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NUMERICAL STUDY ABOUT THE CHANGE IN FLOW SEPARATION AND VELOCITY DISTRIBUTION IN A 90º PIPE BEND WITH/WITHOUT GUIDE VANE CONDITIONS

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ABSTRACT

A single phase, incompressible turbulent flow through a 90º pipe bend with/without guide vane conditions has been studied here. The present work deals with the numerical simulation to investigate the change in flow separation and velocity distribution at the downstream section due to the effect of the guide vane. The k-ε turbulence model has been adopted for simulation purposes to obtain the results. After the validation of existing experimental and numerical results, a detailed study has been performed for three different Reynolds number and four different positions of the guide vane. The value of the Curvature ratio (Rc/D) has been considered as one factor for the present study. The curvature ratio can be defined as the ratio between the bend curvature radius and hydraulic diameter of the pipe. The results obtained from the present study have been presented in graphical form. A flow separation region has been found at the bend outlet for flow through 90º pipe bend without the guide vane. This flow separation region was absent for the cases which dealt with the flow through 90º pipe bend with the guide vane. Velocity distribution at four different downstream positions for different cases and different Reynolds numbers have been compared and reported in the present study.

Keywords: 90º pipe bend; Flow separation; Numerical study; Velocity distribution; With/without guide vane

1. INTRODUCTION

The study of pipe bends and piping systems deserves full attention in modern engineering research, due to its relevance in numerous piping applications. Turbulent flow through pipe bends has commanded significant interest from researchers from both applied research and a basic theoretical viewpoint (Ono et al., 2011; Hüttl & Friedrich, 2001). Pipe bends can be used as a part of several mechanical systems, e.g. heat exchangers (Chang, 2003) reciprocating engines (Hellström, 2010) and nuclear reactors (Yamano et al., 2011). Pipe bends are also used in the oil industry, water supply systems, for fluid and material transportation and to change the direction of flow. So it is important to study single phase flow through pipe bends for minimizing losses by understanding complex flow behavior and improving their performance. W.R. Dean’s efforts, first on theory and then on theoretical expression for flow through pipe bends are well recognized (Dean & Hurst, 1959). Keulegan and Beij (1937) studied pressure losses for fluid flow in curved pipes experimentally. Their article provided empirical formulas for the effective resistance coefficient of an entire bend and the downstream tangent. Later, A.

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White (1964) founded more convenient expressions for flow in pipe bends. When fluid flows through a curved pipe, there will be a force acting in the radial direction outwards of the pipe from the imaginary center of the bend curvature. An experimental investigation has been carried out by Anwer et al. (1989) for a bending curvature of a fully developed turbulent pipe flow, considering the Reynolds number flow and the pipe-to-bend radius ratio, which were 5×10^4 and 0.077 respectively. Large-Eddy-Simulation of turbulent flow in a curved pipe has been investigated by Boersma and Nieuwstadt (Boersma & Nieuwstadt, 1996). They attempt to study the details of secondary motion in the cross-section of the pipe which is caused by centrifugal acceleration due to the pipe curvature. It has also been noted that the secondary motion may consist of one, two or three circulation cells. Rütten et al. (2005) performed LES to investigate turbulent flows through $90°$ pipe bends which featured unsteady flow separation, unstable shear layers and an oscillation of the Dean vortices. They reported that the low-frequency oscillation perceptible on the entire wall is caused by the two Dean vortices. So and Anwer (1993) showed that the mean axial velocity profile at 49D downstream at the bend exit is similar to the measured profile at 18D upstream of the bend curvature. Swirling flow behavior, unsteady nature of secondary vortices, and transition of secondary flow phenomena has been studied by some researchers. These researchers investigated the unsteady flow separation, unstable shear layers and Dean Vortices for turbulent flow through a 90º pipe bend. Turbulent flows in a 90º pipe bend cause flow separation near the inner wall which has effects in the piping system performance and also can excite strong vibration and flow-induced noise. Some researchers have studied structural vibration and noise caused by the boundary layer for turbulent flows through different pipe bends (Pittard & Blotter, 2003; Qing et al., 2006). They came up with the design of the guide vane to reduce structural vibration, noise and pressure loss in elbows with a circular cross section (Imao et al., 1996; Zhang et al., 2013). The present work makes an attempt to study the influence of the guide vane on flow separation and velocity distribution. For this purpose numerical simulations have been carried out for both with and without guide vane conditions. Change in velocity distributions is presented in graphical form.

2. NUMERICAL METHODOLOGY

Study on turbulent flow through pipe bends demands dedication, due to its broad engineering applications. The present study has been carried out, considering the turbulent flow of a single phase, steady, isothermal and incompressible fluid, i.e. water through a 90º pipe bend. Three-dimensional Reynolds Averaged Navier-Stokes (RANS) equations have been solved using a segregated implicit solver to get results. The second order scheme has been used for the calculations, with a pressure-velocity coupling achieved using the SIMPLE algorithm.

2.1. Turbulence Model

The governing equations for incompressible fluid flow with constant properties are as shown in Equations 1 and 2:

$$\frac{\partial u_i}{\partial x_i} = 0 \tag{1}$$

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

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

fi - vector representing external forces,
υ - is the kinematic viscosity.

Turbulent flows are irregular, random and chaotic. The flow consists of a spectrum of different scales (eddy size) and is designed by the fluctuations of the velocity field. These fluctuations can be very small scale and high frequency. It is difficult to analyze the flow problem directly. The right choice of turbulent model is necessary to make the virtual model more realistic compared to the experimental model. The turbulence model needs to be selected based on some considerations, e.g. the physics of the flow, the insight into the capabilities and limitations of turbulence models. The k-ε turbulence model has been implemented for present study purpose because this model achieves better results for single phase flow through pipe bends (Kim et al., 2014; Homicz, 2004; Rahimzadeh et al., 2012; Dutta & Nandi, 2015; Goodarzi et al., 2014; Safaei et al., 2011). In this model, the turbulence kinetic energy (*k*) and the turbulence dissipation rate (ε) are solved to determine the coefficient of turbulent viscosity (μ_t), as shown in Equations 3 and 4 below:

Transport equation for k-epsilon

$$\frac{\partial(pk)}{\partial t}+\frac{\partial(pku_i)}{\partial x_i}=\frac{\partial}{\partial x_j}\left[\frac{\mu_t}{\sigma_k}\frac{\partial k}{\partial x_j}\right]+2\mu_t E_{ij}E_{ij}-\rho\varepsilon \tag{3}$$

$$\frac{\partial(p\varepsilon)}{\partial t}+\frac{\partial(p\varepsilon u_i)}{\partial x_i}=\frac{\partial}{\partial x_j}\left[\frac{\mu_t}{\sigma_\varepsilon}\frac{\partial k}{\partial x_j}\right]+C_{1\varepsilon}\frac{\varepsilon}{k}2\mu_t E_{ij}E_{ij}-C_{2\varepsilon}\rho\frac{\varepsilon^2}{k} \tag{4}$$

where u_i represents velocity component in corresponding direction, E_{ij} represents component of rate of deformation, μ_t represents eddy viscosity.

The equations 3 and 4 also consist of some adjustable constants (Tu et al., 2007), these are as follows:

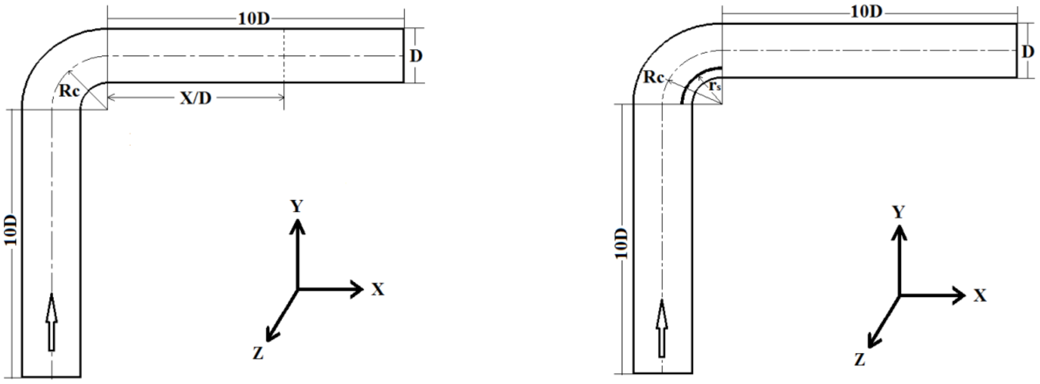
$$C_\mu = 0.09,\ \sigma_k = 1.00,\ \sigma_\varepsilon = 1.30,\ C_{1\varepsilon} = 1.44,\ C_{2\varepsilon} = 1.44,$$

2.2. Problem Definition

The present study focused on the change in flow separation and velocity distribution due to the effect of the guide vane installed in the pipe bend. The problem that has been considered here is a single phase flow through 90º pipe bend, with and without guide vane having an inner diameter 0.1 m and curvature ratio (Rc/D) 1. Curvature ratio can be defined as the ratio between the radius of the bend curvature and hydraulic diameter of the pipe. The study has been carried out for three different Reynolds numbers considering four different positions of the guide vane installed in the bend portion. For that purpose, a total of five different virtual models (Case 1, Case 2, Case 3, Case 4, and Case 5) have been considered in the present study to get the desired results. Case 1 considered a flow through a simple pipe bend (bend without the guide vane), and on the other hand, Case 2 to Case 5 represent the bend with the guide vane in different positions respectively. Both inlet and outlet lengths of straight pipe were set up at 10D to save computational time for all the cases mentioned above. Positions of the guide vane have been determined by radius ratios (ratio of the nominal elbow radius to the inside radius of the elbow curvature Ri of the pipe), which were taken from published literature shown in Table 1 (Zhang et al., 2015). The fluid medium was water having a density (ρ) 998.2 kg/m^3 and dynamic viscosity (μ) of 0.001003 kg/m-s for the present study with a working temperature of 300K. Three-dimensional structured mesh with hexagonal element has been chosen and optimized via a grid independent study, (see Figure 3b). The value of Y+ (non-dimensional distance from wall) is strictly controlled using standard wall treatment function (30<Y+<90) for the present study. The schematic geometry of the bend and computational mesh are shown in Figure 1 and Figure 2, respectively.

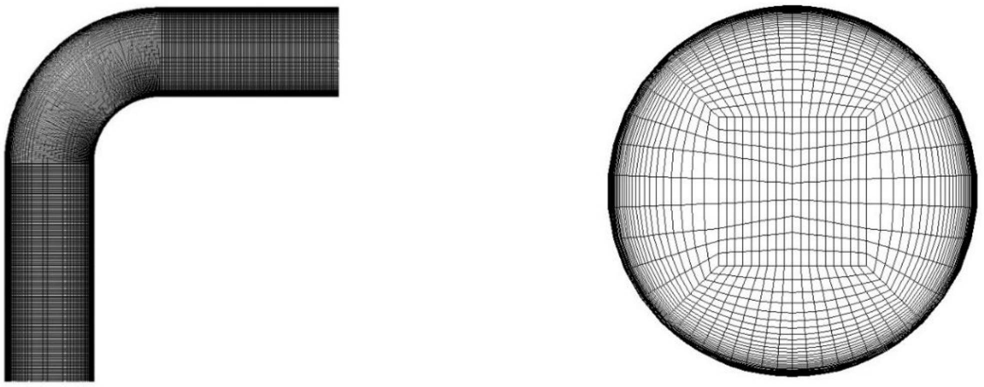
Table 1 Different positions of guide vane installed in the elbow

Case No.	Position of Guide Vane $(r_s - R_i)/(R_o - R_i)$
Case1 (Simple)	0
Case2	0.175
Case3	0.308
Case4	0.493
Case5	0.738



(a) (b)

Figure 1 Schematic Diagram of the bend geometry: (a) Without guide vane; (b) With guide vane

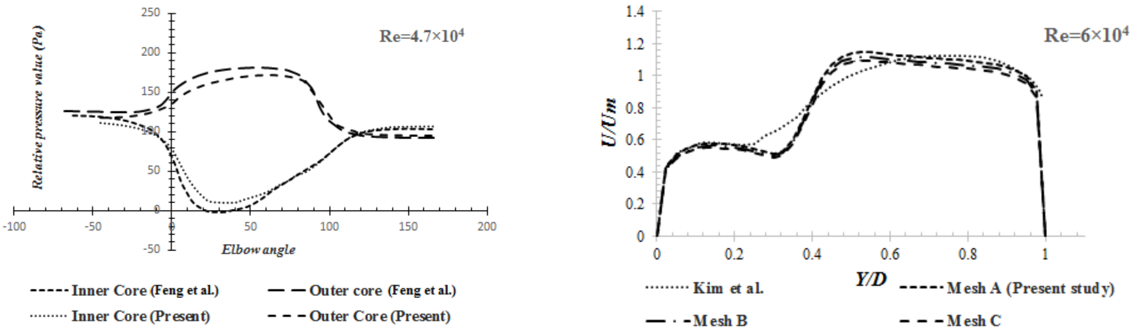


(a) (b)

Figure 2 Computational grid of the geometry

2.3. Validation

Two virtual computational models have been formed to ensure that our models and simulations were realistic to some extent, so that we can go for further study. For that purpose the same geometrical configuration and boundary conditions have been adopted and results obtained from the simulations have been compared against the published experimental and numerical data (Feng et al., 2014; Kim et al., 2014). The authors of the previously mentioned work carried out their studies using a round cross-sectioned 90° pipe bend with curvature ratios (Rc/D) of 1.5 and 2, respectively for their experimental study and numerical simulation of Reynolds number 4.7×10^4 and 6×10^4, respectively. The present study has been carried out on a computational mesh containing 3.5 million hexahedron elements. Figure 3 represents the graphical comparison between the published results and results obtained from the present study. The relative total pressure value at inner and outer core positions throughout the bend portion has been compared with the results published by Feng et al. (2014), as presented in Figure 3a. Normalized axial velocity distribution at the bend outlet position has been compared with the results published by Kim et al. (2014), (see Figure 3b). From Figures 3a, 3b, it has been seen that the present model is in close approximation with the published data. So it may be concluded that the procedure of mesh generation and simulation set up which has been used for validation purposes could be used for further analysis.



(a) (b)

Figure 3 Comparison of: (a) Relative total pressure; and (b) Normalized axial velocity profile of present analysis with published experimental and numerical results

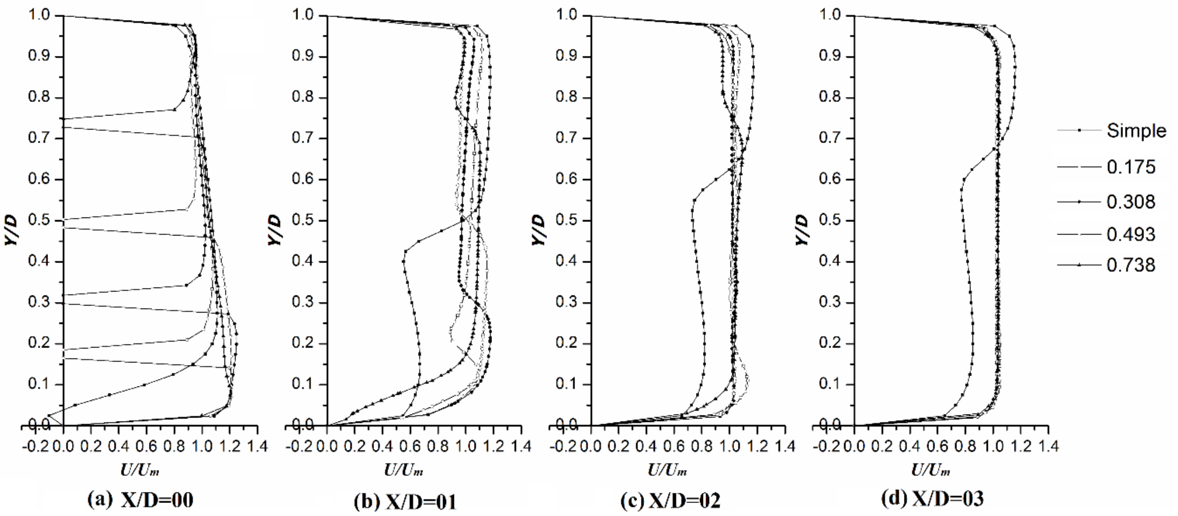
3. RESULTS AND DISCUSSION

The present study has been carried out for a single-phase turbulent flow through a 90º pipe bend with/without guide vane conditions. The primary objective of the present work is to study the effect of the guide vane on flow separation and velocity distribution for three different Reynolds numbers as well as four different positions of guide vane. Four various positions including the bend outlet position along the symmetry plane have been preferred to perceive the change in flow separation and velocity distribution for different cases.

Figures 4 to 6 represents the normalized velocity distribution at four different positions on the downstream at symmetry plane, for three different Reynolds numbers respectively. The four plots in each figure describe the change in velocity distribution of different cases at a fixed position and for a particular Reynolds number. The x-axis of the plots represents the velocity distribution normalized by the mean velocity, and the y-axis represents the non-dimensionalized length of the pipe diameter. Y/D = 0.5 accounts for the center line position of the pipe at symmetry plane, so the minimum value of Y/D < 0.5 refers the inner core side, and Y/D > 0.5 value indicates the outer core side of the pipe. Different line patterns (solid line, dashed line, etc.) in the plots denote the different cases for the present study mentioned in each figure.

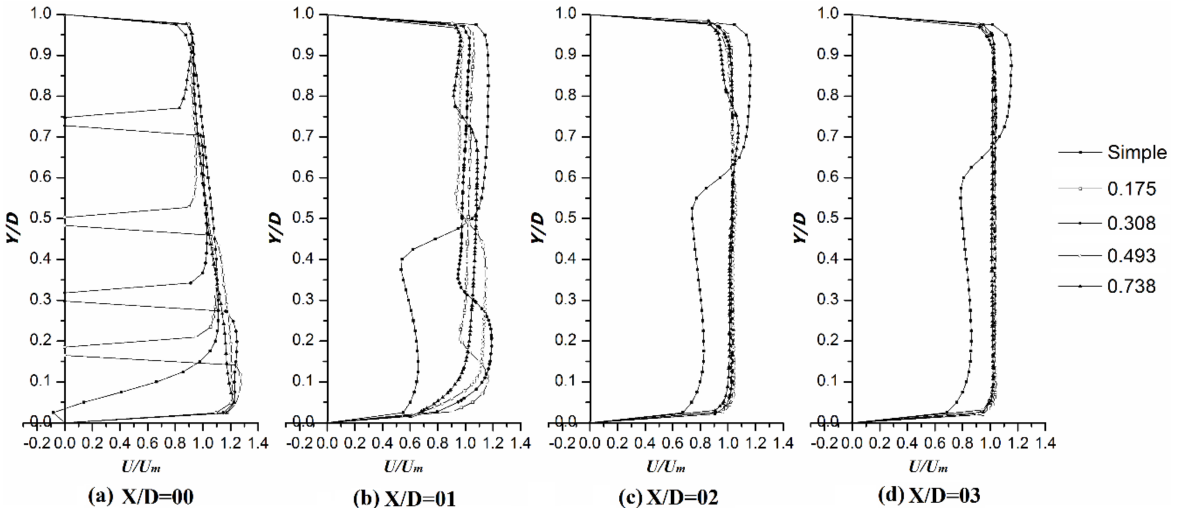
3.1. About Flow Separation

From Figures 4a, 5a, and 6a, a flow separation region has been observed for Case 1 at the bend outlet (X/D=0) position, although the Reynolds numbers are different. It has also been observed that this flow separation region was not the same as in the other four cases. So it is clear that the guide vane effects on flow may be the actual cause for non-appearance of the flow separation region for the last four cases dealing with the guide vane. Whenever a fluid flowed through a curved pipe or pipe bend there was a radial pressure gradient developed, due to the centrifugal force acting on the fluid element. So the pressure will be greater at the outer core and least at the inner core of the bend. Hence the faster-moving fluid particles near the central plane and inner core of the pipe have a tendency to move towards the outer core. Therefore, an adverse pressure gradient will be encountered at the inner core side of bend outlet, and flow separation may occur. Now, on the other hand, the guide vane split the flow at the bend inlet position for Cases 2 to 5. So the radial pressure gradient which mainly developed due to the effect of centrifugal force would not be transferred towards the outer core beyond the guide vane and the flow would be separated.



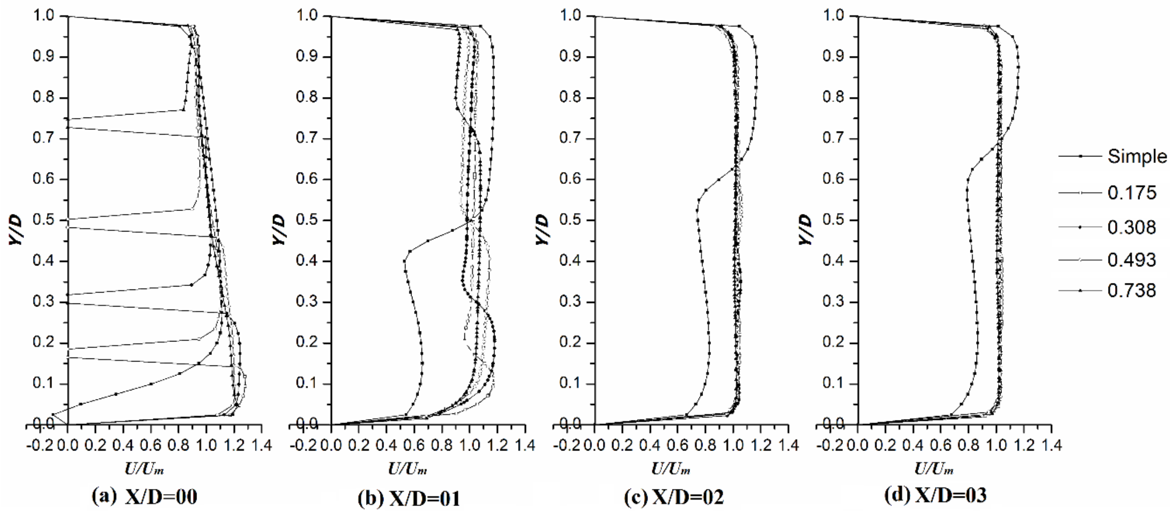
(a) X/D=00 (b) X/D=01 (c) X/D=02 (d) X/D=03

Figure 4 Normalized velocity distribution at different position for Re 1×10^5



(a) X/D=00 (b) X/D=01 (c) X/D=02 (d) X/D=03

Figure 5 Normalized velocity distribution at different position for Re 5×10^5



(a) X/D=00 (b) X/D=01 (c) X/D=02 (d) X/D=03

Figure 6 Normalized velocity distribution at different position for Re 10×10^5

3.2. About Velocity Distribution

Figures 4b, 5b, and 6b show that the normalized velocity distribution profiles for all the cases mentioned above are almost same for three different Reynolds numbers. From Figures 4d, 5d, and 6d, it has been seen that the velocity profile regained its fully developed shape for all the cases except Case 1 (without the guide vane). It may be resolved that the guide vane aids the flow to recover its fully developed shaped earlier compared to the bend without the guide vane. At a distance of X/D = 2 from the bend outlet for Re 10×10^5, it has been observed that the flow become more or less fully developed for all the cases deal with the guide vane. Alternatively, the velocity distribution profile at the same position for Case 2 and Case 5 did not convalesce to its fully developed shape for the Reynolds number 1×10^5. Similarly, for the Reynolds number 5×10^5, only the velocity distribution profile for Case 5 did not gain its fully developed shape, but the rest of the three cases with the guide vane condition were fully developed. For the guide vane conditions, it may be said that the tendency to regain its fully developed velocity profile depends not only on the Reynolds number, but also on the position of the guide vane.

4. CONCLUSION

Single phase incompressible turbulent flow through a 90° pipe bend for with/without the guide vane has been studied numerically using k-ε turbulence model. The present study has been carried out after the validation of the virtual 3D model with various experiments (Kim et al., 2014) and numerical works (Feng et al., 2014). Changes in flow separation and velocity distribution due to the effect of guide vane have been presented.

The conclusions obtained from the present study may be summarized as follows: (1) The flow separation region has been found for Case 1 (without the guide vane) only at the bend outlet; this area is not present for the other four cases (with the guide vane). Due to the presence of the guide vane, the fluid flow divided and pressure at the outer core may least for guide vane condition be compared to without the guide vane condition; (2) The pipe bend with the guide vane may help the flow become fully developed at nearer to the bend outlet compared to the bend without the guide vane.

It may be concluded that the tendency to obtain a fully developed velocity profile depends on not only the Reynolds number, but also the position of the guide vane installed.

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