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Effect of low interfacial tension on flow patterns, pressure gradients and holdups of medium-viscosity oil/water flow in horizontal pipe

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ABSTRACT

In most cited literatures, low-viscosity oils (1–10 cP) or high-viscosity oils (greater than 100 cP), which formed interfacial tension (IFT) of not less than 20 mN/m with water were used in determining the characteristics of oil–water flows and very few studies used medium-viscosity and low-forming IFT oils. Therefore, this experimental study was carried out to investigate the flow characteristics such as pressure gradients, flow patterns and holdups/velocity ratios of medium viscosity oil/water flow with low IFT in horizontal pipe of 30.6 mm-ID. The medium viscosity oil is a mineral oil with viscosity and density of about 24 cP and 872 kg m^{-3} respectively at 25 °C. Measurement of the flow characteristics covered the range of mixture velocities from 0.1 to 1.5 m/s and input oil volume fractions from 0.1 to 0.9. Pressure gradients were found to increase with increase in mixture velocities and input oil fractions. Phase inversions were observed at mixture velocity as low as 0.6 m/s where there were sharp increase in the pressure gradients and the phase inversion points occurred between 0.55 and 0.6 input oil fractions for the whole range of flow conditions. In addition, all the flow patterns identified using visual observation and high speed video camera can be grouped into three categories – stratified, dual continuous and dispersed flow. In terms of mixture velocity, the stratified flow was observed up to 0.2 m/s, the dual continuous flow was between 0.2 and 0.5 m/s and the dispersed flow was observed from 0.6 m/s and above. The velocity ratios were found to increase with increase in mixture velocity except at high input oil fractions where oil was the continuous phase. It was also observed that water was the faster flowing phase at low and medium mixture velocities while the reverse was the case at high mixture velocity. Lastly, the results of the study were compared with existing results from previous works which used medium-viscosity but high-forming IFT oils.

1. Introduction

The simultaneous flow of two immiscible liquids such as oil and water can occur in many chemical industries, but it is most frequently observed in petrochemical industries where they are usually pumped and transported together in wells and surface pipelines before they are separated. This type of flow is even more frequent nowadays because of the ever increasing excessive water production particularly at the later years of the production wells when water content can be as high as 90% of total production. The sources of this water in the wells include the presence of formation water, breakthrough water from adjacent oil reservoirs and deliberate injection of water into oil reservoirs to maintain reservoir pressure and enhance oil recovery [25]. The presence of water therefore must be accurately taken into consideration when designing and predicting the flow behaviour in both wells and pipelines. In addition, the study of oil–water behaviour will assist in downstream separation of the phases, accurately predicting the corrosion of pipelines as well as understanding of more complex flows such as gas–oil–water ones.

Most of the cited works in oil–water flows were carried out with low viscosity oils between 1 and 10 cP [3,4,23,38]. Also, the increase in world energy demand, the large amount of heavy oil reserves and the decline in conventional oils motivated researchers to work and publish papers on high viscosity oils [7,32,37,24]. However, few works on using medium-viscosity oil (20–100 cP) have been reported (Tables 1 and 2). Despite the limited information on oil–water flow patterns, pressure drop and hold up using medium-viscosity oil, there is currently no work available in the literature on the influence of low interfacial tension on these parameters using medium-viscosity oil. In the present work the flow characteristics such as flow patterns, pressure drop and hold-up of water-medium viscosity oil with low IFT are

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Table 1
Experimental oil–water horizontal flow studies using medium-viscosity and high-forming IFT oils.

Author (year)	Fluids	ρ (kg/m^3)	μ (cP)	σ (mN/m)	Pipe material	Pipe diameter (cm)
Guzhov et al. [14]	Mineral oil Water	896 1000	21.8 1	44.8	Steel	3.94
Oglesby [28]	Mineral oil Water	895 1000	32 1	30.1	Steel	4.1
Trallero et al. [35]	Mineral oil (Crystex-AF-M) Tap water	884 1037	28.8 0.97	36	Acrylic	5.01
Nadler and Mewes [26]	Mineral oil (Shell Ondina 17) Water	841 997	22–35 1	–	Perspex	5.9

Table 2
Flow conditions, parameters investigated and observed flow patterns in the oil–water horizontal flow studies using medium-viscosity and high-forming IFT oils.

Author (year)	V_M (m/s)	ε_0	Parameter investigated	Flow pattern measuring methods	Observed flow patterns
Guzhov et al. [14]	0–3	0–1	Flow pattern Pressure gradient	Visual observation	ST, Do/w&w, Dw/o&o, Intermittent flow, Dw/o, Do/w
Oglesby [28]	0–3	0–1	Flow pattern Pressure gradient Holdup	Visual observation	ST, ST&MI, Semi-mixed, Mixed, Annular, Slug, Semi-dispersed, Fully dispersed
Trallero et al. [35]	0.25–3	0–1	Flow pattern Pressure gradient Holdup	Visual observation Photographic Conductance probe	ST, ST&MI, Do/w, Dw/o, Do/w&w, Dw/o&Do/w
Nadler and Mewes [26]	0.3–1.6	0–1	Flow pattern Pressure gradient	Visual observation Conductance probe	ST, ST&MI, Do/w, Dw/o, Do/w&w, Dw/o&w, Dw/o&Do/w&w

investigated in acrylic horizontal pipe. The results are compared with those obtained using medium viscosity oils with high IFT.

2. Literature

2.1. Flow patterns

Ever since the investigation of oil–water flow started during the 1950s, several number of flow patterns have been identified and classified by different researchers. However, it is difficult to draw a general rules governing flow patterns boundaries due to the complex dynamic nature of the flow and large differences in the working fluids used in liquid–liquid experimental studies. According to Angeli and Hewitt [4], flow patterns of each oil–water flow are influenced by pipe diameter and orientation, velocities, volume fractions, densities, viscosities and wetting characteristics of the pipe wall. Some of the notable works on flow patterns can be attributed to [31,5,26,35,23,36]. Trallero et al. [35] in particular proposed flows patterns based on published and acquired data as segregated and dispersed flow patterns. The segregated flow patterns include *stratified flow* (*ST*) and *stratified flow with mixing at the interphase* (*ST&MI*) while the dispersed flow patterns include *dispersion of oil in water and water* (*Do/w&w*) and *oil in water emulsion* (*Do/w*) which are water dominated, and *dispersion of water in oil and oil in water* (*Dw/o&Do/w*) and *water in oil emulsion* (*Dw/o*) which are oil dominated. Lovick [22] gave a more elaborate categorization of all the identified flow patterns in horizontal oil–water flows into three groups, each of which can further be divided into a number of sub-categories. The first is stratified flow (ST) which can either be *stratified smooth* (*SS*) or *stratified wavy* (*SW*). The second category is known as dual continuous flow (DC) and it includes *stratified flow with mixing at the interface* (*ST&MI*), *three-layer flow*, *core-annular flow*, and *dispersion of oil in water and dispersion of water in oil* (*Dw/o&Do/w*). The third one is the dispersed flow which can be water continuous (Do/w) or oil continuous (Dw/o). In water continuous flow, *complete oil in water dispersion* (*o/w*) and/or *a dispersion of oil in water with a layer of water flowing at the bottom of the pipe* (*Do/w&w*) can be found while in oil continuous flow, *complete dispersion of water in oil* (*w/o*) and/or *a dispersion of water in oil with an oil layer* (*Dw/o&o*) can be found. Xu [36] on his part discussed the flow pattern transitions and all the measurement techniques of flow patterns such as visual observation, high speed photographic or video techniques, high frequency impedance probe, conductivity probe, particle image velocimetry (PIV), dual impedance probe, hot-film anemometer, mathematical methods and other techniques.

2.2. Pressure drops and phase inversions

Pressure gradient in oil–water flows mainly depends on the flow regime as well as the properties of the pipe wall such as roughness and wettability [3]. Wettability characteristics of the pipe wall can cause substantial effect on the pressure drop because of different affinities of liquids to materials. In addition, wetting the pipe wall with one of the fluids before the both are pumped into the pipe can affect the wettability of the pipe.

Apart from the experimental determination of pressure drops in oil–water flows, several models and correlations have been developed to predict the pressure drops as well [9,33,34,20,6,13,15,21,1,8]. Among the models are the two-fluid model for stratified flow patterns and homogeneous models for dispersed flow patterns. Although these two models are the prominent, researches have shown that they are limited in adequately predicting the pressure drops especially for medium viscosity oil [1].

Phase inversion phenomenon commonly observed in dispersed liquid–liquid mixtures when, with a small change in the operational conditions like phase volume fraction, the continuous phase changes to dispersed phase and vice versa, causing abrupt change in the rheological characteristics [36]. The main cause of phase inversion has been attributed to coalescence and break-up of the dispersed phase which occur continuously in dispersion flows. This