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Dynamics of the removal of viscoplastic fluids from inclined pipes

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ABSTRACT

The dynamics of the removal of a viscoplastic fluid by a Newtonian fluid is investigated experimentally and theoretically in an inclined pipe based on our previous studies on near-horizontal and highly inclined configurations. The fluids are miscible. The displacing Newtonian fluid is heavier than the displaced viscoplastic one i.e. the configuration is density-unstable. In our earlier work it was found that two major flow regimes, namely center-type and slump-type, might occur depending on the density difference. These flows are explored in great details through measurements of the displacement speeds and hydraulic Reynolds numbers. The residual viscoplastic layer unevenness is characterized revealing that the flows are in the range of *large roughness* regimes. Through an integrated experimental-theoretical approach, estimates of the interfacial and wall shear stresses are given which is of great importance in designing the displacement and cleaning processes involving fluids with yield stress. Accompanied by Ultrasonic Doppler Velocimetry (UDV) data, the dynamics of the removal of the viscoplastic fluid from a pipe is elucidated suggesting three distinct phases in the displacement process namely a plug flow, inertial multi-dimensional flow at the displacing front and steady multi-layer developed flow. Finally, the viscoplastic displacement flow results are compared against the predictions of the *closure* model, previously proved successful for Newtonian and shear-thinning fluids displacement in pipe. It is found that in the case of viscoplastic fluids the closure model always over predicts the displacing front velocity due to the inertial stresses present at the front not captured in the model.

1. Introduction

There exist many industrial processes in which it is necessary to remove a gelled material from a duct. Some examples include oil & gas well cementing [1], waxy crude oil pipeline restarts [2], Enhanced Oil Recovery (EOR) [3], Gas Assisted Injection Molding (GAIM) [4], biomedical applications (mucus [5], biofilms [6]), cleaning of equipment and stubborn soil [7], food processing [8] and personal care [9]. A wide range of models are developed to describe residual deposits in these situations. Some of these flows are turbulent [10], but equally often process limitations dictate that the flows be laminar. We study this laminar-imposed-flow case in the current manuscript.

In the context of cleaning-in-place (CIP) processes, numerous researchers have attempted to characterize the cleaning time as a function of the flow parameters. Fryer et al. [8] found that in CIP processes, increased flow rates induced greater surface shear on the deposit shortening the cleaning time. On the other hand the cost of pumping the cleaning fluid may become excessive at higher flow rates. Depending on the flow conditions, there might exist a threshold below which the mechanical effect of flow is negligible. In some specific cases no significant change in cleaning rate was reported when moving from laminar to turbulent flow. Using temperature, conductivity and turbidity probes, Cole et al. [9] conducted experiments to study the cleaning of toothpaste in a pipe. They found that the removal occurs mainly in three steps: In the first stage named as *core removal*, a core of the viscoplastic fluid is displaced from the pipe. Most of the remaining layer of the material on the wall is then slowly sheared away by fluid action in the second stage known as *thin film removal*. Finally in the third stage called *patch removal*, patches of the deposit left on the surface are gradually removed. While the core removal stage develops over the same time scale as that of the advective flow, thin film removal can take a very long time (majority of the cleaning time). The overall cleaning time was also found to be influenced by temperature and velocity of the cleaning fluid. A recent study by Palabiyik et al. [10] showed that the amount of product recovered in core removal is not a function of flow conditions. However, they interestingly

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found that the conditions during the core removal can significantly affect the two latter thin films and patch removal stages and thus the overall cleaning time. The overall cleaning time could be reduced by at least 25% upon selecting the best removal conditions at different stages.

There are a number of studies in the literature on the displacement of a viscoplastic fluid by an *immiscible* fluid (mostly gas). Although the current manuscript focuses on a *miscible* displacement, many of the underlying mechanism can be similar to an immiscible case. One of the early studies in this field is that of Poslinski et al. [11] which experimentally studied isothermal displacement of a viscoplastic liquid by gas in a horizontal tube with applications to GAIM process. They found that the thickness of the viscoplastic coating at high gas penetration rates approaches 0.35 of the tube radius, the asymptotic limit which was previously observed for Newtonian liquids [12]. However, at low gas penetration rates, the viscoplastic coating can be much thinner than its Newtonian counterpart. Shear-thinning and viscoelastic effects were discussed in [13,14] afterwards. Dimakopoulos and Tsamopoulos [15] later numerically studied the high-capillary number, inertialess displacement of a viscoplastic material by air in straight and suddenly constricted tubes motivated by GAIM and EOR processes. In the case of straight tubes, they reported similar film thickness values to those found in [11]. Counter-intuitively, local small decrease of the film thickness with increasing Bingham number was also found. When there is flow constriction unyielded regions appeared near the recirculation corner, but not around the entrance of the narrower tube. More complex geometries than constricted flows were considered later in [16].

de Souza Mendes et al. [17], experimentally found that the viscoplasticity in capillary tubes alters the flow kinematics which in turn changes the amount of mass left attached at the tube wall dramatically compared to the Newtonian case [12]. It was also observed that there is a critical dimensionless flow rate below which the displacement can be perfect i.e. no observable liquid left attached to the wall. Similar results were observed numerically by de Sousa et al. [18]. They depicted that the fraction of the mass of shear-thinning and viscoplastic materials deposited on the tube wall decreases and the shape of the interface becomes flatter compared to the Newtonian case. Concerning flow patterns, in the shear-thinning and viscoplastic cases de Sousa et al. [18] also found an interesting type of intermediate flow regime which is not present in the transition from *bypass* to *fully recirculating* flows of the Newtonian case [12]. Fields of yielded and unyielded zones for the viscoplastic case were shown later in more details in [19]. In most of the immiscible flow studies, the displacement of a viscoplastic fluid by a *gas* has been considered. Recently, Freitas et al. [20] studied the immiscible displacement of a viscoplastic liquid by a viscoplastic *liquid* in a plane channel using finite element method. The fluids were modeled as Bingham fluids with a regularized viscosity function proposed by Papanastasiou [21]. Increasing the yield number of the displacing fluid or the displaced one induced a thinner film of mass attached to the wall. For the cases analyzed, it was shown that changing the yield number of the displaced fluid has more impact on the flow patterns than changing the yield number of the displacing fluid. The transition flow configurations of the viscoplastic–viscoplastic displacement were also found to be very different from those of the Newtonian–Newtonian displacement problem.

There are also a number of studies in the literature focusing on the displacement of a viscoplastic fluid by a *miscible* liquid which is of more relevance to the current paper. Due to the industrial applications we are interested in high Péclet number regimes where the degree of molecular diffusive transport compared to advective transport is very small. Gabard and Hulin [22] studied the miscible displacement of non-Newtonian fluids in a vertical tube experimentally. For shear-thinning fluids (water-Xanthan solutions), the residual film thickness was found to be 0.28–0.30 of the radius. For viscoplastic fluids (water-Carbopol solutions) this value decreased down to 0.24–0.25 of the radius. However, instabilities at the interface between the two fluids developed downstream, leading to a reduction of the final thickness of the film at longer times which was larger for lower viscosity ratios and higher velocities.

Motivated by the fluid–fluid displacement in a narrow eccentric annulus in primary cementing process, Allouche et al. [23] modeled the displacement of two viscoplastic fluids in a plane channel predicting the *static* wall layers thickness for various range of parameters. Through a lubrication approximation they calculated maximum possible static wall layer thickness. Upon numerically solving the lubrication model developed, it was shown that the interface asymptotically approached the maximum static layer thickness predicted analytically. However, results from fully two-dimensional displacement computations indicated that the displacement front propagates at a steady speed along the channel, leaving behind a static layer significantly thinner than the predicted maximal static layer thickness. This is related to the existence of the 2D flow and inertial stresses at the displacement front. Similar to an immiscible displacement [15], Allouche et al. [23] counter-intuitively found that the computed static layer thickness decreased with an increase in the dimensionless yield stress of the displaced fluid. Recently Swain et al. [24] studied the buoyant displacement flow of a viscoplastic material by a Newtonian fluid using lattice Boltzmann simulations. For the ranges studied, it was revealed that increasing the Bingham number and flow index increases the size of the unyielded region of the fluid in the downstream section of the channel and increases the thickness of the residual layer of the residual fluid left. It was shown that the presence of the unyielded material in the residual film led to the suppression of the interfacial instability at higher Bingham numbers, which in turn, reduced the speed of finger propagation. Preliminary studies of the stability of two-layer flow of a viscoplastic fluid and a laminar and turbulent Newtonian fluid are given in [25] and [26] respectively.

Blel et al. [27] studied the effects of *pulsating* turbulent flows on wall shear stress components in a straight pipe using a series of microelectrodes as a non-intrusive electrochemical method. Their analysis revealed that pulsating flows induce an increase of local velocity gradient at the pipe wall through periodic renewal of the boundary layers and redistribution of eddies size near the wall. They later studied the effect of this pulsating flow on CIP of the adhered bacterial spores, in addition to the effect of the mean velocity of the flow [28]. A high level of the cleaning rate was observed despite the reduction of the magnitude of the mean velocity. Through 2D computations, Wielage-Burchard and Frigaard [29] later studied the effect of inertia and flow pulsation on static wall layer thickness. Thinner layers were found at higher Reynolds numbers due to the increased energy production locally around the finger. Both small and large amplitudes were considered to study the effect of the flow rate pulsation. The conditions on the pulsation frequency and amplitude for mobilizing the static layers were presented for different range of flow and rheological parameters.

The displacement of a yield-stress (viscoplastic) fluid along a pipe or duct can be influenced by a large number of parameters, making a comprehensive study impractical. Our focus in this paper is on situations in which the yield stress of the displaced fluid is high and the displacement is thus *difficult*. Briefly, this means that the yield stress should be the dominant stress in the flows considered. We study flows where the typical viscous stresses generated by the imposed flow are far less than the yield stress. Both inertial and buoyant stresses can be comparable to the yield stress locally, e.g. close to the displacement front. We therefore study the effects