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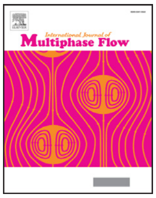

Investigation of oil-water flow regimes and pressure drops in mini-channels

Kevin K. Bultongez, Melanie M. Derby*

Department of Mechanical and Nuclear Engineering, Kansas State University, Manhattan, KS, USA

A R T I C L E I N F O

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Oil-water flow regimes were studied in 2.1 mm and 3.7 mm borosilicate glass tubes; both tubes exhibit Eötvös numbers less than one and therefore surface tension forces may be more important in these mini-channels compared to larger diameter tubes. A closed-loop, adiabatic experimental apparatus was constructed and validated using water. This study focused on tap water and two mineral oils (i.e., Parol 70 and 100) with a density of 840 kg/m^3 but a factor of two difference in viscosity. Experiments included a wide range of oil superficial velocities (e.g., 0.84–6.84 m/s for $D = 2.1$ mm and 0.27–3.30 m/s for $D = 3.7$ mm) and water superficial velocities (e.g., 0.21–7.69 m/s for $D = 2.1$ mm and 0.07–4.96 m/s for $D = 3.7$ mm). Stratified, annular, intermittent, and dispersed flow regimes were observed in both tubes, although the annular flow regime was more prevalent in the smaller tube. Pressure drops increased with decreasing tube diameter and were flow regime dependent. Flow maps were created for these mini-channels and equations adapted from Brauner and Maron (1999) were used to predict the flow regime transitions. The effects of viscosity were modest, although increased oil viscosity enhanced stability of oil-water flows.

1. Introduction

Advancements in technology and breakthroughs in oil processing have enabled the increased activity and growth of deepwater and ultra deepwater exploration (Addison, 2015; Chakhmakhchev and Rushworth, 2010; Dobson and Chatto, 1998; EIA, 2003), with new discoveries frequently occurring at these depths (Chakhmakhchev and Rushworth, 2010). According to the U.S. Energy Information Administration, crude oil-derived fuel sources will continue to have an integral part in the country's present and future supply of energy (EIA, 2003). Crude oil contains undesirable impurities and corrosion agents such as chloride (i.e., salt). Even at low concentrations, salt forms scale and accelerates corrosion in piping equipment resulting in fouling and expensive cleanup (Pereira et al., 2015). Desalting, the removal of formation water from oil, is a vital process in crude oil recovery; however, the process becomes challenging at deepwater and ultra deepwater depths. Current desalting technology relies on a combination of gravitational and electrostatic forces to achieve desired oil-water separation. As crude oil densities approach that of water, in the case of heavy crude, gravitational forces alone become insufficient in separating salt water from oil. In the case of electrostatic forces, voltages in excess of 30,000 V are required (Cameron, 2010a, b, c), which is challenging to supply to the ocean floor. These challenges generate motivation for a different separation approach. The effects of surface tension forces in two-phase oil-water flows may yield a particular set of flow configurations (i.e., annular flows) which combined with membranes could be utilized in addition or as an alternative to current desalting methods. Understanding mini-scale oil-water flow patterns and pressure drops is an initial step towards future surface-tension-driven oil-water separation systems.

Despite the extensive research on gas-liquid flows, flow regime and pressure drop prediction models are not directly transferable to liquid-liquid flows. Density differences in oil-water flows are significantly lower than liquid-gas flows, which can differ by three orders of magnitude and viscosity differences in liquid-liquid flows span a wide range of multiple orders of magnitude (Hadžiabdić and Oliemans, 2007; Hall and Hewitt, 1993; Mandal et al., 2007). Modeling of single-phase liquids cannot be directly applied to liquid-liquid flows since multi-phase shear stresses can exceed single-phase wall shear stress by up to 400% (Hadžiabdić and Oliemans, 2007). These differences are substantial, especially in the case of small diameter tubes where surface tension forces are dominant.

Different types of oil-water flow regimes have been observed and documented in a variety of tube diameters: stratified, annular, intermittent, and dispersed flow are four of the main flows

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* Corresponding author.
E-mail address: derbym@ksu.edu (M.M. Derby).

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Nomenclature

A	area, m^2
β	downward inclination to the horizontal
D	diameter, m
e	tube roughness, m
f	Darcy friction factor
g	gravitational acceleration, m/s^2
j	superficial velocity, m/s
K	loss coefficient
L	length, m
$\dot{m}$	mass flow rate, kg/s
Re	Reynolds number
P	pressure, Pa
V	velocity, m/s
ε	water input ratio
μ	viscosity, mPa s
ρ	density, kg/m^3

Subscripts

1	upper layer, or phase 1
2	lower layer, or phase 2
o	oil
w	water

observed in horizontal tubes (Al-Wahaibi and Angeli, 2007, 2009; Angeli and Hewitt, 2000; Atmaca et al., 2008; Balakhrisna et al., 2010; Bannwart et al., 2004; Brauner and Maron, 1999; Brauner and Ullmann, 2002; Cobos et al., 2008; Coleman and Garimella, 2003; Das et al., 2005; Das et al., 2016; Edomwonyi-Otu and Angeli, 2015; Ismail et al., 2015; Joseph et al., 1997; Mandal et al., 2007; McKibben et al., 2000; Rodriguez and Oliemans, 2006; Salim et al., 2008; Sotgia et al., 2008; Taitel and Dukler, 1976; Tsaoulidis and Angeli, 2016; Tsaoulidis et al., 2013; Zhao et al., 2006). Stratified flows were most prevalent in horizontal tubes with diameters above 10 mm (Al-Wahaibi and Angeli, 2007; Atmaca et al., 2008; Bannwart et al., 2004; Das et al., 2005; Edomwonyi-Otu and Angeli, 2015; Hadžiabdić and Oliemans, 2007; Ismail et al., 2015; Joseph et al., 1997; Rodriguez and Oliemans, 2006; Taitel and Dukler, 1976); researchers noted that gravitational forces separated the denser water from the less dense oil, thereby forming distinct layers. Tube diameter had a strong impact on resulting flow regime. Two researcher groups (Ismail et al., 2015; Rodriguez and Oliemans, 2006) studied oil-water flow regimes in 50.8 and 82.8 mm horizontal pipes, respectively. Stratified and dispersed flows were the dominant flow regimes in these larger diameters, with few appearances of annular or intermittent flows. A review paper noted instabilites often occurred at stratified oil-water interface across several studies (Joseph et al., 1997). Many researchers observed interfacial waves in stratified flows (Al-Wahaibi and Angeli, 2007, 2009; Das et al., 2005; Ismail et al., 2015; Rodriguez and Oliemans, 2006), indicative of the stratified-wavy flow regime and a result of instabilities stemming from different oil and water velocities. These interfacial waves increased droplet entrainment (e.g., oil droplets in water or water droplets in oil) resulting in dispersed flow regimes (Angeli and Hewitt, 1999, 2000; Brauner and Ullmann, 2002; Cobos et al., 2008; McKibben et al., 2000; Rodriguez and Oliemans, 2006; Sotgia et al., 2008).

Intermittent and annular flows were more prevalent at smaller diameters. Intermittent plug or slug flow, a flow regime affected by interfacial forces in small channels, (Tsaoulidis and Angeli, 2016), was found in numerous microchannel applications, including fuel cells, thermal mangement systems, separation processes (e.g., solvent extraction), emulsification, and biochemistry analysis and syntesis. In these applications, desirable tube sizes range from 200 μm to 6 mm (Das et al., 2010; Jovanović et al., 2011; Kashid et al., 2007; Kashid et al., 2011; Kiwi-Minsker et al., 2010; Tsaoulidis and Angeli, 2016; Tsaoulidis et al., 2013). In annular flow regimes, an annular water ring forms around an oil core which has been attributed to surface tension (Das et al., 2010; Das et al., 2016; Kashid and Kiwi-Minsker, 2011; Mandal et al., 2007; McKibben et al., 2000; Salim et al., 2008; Zhao et al., 2006). Charles et al., (1961) studied oil-water flows with similar densities in 25.4 mm tubes and noted intermittent flow regimes. Sotgia et al. (2008) observed stratified, annular, and dispersed flow regimes in 21–40 mm tubes. They noted a reduction in stratified flows, introduction of intermittent flows, and increased prevalence of annular flows in a 26 mm tube compared to a 40 mm tube. At even smaller diameters, the appearance of stratified flows dimished or disappeared in mini-channels for liquid-vapor flows (Agarwal et al., 2007; Coleman and Garimella, 2003; Jayawardena et al., 1997; Thome et al., 2003).

Table 1
Tested fluid property range.

Properties	Water	Oil (Parol 70)	Oil (Parol 100)
Density at 24 °C [kg/m^3]	$\rho_w = 997$	$\rho_o = 840$	$\rho_o = 847$
Viscosity at 23 °C, 40 °C, 40 °C [mPa s]	$\mu_w = 1$	$\mu_o = 11.7$	$\mu_o = 20.8$

The Eötvös number is the ratio of gravitational forces to surface tension forces (Brauner and Maron, 1999), and it has been shown to impact flow regimes, particularly the transition to annular flow and the impacts of surface tension on flow regimes. Bannwart (2001) developed a theoretical core-annular flow model and applied it to experimental data from a 22.5 mm horizontal pipe. The Archimedes number did not influence flow regime transition in the best fit model, but the flow exhibited a strong dependence on the Eötvös number. Brauner and Maron (1999) noted strong impacts of Eötvös number on flow regime. For larger Eötvös numbers with strong influences of gravity, stratified and dispersed flow regimes were observed at low and high flow rates, respectively and the researchers likened the flow regimes to gravity-driven, liquid-vapor flows. For surface-tension-dominated flows (i.e., low Eötvös numbers), annular flows were often more prevalent, similar to micro-gravity systems. Previous research studied horizontal oil-water flows in tubes with the following diameters: 248–498 μm (Jovanović et al., 2011), 269 μm (Kashid and Kiwi-Minsker, 2011), 400 μm (Zhao et al., 2006), 667 and 793 μm (Salim et al., 2008), 12 and 25 mm (Mandal et al., 2007), 14 mm (Edomwonyi-Otu and Angeli, 2015), 24.3 mm (Angeli and Hewitt, 2000), 28.4 mm (Bannwart et al., 2004), 38 mm (Al-Wahaibi and Angeli, 2007), 50.8 mm (Ismail et al., 2015), 53 mm (McKibben et al., 2000), 82.8 mm (Rodriguez and Oliemans, 2006).

The objectives of this work are to investigate the effects of mini-tube diameter and viscosity on horizontal oil-water flow regimes and pressure drop in regimes where surface tension forces may be important. Experiments were conducted in a 2.1 mm and 3.7 mm borosilicate glass mini-channel using tap water and two mineral oils, with a factor of two difference in viscosity, over a range of superficial velocities.

2. Experimental apparatus

2.1. Closed-loop apparatus

Water and mineral oil (i.e., Parol ® 70 or Parol ® 100, Calumet) flows were studied in a closed-loop experimental apparatus showed in Fig. 1; properties of the test fluids are given in Table 1. The fluids are pumped separately from a storage tank via two external gear pumps (GC-M25.PF5S. E, Micropump) with 1HP 3450 RPM motors controlled by their respective variable frequency