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Experimental investigation of viscous oil-water flows in pipeline

W.L. Loh, V.K. Premanadhan*

Department of Mechanical Engineering, National University Singapore, 10 Kent Ridge Crescent, Singapore 117576, Singapore

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ABSTRACT

Pipelines encounter high pressure losses during transport of high viscous crudes, especially at lower temperatures present in deep-waters. With emphasis on flow regimes and pressure drop of viscous oil-water flows, an experimental study was conducted on oil-water two phase flow in a 27.86 mm pipeline, with oils of viscosity 30 cP and 300 cP.

High resolution visualization studies, using high speed camera capture, were conducted to study flow patterns of oil-water two phase flows, that were further developed into flow regime maps. Visualization of the oil-water flow regimes reveals different layers of stratification for separated flow regimes with the existence of a near stationary oil layer on the top for heavy oil(300 cP). While light oil(30 cP)-water flow patterns were comparable to flow pattern maps found in literature, heavy oil-water flow patterns showed considerable deviations. The flow regime transitions have been found to occur at lower superficial velocities for heavy oil, than for light oil-water flows. Pressure drop characteristics of the viscous mixture flows were also investigated and compared with existing experimental results in literature. The studies reveal that phase inversion point occurs at higher phase fractions for heavy oils as opposed to light oils.

1. Introduction

The declining reserves of conventional crudes have led to growing interest into heavy oil, with non-conventional methods of transporting crude oils being experimented (Martinez-Palou et al., 2011; Abdurahman et al., 2012). It is widely known that heating the crude oil shall reduce its viscosity. However, the use of long heated pipelines has high capital and operational costs (Hasan et al., 2010).

With reduction of viscosity being the major benefit and with abundance of water supply, the formation of oil-water mixtures proves to be an attractive option for pipeline transportation. Two commercial emulsion pipeline systems, transporting crudes as oil in water mixtures are located in Indonesia, transporting 6359.6 cubic meter a day over 238 km of pipeline, and in California, transporting heavy viscous crude oil over 21 km (Zaki et al., 2001).

While gas-liquid flows have been extensively studied over the years, liquid liquid flow has received comparatively lesser attention and the available data is still small. A brief review of previous experiments in oil-water flows is presented in Table 1. Initially flow pattern identification was done by visual observation of the flow through a transparent section of the pipe. Different names were given to different flow regimes by different researchers. But in general, stratified and dispersed flow regimes appeared in all works. Initial work of Charles et al. (1961) who using oil with similar density as that of water and by using 3 oils of different viscosities upto 65 cP in a horizontal 1 in. pipeline, observed oil slugs in water and also reported achieving what appeared to be intermittent annular flow regime (Elseth, 2001). He also observed flow pattern transition differences between viscous oil and light oil. Lighter oils displayed oil continuous flow patterns at low oil velocities. He noted the tendency of viscous oil to form droplets at lower transitions.

Identification of oil continuous and water continuous flows can also be done using conductivity and impedance probes which rely on the differences in electrical property of water and oils (Trallero et al., 1997; Nadler and Mewes, 1997; Angeli and Hewitt, 1999). Internal view of the pipe cross-section can be obtained using capacitance tomography and resistance tomography. Nuclear tomography using gamma radiation can be conducted on pipelines, to reveal the density distribution in the pipeline and hence provide estimates of phase fractions within the cross-section.

The studies have led to generation of flow pattern maps for liquid liquid flows. However, they show considerable variation from each other (Angeli and Hewitt, 1999) as there are several variables that influence the flow patterns. Just as is shown in Table 1, the variables of density and viscous ratios vary with each experimenter and so does the pipe size and superficial velocities. It hence becomes cumbersome to isolate the effects of a single parameter and understand the changes that is caused due to the

* Corresponding author.
E-mail address: premanadhan_vk@u.nus.edu (V.K. Premanadhan).

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Table 1
Chronological review of experimental 2 phase oil water flow studies.

Author	Pipe size (mm)	Density (kg/m^3)	Viscosity (cP)	Velocity range (m/s)
Russel et al., 1959	24.5	834	18	0.0354–1.082
Charles et al., 1961	26.4	998	6.29, 16.8, 65	0.03–1.07
Arirachakran et al., 1989	26.6 and 41	869 and 898	4.7 and 2116	0.45–3.657
Trallero et al., 1997	50.13	850	29.6	0.1–1.6
Nadler and Mewes, 1997	59	850	35–28	0.1–1.6
Angeli and Hewitt, 1998	25.4	801	1.6	0.3–3.9
Bannwart, 2001	22.5	989	488	Oil (0.007–2.5), Water (0.04–0.5)
Piela et al., 2006	16	794	2.4–3.9	1–3
Rodriguez and Oliemans, 2006	82.5	830	7.5	Water (0.02–2.55) Oil (0.02–3)
Sotgia et al., 2008	21, 40	900	900	Water (0.05–2.51) Oil (0.17–0.9)
Wang et al., 2011	25.4	952.66	628	Water (0.1–1.2) Oil (0.1–0.8)
Al-Wahaibi et al., 2014	25.4	875	12	Water (0.1–2.6) Oil (0.1–2.0)

parameter under study. With the aim to isolate the viscous effects the current study was undertaken, to investigate the effects of viscous ratio on flow pattern transition and two phase pressure drops.

While early research of flow patterns in pipes were done with lighter, low viscous oils (Elseth, 2001; Al-Wahaibi et al., 2014; Fairuzov et al., 2000; Lovick and Angeli, 2004; Nadler and Mewes, 1997; Rodriguez and Oliemans, 2006; Angeli and Hewitt, 1998) and with simple observation techniques to identify flow regimes, research attention has shifted into studying heavy, viscous oils with more sophisticated techniques of flow pattern identification. This work shall use two oils of different viscosities to experiment the viscous ratio of 30 and 300. The low viscous (30 cP) and the high viscous (300 cP) oil shall be hence forth termed as light and heavy oil for sake of differentiation and better understanding. Although heavy oils are termed 'Heavy' for their high density, they are always highly viscous and it is their viscosity that posses challenges to pipeline transport. In the current work, the density of the heavy oil is in the range of 890 kg/m^3 and viscosity of heavy oil is 300 cP. As stated in the work by Bannwart (2001), an oil of viscosity over 100 cP can be termed as 'Heavy'.

Arirachakran et al. (1989) also conducted experiments with varying viscous ratios of 4.7 and 2000. He observed that while for heavy oils the annular flow pattern was existant, light oil did not display annular flow regime. With water as the continuous phase, no significant difference in flow regime was found between light oil and heavy oil. Nadler and Mewes also studied the effect of viscous ratio of the oil water flows by varying the temperature of the flow which facilitated them to test viscous ratios between 28 and 35 (Nadler and Mewes, 1997).

In general liquid-liquid flow patterns can be classified as separated flows, dispersed and annular flows. Separated flows arise from density differences of the two phases, where the oil(lighter phase) flows over the water(heavier phase) at low superficial velocities. Different interfaces are found in separated flows such as a smooth interface(stratified flow), wavy interface(stratified wavy) or an interface with mixing of oil droplets in water near the interface(stratified with mixing). Stratified, stratified wavy, stratified with mixing at the interface were the three categories of separated flow which were discussed by in the work by Trallero et al. (1997). They also mentioned the existence of water in oil droplets simultaneously with oil in water droplets, which would later on be classified as dual continuous flow regime by the work of Angeli (Angeli and Hewitt, 1998).

At higher flow rates, the oil from the stratified layer is broken off as droplets into water, hence forming a dispersion of oil in water, better described as dispersed flow regime. Dispersed flow can be broadly classified into oil in water(o/W) and water in oil(w/O) dispersions, depending on the continuous phase. When oil gets broken into droplets and is carried by the water, lesser contact occurs between the oil and walls of the pipeline, thus incurring less pressure losses. Phase inversion is a wide area of research for dispersed flow regime. It occurs when one fluid goes from being the continuous phase to being the dispersed phase at a particular phase fraction leading to increased effective viscosity of the mixture, which leads to high pressure drops in the pipeline (Piela et al., 2006).

Core annular flow is the third configuration of the flow regimes possible with liquid liquid flow in pipes that has been to reported in the literature by several authors (Sotgia et al., 2008; Grassi et al., 2008; Balakrishna et al., 2010; Wang et al., 2011; Bannwart, 2001). A good review of core annular flow can be found in the work by Ghosh et al. (2009). Termed as a 'Gift of nature' by many, core annular flow occurs when the high viscous oil forms an inner core and water flows around the core as an annular film, reducing the contact of oil with pipe walls and reducing occuring pressure drop massively. Core annular flows are achieved when the density of the oil is close to that of water, thus reducing the buoyancy forces acting on the oil core (Bannwart, 2001). Theoretical modelling of core-annular flow have been conducted as well, employing the lubricated film model, considering the oil core to be viscous enough to neglect the flow in the core (Ooms et al., 1984).

Reduction of drag (skin friction drag) in pipes is also possible through addition of additives (Virk, 1971, 1975). Experimentally, Wahaibi (Yusuf et al., 2012; Al-Wahaibi et al., 2013b, 2013a) investigated drag reducing polymers, where flow regimes were strongly affected. The addition of the drag reducing polymers caused a decrease in pressure losses and a maximum drag reduction of about 50% was reported for annular flow.

While a fair amount of research has been conducted on light oils, heavy oil-water research is still rather a new area. The secondary motivation behind this current work is to present experimental data on viscous multiphase flow and to develop better understanding of viscous oil-water flow regimes in pipelines. The manuscript is organized as follows. Section 2 describes the test facility used for the current experiments. Section 3.1 discusses the results from light oil-water flow experiments, Section 3.2 discusses the results from heavy oil-water flow experiments, Section 3.3 compares the flow patterns of heavy and light oil flows, Section 3.4 discusses the pressure drop measurements of both heavy and light oil-water flows. A short summary of the experiments and results are given in Section 4.

2. Experimental facility

Two phase oil-water flow experiments are conducted in pipelines, with individual lines for oil and water joining together at a junction (Injection Point) to generate the multiphase flow of oil and water co-mingled together in a single pipe. A transparent