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BUOYANCY-DRIVEN FLOWS OF TWO IMMISCIBLE NEWTONIAN LIQUIDS IN A VERTICAL TUBE

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Abstract. *Plug cementing is an essential operation performed under a variety of well conditions. In general, cement plugs are set for sidetracking, lost-circulation control, zonal isolation, and well abandonment. The cement plugs rarely are found at the intended depth because the cement slurry usually is heavier than the well fluid. Failures are due primarily to migration of the denser fluid downward through the well fluid upon which it is placed. The aim of the research reported in this paper is to develop an understanding of the process of plugging operation in vertical wells. To this end, we performed an experimental and theoretical study of the buoyancy-driven flow of two immiscible Newtonian fluids initially placed in a vertical tube such that the heavier and more viscous one is on top. Since both fluids are Newtonian, the situation is always unstable, i.e., the fluid on top will always flow downwards and displace the bottom fluid upwards, so that the relative positioning tends to invert. The influence of the governing parameters on the interface stability and on the speed of inversion was investigated. Flow visualization was performed with a digital camera, and inversion velocities were obtained through image analysis. Preliminary results show that inversion speed decreases as the tube diameter is increased, increases as the viscosity ratio is increased, and also increases as the density ratio is increased.*

Keywords: *Buoyancy-driven flow, Cement plug, Interface stability*

1. INTRODUCTION

1.1 Motivation

The operation of plugging oil wells is very common in the oil industry and practiced by several reasons, such as sidetracking, lost-circulation control, zonal isolation, and well abandonment.

The aim of the cement plug is to form an impermeable hydraulic seal and a hard mechanical barrier. The cement is placed so as to completely fill the well bore cross-section, either directly on top of drilling mud or above a specially designed viscous pill fluid.

Setting open hole cement plugs has been a difficult task in oil industry. The cement plugs rarely are found at the intended depth because the cement slurry usually is heavier than the well fluid.

The success of the operation is related to the capability of the cement plug to remain on the top of the well (drilling) fluid, while it sets, which can take several hours. However, this situation is highly unstable, since in general the cement density is larger than that of the drilling fluid so that the cement tends to flow downwards (until it develops a sufficient gel strength), due to buoyancy effects. If the displacement occurs in excess, a contamination between fluids will result in an unsuccessful operation. Figure 1 presents an illustration of the plug cementing efficiency. The left image shows the ideal case in which the cement is positioned above the drilling fluid. The right image illustrates a case with cement migration and consequently there is a failure in the operation.

1.2 State of art

1.2.1 Exchange flows and Rayleigh-Taylor instability

The Rayleigh-Taylor instability appears in many natural phenomena and technical applications (Sharp (1984)). In its simplest form, the onset of the instability occurs when a lighter fluid pushes a heavier one, as in the case of plugging oil wells. The general features are for interfacial protuberances to grow and interact in complicated ways. Although several factors, such as compressibility and viscosity, may modify the behavior, it is the density ratio that plays the most important role, but even for the simplest case of inviscid, incompressible fluids, a full treatment of the late stages of the interfacial motion is still beyond numerical studies. Consequently, the focus of most studies has been on the initial stages of the

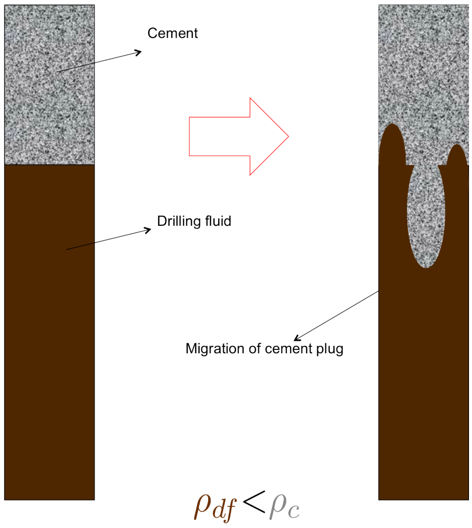

Figure 1. Flow behavior of cement plug: ideal case x operation failure

instability under ideal circumstances.

The steady flow regime of a viscous, buoyancy-driven exchange flow in a vertical pipe is not obvious. The initial evolution of two fluids that are stratified with the dense fluid above the less dense fluid presente an unstable equilibrium: a small perturbation of the interface increases the perturbation indefinitely with the heavier fluid trying to go down and the lighter fluid trying to go up.

Previous experiments suggest that core-annular flow (CAF) with the less viscous fluid in the core may be the dominant regime (Stevenson and Blake (1998); Huppert and Hallworth (2007)). This is in contrast to a unidirectional two-fluid flow in pipes where the preferred geometry is core-annular flow with the more viscous fluid occupying the core and the less viscous fluid migrating to the walls of the pipe, although these flows are rarely, if ever, stable (Kerswell (2011)). It may be that bi-directional CAF with the viscous fluid in the core is unstable to small perturbations in the flow. It is not clear what sets the geometry of the buoyancy-driven vertical exchange flows, in particular whether initial conditions such as which fluid initially fills the pipe, or the mode of the Rayleigh-Taylor instability at the onset of the experiment, set the long-term geometry of the flow.

Stevenson and Blake (1998) conducted laboratory experiments to study the transient exchange flow of viscous fluids in a vertical pipe, where pipes which initially contained two fluids, stratified with the less dense and less viscous fluid on top, were overturned. They found that the less dense fluid rose up the centre of the pipe as a finger with a radius of approximate 60% of the pipe. However, the geometry of the flow below the position of the initial horizontal interface depended on viscosity ratio.

Arakeri *et al.* (2000) and Huppert and Hallworth (2007) have included fluid reservoirs at the ends of the pipes, allowing longer exchange flow durations, although the flows are never strictly steady because the contents of the reservoirs, and hence the pressures in the pipe, change with time.

Arakeri *et al.* (2000) studied natural convection phenomena in a vertical tube due to an unstable density difference. An open-topped tank containing salty water with a removable bung blocking a hole in the base was connected to a pipe and a lower tank, which were both filled with distilled water; hence, the experiments are restricted to viscosity ratios of approximate 1. Arakeri *et al.* (2000) do not report core-annular flow; rather, they observed ‘half-and-half flow’, helical flow, unsteady-laminar flow and turbulent flow, with the flow regime depending on the pipe diameter, pipe length, and density difference.

Huppert and Hallworth (2007) allowed pairs of both miscible and immiscible fluids to exchange in a vertical pipe between two larger reservoirs. The upper reservoir, which had a sealed lid, and the pipe attached beneath it were initially filled with the denser fluid, and the lower reservoir was initially filled with less dense fluid. They state that the predominant flow behavior was concentric CAF with the less viscous fluid occupying the core, but they do note that flow ’may be highly irregular and break into discrete blobs or partially adhere to the sidewall of the conduit’. They also present a theoretical model for laminar bidirectional CAF in a vertical pipe.

Beckett *et al.* (2011) have presented an experimental study exploring the range of possible flow regimes for low-Reynolds-number exchange flow, over a range of viscosity ratios from 2 to 1180, in a vertical pipe between two reservoirs. They observed more than one type of solution depending on the exact density and viscosity ratios of the two fluids. They find that for fluids with a small viscosity ratio ($\leq \mathcal{O}(100)$), the flow typically asymptotes to an axially independent ‘side-by-side’ (SBS) state where each fluid hugs a side of the tube so that their interface starts and finishes at the tube wall. For larger viscosity ratios, however, the late-time flow takes an axially independent axisymmetric CAF, with the less dense fluid ascending in the core and the more dense descending around the outside so that their interface is a closed circle concentric with the tube.

Kerswell (2011) investigated the steady, coaxial flow of two immiscible fluids of different densities and viscosities in a straight vertical cylindrical tube such that their volumetric fluxes balance. Assuming that the interface between the two fluids is either a circular arc or a full circle, the main conclusion is that the flow which optimizes the volumetric flux over all possible pressure gradients is always asymmetric. For viscosity ratios lower than 4.6, he concludes that SBS is the regime with the global maximum volume flux. For viscosity ratios greater than 4.6, it is eccentric CAF with the more viscous fluid in the core that is observed.

Sweeney *et al.* (2013) examined how two fluids of different densities displace each other in a vertical cylinder when released from an unstable initial configuration. The Rayleigh-Taylor linear instability problem was investigated in order to interpret the experimental work from Stevenson and Blake (1998), Arakeri *et al.* (2000), Huppert and Hallworth (2007), and Beckett *et al.* (2011). They find a good agreement between what the linear stability analysis predicts and what the flow actually looks like near to the initial interface, as reported by Beckett *et al.* (2011) and inferred from Stevenson and Blake (1998). The fact that the long-time flow can have a different axial symmetry to that of the original instability indicates that the initial Rayleigh-Taylor instability does not uniquely determine the form of the long-time flow configuration, although it may well strongly influence it.

1.2.2 Optimization of operation for plugging oil wells

Several works in the literature study this problem, aiming to obtain the optimal conditions for the cementing operations, i.e., complete fulfillment of the cross-section with the cement slurry.

Smith *et al.* (1984) observed that the most common causes of plug failure is the heavy weight of the cement plug, and the practice of using open-ended drill pipe. They performed experiments to evaluate the instabilities generated by high density ratios between the cement plug and the drilling fluid, and suggested a new placement technique to improve the stability of the operation. The authors also observed that rheology can also contribute to improve the stability.

Sutton *et al.* (1986) discussed the plug operation process and developed experiments to visualize the cement flow in plug operation, using cement plug placement method with a reactive fluid system. The authors observed some advantages with the analyzed method, which provide a means of successful operations even in severe well conditions.

Munro *et al.* (1996) show a real case of plug setting, using coiled tubing operations in sub-sea conditions. Calvert and Smith (1994) presented a critical review of techniques for well plugging and abandonment. Harestad *et al.* (1997) developed and tested a tool to improve the cement plug placement. Gomez *et al.* (2002) presented a new method for plugging wells, using chemical packers. Tests were performed, showing the viability of the method.

The flow stability in the process of cement plug in inclined wells is analyzed in Frigaard (1998), Crawshaw and Frigaard (1999), and Fenie and Frigaard (1999). Frigaard and Ngwa (2004) analyzed the flow of two Bingham fluids, to simulate the plug cementing process in a slot, and provided a simplified model for the plug cementing process, using perturbation methods to obtain asymptotic approximations for interface velocities and flow rate. Crawshaw and Frigaard (1999) obtained theoretical and experimental results for the same situation, and estimated the yield stress required for stabilization of the cement plug. Fenie and Frigaard (1999) solved the problem numerically, also using two Bingham fluids, and obtained the interface propagation. They observed the presence of shocks, and studied the effect of yield stresses and plastic viscosities in their behavior. Frigaard and Ngwa (2004) analyzed the slow slumping motion of a cement plug in a near horizontal well, using a lubrication theory, and derived expressions for the length of the interface between the two fluids.

Some works present and discuss experimental results obtained in practical situations, while others develop simplified methods to obtain conditions for stability. So far, some methods/conditions were proposed to improve the operation, but many practical situations are still problematic, and further investigations are needed.

1.3 Objectives

The aim of this paper is to understand the physics of the buoyancy driven flow. The combination of governing parameters which ensure stability have never been satisfactorily established and it is this gap which is addressed by the current work.

We performed an experimental and theoretical study of the buoyancy-driven flow of two immiscible Newtonian fluids in a vertical tube such that the heavier and more viscous one is on top.

We intend to propose a characteristic velocity based on simple flows that present solution / analytical approach.

2. METHODOLOGY

This research has the purpose of developing a process for plugging operation in vertical wells. To this end, we performed an experimental and theoretical study of the buoyancy-driven flow of two immiscible Newtonian fluids initially placed in a vertical tube such that the heavier and more viscous one is on top. Since both fluids are Newtonian, the situation is always unstable, i.e., the fluid on top will always flow downward and displace the bottom fluid upwards, so that the relative positioning tends to invert.

The influence of the governing parameters on the interface stability and on the speed of inversion was investigated. Flow visualization was performed with a digital camera, and inversion velocities were obtained through image analysis.

The evolution of the shape of the interface was analyzed through a digital camera, as a function of the geometric, dynamic and rheological parameters.

Figure 2 depict the flow visualization apparatus. The experimental apparatus consists of an acrylic tube, a refrigerated/heated bath circulator, a digital SLR camera (Canon EOS-7D), a thermocouple, and a stopwatch. Depending on the desired blob size, a peristaltic pump or a pipette is used.

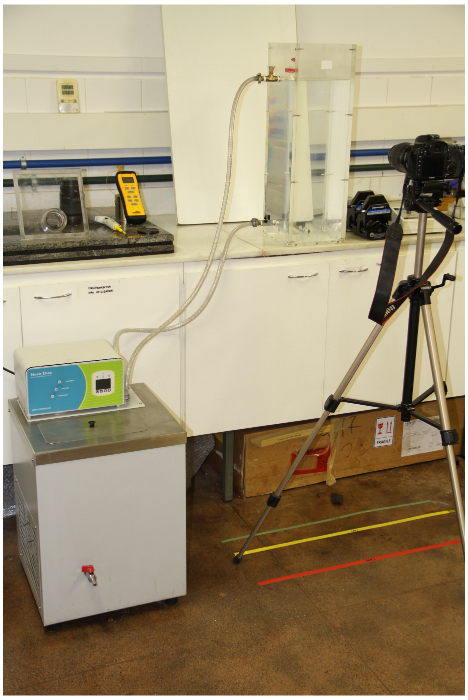

Figure 2. Flow visualization apparatus

The procedure consists on filling a tube with a 60% aqueous ethanol solution, and a mineral oil is used as the driving fluid in the form of blobs. Different tubes and blobs diameters values are investigated to determine the conditions under which inversion occurs. Tube diameters of 16, 20, 22, 24, 26, 32, 34 and 44mm were investigated.

3. DATA REDUCTION

3.1 Dimensionless parameters

There is no universal convention in the literature for presenting the results so a original contribution concerns the proposed dimensionless parameters. The problem is non-dimensionalized in accordance with de Souza Mendes (2007).

The main governing parameters that arise are:

$$\Pi_1 = \frac{L}{D} \tag{1}$$

$$\Pi_2 = \alpha = \frac{d}{D} \tag{2}$$

$$\Pi_3 = \Delta\rho^* = \frac{\Delta\rho}{\rho_1} \tag{3}$$

$$\Pi_4 = \mu^* = \frac{\mu_2}{\mu_1} \tag{4}$$

$$\Pi_5 = Ga = \frac{{\rho_1}^2 D^3 g}{{\mu_1}^2} \tag{5}$$

$$\Pi_6 = Re = \frac{\rho_1 V D}{\mu_1} \tag{6}$$

$$\Pi_7 = La = \frac{\rho_1 D \sigma}{{\mu_1}^2} \tag{7}$$

The parameters that appear in the above equations are: the tube length, L, the tube diameter, D, the blob diameter, d, the density, ρ, the Newtonian viscosity, μ, the mean flow rate, V, and the interfacial tension σ. The fluid positioned above, denser and more viscous, is represented by the index 2 and the fluid positioned below by the index 1. The Galileo number, Ga, it may be regarded as proportional to gravity forces divided by viscous forces. The Reynolds number, Re, is defined as the ratio of inertial forces to viscous forces and consequently quantifies the relative importance of these two types of forces for given flow conditions. The Laplace number, La, is a dimensionless number defined as the ratio of surface tension to viscous forces. It is noteworthy that the effects of surface tension are negligible in field operations. So that's a concern about the employed model.

3.2 Image treatment

Image analysis provides several pieces of quantitative information like boundary motions. A methodology for image processing was developed based on the color histogram of the pictures. Through a evidencing of the difference in the color spectrum of the fluids is possible to identify the interface.

The original pictures were transformed into binary images (Fig. 3), where the black and white pixels are representing a 60% aqueous ethanol solution and mineral oil, respectively. From tracing the shape of the interface, was determined the inversion velocity, V.

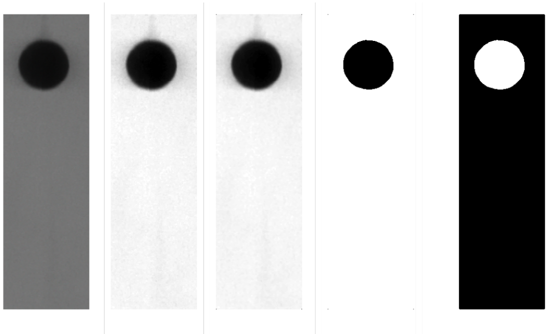

Figure 3. Image treatment main steps

4. SIMILARITY: SIMPLE FLOWS X ANALYTICAL SOLUTIONS

In order to simplify the problem and evaluate a proposal for the critical velocity, some analytical simulations have been implemented to compare the predicted results against experiments. Simulations were performed considering spheres falling in infinite medium, spheres falling inside a tube, cylinder falling within a tube and Hagen-Poiseuille flow.

The terminal velocity of a particle depends on several factors, such as particle format, density, and orientation, bulk properties, size and shape of the reservoir, etc. The selection of cases to be simulated was based on geometric similarity of simple engineering problems with field challenges.

Hagen-Poiseuille flow simulates the flow of one fluid in free fall into an empty tube, i.e., no extra resistance due to the absence of a fluid already filling the tube. It would be the case of a flow dominated by gravitational effects. Equation 8 illustrates Hagen-Poiseuille flow.

$$V_{HP} = \frac{\Delta \rho g D^2}{32\mu} \tag{8}$$

The case of a falling cylinder within a tube filled with a Newtonian fluid is somewhat more conservative, because there is an extra drag force acting on the cylinder. Equation 9 shows the terminal velocity for this case, being $\alpha = \frac{d}{D}$.

$$V_{Cil} = \frac{\Delta \rho g d^2}{16\mu_1}\left(\ln\frac{1}{\alpha} - \frac{1-\alpha^2}{1+\alpha^2}\right) \tag{9}$$

The choice of spheres and drops falling within a tube filled with a Newtonian fluid has been motivated by the fact that we do not know exactly how the cement flows into the tube during the plugging process. Considering a process with mass conservation, if the cement flow downwards, the well fluid should move up. However, it is not obvious how this flow occurs. The cement may go down the tube through the center, by one side or disorderly. The form of this flow depends on geometric, dynamic and rheological parameters. Among the cases investigated, drops and spheres inside the tube are the most conservative cases.

Equation 10 represents the terminal velocity of a rigid sphere falling in an infinite medium containing a Newtonian fluid. Equation 11 represents the terminal velocity of a rigid sphere falling within a tube filled with a Newtonian fluid. It should be applied a correction factor, f, in the fall speed in an infinite medium.

$$V_{T_\infty} = \left(\frac{\Delta\rho g \pi d}{3\rho_1 C_D}\right)^{0.5} \qquad (10)$$

being $CD = f(Re) = f\left(\frac{\rho_1 V_{T_\infty} d}{\mu_1}\right)$ described graphically.

$$V_T = f \cdot \left(\frac{\Delta\rho g \pi d}{3\rho_1 C_D}\right)^{0.5} \qquad (11)$$

5. RESULTS AND DISCUSSION

5.1 Fluid properties

Tests were made with two Newtonian fluids such as the fluid above is denser and more viscous. All tests were performed at 24°C with a 60% aqueous ethanol solution (ρ = 908.9 Kg/m^3 and μ = 2.31mPa.s) and soybean oil (ρ = 917.7 Kg/m^3 and μ = 51.67mPa.s). Thus, the results are valid for a single pair of viscosity and density ratios.

5.2 Flow visualization results

Figure 4 shows an example of images obtained using the pump and Fig. 5 shows an example of results obtained with the pipettes.

Figure 4. 60% aqueous ethanol solution and soybean oil, positioned with a pump, at 24°C and D = 26mm

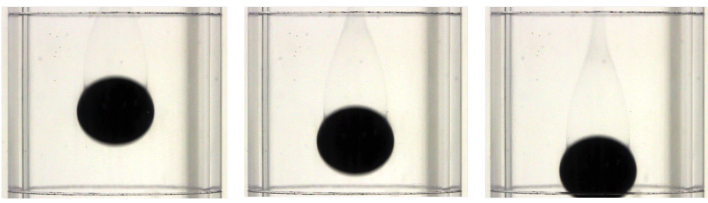

Figure 5. 60% aqueous ethanol solution and soybean oil, positioned with a pipette, at 24°C and D = 26mm

Figure 6 shows the experimental results in a graphical form. The terminal velocity is presented as a function of α. It can be seen that the maximum point of the curve, for every tube diameter, is around α = 0.45. The curve points above α = 0.80 are represented by plugs falling, i.e., in such instances the interface is completely filled with less dense fluid in the initial test time.

There is a measurement uncertainty associated with these results due to pixel resolution and number of frames per second provided by the camera. It can be seen that there is a pattern when considering all tube diameters: an increase in terminal velocity with blob diameter up to a maximum value and then a decrease in a manner similar to a parabola.

With regard to the parameters described in Eqs. 1-7, μ^* and $\Delta\rho^*$ were maintained fixed because only one pair of fluids, in constant temperature, were used. Thus, μ^* = 17.51 and $\Delta\rho^* = 9.68 \cdot 10^{-3}$ for all cases investigated. The

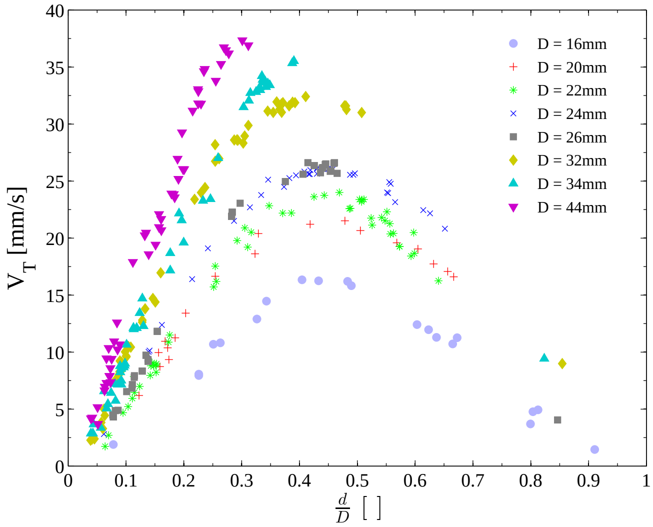

Figure 6. Drops terminal velocity as a function of α

geometric values were also maintained constants: L / D = 15 for drops falling and L / D = 5 for plugs falling into the tube. The other dimensionless parameters are all functions of D.

All cases presented inertia effects because $Re(D) > 1$. The Galileo number has an order of magnitude of 10^7, so there is predominance of gravitational effects to viscous effects. Laplace number is also much higher than 1, thus it is observed that interfacial effects are also dominant to viscous effects.

The main purpose of the analysis of experimental results, in parallel with simulations of analytical solutions, is to present a critical velocity that can represent the terminal velocity of a cement plug. The proposal is to identify a dimensionless characteristic velocity that is close enough to the field values to serve as an estimation for determining the plug positioning. It is also important to chose a conservative value, so that characteristic velocity is lower than the velocity field.

Based on this motivation, some comparisons were made. For practical purposes of results presentation, comparisons will be presented for a unique tube diameter, i.e., D=32mm. Figure 7 demonstrates tests repeatability.

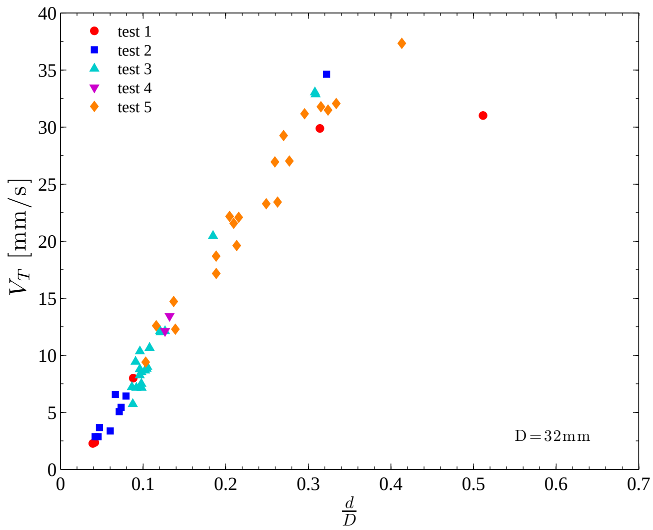

Figure 7. Tests repeatability for D=32mm

Figure 8 shows a comparison between analytical solutions, described previously, against experimental results considering D = 32mm. Figure 9 shows the corresponding maximum velocities for each case presented in Fig. 8. Experimental results and sphere falling in the tube (with correlations due to wall effects) has the same order of magnitude. The velocity of the falling cylinder is around 5 times the velocity observed in experimental case. Modeling the problem by Hagen-Poiseuille equation proved to be inefficient because it is orders of magnitude greater than the experimental case.

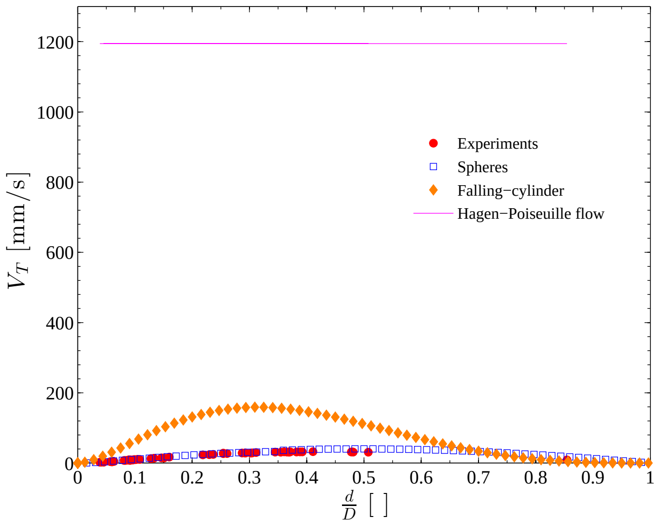

Figure 8. Comparison between analytical solutions against experimental results considering D = 32mm

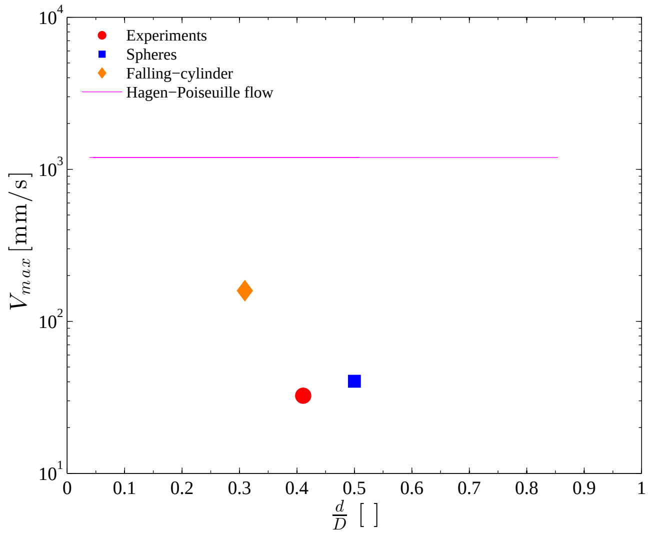

Figure 9. Comparison between analytical solutions against experimental: maximum velocities for D=32mm

It is noteworthy that the experimental case, which has different blob diameters falling within a tube, is more conservative than the real case. The maximum terminal velocity is always greater than the maximum velocity of the plugging operation. Thus, there is a good approximation of critical velocity of a heavier Newtonian fluid falling over a less denser fluid in a tube.

6. FINAL REMARKS

The aim of the research reported in this paper is to develop an understanding of the process of plugging operation in vertical wells. To this end, we performed an experimental and theoretical study of the buoyancy-driven flow of two immiscible Newtonian fluids in a vertical tube. Initially, the heavier and more viscous one is placed on top. Since both fluids are Newtonian, the situation is always unstable, i.e., the fluid on top will always flow downwards and displace the bottom fluid upwards, so that the relative positioning tends to invert.

A systematic study of the influence of the parameters that govern this flow is under way. Flow visualization was performed with a digital camera, and inversion velocities were obtained through image analysis.

Preliminary results shows that inversion speed decreases as the tube diameter increases. On the contrary, inversion speed increases with increasing viscosity and density ratios. The terminal velocity of a rigid sphere falling within a tube filled with a Newtonian fluid is a good approximation to estimate a characteristic velocity for cement plugs operations.

7. ACKNOWLEDGEMENTS

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