Proceedings of the ASME 2010 3rd Joint US-European Fluids Engineering Summer Meeting and 8th International Conference on Nanochannels, Microchannels, and Minichannels
FEDSM-ICNMM2010
August 1-5, 2010, Montreal, Canada

FEDSM-ICNMM2010-31056

VISCOUS OIL-WATER FLOW IN A MICROCHANNEL: FLOW PATTERNS AND FLOW DEVELOPMENT

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ABSTRACT

The flow characteristics of a highly viscous oil and water mixture in a circular microchannel have been investigated. Water and silicone oil with a viscosity of 863 mPa.s were injected into a fused silica microchannel with a diameter of 250 µm. Before each experiment, the microchannel was initially saturated with either oil or water. In the initially oil-saturated case, different liquid-liquid flow patterns were observed and classified over a wide range of oil and water flow rates. As a special case, the flow of water at zero oil flow rate in a microchannel initially filled with silicone oil was also studied. When the microchannel was initially saturated with water, the oil formed a jet in water at the injection point but developed an instability at the oil-water interface downstream and eventually broke up into droplets.

INTRODUCTION

Two-phase flows in microchannels have a wide range of applications in chemical, biomedical and petroleum engineering, among others. Although the gas-liquid two-phase flow characteristics in micro-channels have been investigated in detail by the authors [1-3] and other research groups, liquid-liquid flows in microchannels are still not very well understood. A few studies have examined the flow of immiscible liquid mixtures in microchannels, but the viscosities of both liquids were not high [4]. Numerous investigations have been carried out on viscous oil-water flows in small and conventional pipes. Many of these studies were performed in horizontal and vertical pipes as reviewed by Joseph et al. [5].

In small channels, Anna et al. [6] used a microfluidic device with flow-focusing geometry to produce droplets in water-oil systems. In their experiments, both fluids were forced to flow through an orifice to produce mono-disperse and poly-disperse emulsions. They developed a diagram illustrating the drop size as a function of flow rates and flow ratios. Dreyfus et al. [7] studied liquid-liquid two-phase flow patterns in a microchannel with cross-like injection configuration. They showed that wetting properties strongly control the flow patterns. Kashid et al. [8] studied the hydrodynamics of liquid-liquid slug flow in a Y-type microchannel. Salim et al. [4] studied the oil-water flow patterns and pressure drops in a rectangular, micro T-junction. The viscosity of oil used in their study was 30.6 mPa.s. Cubaud et al. [9] studied the flow of miscible, viscous liquid-liquid two-phase flows in microchannels.

In this work, the flow characteristics of viscous oil-water two-phase flows in a circular microchannel have been studied. The density and viscosity of silicone oil used in this study were 0.97 g/cm^3 and 863 mPa.s which are comparable to those of gas-saturated heavy oil in petroleum reservoirs.

EXPERIMENTAL APPARATUS

The working fluids used in this study were de-ionized water and silicone oil, polydimethylsiloxane**,** from Sigma Aldrich's 200 fluid series. The oil's surface tension was 21.1 mN/m at 20 °C.

A circular microchannel from Polymicro Technologies was used in the present experiments. It was made of fused silica and had an inner diameter of 250 µm. The contact angles of oil and water with the microchannel wall were 25° and 36°, respectively.

The experimental apparatus used is shown in figure 1. Two pneumatic pumps were used to inject water and silicone oil separately. Pneumatic pumps consisted of a cylindrical vessel filled with a liquid and pressurized with a nitrogen gas from a cylinder. One of the pneumatic pumps contained water and the other contained silicone oil. The pressures in the liquid reservoirs were raised to inject liquids into the channel. The pressure regulators on the nitrogen gas cylinders were adjusted to cover certain ranges of water and silicone oil flow rates.

The silicone oil was injected into a microchannel test section through a needle made of stainless steel with an internal diameter of 100 µm and outer diameter of 210 µm. As shown in figure 2, silicone oil was injected at the centre of the microchannel through the needle, while water was injected through an annulus between the needle and the microchannel with an inner diameter of 250 μm and length of 72 mm.

A pressure transducer with an accuracy of 1.7 kPa (0.25 psi) was used to measure the pressure drop between the microchannel inlet and exit which was exposed to the atmosphere. A cross junction was used to connect the needle, water injection line, pressure transducer, and microchannel.

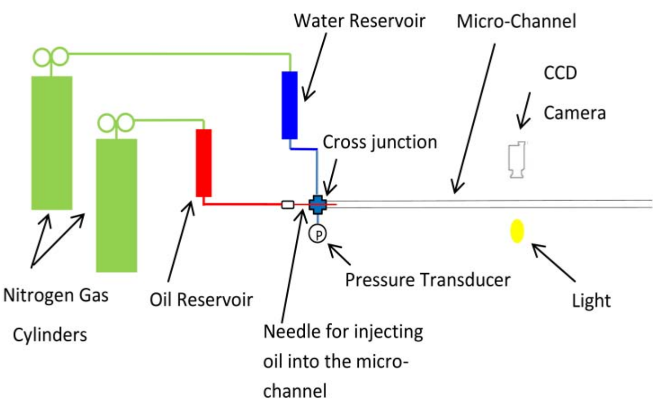

Figure 1: Schematic of the experimental apparatus

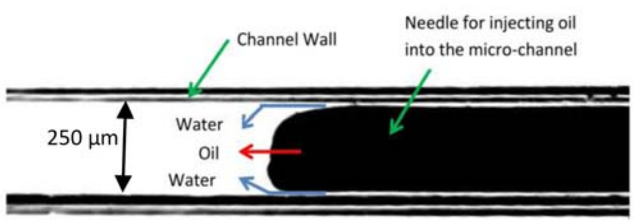

Figure 2: Silicone oil and water injection section

A high-speed video camera was used to capture images of the water-silicone oil flow at a rate up to 125 frames per second. Since a circular micro-channel was used, optical correction was necessary to capture undistorted and clear images inside the entire cross section of the microchannel. To this end, the microchannel was sandwiched between two glass plates and the gap between the two plates was filled with either oil or water to best match the index of refraction of the microchannel. No additional optical correction step such as image processing was performed. Figure 3 shows the effect of optical correction on the images captured by the high speed video camera.

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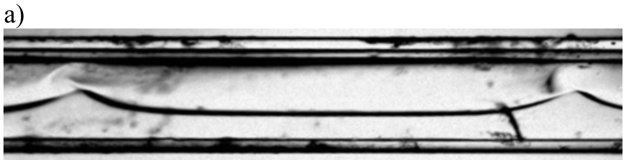

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Figure 3: Effect of optical correction: a) without optical correction, b) with optical correction

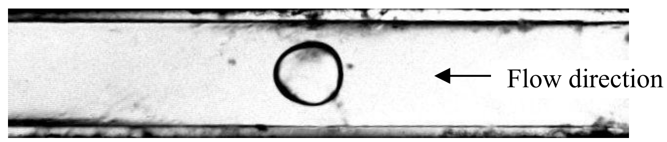
RESULTS AND DISCUSSION

Flow patterns of oil-water flow in microchannels strongly depend on the nature of the first fluid injected into the channels [4]. In other words, different flow patterns are observed depending on with which fluid the channel was initially saturated.

In this section, the flow patterns observed in a microchannel initially saturated with silicone oil is presented first. Then, the flow of water with zero oil flow rate in a microchannel initially filled with oil is discussed. Finally, the oil-water two-phase flow development in a microchannel initially saturated with water is discussed.

Oil-Water Flow Patterns in a Microchannel Initially Saturated with Oil

In this case, the channel was initially saturated with silicone oil by injecting only the silicone oil at a constant flow rate. Then, water was injected into the channel at different flow rates while the oil flow rate was kept constant. Figure 4 shows the flow patterns observed in this system: droplet, slug, annular and mixed flows. The flow direction is from right to left.



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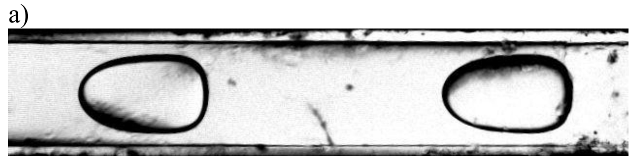

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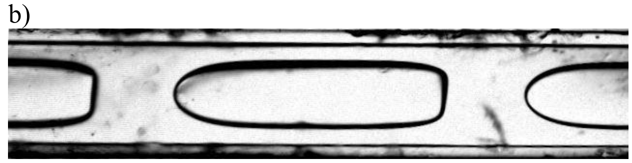

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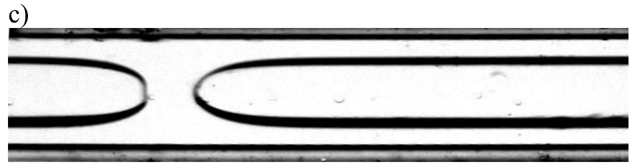

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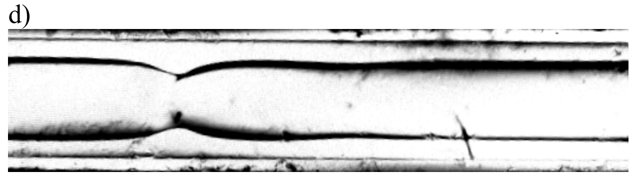

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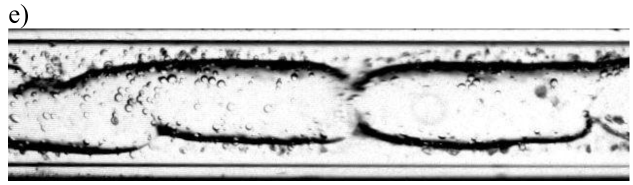

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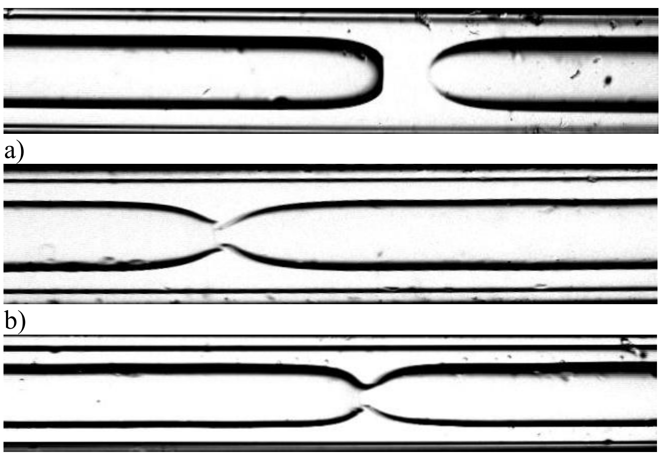
Figure 4: Flow patterns observed in viscous oil-water flow in a microchannel initially filled with oil: a & b) droplet flow - water droplets in continuous oil; c & d) slug flow - water slugs in oil; e) annular flow - water in the core surrounded by oil; and f) mixed flow - water drops and water core flow in oil.

Although the silicone oil was injected at the centre of the microchannel through a needle and water was injected through an annular gap between the outer wall of the needle and the inner wall of the microchannel (Figure 2), water formed the dispersed phase or core-flow and oil was the continuous phase and outer flow since the microchannel was initially saturated with silicone oil.

As mentioned earlier, for the case where the microchannel was initially saturated with oil, the oil flow rate was kept constant, while the water flow rate was increased. At low flow rates of water, the flow pattern was droplet flow. With an increase in the water flow rate, the droplet flow changed to a slug flow. With a further increase in the water flow rate, a transition occurred from slug flow to annular flow. Figure 5 shows the transition boundaries between the slug and annular flow patterns.

Finally, at the highest water flow rates tested, mixed flow patterns of water droplets and annular flow of water in oil were observed. Mixed flow patterns have not been observed in low-viscosity oil and water flows in larger microchannels [4]. The flow pattern map for the current system is presented in figure 6 based on water and oil superficial velocities. The superficial velocity is defined as the single phase volumetric flow rate divided by the microchannel cross sectional area. The maximum water and oil flow rates were 2.3 g/min and 0.06 g/min respectively.


a)
b)
c)
Figure 5: Transition from slug to annular flow: a) slug flow, b) transient flow: slugs merge, and c) annular flow

In Figure 6, the flow pattern is seen to change primarily with the water flow rate over the whole range of oil flow rates tested.

Flow of Water in a Stagnant Oil Annulus

In this section, the flow of water with zero oil flow rate in a microchannel initially saturated with oil is investigated. To initially saturate the channel with oil, the oil was injected into the channel first and the channel was filled completely with oil. Then the oil injection was stopped and water was injected into the microchannel at a constant flow rate. The flow patterns observed in this case are shown in Figure 7.

Under these conditions, the initially injected oil adhered to the inner wall of the microchannel and formed a stagnant continuous layer. After the oil injection was stopped and water was injected into the channel, water flowed as a core in a wavy form through a stagnant annulus of oil.

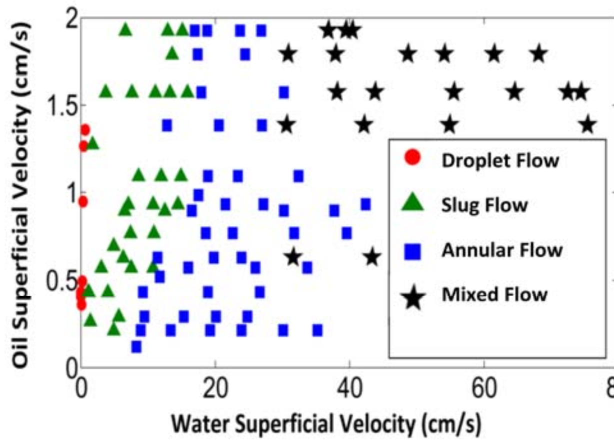
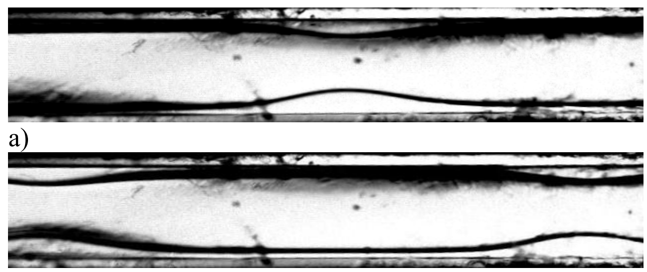


Figure 6: Flow pattern map for silicone oil-water flow in a 250 μm microchannel


a)
b)
Figure 7: a & b) Flow of water in a microchannel initially saturated with oil. Water flows as a core in a wavy form while a stagnant layer of oil adheres to the inner wall of the microchannel.

To investigate whether water would be able to fully wash away the oil, in one experiment, water at a constant flow rate of 0.5 gm/min was injected into the microchannel which had been initially saturated with oil. It was found that the water could not completely wash away the oil layer from the inner channel wall. Instead, the water flowed as a core through a stagnant wavy annulus of oil during the whole experiment. This behaviour may be similar to that of a heavy crude oil and water in small pores of oil reservoirs under a large pressure gradient.

Oil-Water Flow Development in a Microchannel Initially Saturated with Water

In this case, the channel was initially saturated with water by injecting only the water at a constant flow rate. Then, silicone oil was injected into the channel at different flow rates while the water flow rate was kept constant. Since the channel was initially saturated with water, oil formed the dispersed phase or core-flow and water was the continuous phase and outer flow. As shown in figure 8, at low oil flow rates, an oil jet broke up into droplets right after the injection section.

At higher oil flow rates, the oil first formed a uniform jet. As the oil flowed downstream, sinuous perturbations developed at the oil-water interface in the flow direction and the oil-water interface became unstable, forming a continuous wavy pattern.

Finally, the oil core broke up into droplets and formed a fully developed droplet flow of oil in water. Figure 9 shows the oil-water flow development in a microchannel initially saturated with water.

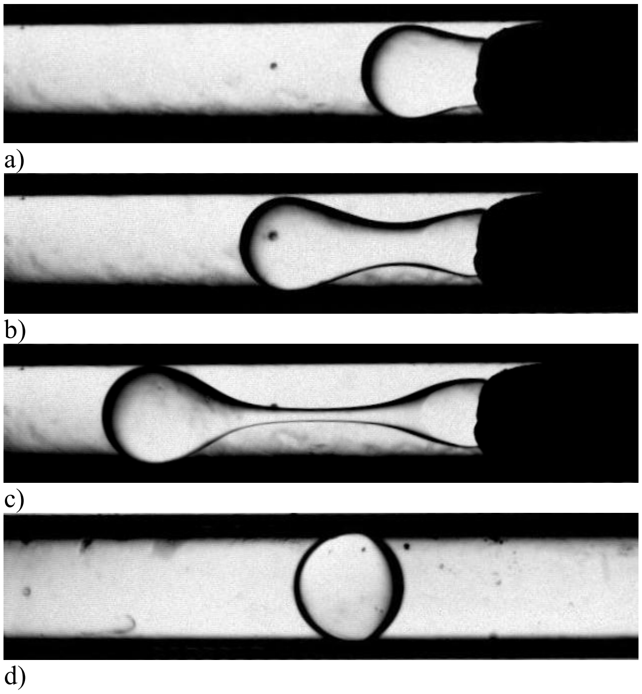
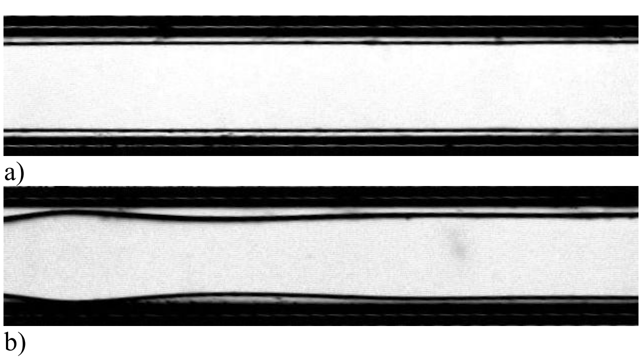


Figure 8: Oil-water flow development in a microchannel initially saturated with water for oil flow rate of 0.006 g/min and water flow rate of 0.021 g/min.

CONCLUSION

An experimental study of water-viscous oil flow in a microchannel of 250 μm diameter initially saturated with oil has been performed. When the microchannel was initially saturated with oil, different flow patterns were observed over a wide range of oil and water flow rates. Since the channel was initially saturated with oil, a stagnant layer of oil would remain on the inner wall of the microchannel which could not be washed away by a continuous flow of water even with the oil flow stopped. The oil-water flow development in a microchannel initially saturated with water was also studied. In this case, oil first flowed as a uniform jet. As the oil flowed downstream, the oil-water interface became unstable. Eventually, the oil jet broke up into droplets and formed a fully-developed droplet flow of oil in water.



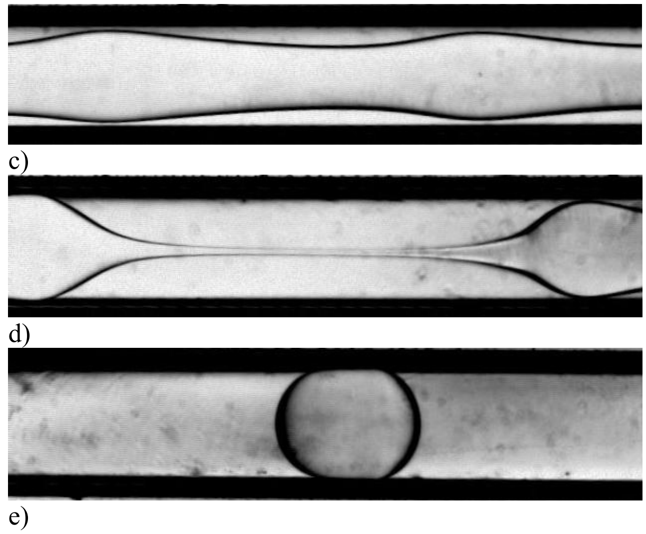


Figure 9: Oil-water flow development in a microchannel initially saturated with water for oil flow rate of 0.033 g/min and water flow rate of 0.021 g/min: a) Uniform oil jet in water; b) The onset of instability at the oil-water interface; c) Unstable wavy oil-water interface; d) Unstable oil jet breaking up; e) Fully-developed droplet flow of oil in water.

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