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NUMERICAL ANALYSIS OF VORTEX FORMATION IN THE NON NEWTONIAN FLUID FLOW IN A SUDDEN CONTRACTION

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Abstract. *Fluid flows through a sudden contraction are common in many engineering applications. Although there exists a number of works involving Newtonian fluids, in the related phenomenon concerning rheological fluids, it seems that a number of parameters and details still need to be addressed. The behavior of a Non-Newtonian fluid flow through a sudden contraction is presented in this work. The laminar, incompressible and axisymmetric flow is modeled by mass and momentum conservation equations and Power Law's model viscosity. Conservations equations were discretized by (FVM) Finite Volume Method, the method SimpleFoam was used for solve coupling pressure velocity. Results are shown for different Power Law indexes and the determined results agreed qualitatively with the physical interpretations, the behavior of the flow was analyzed near the contraction, observing as the fluids with differents characteristics behave when they change the flow direction. Was concluded that the fluid with more viscosity has smaller recirculation when compared with the fluid of smaller viscosity.*

Keywords: *Abrupt contraction, Finite Volume Method, Steady-state Flow, Non-Newtonian fluid*

1. INTRODUCTION

Non-Newtonian fluid's flow is becoming more and more recognized in the petroleum industry, a relevant case is the drilling of oil wells. During this process the fluid pass through regions with sudden contractions, causing many phenomena that can be harmful for the process. Some of them are pressure loss localized, recirculation and *vena contracta*, thus, it has been studied in many works show below. In this context, is very important the choice of fluid with the physical and rheological features appropriate, in the present work was made an analysis of the recirculation's size upstream of the abrupt contraction.

This fluid plays an important role for good performance of the process. As stated in (Sert, 2011a) there are some demands presents in this process, for example, to keep in suspension the cuttings that are distributed along the drilling column in order to avoid sedimentation. (Coradin. et al., 2007) stated that the main objectives of the fluid are clean the bottom of the well and transports the gravels to the surface, exert hydrostatic pressure on the rock formations and stabilize the well wall. Due to this demands the fluids used in this process should have Non-Newtonian properties.

Non-Newtonian fluid used in this process can be modeled as power law fluid when the material exhibits pseudo plastic or dilatant behavior as in this case. Fig. 1 shows Non-Newtonian behavior for some fluids.

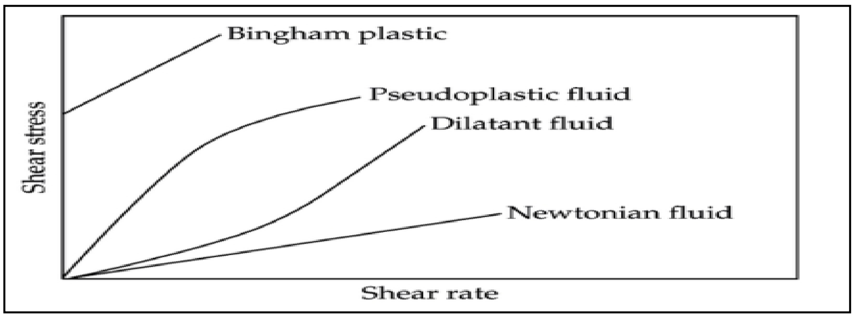

Figure 1. Shear rate vs Shear stress by Newtonian and Non-Newtonian fluids
Available from: http://www.msubbu.in/ln/fm/Unit-I/NonNewtonian.htm

The flow in this kind of geometry has been studied in many works. According (Sert, 2011b) the fluid pass in contraction regions because the geometry of the drill. In recent work (Antunes, 2013) analyzed that the flow in a sudden contraction geometry causes some phenomena that must be diminished, for example pressure drop localized and recirculation. In this case this happen due to changes at the direction and intensity of the flow. Fig. 2 shows some caused phenomena by an abrupt contraction geometry.

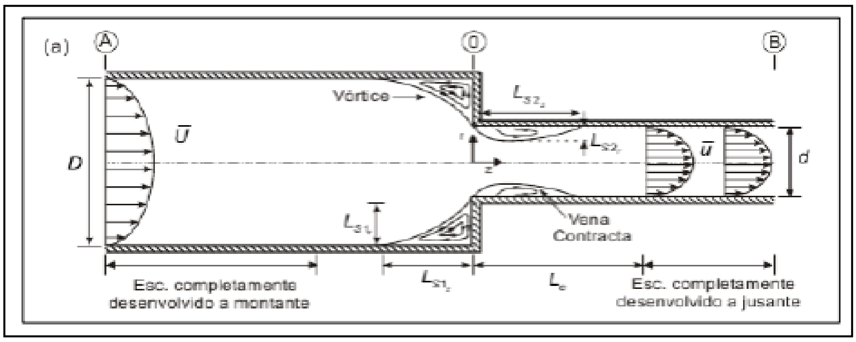

Figure 2. Schematic representation of the flow
Available from: Sanchez (2010)

The literature shows that the behavior of the various type of Non-Newtonian fluids through the geometry of sudden contraction has been studied in many ways, till now contraction flow presents some unresolved issues from fundamental point of view. Hence the need is felt to investigate the contraction flow characteristics with the variation of different flow parameters, (Kfuri,2010) analyzed the pressure drop with the variation of Power Law index, and concluded that for the fluid with Power Law index lower than 1 the pressure drop decreases with increase of Reynolds number, and for Power Law index higher than 1 the reverse occurs. In this work recirculation's size for the upstream region is analyzed varying the Power Law (*n)* and the consistency (*k)* index.

2. METHODOLOGY

2.1 Physical formulation

The problem is described as shown in Fig. 3. In this case the flow enters in the face *inlet* with the profile appropriated for the Non-Newtonian, this profile was found through the simulation of this fluid until reaching the fully developed regime. The aspect ratio is defined as $\beta = D/d$ where D is the diameter of the upstream tube and d is the diameter of the downstream tube, in the present work was used $\beta = 1.97$.

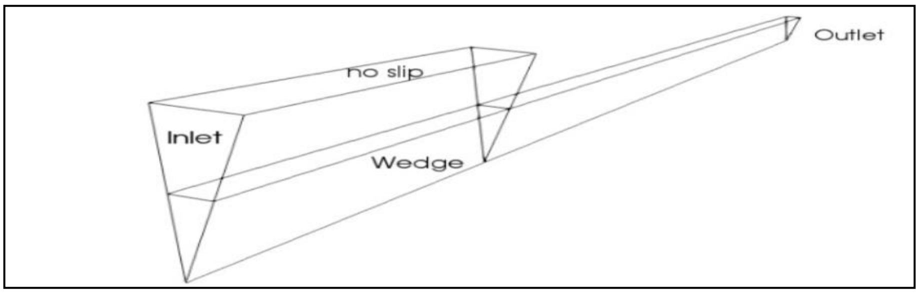

Figure 3: Flow´s geometry

The geometry used for simulate the problem is depicted in Fig. 3. In the same figure are shown the conditions imposed in their respective boundaries, where:

- *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 fully developed for Non-Newtonian fluid;
- *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 the present work, the main hypothesis considering the flow conditions are

- The fluid is incompressible:
- Steady-state
- Turbulent flow
- The flow is axisymmetric

The problem of sudden contraction was modeled with the equation of mass conservation Eq. (1) and momentum conservation Eq. (2).

$$\nabla\vec{u} = 0 \tag{1}$$

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

In order to close the set of unknowns and equations given by Eq. (1) and Eq. (2) additional equation is needed. In this case was used the power law constitutive equation as show Eq. (3)

$$\eta(\gamma) = k\gamma^{n-1} \tag{3}$$

Where in the Eq. (1) and Eq. (2) $\nabla\vec{u}$ is the divergent from $\vec{u}$, g is the gravity and to Eq. (3) k is the consistency index and n is the power law index. In this model the power law index determines if the viscosity decays (*n<1)* or goes up (*n>1)* with the shear rate. The Reynolds's number for the power law fluid was calculated by a more complex equation for power law model introduced by Metzner and Reed (1955) shown below Eq. (4).

$$Re = \frac{\rho.U^{2-n}.D^n}{8^{n-1}.K.(\frac{3.n+1}{4.n})^n} \tag{4}$$

In Eq. (4) ρ is the specific mass of the fluid *U* is the mean velocity and *D* is the diameter of bigger tube.

2.2 Numerical model

In this work the software *OpenFoam* was employed to obtain the numerical solution of the problem, the advantages this software when it is compared with others are free license, open source allowed the intercommunication between the users and the possibility of the user develop your source for specific problem that have not developed yet.

The *OpenFoam* used the FVM (Volumes Finite Method) to get the solution of the Navier Stokes's equations, in this method the flow domain is discretized according the control volumes adopted, the general form of the conservation shown in Eq. (5) are integrated in each control volume and interpolated to the faces for each control volume.

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

In this case $\frac{\partial \phi}{\partial t}$ are the terms of accumulation $\nabla(U\phi)$ are the terms of advection ∇t_ϕ are the diffusive terms and S_ϕ are the terms fonts.

To solve the coupling pressure velocity was used the algorithm Simple that is implemented in *OpenFoam*, this method consists of the following steps

- Set the boundary conditions
- Solve the discretized momentum equation to compute the intermediate velocity field.
- Compute the mass fluxes at the cell faces.
- Solve the pressure equation and apply under-relaxation.
- Correct the mass fluxes at the cell faces
- Correct the velocities on the bases of the new pressure field.

- Update the boundary conditions.
- Repeat till convergence.

In the *OpenFoam* at the system directory is possible set up the interpolation method in the *fvschemes* for the terms of the transport equations, in this case was used centered differences method for the discretization of the spatial terms. For the solution algebraic system, was used the generalized geometric-algebraic mult-grid

3. RESULTS

It was analyzed the recirculation's size near the corner of the abrupt contraction varying the power law index (*n)* and the consistency index *(k)*. For *n* were analyzed two kinds of fluids, in the first case shear thinning fluid with power law index exponent *n=0.2* and a shear thickening one with *n=1.5* and for *k* only the value was changed as show on the Table. 1.

Table 1. Values for *k* and *n* in all simulations

Simulation	*k*	*n*
1º	10^{-5}	0.2
2º	10^{-5}	1.5
3º	10^{-2}	1
4º	10^{-5}	1

The streamlines are show in Fig. 4 and Fig. 5 for shear thinning and shear thickening fluids, in these simulations can be seen that the recirculation's size was bigger for shear thinning fluid, this happens because the momentum quantity near the wall for this fluid is bigger than shear thickening fluid, that is, its viscosity decrease with shear stress increase causing a bigger recirculation's size when the fluid changes its trajectory.

In this kind of the flow is important to analyze the maximum velocity reached by the fluid, because it interferes in the pressure loss. In Fig. 4 from the color scale is possible see that maximum velocity is smaller in this case, as the momentum quantity loss near the wall is less considerable for this fluid, the increase of this in the center tube is smaller.

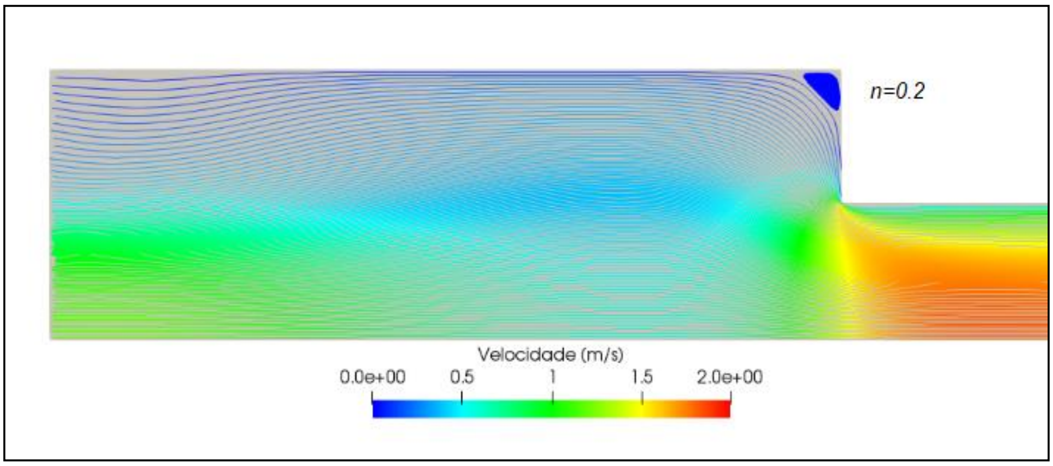

Figure 4. Recirculation near the contraction for the Power Law index 0.2

Fig. 5 shows that the recirculation's size for shear thickening fluid is smaller than when it is related with the case showed previously, this occurs because of the reverse effect near the wall for momentum quantity. Here is possible confirmed what was said before, the maximum velocity is bigger because the conservation of the energy.

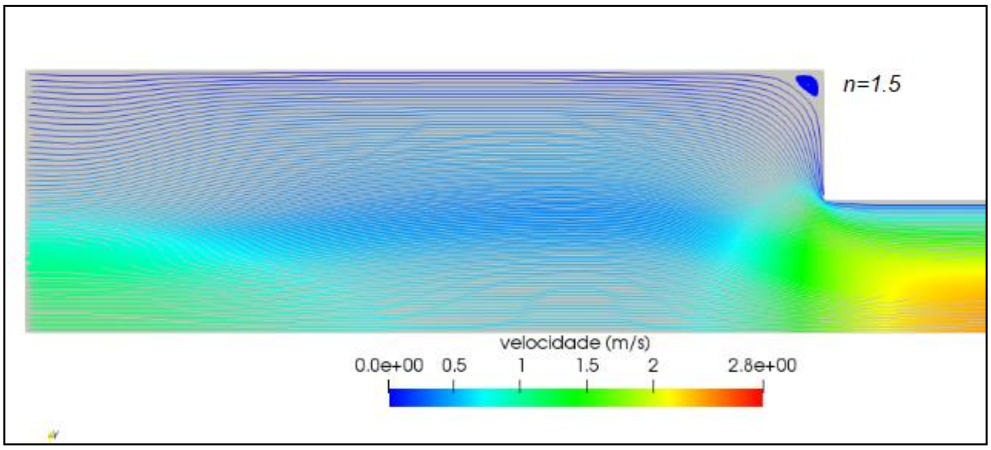

Figure 5. Recirculation near the contraction for the Power Law index 1.5

The consistency index effect is show in Fig. 5 and Fig. 6. Is possible to see a power law index similar behavior for recirculation's size and maximum velocity, that is for higher *k* value the recirculation's size is smaller and for lower *k* value the recirculation's size is smaller. This happens because in this case the consistency index represents the resistance of the fluid to flow and it increases the friction with the wall, then the momentum quantity near the wall for higher value of *k* is smaller causing lower recirculation effect when it changes its trajectory. The recirculation for this case can be seen in Fig. 5. This figure also shows that the maximum velocity is bigger for higher *k*.

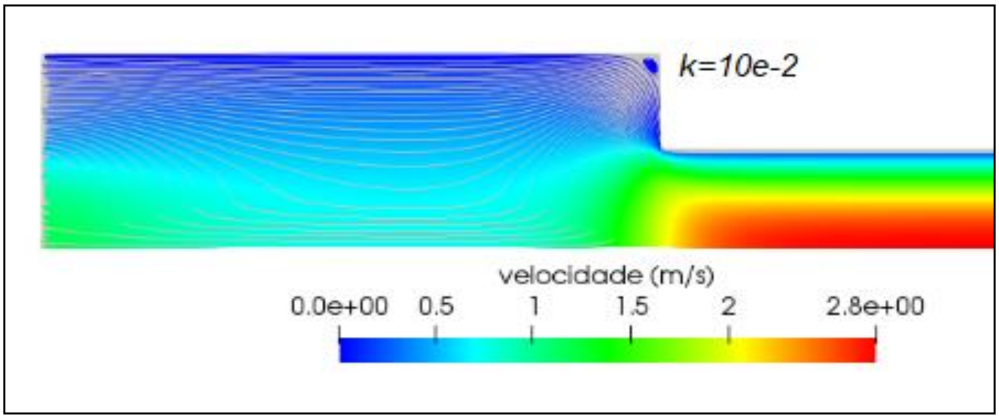

Figure 5. Recirculation near the contraction for the consistency index k= 10e-2

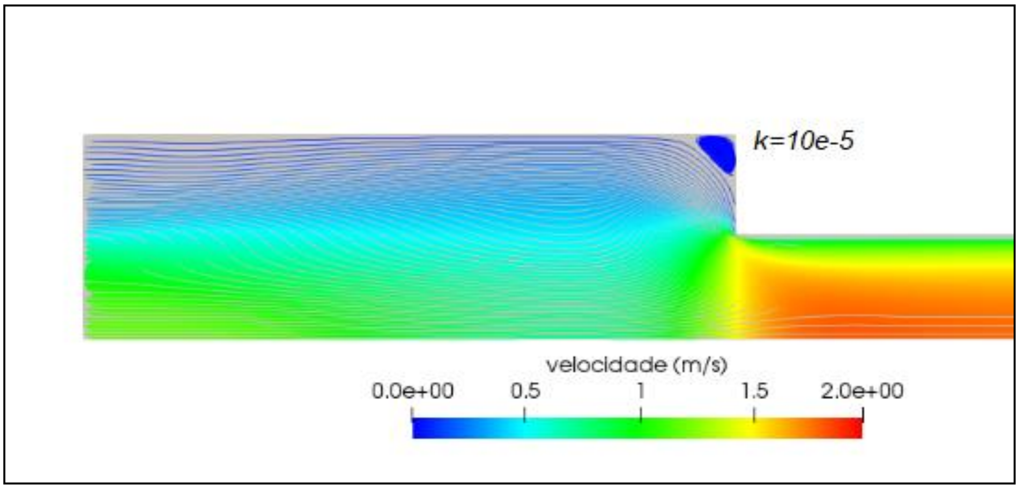

Figure 6. Recirculation near the contraction for the consistency index k= 10e-5

Other important variable to analyze in the flow is the pressure drop caused by the friction of the fluid with walls and the sudden contraction. In this flow the axial distribution for the pressure were plotted to higher viscosity fluid and lower viscosity fluid as show in the Figs. 7 and 8.

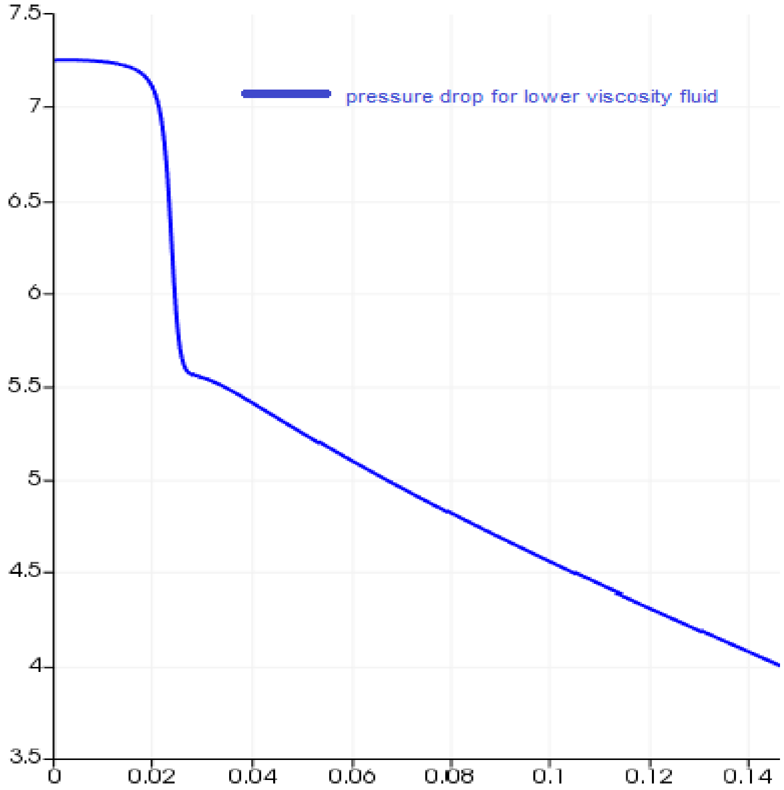

Figure 7. Pressure drop for lower recirculation

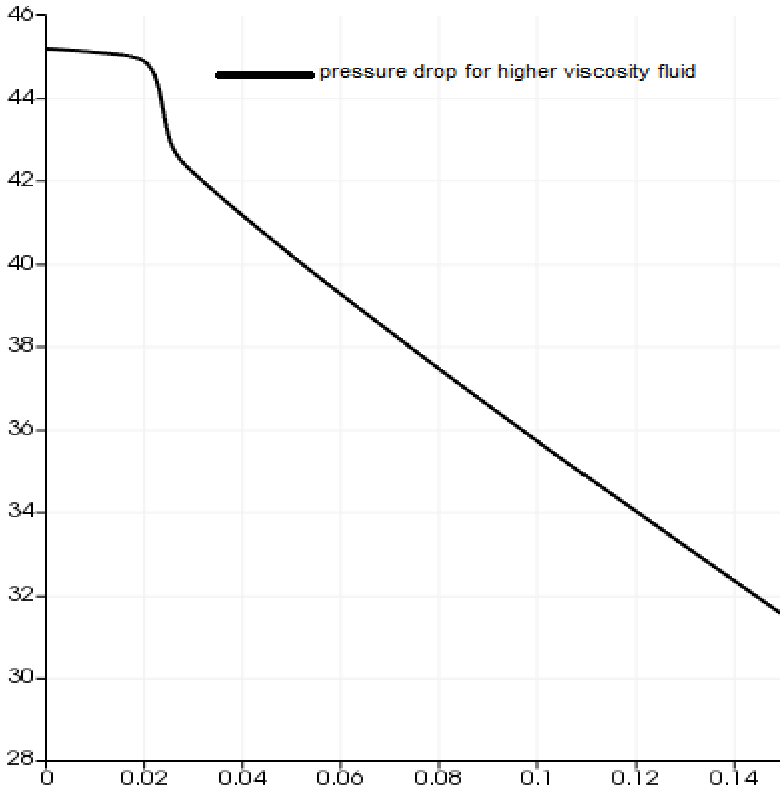

Figure 8. Pressure drop for higher recirculation

In these cases were possible to see that when the fluid with lower viscosity passes through the contraction its pressure drop is bigger than the higher viscosity one, this happens because its velocity increases fast according the Bernoulli principle. Also is possible observe that pressure necessary to do the higher viscosity fluid to flow is bigger what causes a greater need of energy.

4. CONCLUSIONS

During oils wells drilling has been used a fluid to obtain a better performance in this process. In this flow the drill geometry forces the fluid to pass through contractions regions generating phenomena that can be harmful for this process, as was said previously these effects are recirculation, pressure drop, *vena contracta* formation and etc.

In this work was simulated non-newtonian fluid flow in a sudden contraction varying the power law and consistency index, the main effect analyzed with the variation of these parameters was the recirculation's size in the corner of geometry upstream the contraction. The simulations showed that the power law and consistency index increase make the size of the recirculation was smaller and the decrease of the power law and consistency index increase the size of the recirculation.

Was possible to see that the control of viscosity parameters is a way to obtain the decrease of the recirculation, and this is very important because the recirculation is a phenomenon that influence at the energy of the flow.

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6. RESPONSIBILITY NOTICE

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