu + \frac{\rho k}{\omega} \right) \frac{\partial \omega}{\partial x_j} \right]$$ (4)
The equations (3) and (4) consist of some adjustable constants[16], these are as follows:

\[ \sigma_k = 0.5, \sigma_\omega = 0.5, \beta^* = 0.09, \beta = \frac{3}{40}, \gamma = \frac{5}{9} \]

2.2 Problem Definition

The title and author information is immediately followed by the Abstract. The Abstract should concisely summarize the key findings of the paper. It should consist of a single paragraph. The present problem focus on the effect of guide vane position on dean vortices for single-phase, steady incompressible internal turbulent flow through pipe bend. Here 90° pipe bend with fixed curvature ratios (Rc/D=1) and four different positions of guide vane has been considered for the present work. Straight pipe length equal to 10 times of pipe hydraulic diameter has been considered at both the upstream and downstream of the 90° pipe bend. The schematic diagram of the simple pipe bend and pipe bend with guide vane geometry are shown in Fig.1; Fig.1b shows the Guide vane position inside the bend portion. The positions of the guide vanes are determined according to radius ratio (ratio between nominal elbow radius to radius of elbow curvature) suggested in established literature [7]. Different radius ratio values as well as the positions of guide vane from the center of the bend curvature are given in Table 1. The working fluid for the present study considered a single-phase fluid i.e. water at 20° C having dynamic viscosity (\( \mu \)) 0.001003 kg/m-s and density (\( \rho \)) 998.2 kg/m³. Table 1 shows the cases
with different geometrical configurations according to the guide vane and its position inside the bend.

<table>
<thead>
<tr>
<th>Curvature Ratio 1</th>
<th>Value of radius ratio</th>
<th>Position of guide vane (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case 1 (C1)</td>
<td>0</td>
<td>No guide vane</td>
</tr>
<tr>
<td>Case 2 (C2)</td>
<td>With Guide Vane 0.175</td>
<td>0.068</td>
</tr>
<tr>
<td>Case 3 (C3)</td>
<td>Guide Vane 0.308</td>
<td>0.081</td>
</tr>
<tr>
<td>Case 4 (C4)</td>
<td>0.493</td>
<td>0.099</td>
</tr>
<tr>
<td>Case 5 (C5)</td>
<td>0.738</td>
<td>0.124</td>
</tr>
</tbody>
</table>

2.3 Boundary Condition and Validation

The main three boundary conditions which has been applied here are “Velocity Inlet”, “Outflow” & “Wall”. Velocity inlet boundary condition has been applied at the upstream section of the bend geometry. The exit of the fluid at the downstream has been considered as ‘Outflow’ boundary condition and the wall part of the fluid domain by default wall boundary condition. No-slip boundary condition has been applied at the pipe wall. To ensure that the numerical result obtained from the present study is similar to some extent, separate simulation has been carried out considering same geometrical and flow conditions with established literature and compared. Fig. 2 shows the results obtained from the present simulation have a close guesstimate with the results given by Kim [17] and Taknaka [18]. So the further study can be carried out considering same numerical set up in computational domain.

**Figure 2.** Comparison between the present and published experimental, numerical results of Normalized axial velocity distribution profile at bend outlet position
3. RESULTS AND DISCUSSIONS

For flow through curved channel and without guide vane case generally total five types (pairs) of secondary vortex structure are observed inside the curved channel and along the downstream section. These five types are Base (main) vortex, Split Base vortex, Inner Curvature Wall Dean vortex (ICW Dean vortex), Outer Curvature Wall Dean vortex (OCW Dean vortex), Additional Dean vortex defined. Due to the presence of guide vane, the main base vortex splits into two separate base vortex formed at the outer and inner curvature side of the bend. In the present study these two vortices are recognised as Outer Curvature Wall Base vortex (OCW Base vortex) and Inner Curvature Wall Base vortex (ICW Base vortex). Different types of vortices obtained and discussed in this study are presented in figure 3.

Vortex core shifting along the downstream of the pipe bend for all the cases studied here are presented and discussed at different cross-sectional position i.e. from the bend outlet (X/D=0) to X/D=8. The positions of the centre of the Dean vortices for all cases has been first visually

![Figure 3](image_url)

**Figure 3.** Different types of vortices and their development for Curvature Ratio 2, (a) Without Guide vane (Case1), (b) Guide vane near to center at inner curvature wall side (Case3)

recognized based on the sectional streamlines and then identified. This shifting of vortex core along downstream are obtained for each gap of X/D=0.5 for the location, from X/D=0 to X/D=8. The study has been carried out for different Reynolds number (1×10^5, 5×10^5 & 1×10^6) with fixed curvature ratios (Rc/D=1) and four different positions of guide vane inside the bend.
as mentioned in table 1. It has been observed that the development of dean vortices and change in position of vortex core are not influenced largely by the Reynolds number. So, the dean vortices stream traces at different cross-sections along downstream have been presented here only for Reynolds number $5 \times 10^5$.

**Figure 4** Development of vortex for Curvature ratio 1 case 1 (Without guide vane) at Re=$5 \times 10^5$

**Case 1** (Without Guide vane): At location X/D = 0, one pair of vortex (base vortex) is formed for

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without guide vane case see figure 4. These vortices get split into two more vortices at X/D=0.5 and these vortices shift toward the inner wall of the pipe. Two weak inner core vortices are also formed between location X/D=0 to X/D=0.5. The vortices formed from the base vortex are weak and become vanished between X/D=0.5 to X/D=1. So only one pair of base vortex and

**Figure 5.** Development of vortex for Curvature ratio 1 case 2 (with Guide Vane) at Re=5×10⁵
one pair of inner core vortex are present at $X/D=0.1$. This inner core vortex lasts up to $X/D=2$. At $X/D=2$, the base vortices shift a little towards the pipe centre. The inner core vortices near the periphery of pipe get disappeared between $X/D=2$ to $X/D=2.5$. The graphical presentation of the vortex core shifting at radial and axial direction for each case are shown in figures along with the cross-sectional view of stream traces.

**Case 2** (Guide vane position near to the inner curvature wall): Figure 5 show the Change of the vortex core for Case 2. In this case, a guide vane is provided close to the inner curvature wall of the pipe bend. The variation of the vortex core shifting as shown in figure 5 is approximately similar for all three Reynolds numbers. At the location $X/D=0.0$ i.e. at the end of the pipe bend two vortex cores are formed just above the guide vane and another one pair of vortex getting initiated just below the vane. At $X/D=0.5$ the new two vortices are observed and between $X/D=0.1$ to $X/D=1.5$ the inner core vortex appears. These inner core vortices disappear between $X/D=0.4$ to $X/D=4.5$. Vortices near to the centre line move toward the outer core of the cross-section and disappears between $X/D=0.2$ to $X/D=2.5$. The base vortex cores move toward the outer core side as shown in figure 5. The vortex cores originated from the base vortex become weaker at $X/D=2$ and eventually get disappeared between $X/D=2$ to $X/D=3$. The base vortex cores now are shifting a little upward towards the outer periphery of the wall up to $X/D=8$.

**Case 3** (Guide vane position is near to the center line and away from inner wall): Results regarding dean vortices for case 3 are presented in figure 6 for same curvature ratio 1. In this case, a guide vane is provided near to the centre of the pipe and away from the inner pipe wall. Initially at $X/D=0$, four vortex (outer and inner curvature base vortex) cores have been formed i.e. two above the guide vane and two below the guide vane near the wall. In between $X/D=0$ to $X/D=0.5$ two more vortex cores have been formed due to centrifugal force and guide vane effect. Vortex formed at the inner side of guide vane moves towards the inner core centre
Figure 6. Development of vortex for Curvature ratio 1 case 3 (with Guide Vane) at Re=5×10^5 position at X/D=0.5 and get splited into small weak vortex. This vortex disappears in between X/D=0.5 to X/D=01. Base vortex which was formed at the upper side of the guide vane move towards inner side along the periphery and get into merge with the vortex formed initially at the
lower side of the guide vane in between X/D=1 to X/D=2 and form the main single base vortex. The additional vortex get weaker in between X/D=3 to X/D=4 and finally get disappeared between X/D=4 to X/D=6. Further along the downstream there is not much variation of the positions of vortex core from X/D=6 to X/D=8.

Figure 7. Development of vortex for Curvature ratio 1 case 4 (With Guide vane) at Re=5×10^5
**Case 4**: The position of guide vane for case 4 is near to the center and away from the outer pipe wall. Results for case 4 are presented in Figures 7. Figure 7 shows the results for curvature ratio 1. Here also initially total four vortices are present at X/D=0, one pair of vortex at the outer side of the vane and the other pair at the inner side. The additional vortex appears at

![Diagram of vortex development](image)

**Figure 8.** Development of vortex for Curvature ratio 1 case 5 (With Guide vane) at Re=5×10^5
X/D=0.5 then the core moves slightly towards the outer side of the pipe and disappears between X/D=04 to X/D=05. The base vortex at the upper side of the vane shifts towards the inner core side along the periphery of the wall from X/D=0.5 to X/D=03 and gradually became smaller in size. Between X/D=03 to X/D=04, it gets merged with the lower base vortex and make one large vortex. The inner core vortex and the split vortex are not present for case4 with curvature ratio 1.

**Case5:** Results for case5 on dean vortex for different curvature ratios are presented in figure 8. Here the position of the guide vane is near to the outer periphery of the pipe wall cross-section. At X/D=00, total four vortices are formed for case5. The vortex at the outer wall side is small in size compared to the vortex at the inner core side. The additional vortex has been appeared near X/D=0.5. The vortex at the inner side of the vane stretches and gets splitted in between X/D=0 to X/D=0.5 for higher Reynolds number case. The additional vortex disappears between X/D=0.5 to X/D=01. Vortex at the outer wall side gradually becomes smaller in size and get merge with the comparatively strong vortex at the inner wall side between X/D=02 to X/D=03. After that the position of vortex core shifts towards the outer side from X/D=03 to X/D=08.

**4. CONCLUSIONS**

In the present work, turbulent flow of a single phase fluid through 90 degree pipe bend with guide vane have been investigated numerically for three different Reynolds number and curvature ratio 1. Study has been carried out numerically by means of k-ω turbulence model for four different positions of guide vane to understand the effect on dean vortices development. The different combination of vortex are observed here, are namely: (i) Base Vortex (Inner and outer curvature wall), (ii) Split base vortex, (iii) Additional Dean vortex, (iv) Inner core Dean Vortex (ICV). From the results, it has been observed that the formation and pattern change of vortex does not have vital dependency on Reynolds number. However guide vane positions has an effective role on development of vortex at downstream. Only the base vortex exists continuously
throughout the downstream. The other dean vortices formed near to bend outlet and disappear nearly X/D=04 for all the cases. These vortices often formed by splitting the base vortex and disappear by getting merged with the same.

REFERENCES