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"CFD INVESTIGATION OF LAMINAR FLUID FLOW WITHIN 90-DEGREE ELBOW PIPES"

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ABSTRACT

Curved pipe fittings are widely used in petroleum transportation, process industries, hydraulic systems, and other fluid-transport applications. The curvature of an elbow modifies the pressure and velocity fields and produces secondary motion that can influence pressure loss, wall loading, and downstream flow development. This paper presents a three-dimensional computational fluid dynamics investigation of steady, incompressible, laminar flow through a 90-degree elbow pipe. The simulations were performed using the open-source Open FOAM framework with a finite-volume formulation. A pipe diameter of 0.01 m, a 50D inlet section, and a 20D outlet section were used. Four Reynolds numbers—200, 500, 1000, and 2000—were examined with three curvature ratios, Ro = 5.6, 11.2, and 22.4, resulting in twelve simulation cases. A mesh-convergence study was conducted using 1,413,733, 2,321,088, and 3,406,543 cells. The intermediate mesh was selected for subsequent simulations because its velocity profiles showed relatively small deviation from the finest mesh. The computed profiles were compared with published results for validation. The results show that centrifugal effects deform the initially parabolic velocity profile, create pressure gradients, and generate counter-rotating Dean vortices. Secondary-flow intensity increases with Reynolds number and decreases as the curvature ratio increases. The findings provide useful guidance for the hydraulic design and analysis of elbow fittings.

Key Words: *computational fluid dynamics, Open FOAM, elbow pipe, laminar flow, Reynolds number, curvature ratio, Dean vortices, secondary flow.*

I. INTRODUCTION

Pipe elbows are essential components of fluid-transport networks because they allow pipelines to change direction within compact layouts. However, a bend is not hydraulically equivalent to a straight pipe. The curved centerline produces centrifugal forces, cross-sectional pressure gradients, velocity redistribution, and secondary flow. These effects are important in systems such as oil and gas pipelines, offshore facilities, hydraulic machinery, HVAC installations, and biomedical flow passages.

Experimental investigation of internal flow in curved pipes can be costly and may provide measurements only at selected locations. Computational fluid dynamics (CFD) offers a complementary approach by resolving the flow variables throughout the computational domain and allowing geometry, operating conditions, and boundary conditions to be varied efficiently. A reliable CFD study nevertheless requires appropriate governing equations, boundary conditions, mesh quality, convergence monitoring, and validation.

The objective of this work is to numerically examine three-dimensional laminar flow in a 90-degree elbow for different Reynolds numbers and curvature ratios. The specific objectives are to: (i) establish a suitable computational model

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using Open FOAM; (ii) perform mesh convergence and validation; (iii) assess the effect of Reynolds number on velocity and pressure fields; and (iv) identify the effect of curvature ratio on secondary flow and velocity-profile deformation.

II. Review of Related Work

Previous investigations of elbow flow have addressed experimental velocity distributions, numerical prediction of secondary flow, erosion and particle deposition, and the influence of elbow geometry. The literature summarized in the source thesis indicates that curvature ratio is a dominant geometric parameter: tighter bends generally intensify cross-sectional pressure gradients and secondary motion, while larger bend radii produce milder flow redistribution. Reynolds number controls the relative importance of inertial and viscous effects and therefore influences the strength of the secondary flow.

Studies of curved pipes have also shown the relevance of elbow flow to aerosol transport and respiratory-airway modelling. In addition, turbulent elbow-flow studies have examined velocity profiles, pressure loss, flow separation, and erosion. The present study complements these works by concentrating on steady three-dimensional laminar flow and by systematically combining four Reynolds numbers with three curvature ratios.

III. Materials and Methods

3.1 Computational domain

The computational domain consists of a straight circular inlet, a 90-degree curved section, and a straight outlet. The inlet length is 50D and the outlet length is 20D, where D is the pipe diameter. The pipe diameter used for the simulation cases is 0.01 m. The bend radius is varied to obtain curvature ratios $Ro = Rc/Rp$ of 5.6, 11.2, and 22.4, where Rc is the elbow centreline radius and $Rp = D/2$ is the pipe radius. In the geometric representation, these cases correspond to bend radii of approximately 2.8D, 5.6D, and 11.2D.

Parameter	Value
Elbow angle	90°
Pipe diameter, D	0.01 m
Inlet length	50D
Outlet length	20D
Curvature ratios, Ro	5.6, 11.2, 22.4
Mean inlet velocity	1 m/s
Reynolds numbers	200, 500, 1000, 2000

3.2 Governing equations

The flow is modelled as steady, incompressible, and Newtonian. The continuity equation is:

$$\nabla \cdot U = 0 \qquad (1)$$

The momentum equation is:

$$\nabla \cdot (U\,U) = -\nabla p/\rho + \nu \nabla^2 U \qquad (2)$$

Where U is the velocity vector, p is pressure, ρ is density, and ν is kinematic viscosity. No-slip conditions are applied at the solid wall. The Reynolds number is defined as $Re = \rho\, U_{avg} D/\mu$, and the Dean number used to interpret the secondary-flow behavior is proportional to Re multiplied by the square root of the ratio of pipe radius to bend radius.

3.3 Mesh generation and boundary conditions

The geometry and mesh were generated using G msh and converted to an Open FOAM-compatible format using the g mesh to Foam utility. The mesh was refined in the elbow and near the wall to resolve large velocity gradients associated with the no-slip condition and curvature-induced flow structures. Three meshes were used for the grid-convergence assessment.

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A fully developed parabolic velocity profile with a mean velocity of 1 m/s was prescribed at the inlet. Zero normal gradients were used for pressure at the inlet. The pipe wall used no-slip velocity and zero normal pressure gradients. At the outlet, velocity was assigned a zero normal gradient and pressure was set to a reference value of zero.

Mesh	Number of cells
Mesh 1	1,413,733
Mesh 2	2,321,088
Mesh 3	3,406,543

3.4 Numerical solution procedure

The steady incompressible simple Foam solver was used with the SIMPLE pressure–velocity coupling algorithm. Open FOAM case files were organized into the 0, constant, and system directories. Residuals and a pressure probe located within the elbow were monitored to confirm that the solution reached a steady state. Para View was used for post-processing velocity contours, pressure contours, and velocity profiles extracted at the 90-degree elbow outlet.

3.5 Mesh convergence and validation

The convergence study was performed for Re = 2000 and Ro = 5.6. Velocity profiles along the A–A and B–B diameters at the elbow outlet were compared for the three meshes. Mesh 1 showed noticeable deviation from the two finer grids, whereas Mesh 2 and Mesh 3 produced comparatively similar profiles. Mesh 2, containing 2,321,088 cells, was therefore selected as a compromise between accuracy and computational cost.

For validation, the Mesh 2 results at Re = 1000, Ro = 5.6, and D = 0.01 m were compared with published velocity-profile results reported in the thesis. The profile shapes and near-wall peak values showed generally good correspondence, although some deviations were observed. The thesis attributes possible differences to variations in inlet-pipe length and other modelling details.

IV. Result and Discussion

4.1 Flow development and velocity redistribution

The inlet flow develops as a conventional laminar pipe flow with an approximately parabolic axial velocity profile. The velocity is close to zero at the wall and reaches its maximum near the pipe centreline. As the flow enters the elbow, centrifugal effects redistribute the axial momentum across the cross-section. The outer-curvature region carries a higher-velocity stream, while the inner-curvature region exhibits lower velocity and a stronger tendency toward separation.

The initially symmetric parabolic profile becomes asymmetric at the elbow outlet. The deformation is more pronounced at higher Reynolds numbers and in tighter elbows. For a larger curvature ratio, the bend is gentler and the resulting velocity profile remains closer to the straight-pipe profile.

4.2 Secondary flow and Dean vortices

Cross-sectional velocity contours reveal a pair of counter-rotating helical secondary-flow structures, commonly referred to as Dean vortices. These vortices arise because the centrifugal force associated with the axial motion is balanced by a cross-sectional pressure gradient. The resulting transverse motion transports high-momentum fluid toward one part of the cross-section and returns lower-momentum fluid elsewhere.

The simulations show that vortex intensity increases as Reynolds number increases. Conversely, increasing the curvature ratio reduces the strength of the swirling motion. Thus, the most pronounced secondary flow occurs for the combination of high Reynolds number and small curvature ratio, while low Reynolds number and large curvature ratio produce weaker cross-sectional circulation.

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4.3 Pressure field

Pressure contours demonstrate a strong pressure variation across the elbow. A low-pressure region develops near the inner curvature and a relatively high-pressure region occurs toward the outer or obstructing side of the bend. The low-pressure region shifts downstream as the curvature ratio increases, while the overall pressure difference becomes smaller for the larger-radius elbows.

These pressure variations have practical implications for elbow design. Localized pressure gradients can increase wall loading and contribute to flow separation. In engineering systems, such information can be used to assess pressure loss, identify regions requiring structural attention, and select bend radii that limit undesirable hydraulic effects.

4.4 Summary of parametric effects

Parameter increase	Observed effect
Reynolds number	Stronger secondary flow, greater profile deformation, and more evident separation/shear-layer behavior
Curvature ratio	Weaker swirling, smaller pressure difference, and velocity profiles closer to the straight-pipe form
Dean number	Higher secondary-flow intensity and more prominent Dean vortices
Mesh resolution	Mesh 2 and Mesh 3 give closer velocity profiles than Mesh 1

III. CONCLUSION

A three-dimensional CFD investigation of steady laminar flow through 90-degree elbow pipes was conducted using Open FOAM. Twelve cases were studied by combining Reynolds numbers of 200, 500, 1000, and 2000 with curvature ratios of 5.6, 11.2, and 22.4. The main conclusions are:

- A mesh-convergence assessment showed that the 2,321,088-cell mesh provided a suitable balance between solution consistency and computational cost.
- Validation against published velocity profiles showed generally good agreement in profile shape and near-wall behavior, although differences remained in some regions.
- Curvature deforms the parabolic inlet profile and produces higher velocity toward the outer curvature and lower velocity toward the inner curvature.
- Counter-rotating Dean vortices form at the elbow outlet because of curvature-induced centrifugal forces and cross-sectional pressure gradients.
- Secondary-flow intensity increases with Reynolds number and decreases with curvature ratio.
- Pressure contours show low-pressure regions associated with flow separation and high-pressure regions related to the interaction between the flow and the curved wall.

Future work should extend the analysis to turbulent flow, compare turbulence models, investigate other bend angles and pipe fittings, and examine multiphase flow and particle erosion in curved passages.

Data Availability

The numerical setup, geometry description, mesh information, operating conditions, and principal observations reported in this paper are derived from the dissertation supplied for this manuscript. The original OpenFOAM case files and raw numerical data were not included in the supplied document.

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