TURBULENT DISPLACEMENT FLOW IN ANNULAR SPACE

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Abstract. *The cementing process is an important step in the construction of oil and gas wells. During cementing, it is necessary to displace the drilling mud by the cement slurry. To avoid mixing of these liquids, spacer fluids are usually used. Therefore, it is common to have three or more liquids flowing through the eccentric annular space. Non-uniform liquid displacement may lead to severe problems to the well structure and safety. Hence, fluid properties and process condition should be designed to minimize non-uniformities on the displacement front. A complete analysis of the annular flow that occurs during cementing is extremely complex, because of the presence of different liquids that often present non-Newtonian characteristic and the flow is three dimensional and transient. In some cases, the flow in the lower viscosity liquid phase may become turbulent. A complete model has a prohibitive high computational cost. Simplified models are available in the literature and are used by the oil industry in commercial simulation software for cementing. The available models are not able to accurately describe turbulent flow regime. In this work, we extend the lubrication based model in cylindrical coordinates developed by Gomes and Carvalho (2010) to include turbulent flow regimes. The predictions agree with experimental observations that turbulent flow may lead to unexpected stable displacement front.*

Keywords: *Cementing Process, Lubrication theory, Turbulent flow, Annular space*

1. INTRODUCTION

The cementing process is a very important stage during the drilling of a new well. The cement not only ensures the adhesion between the casing and the rock, but also isolates and prevents the contamination of the interior of the well by water or other fluids that may be found in different zones.

During cementing, the cement slurry is pumped through the well, displacing the drilling fluids. In order to have a successfully cementing operation it is necessary to completely remove the drilling or spacer fluids and avoid mixing between them. If failures occur the structure and the safety of the well may be compromised. The Figure 1 illustrates different steps of a well cementing.

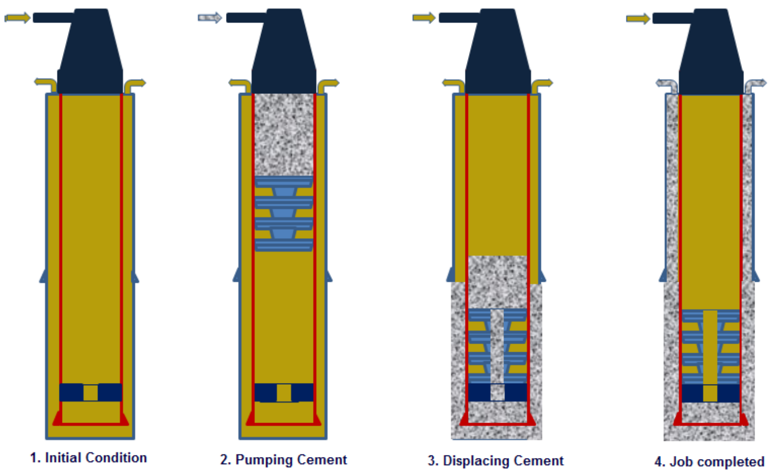

Figure 1. Stages during the cementing process.

There are several phenomena that can cause failures during cementing process. For example, the well geometry may complicate the full mud displacement. Besides, the rheology of the fluids, the flow rate and the pumped volume also influence the process efficiency. Therefore, it is necessary to study the effect of the process conditions on the displacement in order to avoid undesired behavior.

Modeling the cementing process is a complex task. This process involves different types of fluids, which often present non-Newtonian behavior. Moreover, the flow is three dimensional and transient. The full solution of the equation that describes the flow is extremely expensive. Hence, simplified models to describe the cementing process have been developed.

Bittleston *et al.* (2002) developed a model that considers the eccentricity of a well and uses a Cartesian coordinate system to represent the geometry of the annular space. The model is only accurate for radii ratio R_i/R_0 close to 1. An asymptotic method solves the 2D problem as a sequence of 1D problems. As discussed in the work, the main focus was to solve the problem with low computational cost without a major concern with the accuracy of the solution.

The work of Pina and Carvalho (2006) presented a model to describe the flow through annulus using lubrication theory and a cylindrical coordinate system. The model produces very accurate results for a larger range of radii ratio R_i/R_0. However, the analysis was restricted to simple phase laminar flow of Newtonian fluids.

The model developed by Gomes and Carvalho (2010) extended the previous work to study the cementing process as a 2D flow of non-Newtonian fluids using lubrication theory and a cylindrical coordinate system to describe the annular space. It was also limited to laminar flows.

In some practical applications, with low viscosity liquids, the displacement flow may become turbulent. It is important to have models that are able to describe these situations.

The goal of this work is to develop an asymptotic model to study the displacement of different liquids through an annular space in turbulent conditions. As done in previous models, lubrication theory is used to simplify the complete three dimensional set of differential equations to a single two dimensional equation that describes the pressure field.

2. MATHEMATICAL FORMULATION

As mentioned before, the flow is three dimensional and transient, with moving boundaries and one or more liquids may present non-Newtonian behavior. Therefore, a complete model has a prohibitive high computational cost.

Some aspects of the flow in the annular space that occurs during cementing have been previously discussed by Gomes and Carvalho (2010). As an extension of that work, the present research develops an asymptotic model based on the lubrication theory to study the displacement of different liquids through an annular space considering turbulent conditions. These turbulent conditions may have an important impact on the flow and, consequently, on the displacement efficiency.

In order to simplify the governing equations, lubrication theory was applied. The velocity profiles are used in the integrated mass conservation equation to obtain a differential equation that describes the pressure distribution of the flow $P(z,\theta)$:

$$\frac{\partial}{\partial z}\left[C_1\frac{\partial P}{\partial z}+C_2\right]+\frac{\partial}{\partial \theta}\left[C_3\frac{\partial P}{\partial \theta}+C_4\right]=0 \tag{1}$$

Where the functions C_i are defined as a function of local geometry and liquid properties:

$$C_1=\frac{1}{4\mu}\left[\frac{R_0^4-R_i^4}{4}-\frac{\left(R_0^2-R_i^2\right)\left(R_0^2+R_i^2\right)}{2}+\frac{\left(R_0^2-R_i^2\right)^2}{4\ln R_0/R_i}\right] \tag{2}$$

$$C_2=-\frac{\rho g z}{4\mu}\cos\alpha\,\frac{d\alpha}{dz}\left[\frac{R_0^4-R_i^4}{4}-\frac{\left(R_0^2-R_i^2\right)\left(R_0^2+R_i^2\right)}{2}+\frac{\left(R_0^2-R_i^2\right)^2}{4\ln R_0/R_i}\right] \tag{3}$$

$$C_3=\frac{1}{36\mu\left(R_0+R_i\right)}\left[2R_0^4+2R_0^3R_i+12R_0^2R_i^2\ln R_i/R_0-2R_0R_i^3-2R_i^4\right] \tag{4}$$

$$C_4=\frac{\rho g\cos\alpha\cos\theta}{36\mu\left(R_0^5+R_0^4R_i-8R_0^3R_i^2+8R_0^2R_i^2-R_0R_i^4-R_i^5\right)} \tag{5}$$

These constants are derived for laminar flow of Newtonian liquids and depend on the viscosity of the fluid μ. As it was done by Gomes and Carvalho (2010) for non-Newtonian liquids, turbulent flow is described here using the concept of equivalent Newtonian viscosity. The equivalent viscosity is the viscosity that a Newtonian fluid in laminar flow condition would have to have in order to yield the same local flow rate - pressure drop relationship of the turbulent flow. Using this concept, the equivalent Newtonian viscosity $\bar{\mu}$ of a turbulent flow is:

$$\bar{\mu} = \frac{R_0^2 T}{8} \left[-\frac{dP}{dx} \right]^{1/2} \frac{1}{\left(1 - \frac{R_i^2}{R_0^2}\right) \left[\frac{4(R_0 R_i)}{\rho f}\right]^{1/2}} \tag{6}$$

Where T is a geometric parameter and is defined as:

$$T = \left(1 - k^2\right) - \frac{\left(1 - k^2\right)^2}{\ln\left(1/k\right)}, k = R_i/R_0 \tag{7}$$

It is important to notice that the equivalent viscosity depends on the physical characteristics of the well, the density of the fluid, the local pressure gradient and the friction factor.

In this work, we used a modified Blasius (Fredrickson *et al.* (1958)) equation in order to evaluate the friction factor for turbulent flow in an annular space:

$$f = \frac{0,316}{\left[Re\left(\frac{1+k^2}{(1-k)^2} - \frac{1+k}{(1-k)\ln 1/k}\right)\right]^{0.25}} \tag{8}$$

The model is non linear since the functions C_i depend on the local pressure gradients and on the local friction factor. The iterative procedure used here to solve the non linear problem at each time step is the same one used by Gomes and Carvalho (2010), for non-Newtonian flow.

3. RESULTS

The effect of turbulence in the displacement efficiency is illustrated in the following example. A high viscosity liquid ($\mu_1 = 1.02$ Pa.s) placed in a vertical concentric annular space ($R_i = 0.11$ m, $R_0 = 0.15$ m, $L = 100$ m) is displaced by a low viscosity liquid ($\mu_2 = 4.8 \times 10^{-4}$ Pa.s). Because of the very high viscosity ratio, the displacement process is expected to be unstable, leading to non-uniform displacement fronts.

Figure 2 shows the evolution of the displacement front at low and high flow rate such that in the former the flow is laminar and in the later, the flow of the low viscosity liquid (2) becomes turbulent. The results clearly show the stabilization achieved by considering the turbulent flow conditions.

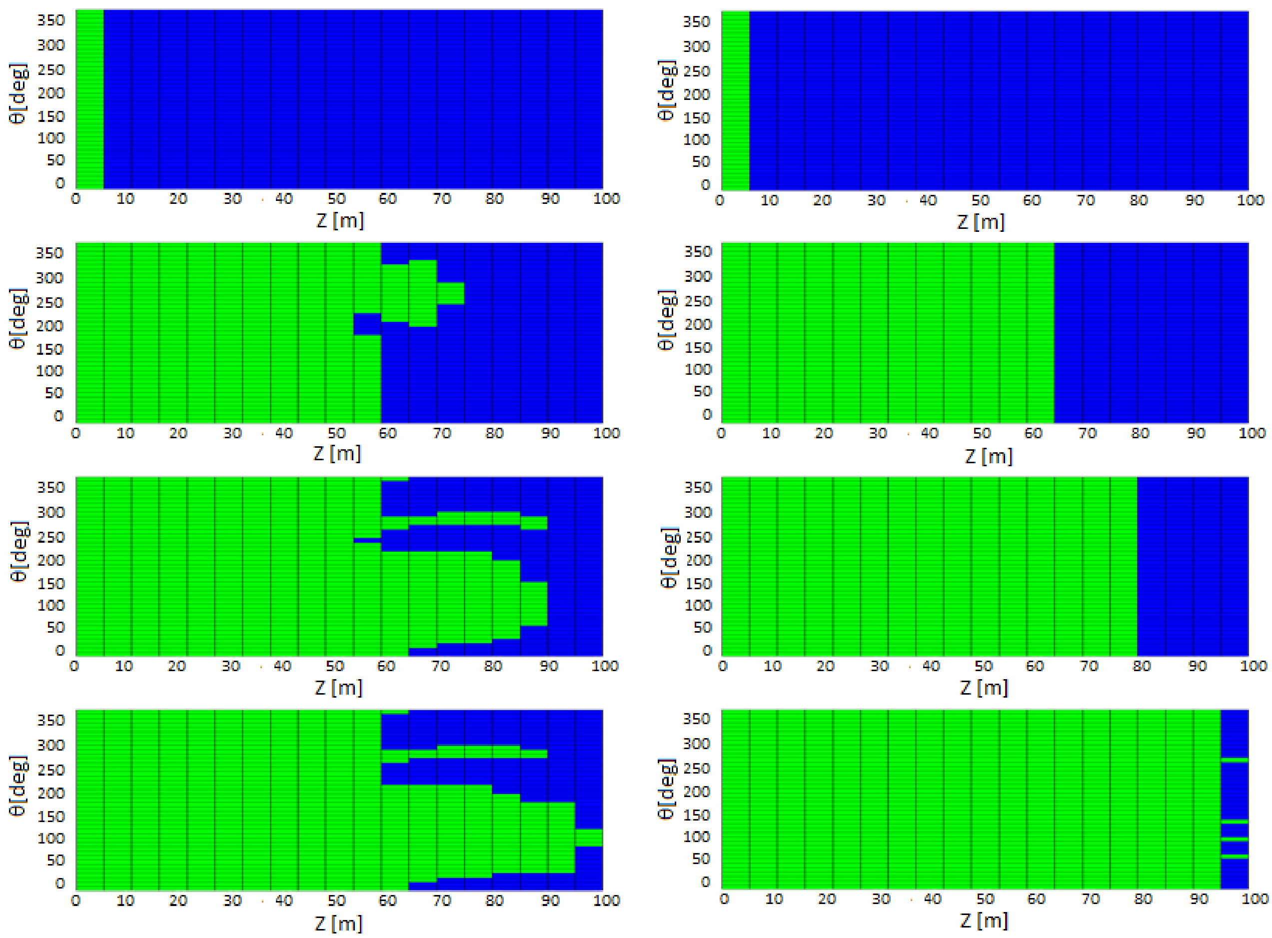

Figure 2. Comparative results considering only laminar flow (left column) and considering turbulent flow (right column).

In order to analyse the bahavior of the turbulent displacement in a vertical eccentric annular space, a second example is presented. In this example, a 0.04 Pa.s viscosity liquid is displaced by a 0.004 Pa.s viscosity liquid. The eccentricity was considered constant along the annular space and equal to 1.8mm in relation to y axis ($R_i = 0.04$ m, $R_0 = 0.08$ m, $L = 1192$ m).

Results at low ($Q_1 = 0.001$ m^3/s) and high ($Q_2 = 0.05$ m^3/s) flow rate are presented in Figure 3. At low flow rate the flow is laminar and at high flow rate it becomes turbulent.

Figure 3 shows the evolution of the eccentric annular displacement. Even though the viscous fingering phenomenon can be noticed in both cases, the displacement is more stable in the presence of the turbulent regime.

This stabilization effect agrees with experimental evidences reported by Aranha *et al.* (2012).

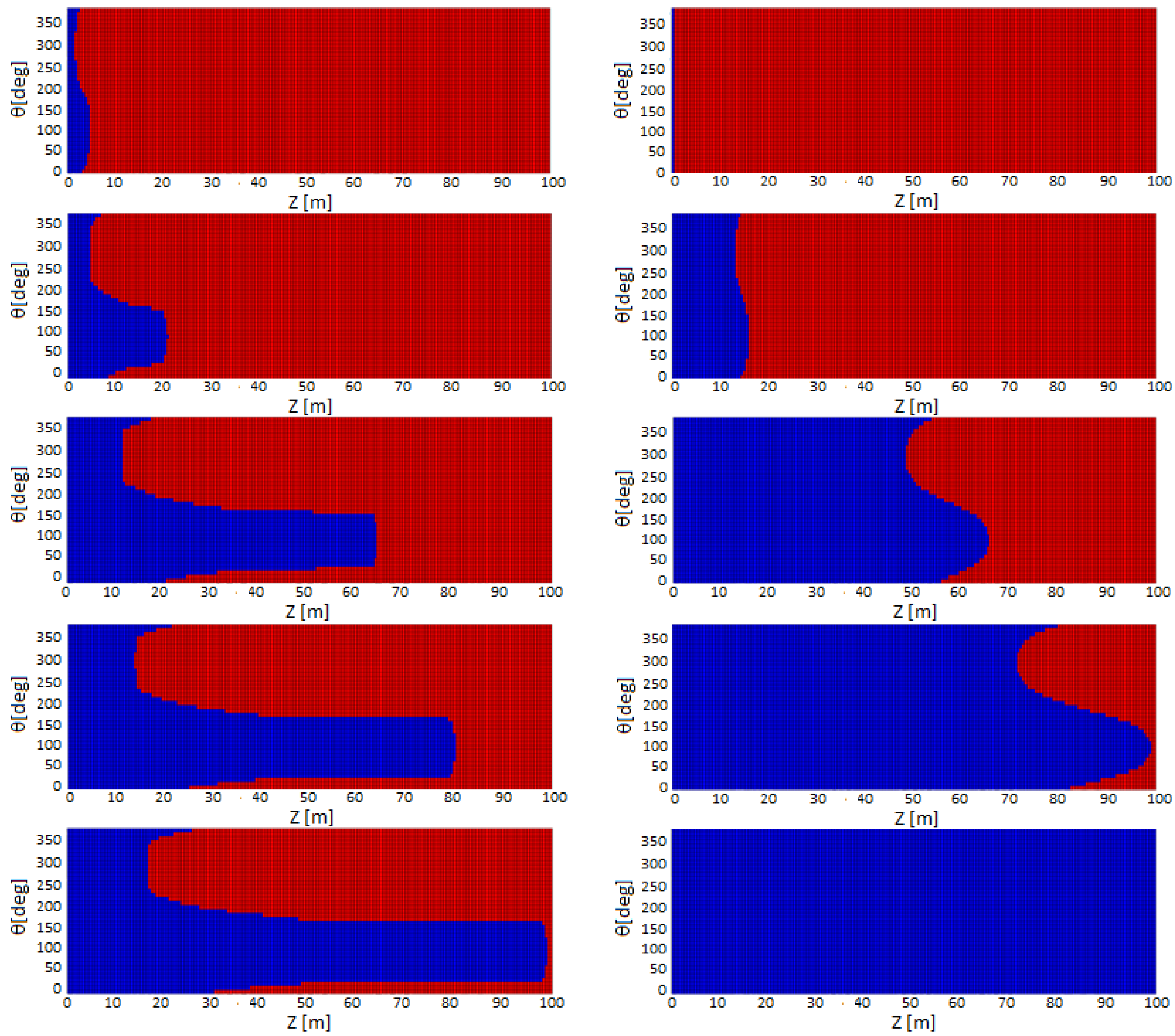

Figure 3. Comparative results for laminar (left column) and turbulent flow (right column) in a eccentric annular space.

4. FINAL REMARKS

A lubrication based model for the displacement of a liquid by another liquid inside an annular space in turbulent flow condition is presented. It is an extension of previous development of a model for displacement of non-Newtonian liquids under laminar flow conditions. The results show not only the importance of considering turbulent conditions in turbulent flows, but also the stabilization effect of turbulent flow, which agrees with experimental observations.

5. REFERENCES

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