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Experimental Determination of Flow Patterns and Water Holdup of Low Viscosity Oil-Water System in Horizontal Pipes

(Penentuan Secara Uji Kaji Corak Aliran dan Air Tertahan bagi Sistem Minyak Berkelikatan Rendah-Air di dalam Paip Mendatar)

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ABSTRACT

Fluids with different properties would exhibit different flow behaviour in any multiphase flow system at a given operating condition. Therefore, an in-depth knowledge of the operational and flow behaviour of any known fluid properties in a multiphase flow system of either liquid-liquid two-phase flow (oil and water) or gas-liquid-liquid three-phase flow (gas, oil and water) would be helpful in designing of pipelines and optimization of the production, separation, transportation and distribution systems, as may be found in oil and gas and allied petro-chemical industries. This paper presents the experimental observation of the flow patterns and water holdup for a two-phase low viscosity oil-water flow in horizontal pipes. The test fluids comprised of tap water and 2D-diesel which has a density of 832 kg/m^3, viscosity of 3.24 mPa.s, surface tension of 0.030 N/m and flash point of 79°C. A total of 30 runs has been accomplished and the experimental results showed three different flow patterns identified as stratified flow (ST), stratified flow with mixing interface (ST&MI) and water-in-oil dispersed flow (), with superficial velocities of oil and water in the ranges of 0.32 - 0.87 m/s (V_{os}) and 0.20 - 0.90 m/s (V_{ws}), respectively. However, analysis of water holdup in the commingled flows of the test fluids showed its dependency on the fluid flow patterns and superficial velocity of water.

Keywords: Dispersed flow; flow pattern; low viscosity oil; two phase flow; water holdup

ABSTRAK

Bendalir dengan sifat yang berlainan memberikan tingkah laku aliran yang berbeza dalam sebarang sistem aliran pelbagai fasa bagi suatu keadaan operasi yang diberi. Oleh yang demikian, pengetahuan yang mendalam tentang operasi dan tingkah laku aliran bagi sebarang sifat bendalir yang diketahui dalam suatu sistem aliran pelbagai fasa, sama ada aliran dua fasa cecair-cecair (minyak dan air) atau aliran tiga fasa gas-cecair-cecair (gas, minyak dan air), adalah berguna ketika mereka bentuk talian paip dan pengoptimuman sistem pengeluaran, pemisahan, pengangkutan dan penghantaran dalam industri minyak dan gas serta industri kimia. Kertas ini mengetengahkan pemerhatian secara uji kaji terhadap corak aliran dan air tertahan bagi aliran dua fasa minyak berkelikatan rendah-air di dalam paip mendatar. Bendalir kajian terdiri daripada air paip dan diesel-2D dengan ketumpatan 832 kg/m^3, kelikatan 3.24 mPa.s, tegangan permukaan 0.030 N/m dan takat kilat 79°C. Sebanyak 30 uji kaji telah dijalankan dengan hasilnya menunjukkan tiga jenis corak aliran telah dikenal pasti. Corak aliran terbabit ialah aliran berstrata (ST), aliran berstrata dengan percampuran antara muka (ST&MI) dan aliran terserak air dalam minyak (Dw/o), dengan halaju pada permukaan minyak dan air masing-masing dalam julat 0.32 - 0.87 m/s (V_{os}) dan 0.20 - 0.90 m/s (V_{ws}). Walau bagaimanapun, analisis yang dilakukan terhadap air tertahan dalam aliran tercampur bendalir kajian mendedahkan kebergantungannya kepada corak aliran bendalir dan halaju aliran air.

Kata kunci: Air tertahan; aliran dua fasa; aliran terserak; corak aliran; minyak berkelikatan rendah

INTRODUCTION

Liquid-liquid (i.e. oil and water) two-phase flow in pipes has been an integral part of multiphase flow which includes the simultaneous flow of gas, oil and water (i.e. three-phase flow) in either a vertical, horizontal or inclined pipelines during production in any oil or associated gas fields and allied chemical industries. However, Atmaca et al. (2008) have described two-phase liquid-liquid flow as a simultaneous flow of two immiscible liquids in pipes.

The complex properties of fluids at different operating conditions have affected the development of a distinct model that could be used to generalise the flow behaviour of commingled immiscible fluids in a multiphase flow system (Flores et al. 1999). An accurate correlation of flow behaviour of oil-water flow, such as flow pattern and water holdup are crucial to many engineering companies as that would enable them in the designing of pipelines, production optimisation, production logging interpretation, optimum string selection, downhole metering and artificial lift design and modeling (Brauner & Ullmann 2002; Melissa et al. 2000).

Owing to the consistent relevance of multiphase flow in oil and gas industries, researchers have developed specific models for fluid flow behaviour in a multiphase system that could be correlated with fluids that have similar properties at the given operating condition. Charles et al. (1961) and Russell et al. (1959) were among the earliest researchers that worked on two-phase liquid-liquid flow. In their research, they focused on identifying the flow pattern of fluids, pressure drop and liquid holdup. The former observed the following patterns in his study; bubbly, stratified and mixed flows with fluid of viscosity 18 mPa.s and density 834 kg/m^3 with superficial velocity of water (ranging from 0.035 to 1.08 m/s. They also concluded that water holdup was closely related to liquid input ratio and viscosity, while the latter observed four different flow patterns in their oil-water flow which were water droplets in oil flow, concentric water with oil flowing as core and oil slugs in water flow. They also concluded that flow patterns were affected by viscosity.

In the same vein, Moosawy et al. (2008), Ndler and Mewes (1997) and Trallero (1995) has in their respective experimental works on oil-water flow patterns in horizontal pipes observed the following patterns which they classified as segregated and dispersed flow. The segregated flow was further grouped as stratified flow (ST) and stratified with mixing interface flow (ST&MI), while that of dispersed flow was grouped as dispersion of water in oil flow ($D_{w/o}$) or emulsion of water in oil flow ($E_{w/o}$) (oil dominant) and dispersion of oil in water ($D_{o/w}$) or emulsion of oil in water ($E_{w/o}$) (water dominant). However, other flow patterns which are different from the aforementioned have also been observed by past investigators like Ismail et al. (2015), Vielma et al. (2007), Vuong et al. (2009) and Wang and Gong (2010). In the study by Wang and Gong (2010) on the flow regimes and transition behaviour of a high-viscosity oil-water two-phase flow (mineral oil-water), they observed seven types of flow patterns exhibited by their test fluids which they named as water in oil dispersed flow ($D_{w/o}$), dispersed flow of water in oil and stratified water flow ($D_{w/o}$ & *ST*), dispersed flow of water in oil and separated water droplet flow, dispersed flow of oil in water core and dispersed flow of water annulus, dispersed flow of water in oil and semi-water annular flow, intermittent flow of water and dispersion of water in oil semi-annular and dispersion of water in oil and water annular flow.

Therefore, this paper presents its findings on the flow pattern and water holdup of a typical low viscosity oil-water two-phase flow in horizontal pipes, simulated with 2D-diesel for the targeted crude oil of Tapis oil fields in offshore Terengganu, Malaysia and also for it to be a reference work for applications in relevant case for fluids with related properties at similar operating conditions.

Experimental Details

Test Facility

Figure 1 shows the schematic diagram of the experimental setup used in this study. The equipment was designed and developed to achieve the set objectives of this study. It comprised of two-parallel 10 m long and 2.54 cm internal diameter of horizontal PVC pipes which were inter-linked at one end with a 5 m long L-shaped PVC pipe. The PVC pipes were used as the test section for the simulated horizontal pipelines. A window section was integrated along the pipe length with a 1 m long transparent PVC pipe which furnished the visualization point for the flow pattern's study and it was positioned 8 m from the entrance point of the pipe section in order to allow the full development of the flow pattern. Two fast closing ball valves were installed at the entrance and exit points of the window section, which were meant to facilitate the measurement of the water holdup and a drain valve was provided beneath the window section to allow the collection of the trapped fluid phase after valve closure. Two separate tanks of 120 L capacity each served the purpose for the storage of oil and water and received its supply back from the pipes after fluids separation has been done by the settlement tank. The storage tanks were connected to variable speed 2hp centrifugal pumps that transported oil and water into the test section through a T-connector that converged and enhanced the mixing of the test fluids. The flow rates for both oil and water were controlled using a pump frequency inverter, while two ultrasonic flowmeters were used to record the velocities and flow rates.

Test Fluids

Table 1 summaries the projected test fluids and their respective properties at ambient conditions that were evaluated for their suitability to be used in simulating for the Tapis crude oil of offshore Terengganu, Malaysia. Based on the closeness in properties of 2D type diesel to that of the reference Tapis crude, it was selected against the other fluids and was used in commingling with the tap water from Malaysia for the two-phase oil-water flow pattern and water holdup study.

Methods

The selected test fluids (i.e. diesel and water) were poured into their respective storage tanks for transportation through the pipes. Oil and water were transported simultaneously into the pipes using the variable speed centrifugal pumps with superficial velocity of oil (V_{os}) ranging from 0.32 - 0.87 m/s and for water (V_{ws}) 0.20 - 0.90 m/s. However, a high speed video camera was positioned strategically at the window section of the pipe networks (observation point) to capture all the permissible flow patterns of this study and it was compared with that obtained by eye visualization and high speed photography for the sake of clarity of the obtained images and error bar control. The water phase was coloured with a red dye to enhance disparity between oil and water phase for ease of flow pattern identification. Water holdup was measured during the runs by abruptly closing the two valves at both ends of the window section for trapping the flowing mixture of oil and water after which it was discharged into 1000 mL graduated cylinder through the drain valve beneath the

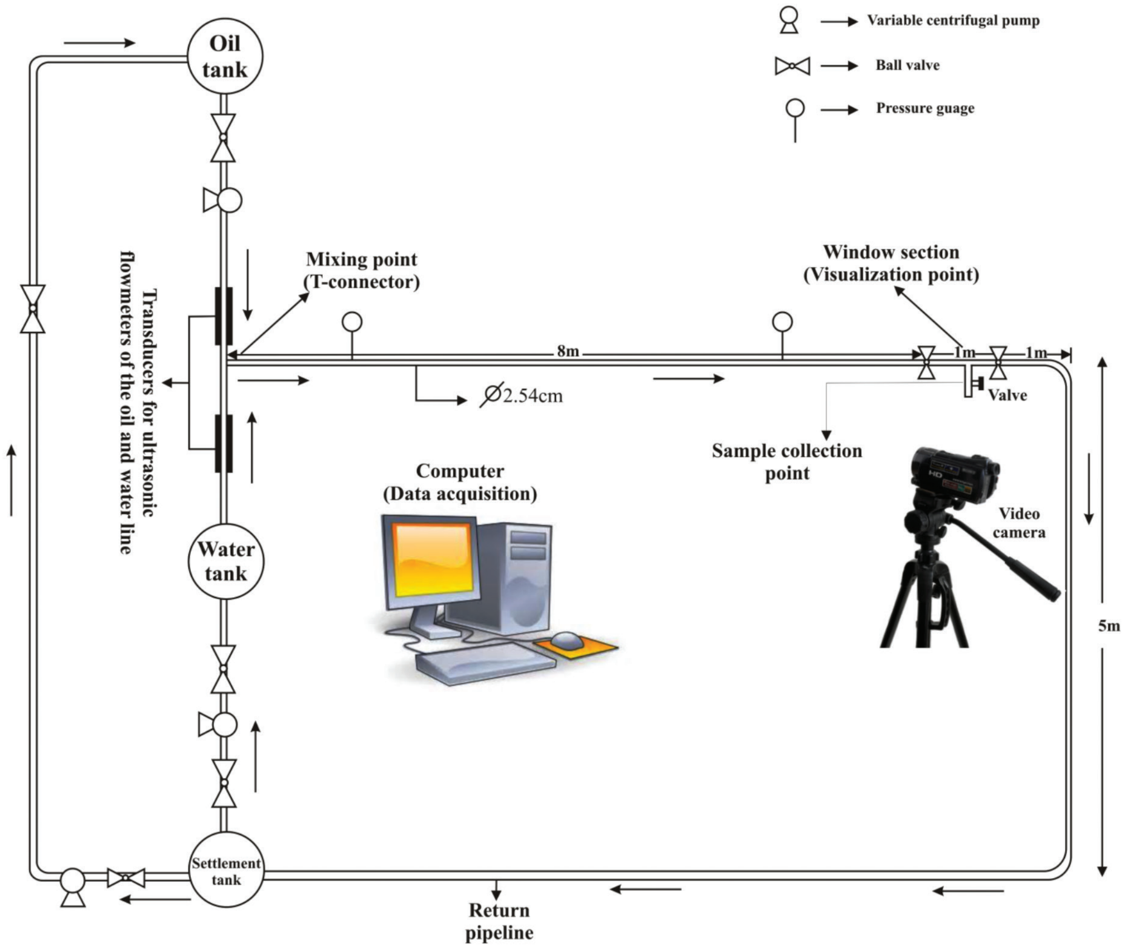

FIGURE 1. Schematic diagram of the experimental flow setup

TABLE 1. Projected test fluids and its properties

Fluid type	Viscosity (mPa.s)	Density (kg/m^3)	Flash point
Tapis crude oil	2.42	805	55 - 70
Diesel (2D type)	3.24	832	62
Kerosene	1.3	780	65
Palm oil	77.17	887	> 62

section. Hence, the collected fluid mixtures were allowed to stay for 24 h undisturbed to enable the separation of the mixtures into their constituents phase by gravity effect and density difference. After the separation, it was then easier to measure the water holdup accruable with the given superficial velocities of oil and water. Lastly, the fluid mixtures were passed through the settlement tank which enabled separation into their respective constituents phase and were re-injected into their various tanks. A total of 30 runs had been accomplished in this research work.

RESULTS AND DISCUSSION

The research findings of this study have successfully showed three flow patterns which were named following that of Al-Wahaibi et al. (2012), Brauner and Maron (1989), Ndler and Mewes (1997), Trallero (1995), Wang and Gong (2010), Yao et al. (2009) and Zhang et al. (2010). The identified flow patterns were stratified flow, stratified with mixing interface flow and water-in-oil dispersed flow.

STRATIFIED FLOW (ST)

Figure 2 shows the pictorial display of this flow pattern while Figure 5 relates the superficial velocities of oil (V_{os}) and water (V_{ws}) in the form of flow pattern map that were responsible for this type of flow behaviour. Critical analysis of Figure 5 shows that the stratified flow pattern occurred at low superficial velocity of oil and water at 0.32 and 0.20 m/s, respectively. The reason to this segregated behaviour was due to the density and viscosity difference between

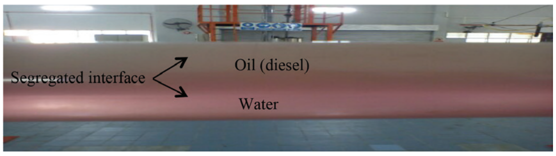

FIGURE 2. Stratified flow pattern (ST)

the oil and water phase which became pronounced when the mixture velocity of oil and water produced a Reynolds number of 2500, which was marginally above the boundary value of laminar flow. This result has consolidated the confirmation made by Al-Wahaibi et al. (2012), Ndler and Mewes (1997) and Trallero (1995) that stratification of fluid flow is a function of their density ratio ρ_o/ρ_w (which is usually less than unity and also their relative movement. They added that, interaction between the surface tensions of the fluids and their viscosity differences play a vital role as well in the segregation of the two immiscible fluids. Their stratified flow occurred at 0.48 m/s superficial velocity of water (V_{ws}) and 0.33 m/s for that of oil (V_{os}).

STRATIFIED WITH MIXING INTERFACE FLOW (ST&MI)

Figure 3 shows the pictorial display of this flow pattern while Figure 5 relates as well the superficial velocities of water and oil for which this flow pattern exist. This type of flow pattern was observed when the superficial velocity of water (V_{ws}) was increased from 0.54 - 0.90 m/s while the superficial velocity of oil (V_{os}) was kept constant at 0.32 m/s. The same flow pattern continued when the superficial velocity of oil (V_{os}) was from 0.63 - 0.77 m/s while that of water was maintained at 0.20 m/s. However, it was observed that the same flow condition persisted as both fluids' superficial velocities were increased simultaneously.

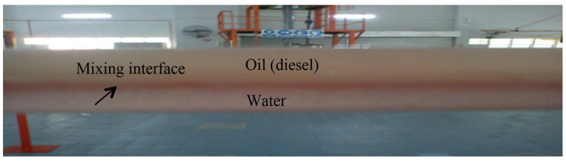

FIGURE 3. Stratified with mixing interface flow pattern (ST & MI)

Precisely, the rationale behind this flow pattern could be said to be caused by the waves generated at the interface between oil and water from intermittent to high turbulence of the mixture fluids movement which has increased Reynolds number from about 4000 to 9000. In spite of these high superficial velocities of oil and water, droplet flow of either oil or water phase was not observed in this study. The reason attributed to this stability was due to the high interfacial tensions that co-existed between oil and water. This inference was supported by the EÖtvÖs number which was calculated to be 1.11. Brauner and Moalem-Maron (1992) proposed this number that establishes which force has dominant effect on the flow pattern of immiscible fluids in pipes. The following equation shows the mathematical expression of the EÖtvÖs number.

$$E_o = \frac{4\pi^2\sigma}{(\rho_w - \rho_o) g D^2}, \qquad (1)$$

where σ is the surface tension; ρ_w is the density of water; ρ_o is the density of oil; g is the gravity; and D is the pipe diameter.

Brauner and Moalem-Maron (1992) stipulated that when $E_o > 1$, it indicates that surface tension force dominates other forces for the obtained flow pattern. However, other forces that have influenced on fluid flow patterns are viscous and momentum forces.

DISPERSION OF WATER-IN-OIL FLOW ($D_{w/o}$)

Figure 4 shows the pictorial display of this flow pattern while Figure 5 also shows the superficial velocities of oil and water that were responsible for this flow pattern. From Figure 5, it could be seen that the dispersal flow of water in oil occurred when superficial velocity of oil (V_{os}) was increased to 0.87 m/s while that of water (V_{ws}) was kept constant at 0.20 m/s. Furthermore, this flow pattern was seen to have persisted when the superficial velocity of water was increased from 0.54 - 0.90 m/s while keeping constant the superficial velocity of oil at 0.87 m/s. The persistency of this flow pattern in spite of the increment in the superficial velocity of water has explained the relative degree of interactive forces the oil molecules had over that of water molecules. It borrowed a leaf also in explaining the interfacial shear between oil and water in pipe flow. Based on this preceding concept, the oil phase had more cohesive forces between its molecules than the molecules of water phase, and as such, the instability at the fluids interface became very high due to high wave created as a result of high superficial velocities of oil (V_{os}) and water (V_{ws}) which have produced a Reynolds number of up to 11000 for the oil-water mixture. Hence, this turbulent flow caused the sufficient supplied energy to break the water molecules into small droplets which led them to be dispersed in the oil phase. Yao et al. (2009) have also identified the effect of fluid's interactive forces on phase transition. In their research, they observed that increase in the volume fraction of water in the two-phase system would lead to the transition of water-in-oil dispersion ($D_{w/o}$) to a continuous flow of water phase. They concluded that it was due to the more interactive forces of the water molecules as the water phase became more dominant.

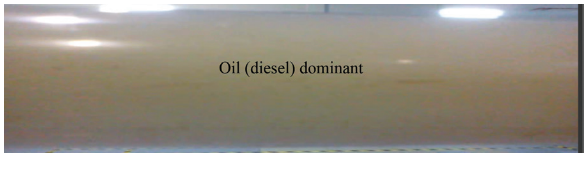

FIGURE 4. Water-in-oil dispersion flow pattern ($D_{w/o}$)

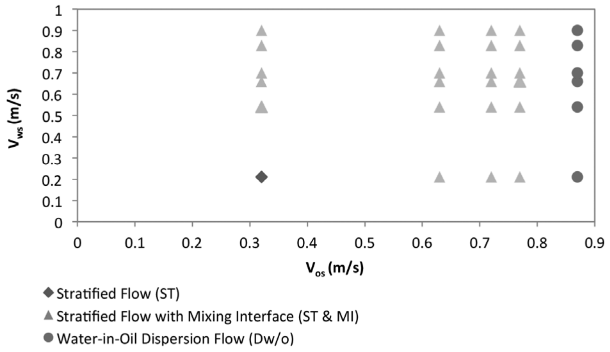

FIGURE 5. Flow pattern map

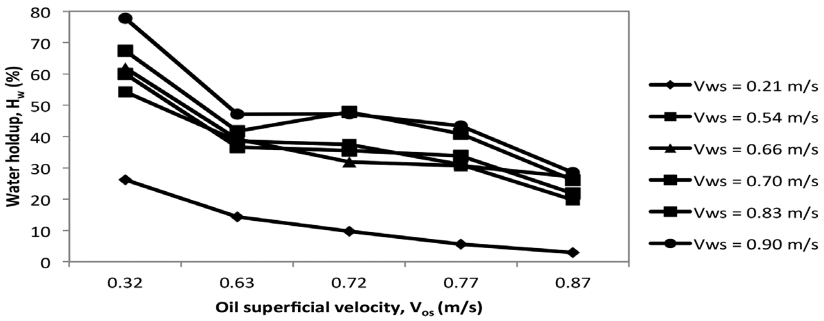

FIGURE 6. Water holdup *vs*. superficial velocities of oil and water

WATER HOLDUP ANALYSIS (H_w)

A method known as quick closing valve was adopted in conducting this study. Oddie et al. (2003) used this method as well in their research work on water holdup study. Figure 6 shows the water holdup results evaluated at varying superficial velocities of oil and water. It could be seen that the higher the superficial velocity of water (V_{ws}), the more the percentage of water holdup (H_w). This has proven that the more water cut that exists in oil-water two-phase flow in pipes, the more would be the water holdup (H_w). Xu et al. (2008) also confirmed that water holdup (H_w) behaviour was dependent on the flow pattern and input water fraction.

Furthermore, a correlation between the observed flow patterns of this study and the evaluated *in-situ* volume fraction of water (water holdup) at all the superficial velocities investigated, has shown that dispersion of water-in-oil flow pattern had the least water holdup (H_w) as against the other two flow patterns identified. This distinct observation has confirmed the assertion made by Xu et al. (2008) on the parameters they said that have great effect on water holdup in two-phase flow of oil and water in pipes.

CONCLUSION

Conclusively, the research findings of this study have posed superficial velocities of oil and water to have a great influence on the flow pattern of fluids in horizontal pipes. However, stratification of fluid flow was found to be a function of the density differences between the liquids involved and their relative velocities. Furthermore, water-in-oil dispersed flow pattern has shown to have the least of water holdup as compared to other flow patterns identified, thereby making it to have less corrosion effect on pipelines. Finally, water holdup in two-phase oil-water flow in pipes was seen to be depended on the input water fraction and flow patterns involved.

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