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Experimental investigation of oil–water two-phase flow in horizontal pipes: Pressure losses, liquid holdup and flow patterns

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ABSTRACT

Flow experiments have been conducted for oil–water two-phase flow in a horizontal 5.08 cm ID flow loop at a length to diameter ratio of 1311. The fluids were light Malaysian waxy crude oil from the offshore Terengganu (ρ_o=818 kg/m^3, μ_o=1.75 mPa s and wax content=16.15 wt%) and synthetic formation water. The water-cut was varied between 10 to 90% at nine mixture flow rates of 2.0 to 16.2 cm^3/s. Measuring the changes in pressure drop and liquid holdup at different flow rates of oil–water two-phase flow, a new flow pattern was identified. Strong dependence of the oil–water slippage on the minimum flow rate was observed. The highest pressure drop of 11.58 kPa was obtained at maximum flow rate of 16.21 cm^3/s and oil fraction of 0.9; while the lowest pressure drop of 1.31 kPa was recorded at the lowest flow rate of 2.03 cm^3/s and water fraction of 0.9. The experimental results could be used as a platform to understand better a more complex case of gas/oil/water concurrent flow in a pipeline.

1. Introduction

The need for reliable experimental studies on many engineering applications of flow assurance has been the driving force behind extensive research efforts in the area of multiphase flow. Liquid–liquid flow could be defined as the simultaneous flow of two immiscible liquids in a pipe. Previously, multiphase flow research works were mainly focused on gas–liquid flow; among the earliest studies in the gas–liquid field were Beggs and Brill (1973), Wicks and Dukler (1960), Hagedorn and Brown (1964), Gregory and Aziz (1975) and Cornish (1976). Nevertheless, the industry attention has shifted towards the understanding of the simultaneous flow of gas–oil–water mixtures (Trallero et al., 1997). Despite the extensive studies on gas–liquid two phase flow, liquid–liquid flow has received inadequate research attention (Atmaca et al., 2009). In the oil and gas industry, simultaneous transport of water and oil in pipelines occurs frequently. For oil fields operating at high water-cuts and low wellhead pressures, the effect of the water phase with respect to pressure drop is of particular importance. Lack of knowledge of the flow patterns, pressure drop and in-situ distributions of the liquids could be hampered the safe and economic transport of these fluids. The gained knowledge via experimental analysis can contribute to accurate modelling and prediction of oil–water flow in pipes.

Due to the dwindling of conventional light crude oil or 'easy oil' reserves and the existence of lots of mature oilfields around the globe, especially in the Malaysian oilfields, the phenomenon of concurrent flow of oil and water in pipelines has been the main subject of research studies in petroleum production and enhanced oil recovery with water injection. Furthermore, there are many cases where high water cut is present but the wells are still considered economically viable to operate. Understanding the behaviour of oil–water flow in pipelines, such as flow pattern, pressure drop, and liquid holdup is crucial for many engineering applications such as design and monitoring of the separation process, interpretation of production logs, and operation of flow lines and wells (Atmaca et al., 2009).

Some of the oilfields around the world are producing waxy crude oil. This phenomenon is due to the presence of paraffin (C_{18}–C_{36}) and/or naphthenic (C_{30}–C_{60}) hydrocarbons in the crude oil (Mansoori, 1993). When a crude oil contains waxes, the properties of the oil, especially the viscosity, will greatly change. There were numerous two phase flow experimental studies on the significance of viscosity, such as Russell et al. (1959), Arirachakaran et al. (1989), Oglesby (1979), Trallero (1995), Alkaya (2000) and Mckibben et al. (2000). All of these prominent researchers have found that the viscosity was greatly affecting the flow pattern, pressure drop, and liquid holdup.

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Aside, dealing with an oil–water mixture in a pipeline leads to unique and complex problems in the oil and gas industry due to its complicated rheological behaviour, and vast difference in pressure gradient encountered for different flow patterns (Arirachakaran et al., 1989). Although two phase flow of oil and water is normally occurred in pipes during production or transportation of petroleum fluids, its hydrodynamics behaviour under a wide range of flow conditions and inclination angles still creates a relevant unresolved issue for the oil industry (Flores et al., 1999). Actually, the main reported laboratory works on liquid–liquid two-phase flow were accomplished using gas oil, mineral oil, or refined oil, and limited experimental studies were performed on waxy crude oil. Therefore, an unexplored territory arises in terms of the flow behaviour in a pipeline when a waxy crude oil is introduced in a two-phase flow system. Accordingly, this crude that contains waxes would affect the flow behaviour due to its viscosity changes, complex interfacial chemistry, and natural emulsion effect.

Flow pattern is a particular type of geometric distribution of the components in a pipe and many of the names given to these flow patterns are now quite standard (Brennen, 2005). As emphasized by Trallero et al. (1997), the subject of oil–water flow can't be addressed in a unified way. That's because of the diversity of oil properties (e.g., viscosity, density, rheological behaviour, etc.), which makes their investigation not only too broad and contentious but also important and worthwhile.

Generally, we need an accurate prediction of waxy crude oil multiphase flow behaviour to produce and transport the waxy crude oil safely and economically. Waxy crude oils have complex flow properties; although considerable research has gone into the solution of specific industrial pipelining problems, a study devoted to the understanding of the behaviour of this material has not been appeared in the literature. Thus, an experimental investigation has been conducted to study the flow behaviour (i.e., flow pattern, pressure drop, and water holdup) of Malaysian waxy crude oil–water flow in horizontal pipes. This study addresses the determination of oil–water flow pattern for Newtonian and low-viscosity Malaysian waxy crude oil above wax appearance temperature (WAT).

2. Literature review

Crude oil from reservoirs is pushed to the surface by the high underground pressure (natural drive) and is flowed through their respective wellheads and pipelines for further processing. Normally, crude oil pipelines contain a fraction of water due to water encroachment from an aquifer and among others; and water percentage tends to increase in pipes over time. The situation is worsened when the wells are still operating even though the production stream is producing at high water-cut (Ngan, 2010). In liquid–liquid flow studies, the necessity to understand the nature and flow behaviour of this type of multiphase flow is crucial due to the existence of different mechanisms governing them and various flow patterns configuration. Russell and Charles (1959), Russell et al. (1959) and Charles et al. (1961) were among the earliest researchers who conducted studies on liquid–liquid flows. Most of their results became a reference for the subsequence studies and also provided a basic knowledge in understanding better the behaviour of a liquid–liquid flow. This scenario has attracted numerous extensive research works on this area after a decade, such as Guzhov and Medredev (1971), Guzhov et al. (1973) and Hughmark (1971). Brauner (2002) found that a liquid–liquid system is characterized by a low density difference between phases and this finding was supported by Atmaca et al. (2009). They explained that the oil–water system usually has similar densities, a large difference in viscosities, and more complex interfacial chemistry compared to gas–liquid systems (Fig. 1). However, a small density difference in terms of oil properties (e.g., API 45 to API 10) implies tremendous differences in composition, viscosity, etc.

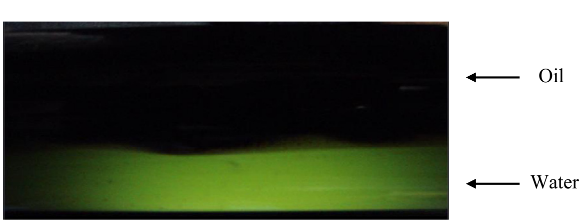

Fig. 1. Examples of oil–water flow in a horizontal pipe.

Nadler and Mewes (1997) explained that the flow behaviour of oil and water in pipes is heavily relied on the droplet distribution of the dispersed phase and volume fraction of the phases. This dependency is due to the effect of finite density difference between the oil and water phases that is contrary to gas–liquid flow system that possesses a great density difference. A simultaneous flow of oil and water will create an oil–water emulsion since they mix together when flowing in pipes. This phenomenon completely changes the physical properties of the liquids. An emulsion which is formed in a dispersed system consists of two immiscible liquids. An unstable emulsion formed during a dispersed flow could be separated into its original phases when it was left in stationary at a reasonable amount of time (Arirachakaran et al., 1989). Besides, these emulsions may appear to be a non-Newtonian or Newtonian rheological behaviour (Brauner, 2002). The differences in characteristics are triggered mainly by the small buoyancy effect, lower free energy at interface, smaller dispersed phase droplet size, and high momentum transfer capacity in liquid–liquid flows (Vielma et al., 2007).

An accurate prediction of oil–water flow behaviours, such as pressure drop, flow pattern, and water holdup are imperative in many advanced engineering applications (Brauner, 2002); such as designing and monitoring downhole metering, water-lubricated pipelines, production optimization, artificial lift design and modelling, optimum string selection, and production-logging interpretation (Flores et al., 1999). Russell and Charles (1959) extensively studied the flow behaviour of oil–water system by considering the flow pattern, pressure drop, and liquid holdups. Russell et al. (1959) have successfully observed the flow characteristics of oil–water in a horizontal condition using a 2.05 cm ID pipe. They found three types of flow pattern, namely bubble, stratified, and mixed flows. They also observed that water holdup was greatly influenced by liquid input ratio and viscosity. In principle, co-current flows of liquid–liquid mixtures in pipes are stable by considering the flow parameters (i.e., superficial velocity of each phase, the mixture flowrate, the pipe diameter, the surface tension, the finite density difference, pipe wettability, and the ratio of viscosity of fluids, as well as the shear stress between the liquid phases). In spite of the parameters mentioned above, pipe plane inclinations also affect the flow pattern. This flow pattern includes horizontal and vertical flow conditions which has significant differences in terms of flow pattern identifications (Oddie et al., 2003). Charles et al. (1961) conducted a study on oil–water flow in horizontal pipelines, and they encountered four types of flow pattern namely; water droplets in oil, concentric water with oil flowing in the core, oil slugs in water and oil bubble in water. They explained that the viscosity and low density difference between oil and water were affecting the flow patterns significantly. Generally, in an experimental study, there are many possible flow patterns that can be observed in horizontal conditions apart from those mentioned by Charles et al. (1961) as found by other researchers like Brauner (2002) and Trallero et al. (1997).

Researchers like Vuong et al. (2009), Vielma et al. (2007) and Trallero et al. (1997) found that the pressure drop was strongly depended on the flow patterns and flow rates. On the other hand, Atmaca et al. (2009) and Sridhar et al. (2011) stated that pressure