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Experimental Study on Waxy Oil-Water Horizontal Flow above the Wax Appearance Temperature

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ABSTRACT

Temperature sensitivity of waxy crude oils makes it difficult to study their flow behaviour in the presence of water especially near their wax appearance temperatures (WAT). This mini-review provides an overview of the challenges faced by researchers in operating a multiphase flow facility while using a typical Malaysian waxy crude oil. The outcomes of applying a new technique for controlling of the mixture temperature are also highlighted. Since the waxy crude oil in two-phase flow is a relatively uncharted area of study, the results of this study can provide a platform for furthering research.

Keywords: Oil-water two-phase flow, Flow pattern, Wax appearance temperature, Waxy crude oil, Water-in-oil emulsion, Flow assurance

INTRODUCTION

Progressive achievements in offshore oil exploration and drilling technology have recently made it feasible to explore and develop new remote deep water oil reservoirs, which had been once unobtainable [1-3]. The transport of the extracted fluids (i.e., oil, water and gas) from such reserves often takes place through long-distance (sometimes over 200 km) subsea multiphase pipelines to reach various destinations [4]. This vast distance makes it unprofitable to have distinct pipelines for each phase. The alternative is to transport the fluids through one single pipe (three-phase flow) or at least two pipelines (one for the gas and the other for the liquids). In either of the cases, the transport is accompanied with great difficulties owing to the nature of formation water and its accompanied components (i.e., salt and sediments). Corrosion, paraffinic wax deposition, reduction of oil flow area in pipe, emulsions and hydrates formation are some common examples of flow assurance problems caused by the presence of water in pipelines. To offer a safe and economical transport solution, flow assurance engineers overcome the challenges, firstly by anticipating the potential difficulties that may arise at different stages of production and secondly by proposing the most effective production plan prior to operation. Thus, attempts are needed to investigate multiphase flow behaviour under diverse flow conditions to identify influential parameters for controlling possible problems during fluids transport.

The presence of paraffinic waxes, regardless of their proportion, in all types of crude oils highlights the significance of any type of multiphase flow study with respect to these components [5]. Nevertheless, research works done on oil-water two-phase flows have mostly been restricted to the use of model oils (i.e., synthetic or mineral oils) rather than actual crude oils [6-8]. Although this practice is accepted as an attempt to improve the general knowledge on the subject, recent studies have shown that overly simplistic model oil cannot be a perfect representative of complex crude oils in terms of flow behavior. Therefore, as the first attempt, this research was aimed at studying the flow behavior of a typical Malaysian waxy crude oil in an

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-water two-phase flows have mostly been restricted to the use of model oils (i.e., synthetic or mineral oils) rather than actual crude oils [6-8]. Although this practice is accepted as an attempt to improve the general knowledge on the subject, recent studies have shown that overly simplistic model oil cannot be a perfect representative of complex crude oils in terms of flow behaviour. Therefore, as the first attempt, this research was aimed at studying the flow behaviour of a typical Malaysian waxy crude oil in an oil-water two-phase flow system at temperatures slightly above the initial crude oil wax appearance temperature (WAT). As a complement, the potential effect of water presence on WATs of water-in-waxy-crude-oil emulsions was also scrutinized.

EXPERIMENTAL SETUP AND MEASUREMENTS

To accomplish this study, a flow test facility was designed, constructed, and commissioned at the Malaysia Petroleum Resources Corporation Institute for Oil and Gas (UTM-MPRC Institute for Oil and Gas), Universiti Technology Malaysia (UTM). The facility is capable of simulating single or two phase flow of oil and water in a horizontal pipe. It should be noted that, in this study, the focus is only on the concurrent flow of local tap water and a typical Malaysian waxy crude oil at three mixture temperatures (i.e., 26, 28 and 30°C) under various flow conditions. To facilitate the temperature control of the system, a method was also proposed and implemented to predict mixture temperatures prior to the experimental flow of the oil and water in the designed horizontal multiphase flow loop. To observe this method in action, mixture temperatures, pressure drops and liquid holdups were experimentally measured for mixture velocity ranging from 0.2 to 1.7 m/s in a carbon steel horizontal pipe. Accordingly, flow patterns were determined by considering a combination of visual observations, pressure drop interpretations and free water measurements. Moreover, water-in-oil emulsion samples of different water-cuts (10 to 70%) under three distinct rotational speeds (600, 900 and 1200 RPM) were prepared for thermal analysis. Upon the preparation of the samples, small specimens were collected for differential scanning calorimetry test to examine the effect of emulsified water droplets on accelerating the wax crystallization process above the WAT.

RESULTS AND DISCUSSION

The results showed the success of the proposed method in predicting the mixture temperature with an accuracy of ± 0.5°C (**Figure 1**). The results of pressure drop revealed a dependency on mixture velocity, input water fraction, flow pattern and the parameters that flow pattern is a function of (such as pipe wettability, superficial velocities and oil composition). Despite operating the experiments above the WAT, the deposition of wax crystals on the pipe wall was evidenced for some of the flow patterns which, by implication, authenticate the influence of emulsified water on elevating the WAT in dynamic flow conditions. Classification of the flow patterns based on the wax deposition yielded an original flow pattern map (**Figure 2**) composed of nine patterns among which new configurations were evidenced for annular flows. In addition, all the flow patterns were affected by the entrance effect and a layer of water-in-oil emulsion was observed for all the flow conditions. From the experiments under the static conditions, a sharp increase in the WAT was found with the presence of water in the system, regardless of the volume of water.

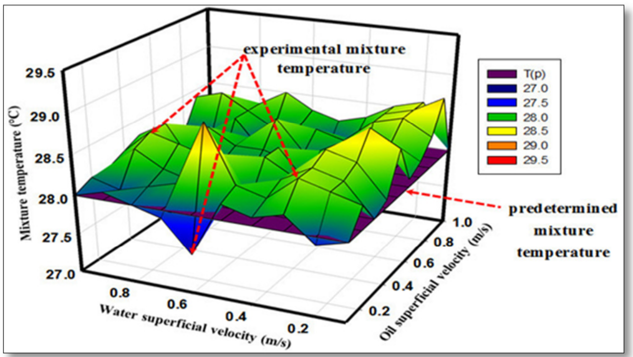

Figure 1. Illustrating the success of the method used in controlling oil-water mixture temperature flowing in a pipeline by temperature data comparison between experimental results and the predetermined temperature (28°C).

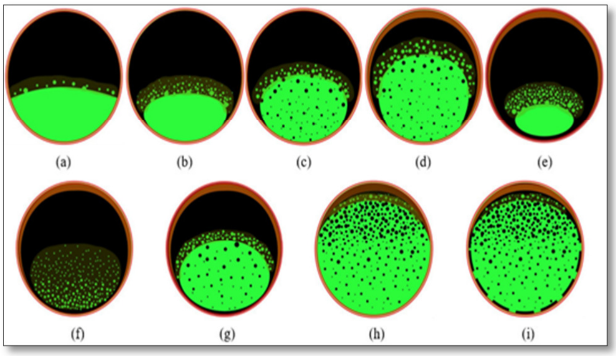

Figure 2. Flow pattern classification for waxy crude oil-water in a horizontal two-phase flow system at 28°C and WAT of 24°C: (a) stratified flow with partial emulsion of water in oil at interface (ST-PE), (b) stratified wavy flow with partial emulsion of water in oil at interface (SW-PE), (c) dual continuous flow (DC), (d) wax deposit and dual continuous flow (WDC), (e) wax deposit and eccentric annular flow with partial emulsion of water in oil at interface (WEA-PE), (f) wax deposit and eccentric annular flow with full emulsion of water in oil (WEA-E), (g) wax deposit and eccentric annular flow of dual continuous (WEA-DC), (h) wax deposit and fine dispersion of oil in water with thin layer of oil at the top of the pipe (WFDo/w-TLo), and (i) wax deposit and fine dispersion of oil in water with streaks of oil at the pipe wall (WFDo/w-So).

Greater deviations became apparent at higher water volume fractions and rotational speeds, which resulted in the formation of a larger number of droplets. As a final analysis, it is not suggested to extend the obtained results of any liquid-liquid two-phase flow systems including model oils or non-waxy crude oils to those of waxy crude oils. Such comparisons are hardly plausible and further studies on waxy crude oils under two-phase flow conditions are still essential.

COMPARATIVE REMARKS ON THE FLOW PATTERNS

A comparison between the presented flow patterns and those obtained by preceding investigators is, by and large, difficult and intricate. This emanates from the extensive experimental variables involved in the perception and definition of the flow patterns, including fluid properties, implemented methods, operational conditions and inconsistent nomenclature and terminology. Despite all the mentioned impediments, the most similar classification found in the literature to this work is from the studies using crude oils rather than model oils such as the one proposed by Wang et al. [9] for heavy crude oil/water flows. In the studies pertinent to model oil/water flows [1,2,4]. The onset of entrainment and mixing of the phases at the interface have been evidenced upon the emergence of stratified wavy flows at relatively higher mixture velocities. However, all the flow patterns observed in this study, including stratified smooth flow, were accompanied with water-in-oil emulsions which are in line with the findings by Wang et al. [9]. Apart from this fact, the observed flow patterns in this study are more or less analogous to those defined by previous investigators, though not all of them can be found in a single previous study due to the differences in the conditions under which they occurred. Yet, there is an explicit diversity in the phase configuration and flow characteristic of annular flows observed in this study from the conventional annular flows found in the literature.

Thus far, the phases involved in any type of annular flows are reported to maintain their continuities even for the cases where there has been dispersion between the phases [3]. However, the findings of this study show that annular flow may exist even at the time when one of the phases loses its continuity and becomes fully dispersed in the other. For instance, in WEA-E flows, full distribution of the water phase in the form of dispersed droplets closely resembles dispersed flow patterns while the resultant pressure drop for this type of flow pattern was still controlled by the oil film which was in direct contact with the pipe wall representing flow characteristic of annular flows. This is not only owing to the strong oil-wetness of the wall but also the compact distribution of the water droplets at nearly the centre of the pipe, which restricts the contribution of the dispersed water droplets in the wall frictional pressure drop. To put it simply, the response of pressure drop to this pattern represents the characteristic of annular flows while the phase configuration reflects the property of dispersed flows. Another striking feature in this research work is pertinent to the wax deposition during the flow. The inclusion of this phenomenon in the flow pattern classification of this study is a new attempt to relate the structure of the deposited layer to specific flow conditions in a pipeline. This in turn provides insights into the understanding of the flow behaviour of waxy crude oils and the associated challenges in the field conditions.

CONCLUSION

Based on the fact that paraffinic waxes are present in all types of crudes regardless of their proportion, it highlights the significance of this study which considered waxes in its two-phase flow research work. It can be deduced from the results that using the WAT of dried oil as the WAT of its emulsion are subject to substantial errors. If the possible thermal effects of the presence of water on the emulsion WAT are neglected, the consequence could be the unwanted deposition of wax crystals at temperatures greater than the WAT of that crude oil. This could threaten the success of flow assurance operations, especially for temperature-sensitive systems, such as the offshore pipeline transport of waxy crude oils.

The results of this study provide a progressive introduction to help flow assurance engineers to understand the process of wax crystallization and deposition under two-phase flow conditions in horizontal pipelines and to ultimately develop more effective wax management strategies.

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