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Incomplete fluid–fluid displacement of yield stress fluids in near-horizontal pipes: Experiments and theory

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ABSTRACT

We present results of a primarily experimental study of buoyant miscible displacement flows of a yield stress fluid by a higher density Newtonian fluid along a long pipe, inclined at angles close to horizontal. We focus on the industrially interesting case where the yield stress is significantly larger than a typical viscous stress in the displacing fluid, but where buoyancy forces may be significant. We identify two distinct flow regimes: a central-type displacement regime and a slump-type regime for higher density ratios. In the central-type displacement flows, we find non-uniform static residual layers all around the pipe wall with long-wave variation along the pipe. In the slump-type displacement we generally detect two propagating displacement fronts. A fast front propagates in a thin layer near the bottom of the pipe. A much slower second front follows, displacing a thicker layer of the pipe but sometimes stopping altogether when buoyancy effects are reduced by spreading of the front. In the thin lower layer the flow rate is focused which results in large effective Reynolds numbers, moving into transitional regimes. These flows are frequently unsteady and the displacing fluid can channel through the yield stress fluid in an erratic fashion. We show that the two regimes are delineated by the value of the Archimedes numbers (equivalently, the Reynolds number divided by the densimetric Froude number), a parameter which is independent of the imposed flow rate. We present the phenomenology of the two flow regimes. In simplified configurations, we compare computational and analytical predictions of the flow behaviour (e.g. static layer thickness, axial velocity) with our experimental observations.

1. Introduction

There are many industrial processes in which it is necessary to remove a gelled material or soft-solid from a duct. Examples include bio-medical applications (mucus [27,34], biofilms [7,52]), cleaning of equipment and food processing [6,8], oil well cementing and waxy crude oil pipeline restarts. A wide range of material models are used to describe residual deposits in these situations. Some of these flows are turbulent, but equally often process limitations dictate that the flows be laminar. It is this case that we study here. Our industrial motivation comes from the oil industry, and we consider that the fluid to be removed is either a drilling mud or a pipeline full of waxy crude oil, and that these fluids have a yield stress. We study downward displacement flows along pipes that are inclined at angles close to horizontal (but not horizontal), as for Newtonian fluid flows we can see significant differences when fully horizontal. We have recently studied in detail such displacement flows, in the Newtonian fluid setting, in [44–47].

The main feature of a yield stress fluid is that the fluid does not deform until a critical shear stress is exceeded locally. Therefore, when these fluids fill ducts and are displaced by other fluids, there is a tendency for the yield stress fluid to remain stuck to the duct walls and in particular in parts of the duct where there are constrictions or corners. This type of feature was first recognised in the context of oil well cementing by McLean et al. [33], who identified potential bridging of a static plug of mud on the narrow side of an eccentric annulus. Avoidance of this feature has since been an ingredient of industrial design rules for oilfield cementing [10,29,40], and latterly also simulation based design models [3,41]. Further features of oilfield cementing are discussed in [36], but here our geometry is simpler.

In waxy crude oil pipeline restarts (see [5,12,42,49]) a large pressure is applied at one end of the pipe, to break the gel of the waxy oil. The waxy state has formed due to a drop in temperature below the wax appearance temperature, often related to stopping the pipeline for maintenance or other issues. Temperature is not particularly

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important in the restart process itself [51]. It is common to displace the in situ oil with an oil of different physical properties (often this is the same oil at higher temperature and thus with a Newtonian viscosity). In the displacement it is possible for static residual layers to form on the walls of the pipeline; see [17,50].

The phenomenon of a static wall layer in a plane channel was first studied by Allouche et al. [2] who studied symmetric displacement flows of two visco-plastic fluids. As is intuitive, a necessary condition for the existence of a static wall layer is that the yield stress of the displaced fluid exceeds that of the displacing fluid (if there is one). In [2] a constant displacement flow rate was imposed. A number of two-dimensional (2D) simulations were performed with no density difference, and the static layer thickness was measured from the results. Additionally, expressions were derived for the maximal static layer thickness (for vertical plane channels in the presence of a density difference), and for a prediction of the actual layer thickness (no density difference). Frigaard et al. [20] extended this approach, showing that in a steady displacement flow with a uniform static wall layer the thickness of the layer and the shape of the interface are non-unique for the steady displacement problem and consequently must result from transient aspects of the flow. The concept of maximal static wall layers was further explored in [18]. More recently in [53], an extensive computational study of static layer thickness in iso-density fluid displacements (Newtonian fluid displacing Bingham fluid) was performed, including the effect of flow rate oscillations. This has shed further light on the effects of the main three dimensionless parameters (Reynolds number, Bingham number and viscosity ratio), in the absence of density differences.

In contrast to the amount of computational work, there are relatively few experimental studies of displacement of yield stress fluids by other fluids. Gabard [21], and Gabard and Hulin [22] investigated iso-density miscible displacements in which a more viscous fluid is displaced by a Newtonian fluid. In their experimental investigation the geometry used was a vertical tube. They observed the effect of rheology of the displaced fluid and the flow velocity on the transient residual film thickness during the displacement process. They showed that in displacements of shear-thinning fluids the residual wall layer thickness decreases compared to Newtonian fluid displacements. The shear thinning fluid displacements were characterised by slowly evolving interfacial instabilities of (inverse) bamboo type, which further reduced the initially symmetric residual wall layer. For yield stress fluids static residual wall layers were observed of uniform thickness. Axisymmetric computations were also carried out in [21] with results which were qualitatively similar to the experimental results.

Other experimental studies involving two fluid flows of yield stress fluids in the pipe geometry include [11,32] who have studied the exchange flow problem (i.e. buoyancy driven flow in a closed ended pipe). The focus of these studies is stopping the motion using the yield stress of one of the fluids. Huen et al. [28] and Hormozi et al. [26] have studied core–annular flows, using a yield stress fluid for the outer lubricating layer and a range of different Newtonian and non-Newtonian fluids for the core. The start-up phase of these experiments is displacement-like, although the final steady state is a multi-layer flow.

In the Hele-Shaw geometry, Lindner et al. [30,31] studied the Saffman–Taylor (viscous fingering) instability while displacing yield stress fluids. They observed a yield stress dominated regime at low velocity and a viscous dominated regime when the velocity was higher. The former regime shows branched patterns because in simple words each finger does not really feel the presence of walls or other fingers due to the fluid's yield stress. In the viscous dominated regime, yield stress does not play an important role. Other investigations of viscous fingering (with stability analyses) include [9] and the earlier Darcy-flow analogues of [37–39].

Finally, a number of authors have considered the displacement of yield stress fluids by a gas. De Souza Mendes et al. [13] investigated the displacement of viscoplastic flows in capillary tubes experimentally through gas injection. They showed that below a certain critical flow rate, the visco-plastic liquid is completely displaced by the displacing fluid. However above this critical flow rate small lumps of unyielded liquid will remain on the walls. For increased values of imposed flow rate a smooth liquid layer of uniform thickness forms. They reported that the thickness of this layer increases with the dimensionless flow rate. There have also been extensive computational studies of these flows; see [14,15,43,48]. Finally, there is a limited amount of analytical work concerning bubble propagation/displacement in Hele-Shaw geometries; see [1].

The aim of our study is to deepen our understanding of yield stress fluid displacements in pipes in a regime that has not been previously studied. Namely we study displacement of fluids with large yield stress and where buoyancy is significant. Near horizontal pipelines and wells lead to situations in which buoyancy forces promote slumping and asymmetry for Newtonian displacement flows. When a yield stress fluid is involved the displaced fluid rheology may counter the tendency to stratify, but these flows are poorly understood. The situations of primary industrial interest are those in which the yield stress is very large, so that static residual layers may persist.

The outline of our paper is as follows. In Section 2 we outline the scope of our study and the experimental methods used. Results are presented in Section 3. We first describe the main finding of the paper, namely the observation of two principal types of flow delineated by the ratio of Reynolds number to densimetric Froude number (equivalent to the square root of the Archimedes number). We then describe in more detail the features of the central (Section 3.2) and slump (Section 3.4) type displacements. The paper ends with a brief summary.

2. Scope of the study and methodology

As explained in the introduction, the aim of our study is to better understand displacement flows of visco-plastic fluids in near-horizontal pipes. The choice of a near-horizontal pipe follows from our previous work on Newtonian–Newtonian fluid displacements, where this range of pipe inclinations is found to exhibit interesting transitions between inertia-buoyancy and viscous-buoyancy dominated regimes; see [44]. In moving from an iso-viscous buoyant Newtonian–Newtonian fluid displacement to a displacement flow of a typical shear-thinning visco-plastic fluid by a Newtonian fluid, we have at least three more dimensionless parameters, e.g. for a Herschel–Bulkley model. Although we consider pipe inclinations $\beta \approx 90°$, a comprehensive experimental study of flow variations with the remaining six dimensionless parameters is infeasible. Therefore, we focus on displacing visco-plastic fluids with *large* yield stress, with the motivation that these are the flows that are most problematic from an industrial perspective. However, the idea of *large* yield stress needs qualifying.

Suppose we displace a yield stress fluid (with yield stress $\hat{\tau}_Y$) with a Newtonian fluid of viscosity $\hat{\mu}$, by imposing a flow rate $\widehat{Q} = \pi \widehat{V}_0 \widehat{D}^2/4$, through a long pipe of diameter $\widehat{D}$, i.e. $\widehat{V}_0$ is the mean velocity. Inevitably the fluid will finger through some part of the pipe cross-section, potentially leaving behind residual layers as the displacement front propagates. Apart from close to the tip of the finger we might suppose that the Newtonian flow in the bulk of the finger becomes near-parallel and generates viscous stresses of order $\hat{\tau}_v = \hat{\mu}\widehat{V}_0/\widehat{D}$. If we wish to study flows in which it is possible for the visco-plastic fluid to be left behind as the displacement