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Experimental and Computational Investigation of Miscible Non-Newtonian Fluid Displacement in a Vertical Channel

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ABSTRACT

We study the miscible displacement of a shear thinning fluid by a Newtonian fluid in a vertical rectangular duct experimentally and by numerical simulations. We vary the viscosity of the displaced fluid, from nearly Newtonian to strongly non-Newtonian, and focus in particular on how the displaced fluid viscosity affects the interfacial region between the pair of fluids during displacement. Experiments are performed in a transparent duct, and high-speed video imaging and a high-intensity lighting source are used to visualize the interface between the fluids during displacement. In this work, we focus on nearly iso-dense displacements, so that the non-Newtonian behavior of the fluids can be isolated and better observed. The evolution of the interface and the displacement process are tracked for each experiment and compared to results from three dimensional numerical simulations of the experiments. We observe significant sensitivity of the interface to the viscosity of the displaced fluid. In the strong non-Newtonian regime, a unique channel in the middle of the displaced fluid is formed, and all of the displacing fluid flows through this central channel leaving a very thick wall layer. In the transitory non-Newtonian regime, several finger shaped channels are carved across the length of the duct, and all fingers progress to the outlet. A Kelvin-Helmoltz type of instability is then observed in the remaining wall layer. For the quasi-Newtonian regime, the displacement progresses as a typical multi-phase Newtonian fluid displacement with no visible wall layer formation.

INTRODUCTION

Removal of non-Newtonian fluids is considered a critical operation in many industries. Examples include the food and chemical processing industries where effective fluid removal and surface cleaning are critical, and within the energy industry where geothermal well integrity depends on the cleaning and cementing of the annular space between casing and formation. Understanding how rheology affects the bulk displacement, the mixing zone, front dynamics and the existence or removal of fluid wall layers is important for optimizing displacement operations.

In this work, non-Newtonian fluid displacements are studied both experimentally and numerically. Displacement experiments are performed with pairs of Newtonian and shear thinning fluids in an acrylic duct of rectangular cross section. Visualization of the flow field is obtained through high-speed video imaging with a high-intensity lighting source. Image analysis is performed to extract the interface front velocity and profile, and compared to numerical simulations of the displacement experiment.

METHODOLOGY

Experimental setup

A schematic diagram of the experimental setup is shown in Fig. 1(a). This setup is a laboratory-scaled system that allows optical access to visualize the flow field while maintaining a precise control of inlet flow velocity. The rectangular duct has a uniform cross section of 17 cm by 1.7 cm, and a height of 100 cm.

The two miscible fluids are initially separated by a special-designed fluid separator to minimum initial mixing and that promotes a well-defined horizontal interface between the fluids when the experiment begins. The displacing fluid is colored with black ink for visualization purpose. Flow visualization is achieved by high-speed video imaging with a high intensity lighting source.

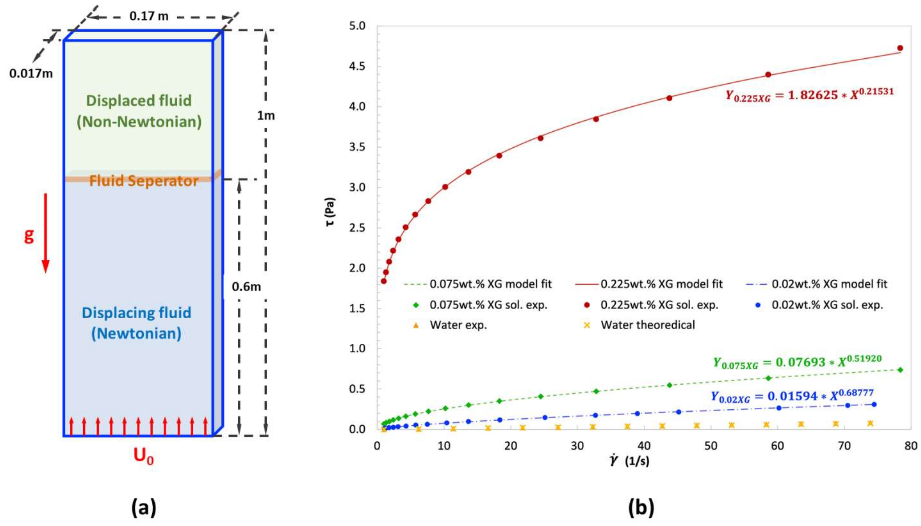

FIGURE 1: (a). Schematic of the vertical channel and (b). Flow curve and fitting to a shear thinning viscosity model

Flow and fluid properties

The volumetric flow rate for each case is set to be constant at 4.5 l/min. A centrifugal pump is used to pump the displacing fluid and an ultrasonic flowmeter from Sensata Technologies (model UF25) is used to measure the flow rate. This flow rate will ensure that the flow remains laminar while viscous stresses dominate buoyancy. To investigate how the viscosity contrast between the fluids affect the displacement, each pair of fluids is composed of a Newtonian fluid and a non-Newtonian shear thinning fluid, both of which are water-based. The Newtonian fluid used in this work is liquid water, and the non-Newtonian fluid is an aqueous solution of xanthan gum, prepared with concentrations of 0.02 wt.%, 0.075 wt.% and 0.225 wt.%.

Xanthan gum is chosen as viscosifier, as it is commonly used in petroleum, pharmaceutical, and food industry to adjust both the overall viscosity, and to control non-Newtonian behavior. Xanthan gum is a high molecular weight polysaccharide which, when added to a liquid, quickly disperses and creates a viscous and stable solution.[1] Xanthan gum solutions are shear-thinning fluids, and its rheology behavior is well described by a power law.[2]The rheological flow curves of different concentrations of xanthan gum are measured with an Anton Paar MCR302 scientific rheometer using a concentric cylinder measurement geometry. Measurements are fitted using the Herschel-Bulkley rheological model, $\tau = \tau_0 + \kappa\dot{\gamma}^n$, where τ and τ_0 are the shear stress and yield stress respectively, $\dot{\gamma}$ is the shear rate and κ is the consistency index. The measured properties of solutions used in this study with Herschel-Bulkely model fitting is shown in Fig. 1(b). In all the model fittings, τ_0 seems to converge to 0, resulting in a power law fitting.

We maintain a small density difference between the two fluids. The Atwood number is set to be 0.001 for all cases, with the displacing fluid slightly denser than the displaced fluid. The small density difference is deliberately introduced to stabilize the flow during experiments, and allow the non-Newtonian behavior of the fluids to be isolated and better observed.

Dimensional Analysis

In this study, we introduce a dimensionless number, χ, to describe the relative importance of buoyancy and viscous effects. The definition of χ is $\chi = 2Re/Fr^2$, where Re is the Reynolds number and Fr is the densimetric Froude number, and both numbers have their usual physical meaning. The viscosity is approximated using geometric mean of the Newtonian and the effective xanthan gum viscosity for the different xanthan gum concentrations. The three calculated χ value for xanthan gum with concentrations of 0.02 wt.%, 0.075 wt.% and 0.225 wt.% are 68, 35, and 15 respectively. From the calculated χ value, one can see that the balancing of viscous stresses to buoyancy is different for the three xanthan gum concentrations, which means that the "degree of flattening" of the interface will be different for three cases. The density difference is the most prominent for the case with lowest xanthan gum concentration of 0.02 wt.%, and least prominent for the case with the highest xanthan gum concentration of 0.225 wt.%.

Computational tool

All the computations are performed using OpenFOAM: an open source CFD software with many useful modelling features. Regarding multi-phase fluid simulations, OpenFOAM has several solver options. In this study, the `interIsoFoam` solver is used, which is an upgraded version of the volume of fluid (VOF) solver `interFoam` featuring the `isoAdvector method` for retaining sharp interfaces[3].

The `interIsoFoam` solver was initially developed for modelling of incompressible and immiscible two-phase flows. In this study, although the fluid pairs happen to be miscible, the timescale of mixing due to diffusion is much longer than the timescale of the imposed flow. Moreover, the flow around the interface is for the most part laminar, which means that the clean interface that separates the fluids initially is likely to be preserved throughout the experiment. Therefore, the fluid pair can be considered as "immiscible" in this study. When using the `interIsoFoam` solver for miscible fluids, the setting for surface tension between two fluids should be lowered to a value near 0 N/m.

The mesh was made using 20 cells in width, 160 cells in the length and 256 cells in the height of the channel and is refined close to the walls. The results presented in this work were generated using 8 processors in parallel. The mesh was divided across the height of the duct creating 8 evenly distributed blocks, each consisting of 102400 cells.

RESULTS and ANALYSIS

High concentration of xanthan gum solution

For a xanthan gum concentration of 0.225 wt.%, the highly viscosity-unstable case, the experiments shown in Fig. 2 shows that Newtonian fluid channeling through the center of the highly viscous xanthan gum. The interface is gradually move upwards in the finger shape forming a thick wall layer on its way to the outlet, as expected. Fig. 3 shows that the simulation displays a similar behaviour. Note that in the experimental results, the evolution of the interface is not smooth and forms a heterogeneous column with a larger wall layer.

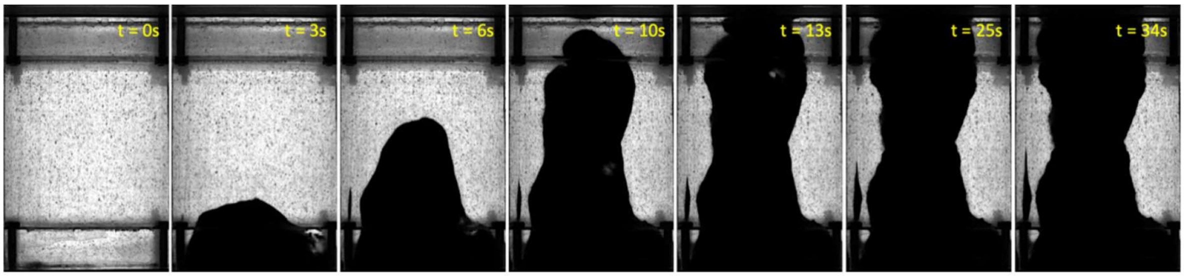

FIGURE 2: Experimental visualization of interface evolution of water displacing 0.225 wt.% xanthan gum solution

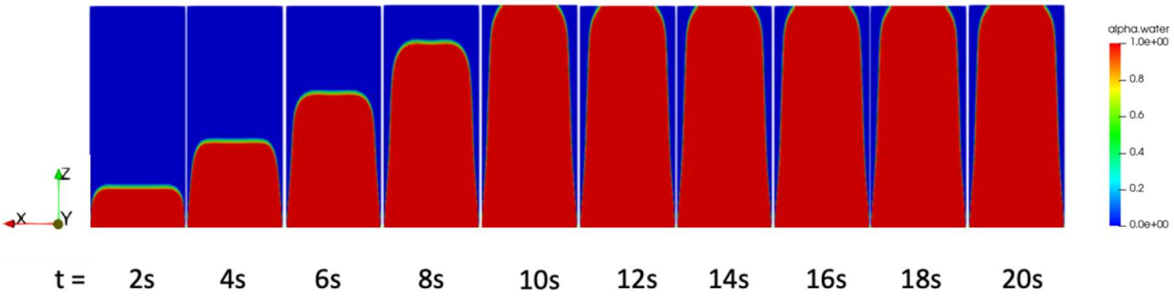

FIGURE 3: CFD simulation of interface evolution of water displacing 0.225 wt.% xanthan gum solution

Qualitatively speaking, the model is validated by this result. The rough edges of the column in the experiments are possibly caused by slight heterogeneity in the mixing of the xanthan gum solution. On the other hand, for such highly viscosity-unstable configuration, small perturbations can grow and cause discrepancies between CFD and experiments. The CFD simulations are the ideal condition with perfectly vertical duct and symmetry, however in experiments, small imperfections for the initial interface are hard to avoid.

An important feature that the experiment and the model agree upon is the dynamic behavior of the xanthan gum solution over time. The displacing fluid generates first a central column toward the outlet of the duct. After breakthrough of displacing fluid, the remaining xanthan gum solution is largely static within the duct, suggesting channeling of the displacing fluid and poor displacement toward either side of the duct. The displacing fluid passes through the newly formed channel in the middle of the displaced fluid as though it was solid. This behavior can be observed in Fig. 2 between $t = 25$ s and $t = 34$ s where the interface has not moved at all even though the water, colored in black, has been flowing through the channel steadily. In the simulation shown in Fig. 3, the channel becomes steady after $t = 12$ s and the interface stagnates from that point on.

Intermediate concentration of xanthan gum solution

The intermediate concentration of xanthan gum was chosen to be 0.075 wt.%. The experiment in Fig. 4 shows considerably different behavior when compared to the high concentration solution in Fig. 2. In Fig. 4, instead of a unique channel in the center, the displacing fluid is carving several smaller finger-shaped channels across the width of the duct. Further, improved displacement is observed toward either side of the duct compared to Fig. 2. The interface reaches the outlet across the whole length of the duct save for a relatively thin wall layer. The wall layer develops a Kelvin-Helmholtz-type instability after the interface in the middle of the channel has reached the outlet. The instability then takes the shape of small waves moving upward along the walls.

As shown in Fig. 5, the simulation performed with OpenFoam also displays the formation of separated finger-shaped channels. There are only two fingers created and, unlike the more random patterns of the experiment, they seem perfectly symmetrical. The simulation does not capture the wall layer instability observed in the experiment in Fig. 4. On the other hand, simulation displacement seems to occur faster than experiment. A possible reason could be the uncertainty in experimental flow rate due to the inconsistent supply pressure from the centrifugal pump which can result in a slightly variant flow. Although the simulation predicts behavior that is different from that observed in the experiment, it confirms the development of finger-shaped patterns as the concentration of xanthan gum is reduced.

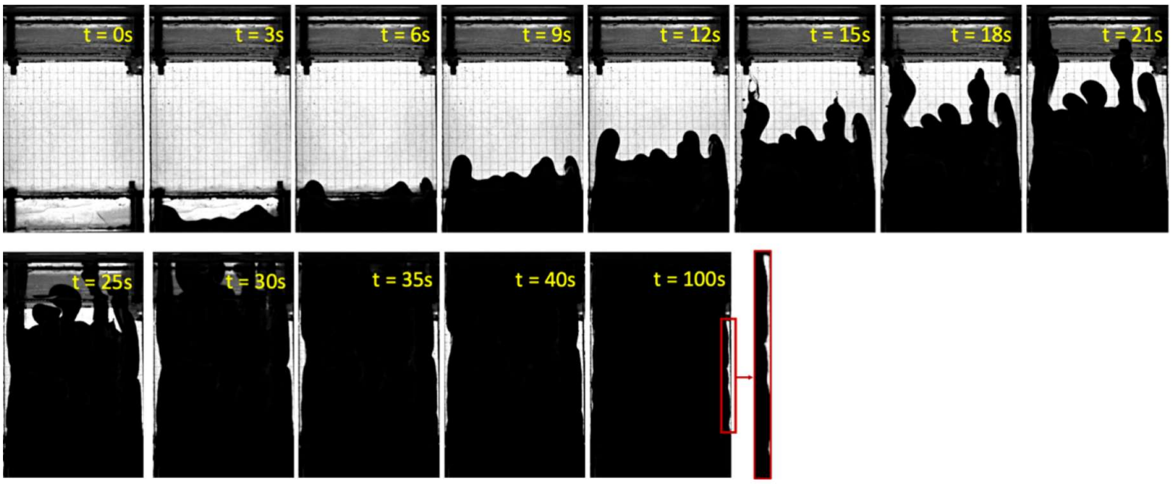

FIGURE 4: Experimental visualization of interface evolution of water displacing 0.075 wt.% xanthan gum solution

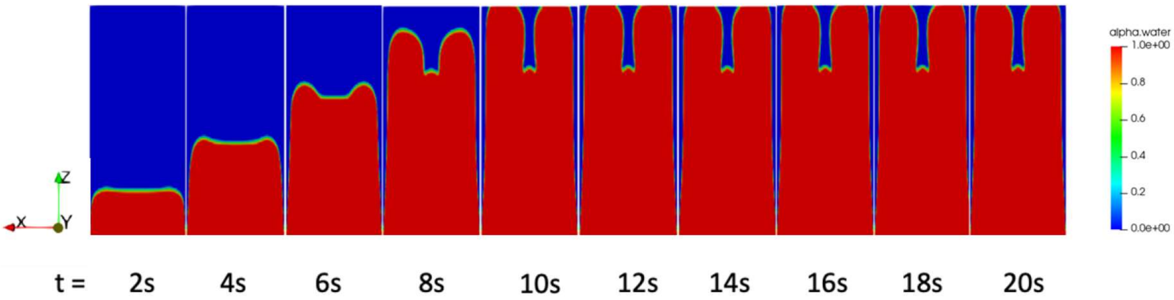

FIGURE 5: CFD simulation of interface evolution of water displacing 0.075 wt.% xanthan gum solution

Low concentration of xanthan gum solution

The last studied concentration of xanthan gum is of 0.02 wt.%. The experiment in Fig. 6 shows a displacement reminiscent of iso-viscous fluids. The interface appears to move upwards in a steady and uniform fashion, contrasting the behavior observed in the previous two sections. This is expected, since reducing the xanthan gum concentration makes the displaced fluid more similar to pure water. In this case, no channels are formed, and no instabilities are visually observable.

The simulation using the power law model shown in Fig. 7 disagrees with what the experiment shows. The model considers that the finger shaped channels should still be formed for these conditions, thus generating a result very close to the intermediate concentration simulation.

A possible conclusion is that the model does not connect the non-Newtonian behavior of the fluid at high concentrations of xanthan gum with the Newtonian behavior of the low-concentration solution in a continuous way. The case was simulated one more time with a Newtonian assumption for the displaced fluid, using an equivalent Newtonian viscosity based on the characteristic shear rate $\dot{\gamma} = 3U_0/l$, with U_0 as the bulk velocity, and l is the duct gap width of 1.7cm. The mean shear stress is extrapolated from the flow curve in Fig. 1(a) with the calculated shear rate.

For comparison, Fig. 8 is a simulation that instead treats the displaced fluid as Newtonian, with a constant viscosity equal to the actual power law evaluated at the shear rate $\dot{\gamma} = 3U_0/l$. Interestingly, the Newtonian displacement simulation appears to better match the experimental result in Fig. 7.

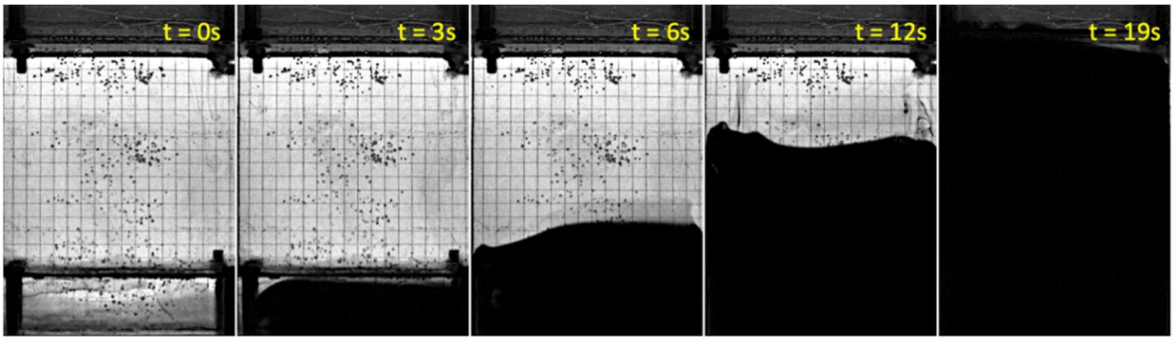

FIGURE 6: Experimental visualization of interface evolution of water displacing 0.02 wt.% xanthan gum solution

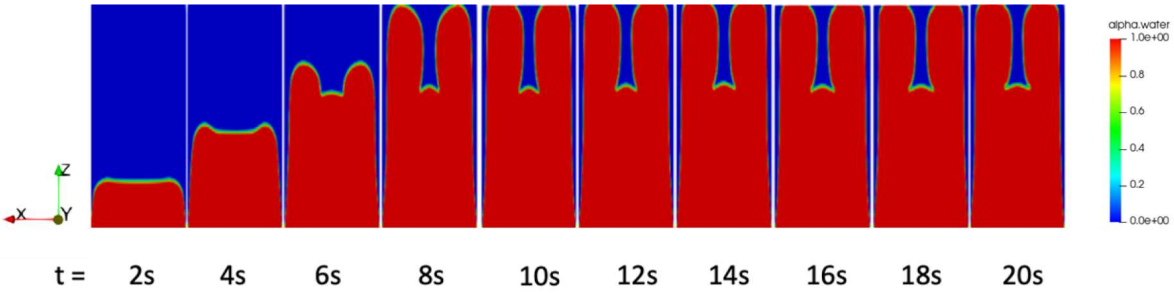

FIGURE 7: CFD simulation of interface evolution of water displacing 0.02 wt.% xanthan gum solution

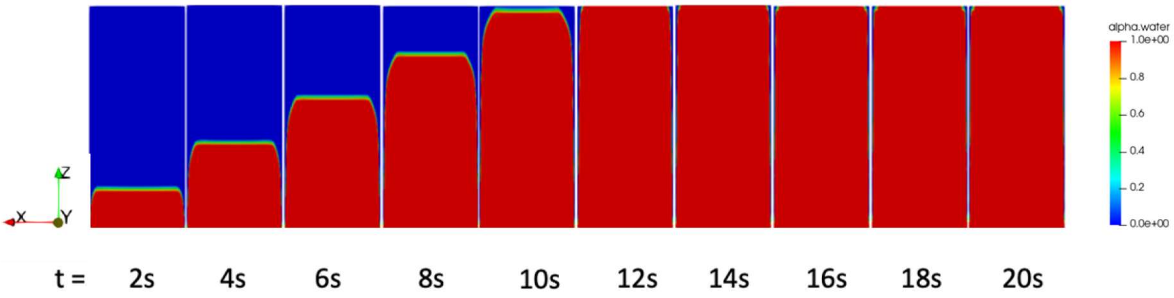

FIGURE 8: CFD simulation of interface evolution of water displacing 0.02 wt.% xanthan gum solution using an equivalent Newtonian viscosity

DISCUSSION

Comparing different concentrations of xanthan gum solution, the displacement process shows a very different physical behavior. This behavior can be categorized into three different regimes – strong non-Newtonian regime, an intermediate and a weakly non-Newtonian regime. The strong non-Newtonian regime is achieved with high concentrations of xanthan gum, while the weakly non-Newtonian regime is reached with the lowest concentrations.

As shown in the Results and Analysis section, the strong non-Newtonian regime allows the displacing fluid to form a unique channel through the displaced fluid. The displaced fluid quickly thickens and stops moving, forcing the displacing fluid to accelerate through the relatively thin channel formed to reach the outlet. This creates a large wall layer and prevents the complete displacement of the fluid.

Experimentally, the intermediate non-Newtonian regime shows the formation of several smaller finger-shaped channels with no apparent stagnation of the displaced fluid over time. This allows the complete displacement of the non-Newtonian fluid save for a relatively thin wall layer that displays a mild instability.

In experiments, the weakly non-Newtonian regime behaves identically to a two-phase Newtonian flow with no formation of channels or obvious instabilities in this experimental setup. The displacement resulting from this regime is complete save for a thin wall layer.

Qualitative agreement has been observed between experiments and simulations for the two highest xanthan gum concentrations considered in this study. While simulations suggest increasing tendency toward finger-formation as the displaced fluid becomes less viscous, experiments suggest a more stable displacement at the lowest polymer concentration that is reminiscent of iso-viscous displacements. Future work could explore the selection of interface shape and viscosity hierarchy for other, intermediate xanthan gum concentrations, and better understand the role played by shear thinning and possibly yield stress behavior.

CONCLUSIONS

In this work, we study the non-Newtonian fluid displacement using fluid pairs of water and different concentrations of xanthan gum solution. All studies are made with very small Atwood numbers, and with one fixed flow rate. The small density difference between two fluids have a small stabilizing effect, and lead to a slight flattening of the interface. Moreover, in this regime, and the viscosity contrast between the fluids is expected to dominate the physics of the displacement.

It is observed that the evolution of displacement process shows a considerably different physical behavior for high, intermediate, and low concentrations of xanthan gum, which can be categorized into three different regimes - strong non-Newtonian regime, transitory non-Newtonian regime, and quasi-Newtonian regime.

Within the strongly non-Newtonian regime, the displacing fluid forms a unique channel at the middle of the displaced fluid. All the injected displacing fluid is seen to flow through the central channel, leaving behind a considerable volume of non-displaced fluid adjacent to the side walls of the duct.

In the transitory non-Newtonian regime, the displacing fluid forms several finger shaped channels across the whole length of the duct. All these finger-shaped channels progress to the outlet, thus the displacement of non-Newtonian fluid is relatively complete leaving a thin wall-layer. As the displacement process is completed, a Kelvin-Helmholtz-type instability forms at the interface next to the walls of the duct.

The displacement of non-Newtonian fluid in the quasi-Newtonian regime behaves like a typical Newtonian flow. The displacement is complete with a thin or non-existent wall layer, and there is no formation of channels or instabilities.

Computational simulations have been performed using OpenFOAM, and the results compared to experimental observation for all three regimes. Simulation results and experiments are in qualitative agreement at the two highest concentrations of xantham gum. The interface predictions are qualitatively different for the lowest xanthan gum concentration, where simulations suggest two pronounced fingers advancing on either side of the center of the duct, while experiments suggest a more stable, flat interface. Future studies are required to explore the selection criteria for finger-formation, and how this is linked to duct aspect ratio and viscosity hierarchy.

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