Viscoplastic Fluid Displacement Flow in Pipes: the Effects of Pipe Axial Rotation

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Abstract—This study investigates experimentally the influence of a pipe axial rotation on the buoyant miscible displacement flow of a Newtonian fluid by a viscoplastic fluid in a vertical pipe. Within the range of operational flow and fluid parameters examined in this study, the emergence of separation and non-separation flow regimes was observed as the heavy fluid was imposed. The effects of the pipe axial rotation on these flow regimes and front velocities were compared. The results indicate that the addition of axial rotation to the pipe at low values of the imposed flow rate can result in a transition from the separation regime to the non-separation regime. However, for high values of the imposed velocity, the displacement flow regime remains largely unchanged when the pipe axial rotation is applied. Additionally, the displacement front velocity ($V_f$) decreases in the domain where the separation regime occurs when rotational speed is increased.

Keywords: Miscible displacement flows; Non-Newtonian fluids; Pipe axial rotation

I. INTRODUCTION

Displacement flows are prevalent in natural and industrial phenomena, especially in the oil and gas industry, e.g. the primary well cementing [1]. A displacement flow simply describes removing/displacing an in-place fluid by injecting another fluid with different properties. Such a flow has been widely investigated in confined geometries, such as pipes, for both Newtonian and non-Newtonian fluids [2, 3, 4]. Besides the rheological effects of the fluids, many effective parameters such as the viscosity and density of the fluids (in other words the physical properties of the fluids), the geometry configuration (pipe, annulus, etc.), the geometry movement (oscillation, axial rotation), the operational conditions in terms of the imposed velocity, the geometry inclination, etc., highly influence the displacement flow, leading to the development of a variety of flow regimes. The combined effects of the aforementioned parameters on the buoyant miscible displacement flows in the stationary vertical pipes are studied in detail in the literature [5, 6], both experimentally and numerically. In addition to effective fluid properties and flow parameters, on-site tests and various theoretical, experimental, and numerical studies have demonstrated the positive effects of pipe rotation on displaced fluid removal efficiency [7, 8, 9], especially for primary well cementing applications. Modeling the effects of the density difference between fluids indicates that the buoyancy force is relatively weakened by applying pipe axial movement [10], resulting in improving the in-place fluid displacement. However, despite its potential to enhance displacement efficiency, the use of rotation in industry is limited due to a lack of theoretical and fundamental knowledge regarding its effects on displacement flows. In fact, fewer than 6% of wells in the oilfield in North America utilize pipe (casing) movement to improve displacement flows in primary well cementing applications [11].

In this work, we examine displacement flows of a Newtonian fluid by a viscoplastic fluid in an axially rotating pipe and are motivated by two gaps in the literature. First, as previously mentioned, there is a general lack of knowledge regarding the effects of pipe rotation on displacement flows. Second, previous studies have largely focused on the displacement flow of viscoplastic fluids by Newtonian fluids [7], with only a few investigating the displacement of a Newtonian fluid by a viscoplastic fluid [12, 13]. Given the poorly developed state of the literature on these two aspects, we seek to experimentally study the buoyant miscible displacement flow of a Newtonian fluid (water) by a viscoplastic fluid (Carbopol solution) in a vertical pipe with axial rotation, with potential applications in the primary well cementing process [1].

II. EXPERIMENTS

The schematic of the experimental setup of the current study is shown in Fig. 1. The setup consists of a transparent acrylic pipe, with the inner diameter of 19.05 (mm) and the length of 3 (m). The pipe is separated by an automated pneumatic gate valve (VAT, Inc) into two sections of 0.7 (m) and 2.3 (m) from the top. Due to image capturing limitations, we are only able to collect data from 1 (m) below the gate valve. The stable opening and closing of the gate valve and pipe rotational speed ($\omega$) are powered by a stepper motor and various connectors, controlled by a custom-written program. To fill the lower part of the pipe below the gate valve, a reservoir located at a high position is used, to fill the pipe with the light Newtonian fluid (deionized water-sugar solution) via gravity. The upper part of the pipe is filled with a viscoplastic heavy fluid (Carbopol solution, Carbomer 940, Making Cosmetics Co.), colored by ink, via a gear pump at small pumping rates (Ismatech 405A), to avoid any property alterations. During the experiments, a fixed, stable imposed flow rate, $V_f$, is adjusted by this pump. For each experiment, the pump starts to impose the heavy fluid into the
pipe when the gate vale is opened, in order to remove the light fluid. The properties of fluids and dimensions of the experimental setup are summarized in Tab. 1.

A wide angle lens digital camera (Basler acA2040 with 212 gray-scale levels) is utilized to capture the flow development, and it is connected to the computer to deliver/record the experimental images. To make the Carbopol solution, Carbopol powder is initially mixed with deionized water-sugar solution and then the mixture is neutralized with sodium hydroxide (NaOH), based on established methods [13]. A digital rheometer (DHR-3 TA Instrument) with a parallel-plate geometry with the diameter of 40 (mm) and the mean gap of 1 (mm) is utilized. To avoid any wall slip effects at low shear rates, fine sandpapers are attached to the surface of the plates as rough surfaces [13]. The flow curve of the Carbopol solution, obtained from the rheometer measurements, is illustrated in Fig. 2. The rheological properties can be well fitted by the Herschel-Bulkley model [13]:

\[
\begin{align*}
\hat{\tau} &= \tau_y + \hat{\kappa}\hat{\gamma}^n, \\
\hat{\gamma} &= 0, \\
\hat{\tau} &\leq \hat{\tau}_y
\end{align*}
\]  

(1)

where \(\hat{\tau}\) is the shear stress, \(\hat{\gamma}\) the shear rate, \(\hat{\tau}_y\) the yield stress, \(\hat{\kappa}\) the consistency index, and \(n\) the power law index. Additionally, the effective viscosity of the heavy fluid can be described by:

\[
\hat{\mu}_H = \hat{\tau}_y \left(\frac{V_0}{R}\right)^{-1} + \hat{\kappa} \left(\frac{V_0}{R}\right)^{n-1}
\]  

(2)

Tab. 1 and Tab. 2 present the ranges of these parameters for our Carbopol solution sample, prepared for the experiments.

### TABLE I. DIMENSIONAL PARAMETER RANGES AND DEFINITIONS.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Name</th>
<th>Range or value</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\hat{\omega}) (rpm)</td>
<td>Rotational speed</td>
<td>0 – 90</td>
</tr>
<tr>
<td>(\hat{V}_e) (mm/s)</td>
<td>Mean imposed flow velocity</td>
<td>0.91 - 20</td>
</tr>
<tr>
<td>(\hat{\rho}_H) (kg/m³)</td>
<td>Density of heavy fluid</td>
<td>1017.20</td>
</tr>
<tr>
<td>(\hat{\rho}_L) (kg/m³)</td>
<td>Density of light fluid</td>
<td>997.70</td>
</tr>
<tr>
<td>(\hat{\mu}_H) (Pa.s)</td>
<td>Viscosity of heavy fluid</td>
<td>2.55 – 41.57</td>
</tr>
<tr>
<td>(\hat{\mu}_L) (Pa.s)</td>
<td>Viscosity of light fluid</td>
<td>0.001</td>
</tr>
<tr>
<td>(\hat{g}) (m/s²)</td>
<td>Gravitational acceleration</td>
<td>9.81</td>
</tr>
<tr>
<td>(\hat{R}) (mm)</td>
<td>Pipe radius</td>
<td>9.52</td>
</tr>
<tr>
<td>(l) (m)</td>
<td>Studied domain length</td>
<td>1</td>
</tr>
<tr>
<td>(\hat{\tau}_y) (Pa)</td>
<td>Yield stress</td>
<td>4.11</td>
</tr>
<tr>
<td>(\hat{\kappa}) (Pa.sⁿ)</td>
<td>Consistency index</td>
<td>0.86</td>
</tr>
<tr>
<td>(\hat{D}_m) (m²/s)</td>
<td>Molecular diffusivity</td>
<td>(\sim 10^{-9})</td>
</tr>
</tbody>
</table>

Following Tab. 1 and a dimensional analysis, the effective dimensionless parameters can be obtained and are summarized in Tab. 2. The hat symbol is utilized to distinguish the dimensional parameters from the dimensionless ones. The effect of \(Pe\) is negligible due to its high values. As the rheological and physical parameters of the sample is fixed during each experiment, \(n\) and \(At\) are constants. However, as the axial rotation and the imposed flow rate vary, the Rossby number \((Rb)\), as well as the groups of Froude number \((Fr)\), the Bingham number \((B)\), the viscosity ratio \((M)\), and the Reynolds number \((Re)\) change. Indeed, in this study we are mostly motivated to study the effects of axial pipe rotation on the flow behavior, quantified via \(Rb\).
TABLE II. DIMENSIONLESS NUMBERS RANGES AND DEFINITIONS.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Name</th>
<th>Definition</th>
<th>Range or value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$At$</td>
<td>Atwood number</td>
<td>$\frac{\hat{\rho}_H - \hat{\rho}_L}{\hat{\rho}_H + \hat{\rho}_L}$</td>
<td>$96 \times 10^{-4}$</td>
</tr>
<tr>
<td>$Rb$</td>
<td>Rossby number</td>
<td>$\frac{V_0}{\hat{\rho}R}$</td>
<td>$0.04 - 4\times 10^2$</td>
</tr>
<tr>
<td>$Fr$</td>
<td>Froude number</td>
<td>$\frac{V_0}{\sqrt{At \hat{\rho}R}}$</td>
<td>$0.03 - 0.47$</td>
</tr>
<tr>
<td>$Re$</td>
<td>Reynolds number</td>
<td>$(\hat{\rho}_H + \hat{\rho}_L)\hat{V}_e R \hat{\rho}_H$</td>
<td>$(0.2 - 7) \times 10^{-2}$</td>
</tr>
<tr>
<td></td>
<td>(defined for heavy fluid)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$B$</td>
<td>Bingham number</td>
<td>$\frac{\hat{\tau}_B \hat{R}}{\hat{\rho}_H \hat{V}_e}$</td>
<td>$0.76 - 0.93$</td>
</tr>
<tr>
<td>$M$</td>
<td>Viscosity ratio</td>
<td>$\frac{\hat{\mu}_L}{\hat{\mu}_H}$</td>
<td>$(0.2 - 3) \times 10^{-4}$</td>
</tr>
<tr>
<td>$Pe$</td>
<td>Peclet number</td>
<td>$\frac{\hat{V}_e \hat{R}}{\hat{D}_m}$</td>
<td>$(8.6 - 190) \times 10^4$</td>
</tr>
<tr>
<td>$n$</td>
<td>Power law index</td>
<td>-</td>
<td>0.52</td>
</tr>
</tbody>
</table>

The dimensional parameters of lengths, velocities, and time are made dimensionless by, $\hat{R}$, $\hat{V}_0$, and $\hat{V}/\hat{V}_0$, respectively, in the whole text.

III. RESULTS

In this section, the results are discussed. First, an overall behavior of the flow is shown; then, qualitative and quantitative results are presented. We observed different flow behavior and features, which will be analyzed in the following subsections.

A. General Observations

Fig. 3 indicates the overall flow behavior during imposing the viscoplastic fluid at a fixed small value of imposed flow rate ($\hat{V}_0$), fixed density difference ($At$), and zero rotational speed ($\hat{\omega} = 0$). Also, the yield stress of the Carbopol solution is in the moderate range and it is fixed. Hence, we do not consider how altering the yield stress may change the flow behavior. In Fig. 3a, at early stages of the experiments, the heavy viscoplastic fluid advances downward with a constant cylindrical shape and a thickness more or less equal to the diameter of the pipe. In this case, the applied stresses on the imposed heavy fluid are less than the yield stress of the viscoplastic fluid and, therefore, it seems that the downward displacing fluid remain largely unyielded. However, at some point the buoyancy force dominates the flow and the yield stress is overcome. Hence, the displacing fluid layer is yielded, becomes radially thin and is eventually separated from the displacing fluid at the yielded position. As the large buoyancy force is one of the reasons of the occurrence of fluid separations, increasing the density difference of the fluids enhances the possibility of the separation (results not shown for brevity).

B. Effect of Rotation

By introducing the rotational speed of $\hat{\omega} = 30$ (rpm) in Fig. 4, while other parameters remain unchanged in comparison to Fig. 3, the rotational inertia shows up, weakening the relative effects of the buoyancy force. Indeed, the buoyancy force loses its dominance in characterizing the flow behavior. Therefore, as it is obvious from Fig. 4, the separated pieces previously appeared due to the effects of the buoyancy force, disappear and a uniform volume of the heavy fluid travels downward through the whole flow domain, without any separation, i.e. the non-separation flow regime.

Figure 3. a) Time sequence of experimental snapshots for $t = [7.71, 23.12, 35.29, 56.18, 60.87]$; b) Spatiotemporal diagram; c) Depth-averaged concentration profiles of separation regime for $Fr = 0.23$, $B = 0.8$, $M = 1 \times 10^{-4}$, $Re = 0.0$, without pipe rotation. In the concentration profiles and color bars, $C = 1$ and $C = 0$ corresponds to the purely viscoplastic and Newtonian fluids, respectively. The field of view is $2 \times 100$ on all subfigures. Flow direction is downward. The dashed line at b) represents $V_f = 1.81$. The arrow shows time evolution at c).
Let us now analyze the data in a more quantitative way. Fig. 5 shows the variation of the front velocity (where the dimensionless value is obtained from the slope of the depth-averaged spatiotemporal diagram, marked by dashed line in Fig. 3b and Fig. 4b) versus the imposed velocity, with (diamond symbol) or without (circle symbol) rotational speed. The yellow and red symbols represent the separation and non-separation flow regimes, respectively. Generally, \( \bar{V}_f \) increases with \( \bar{V}_0 \) in both flow regimes. Also, the front velocity is greater than the mean imposed velocity in the separation flow regime, which takes place at low values of the imposed velocity. It can also be seen that the pipe rotation tends to reduce the difference between the two velocities in the same flow regime.

Interestingly, the data show that the front velocity follows the mean imposed velocity only when there is no phase separation, usually at high imposed velocity, and regardless of the presence or absence of rotation. However, the pipe rotation stabilizes the flow so that the non-separation regime extends in this condition to much lower imposed velocities. Also, the results of Fig. 6 indicate that by increasing the rotational speed of the pipe, the transition from separation regime to non-separation regime occurs at smaller values of the front velocity, due to the fact that, by increasing the rotational inertia, the relative effects of buoyancy on the flow behavior weaken. This dimensional regime map versus the rotation speed shows that the rotational speed directly affects the separation regime boundary. At last, a more in-depth study will be necessary to explain this phenomenon more precisely.

A deeper look at the separation and non-separation flow regimes is provided in Fig. 3b, Fig. 3c, Fig. 4b, and Fig. 4c, using the depth-averaged spatiotemporal diagrams and concentration fields. In Fig. 3b, the existence of the light fluid between separated pieces is demonstrated by the domains with the concentration of near zero, surrounded by the regions with the concentration of the heavy fluid, i.e. 1 and each cut line represents one separated piece. However, in Fig. 4b, no cut line is demonstrated and the flow is uniformly penetrating downward, without any significant alterations in its behavior. Sudden jumps in the depth-averaged concentration field of heavy fluid versus the length of the pipe in Fig. 3c and its return to nearly the same previous value roughly indicate that mixing is not significant in the positions where separations occur. In contrast, the sudden decrease in Fig. 4c that occurs immediately after the advancing front, indicates the existence of the Newtonian fluid after the position of front tip up to the end of the flow domain.

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regime, that helps to stabilize the flow behavior. However, at larger values of the imposed velocity, the behavior of the non-separation flow regime and the front velocity remain unchanged. Generally, the front velocity increases with the imposed flow rate, and the relative buoyancy effects are weakened by the rotational inertia.

![Figure 6. The variation of $\dot{V}_f$ versus $\dot{\omega}$ for the non-separation (red diamond symbols) and separation (yellow circle symbols) behaviors.](image)

REFERENCES


