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NUMERICAL ANALYSIS OF NEWTONIAN FLUID FLOW VARYING THE CONTRACTION GEOMETRY USING OPENFOAM

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Abstract. *Newtonian fluid flow are seen in many engineering applications, thus many works have been performed in this area in order to understand the characteristics of this type of flow and optimize industry processes. Due to this, there are many works involving flow in a sudden contraction for common contraction geometries. In these works are analyzed velocity fields, pressure drops and vortex formation just varying the contraction ratio. In this work was studied how the contraction geometry variation impacts in the previously mentioned phenomena. The laminar, incompressible and axisymmetric flow is modeled by the mass and momentum conservation equation and the method deployed to solve these equations is the Finite Volume Method (FVM) which is a method wide used in fluid flow problems. The mesh used in this work is a block-structured mesh and is simulated just a geometry slice with the OpenFOAM tool called Wedge. Therefore, to vary the contraction geometry is used a tool called spline and the mesh was constructs in Python in order to automate it. In conclusion, are presented results of pressure loss, velocity fields and vortex characteristics through graphs and color scale and through comparing results for the two different geometries.*

Keywords: *contraction, Newtonian, finite volume method*

1. INTRODUCTION

Flow in a sudden contraction are seen in many engineering applications such as polymer processing, various manufacturing processes, injection molding, petroleum industry and etc. Among previously mentioned applications, the behavior of the wells drilling fluid have been studying by petroleum oil industry. According to Coradin et al. (2007), the flow through a contraction presents a great hydrodynamic complexity and does not have analytical solutions, thus, numerical methods are necessary to fully describe the flow.

Recently (Sanchez, 2012) studied the Newtonian fluids flow through a sudden contraction in laminar and turbulent regime by the Particle Image Velocimetry (PIV) with a contraction ratio $\beta=D/d=1.97$. Lastly, in the laminar flow was concluded that ΔP decreases when the Reynolds increases, although the values of ΔP remain approximately constant when Reynolds increase for turbulent flow. Experimental and numerical work were presented by Durst and Loy (1985), using the LDA method. The authors studied the velocity profiles by measuring axial and cross-velocity and for it they used finite-difference computations and a non-structured mesh. They found some measurement uncertainties and was suggested a correction of the measurements for future works. Ray et al. (2012) investigate the Newtonian fluid flow through a two-dimensional sudden expansion and contraction. The study has been performed with a contraction ratios $\beta=2,4$ and $\beta=8$, for two different flows for the same geometry. The work concludes that the sudden contraction, compared to sudden expansion, is seen to have drastic impact on the flow field for the same contraction and expansion ratio and the gain of axial velocity along the center line is maximum at the point of contraction.

The goal of the present study is assessing the impact of the change in the contraction geometry in relevant characteristics of the Newtonian fluid flow, such as, pressure drop, velocity field and vortex.

2. METHODOLOGY

2.1 Physical formulation

The problem was studied through two geometries described as shown in Figs. 2 and 3. A small change in the contraction geometry was made using a sigmoid curve in order to decrease phenomena caused by a sudden change in fluid flow path, like shown in Fig. 3. In both cases the flow is axisymmetric, that is, a slice of the flow represents all the flow where is used the wedge to simulate all the flow, which considerably reduces the computational domain and the simulation time.

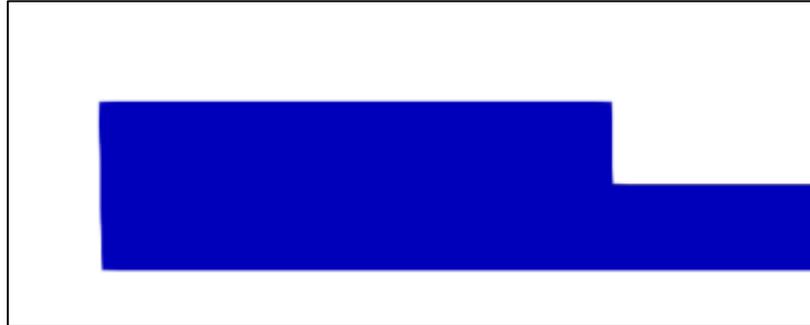


Figure 1. Sudden contraction

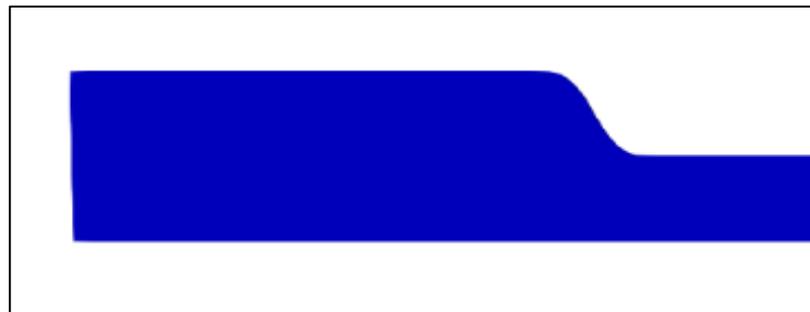


Figure 2. Gradual contraction

The boundary conditions are described below and in Fig. 4 is depicted each one of them:

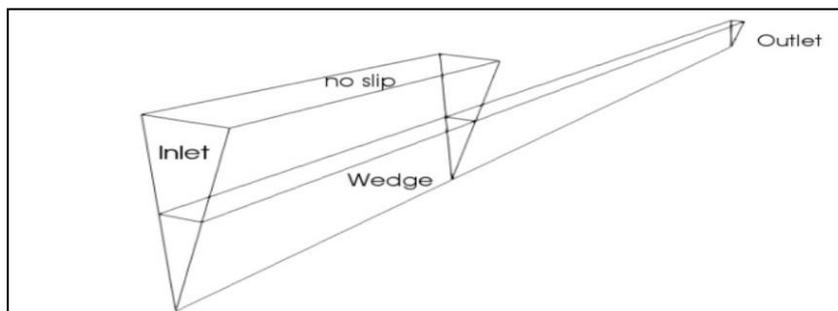


Figure 3. Boundary conditions

- *Inlet*: For the pressure was used the zero gradient, imposing that gradient between the faces of control volumes is zero and for the velocity was used fixed value (Dirichlet) with the profile described through Eq. (4);
- *Outlet*: Fixed value for pressure and advective condition for the velocity;
- *Azimuthal direction*: The wedge condition for the pressure and velocity, this condition enforces a cyclic condition between a pair of boundaries.
- *Radial direction*: No slip condition for the velocity and the zero gradient for the pressure.

In this work the simplification hypothesis used were:

- The fluid is Newtonian
- The fluid is incompressible:
- Steady-state
- Bi-dimensional flow
- Laminar flow
- The flow is axisymmetric

The governing equations for Newtonian and incompressible fluid flow are the mass and momentum conservation, like is

shown in the Eqs. (1) and (2), respectively, where ρ is the specific mass, \vec{u} is the velocity vector, μ is the viscosity and g is the gravity.

$$\nabla \cdot \vec{u} = 0 \quad (1)$$

$$\frac{\partial u}{\partial t} + \vec{u}(\nabla \vec{u}) = -\frac{1}{\rho} + \mu \cdot \nabla^2 u + g \quad (2)$$

The Reynolds's number for the Newtonian fluid is calculated with simple way through the Eq. (3)

$$Re = \frac{VD}{\nu} \quad (3)$$

Where V is the average velocity, D is the tube diameter and ν kinematic viscosity.

The profile of the velocity in the tube for a Newtonian is knowledge how is described in (Fox,2008), this profile is described by the Eq. (4)

$$\frac{v}{U} = 1 - \left(\frac{r}{R}\right)^2 \quad (4)$$

Where u is the average velocity, U is the máx velocity, r is the smaller tube radius diameter and R is the bigger radius.

2.2 Discretization

The free software *OpenFoam* is used to solve the differential equations that govern the problem, this software used the FVM (Finite Volume Method) to obtain the solution of Navier Stokes's equations, in this method each term of the Eq. (5) is integrated in each control volume and interpolated to the faces of them.

$$\frac{\partial \phi}{\partial t} + \nabla \cdot (U\phi) = \nabla \cdot t_{\phi} + S_{\phi} \quad (5)$$

In this case $\frac{\partial \phi}{\partial t}$ are the terms of accumulation $\nabla \cdot (U\phi)$ are the terms of advection $\nabla \cdot t_{\phi}$ are the diffusive terms and the S_{ϕ} are the terms fonts.

The refinement of the mesh was higher close to tube wall and the contraction, like is shown in both Fig. 2 and Fig. 3, due to higher velocity gradients in these regions and the solution need to be more accurate.

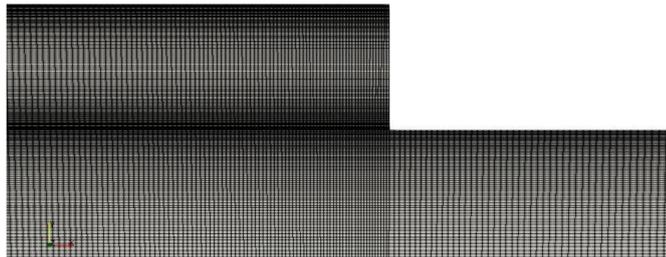


Figure 4. Sudden contraction mesh

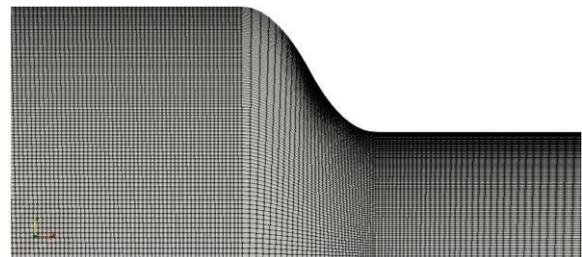


Figure 5. Gradual contraction mesh

The division, number of cells for x and y, and the refinement rate for two geometries are show in Tabs. 1 and 2:

Table 1. Number of cells and size for the mesh 1.

Direction	Cells numbers	greater radius size (m)	minor radius size (m)
X	768	0,03	0,717
Y	128	0,01195	0,00606
Z	1	0,00104	0,00104

Table 2. Number of cells and size for the mesh 2.

Direction	Cells numbers	greater radius size (m)	minor radius size (m)
X	510	0,03	0,717
Y	128	0,01195	0,00606
Z	1	0,00104	0,00104

3. RESULTS

It was simulated two cases as shown in Tab. 3 varying the Reynolds number. In each case was analyzed the recirculation's

size for geometry with sudden contraction and gradual contraction.

Table 3. Reynolds and transport properties values

Simulation	Cinematic Viscosity $\nu(m^2/s) \cdot 10^{-6}$	Average Velocity $V (m/s)$	Reynolds Re
1°	8.64	0.359	993
2°	8.072	0.179	530

The streamlines for sudden contraction and gradual contraction are shown in Figs. 7 and 8 for a Reynolds number 993. It is possible to see from the color scale that the velocity of the fluid increases as it approaches the region of contraction, and the velocity is zero on the tube wall due to non-slip condition. An important result in these images are the differences in the recirculation's size for two geometries. The same thing is seen in the Figs. 9 and 10, for a Reynolds number 530.

In the first case to mesh with gradual contraction is possible to see the effect of the geometry when the fluid approaches of the contraction, in this case the trajectory change of fluid happens in gradual way preventing the recirculation formation. In other case to mesh 2 the trajectory change happens in abrupt way causing the recirculation formation, this phenomenon is very harmful to this process consuming energy from the flow, consequently, increasing the pressure loss. This shows that the geometry is very important factor during this process and this can be used to decrease losses in the flow, consequently optimizing it.

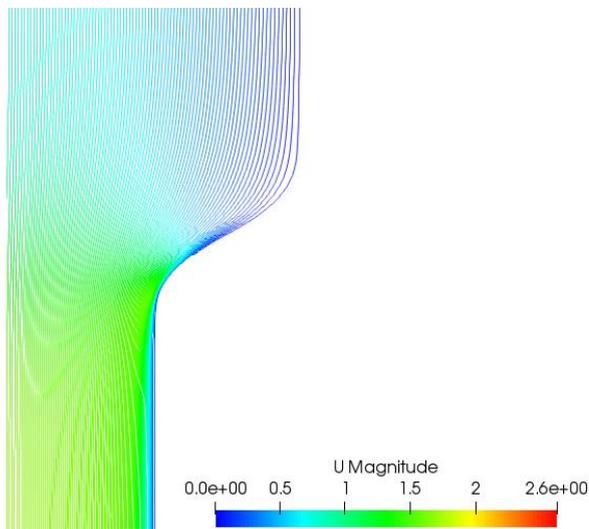


Figure 6. Streamlines (gradual contraction mesh)

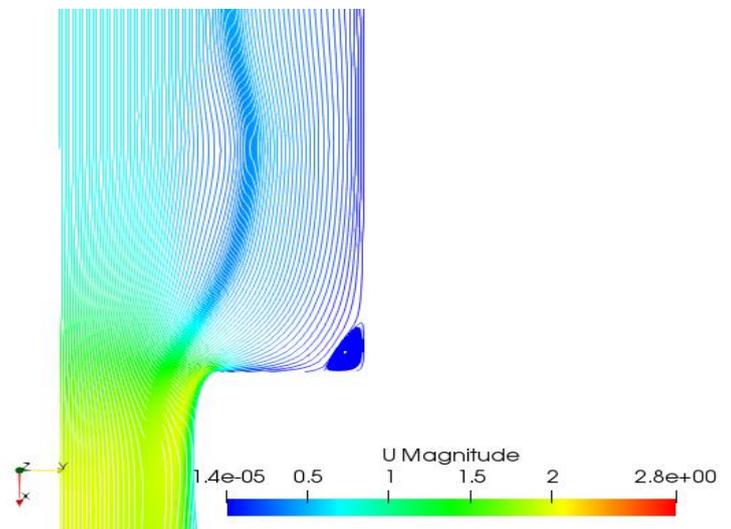


Figure 7. Streamlines (sudden contraction mesh)

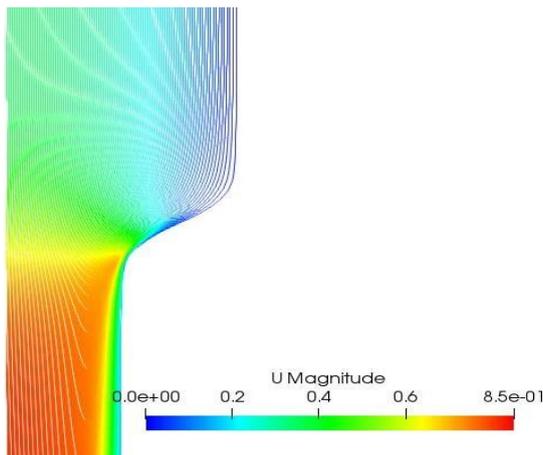


Figure 8. Streamlines (gradual contraction mesh)

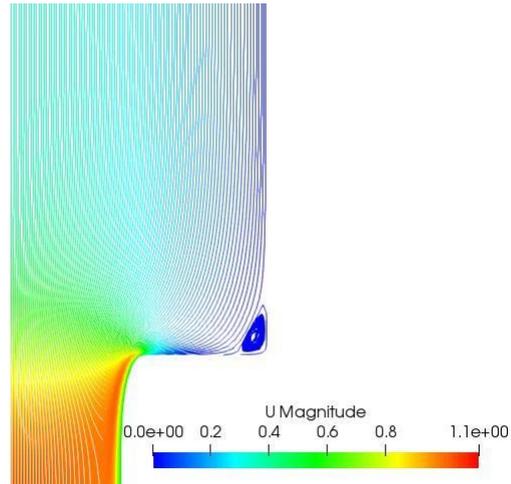


Figure 9. Streamlines (gradual contraction mesh)

To validate these simulations the results to the velocity profile was compared with the experimental results of (Sanchez et al., 2011). In Fig. 11 is presented the comparison of velocity profile with a Reynolds number of 993, in this case the black curve represents the experimental results and the red curve represent the results simulated in *OpenFoam*, that is possible to see that it is in quantitatively agreed with the literature data.

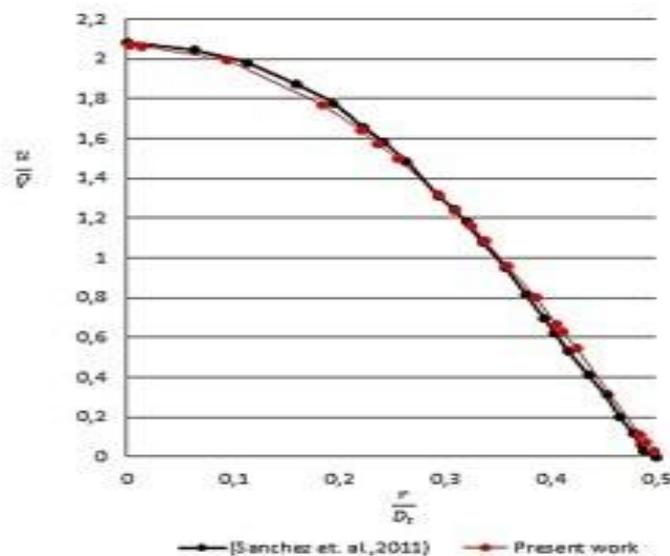


Figure 10. Comparison between experimental and simulated data

4. CONCLUSIONS

The Newtonian fluid flow in sudden contraction has been seen in many engineering applications and the phenomenon provoked by this kind of geometries has been studied in many works as was shown previously. An application of that situation is during the drilling oil of wells, in this case there are contraction regions in drill geometry.

This work studied the impact of geometry change in the recirculation formation through change of the contraction geometry, was possible to conclude that in the geometry with gradual contraction didn't happen the recirculation formation, on the other hand, the geometry with sudden contraction the phenomenon of recirculation happened.

5. REFERENCES

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