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OIL-WATER DISTRIBUTIONS IN LARGE DIAMETER HORIZONTAL PIPELINES

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ABSTRACT

Oil-water flow is a common occurrence in the petroleum industry. The presence of water layer at pipe wall can cause extensive corrosion problems. Addition of surfactants to the oil-water flows can enhance oil-water mixing and oil-wetting of the pipe wall, thus reducing corrosion.

Flow characteristics and the effect of surfactant have been determined at temperature of 25°C and pressure of 0.136 MPa in a 10 cm diameter, 40 m long horizontal pipeline. Oil-water distributions have been studied at input water cuts of 20, 40, 60, and 80%. ASTM standard seawater and oil (viscosity 3 cP at 25°) were used at superficial liquid velocities ranging from 0.4 to 3.0m/s.

Holdup (of water) is strongly affected by superficial mixture velocity and existence of surfactant. At low mixture velocity below 1.2 m/s, little water can reach the top of the pipe and no oil can contact the bottom of the pipe without surfactant. For the mixture velocity range of 1.6 ~ 2.0 m/s, large percentage of oil is entrained into the water and reaches the bottom and certain amount water finds its way to the top of the pipe. With the adding of surfactant, the homogenous flow pattern can be obtained at lower velocity.

The input water cut, mixture velocity and surfactant have influence on the velocity distribution. At low water cut of 20%, the water layer moves at lowest velocity. At 40% and above, the water layers move faster and the mixed layer moves fastest.

Oil and water are much easier to be mixed at the medium input water cut of 60%. They begin to mix at higher superficial velocity at 20% input water cut. The area occupied by mixture is larger when surfactant was added.

1. INTRODUCTION

Water produced by maturing oil wells increases work time. Compared to gas-liquid two phase studies, there are few studies concerning the oil/water two immiscible liquid flows. However, flow characteristics of oil-water flows are much different from gas-liquid two-phase flow. Understanding the distinctive features in oil-water flows is not only extremely important for designing the pipelines, and for production logging instruments, but also crucial in predicting the amount of free water in contact with the pipe wall that could cause corrosion problems.

Different oil/water flow patterns are observed as the transition occurs from stratified to completely mixed flow, with an increase in the total superficial velocity of the mixture and a change in the input concentrations of the two phases. The flow patterns play an essential role in oil-water flows. Russel et al. (1959) found three flow patterns in horizontal pipeline: bubble, stratified and mixed flow. Four flow patterns were defined by Charles et al. (1961), including water droplets in oil, concentric water with oil flow in the core, oil slugs in water and oil bubble in water. They studied an equal density oil/water flow in 2.5 cm pipe and found the oil-water flow patterns were mostly independent of the oil viscosity.

Oil-water flow patterns observed by Oglesby (1979) are shown in Figure1. At low velocity, the flow is stratified. The flow of the liquid is in two distinct layers, with no mixing at the interface. As some mixing occurs at the interface by increasing the mixture velocity, the flow pattern is called semi-segregated flow. Semi-mixed is defined as a segregated flow of a dispersion and a 'free' phase and the dispersion volume is less than half the total pipe volume. When the oil-water dispersion occupies more than half the pipe volume, mixed flow occurs. At high mixture velocity, the flow pattern is termed as semi-dispersed and with further increase in velocity the flow pattern is homogeneous flow. There is a steep concentration gradient in semi-dispersed flow while homogenous flow has no appreciable change in concentration. Ariachakaran et al. (1989) developed experimental oil-water flow pattern maps, and found that the flow pattern in oil-water mixture depended primarily on mixture velocity, input water fraction and oil viscosity when oil is the continuous phase.

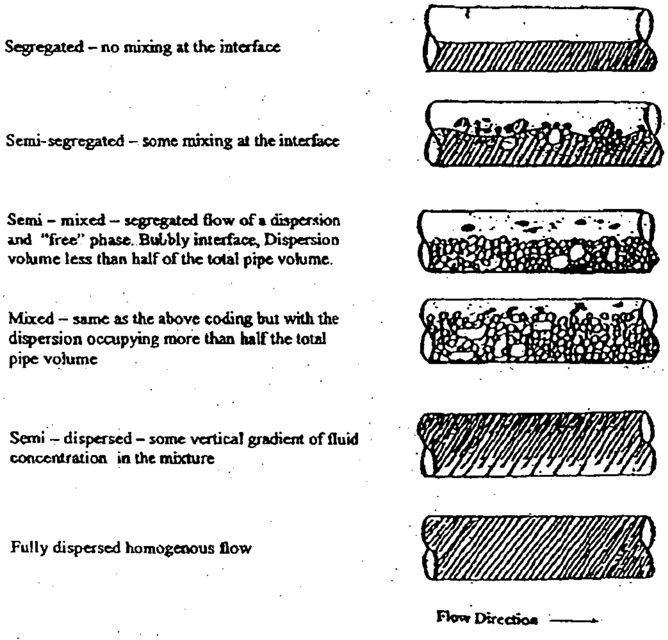
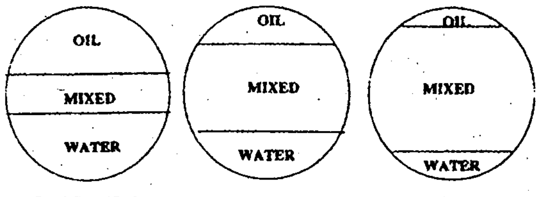


Figure 1 Description of Flow Pattern Classification for Oil – Water Flow (Oglesby, 1979)

Holdup is necessary in the modeling of oil-water flow for designing production-logging instrument. Production logging tools provide an accurate measurement of density, velocity and holdup at the point of measurement. However, extrapolation to entire pipe cross-section could lead to wrong results. Moreover, in stratified flow, holdup is the fraction of the cross section area occupied by water and hence is a measure of the in situ velocities of the two fluids. Mukherjee et al. (1981) presented the empirical holdup correlations for upward and downward flow in his study of the oil-water flows in inclined pipeline for inclinations ranging from ± 30° to ± 90° from horizontal in a 1.5 inch diameter pipe. Vigneaux et al. (1988) studied the effect of inclination, mixture velocity, and input water cut on holdup in 10 cm and 20 cm diameter pipelines. He found water fraction profiles depend only on the mean volume composition of the mixture and inclination. Malhotra (1995) has done extensive work on the holdup for two oils (viscosity 2 cp and 100 cp) in 10 cm ID, horizontal pipeline. Vedapuri (1997) studied oil-water flows both in horizontal and inclined pipeline. A mechanistic model was developed to predict the hold up and pressure drop in



Semi-Stratified Semi-Mixed Semi-Dispersed

Figure 2 The Cross Section for the Three Flow Patterns (Vedapuri, 1997) semi-stratified and semi-mixed flows. Here, as shown in Figure 2, oil-water flow has been treated as a three phase stratified flow with a water layer at the bottom, an oil layer at the top and a mixed layer, which is an oil-water dispersion, at the center of the pipe. Sarica et al. (1997) found that holdup was strongly affected by oil-water flow patterns, water cut, and inclination.

Wicks et al. (1975) reported that corrosion in pipelines was generally associated with water. The area in which water is settled out was much likely has the corrosion problems. In highly turbulent flow the corrosion rates were much lower than when the flow was intermitted. He found the critical flow velocity to entrain water increases with pipe diameter. Equations were proposed to calculate the minimum oil velocity required entraining the water droplets.

Crude oil contains natural surfactants, which changes the surface and interfacial tensions of the fluids and enhances the oil-water mixing. The major objective of this work is to examine the effect of surfactant on the oil-water distribution.

2. EXPERIMENT SETUP AND PROCEDURE

2.1 Experiment Setup

Figure 3 shows the experimental layout of the flow loop. A specified amount of oil-water mixture is placed in a 1.2 m^3 stainless storage tank (A). The tank is equipped with two 1kW heaters (B). In addition, the tank is equipped with 6 m (2.5 cm ID) stainless steel cooling coils to maintain the temperature. A 5hp centrifugal pump (C) is used to pump oil-water mixture into a 7.5 cm ID PVC pipeline. It also controls the flow rate. By-pass system (D) serves to agitate the oil-water mixture in the tank. Flow metering is done by an orifice plate. A T-junction fitted with a ball valve is present at the exit of the pump. Liquid samples are withdrawn at regular intervals from this junction, before the start of the experiments and while the experiment is in progress, to ensure the flowing water percentage is maintained.

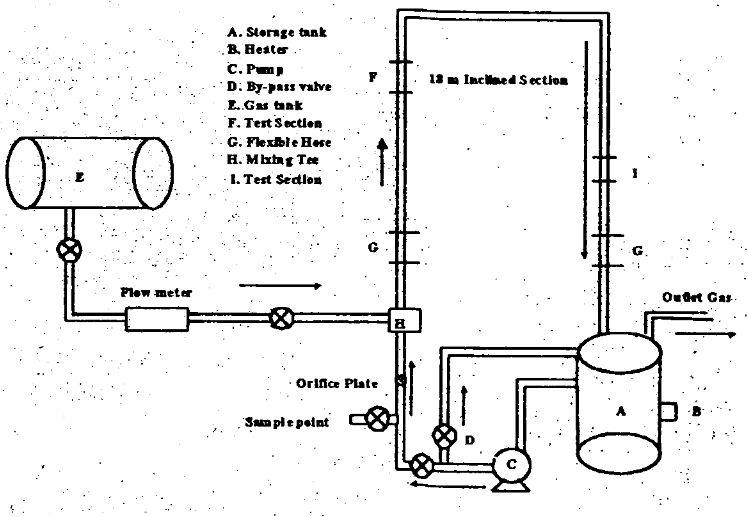


Figure 3 Experimental Layout of the Flow Loop

The oil-water mixture enters the inclinable plexiglass section through a 10.16 cm ID, 2 m long flexible hose and passes the 36m long and 10.16 cm I.D Plexi-glass section and then returns to the tank. The system pressure can be maintained using carbon dioxide from gas tank (E).

The 2 m long test section is shown in Figure 4. The sampling tube (B) is used to measure the holdup. The velocity profile is determined by a Pitot tube. Red oil soluble dye is added in the oil to help the observation, and a VHS video camera was used to record the flow.

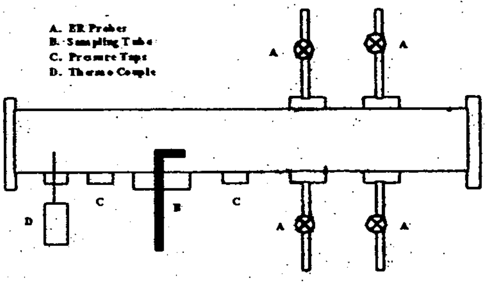


Figure 4 Test Section

2.2 Test Matrix

The test matrix is described in Table 1.

Table 1 Experimental Test Matrix

• Inclination	0°
• Liquid phase	Oil (3 cP at 25 C), Standard ASTM salt water
• Surfactant Concentration	0 ppm, 15 ppm
• Temperature	25 °C
• Liquid Velocities	0.4 ~ 3.0 m/s
• Water Cut	0%, 20%, 40%, 60%, 80%, 100%

3. RESULTS AND DISCUSSION

A water dispersible surfactant, (an alkoxylated alkyl phenol), was used as surfactant in the experiments. It reduces interfacial tension from 33.4 to almost zero at 15 ppm (Tulshyan, 1996). This may suggest that an emulsion is being formed at the lighten dosages.

An interesting observation while measuring holdup was that it took less than a minute for oil and water to separate in the holdup cylinder without surfactant while several minutes was needed on an average before separate layers of oil and water can be seen when 15 ppm surfactant was added.

3.1 *In situ* Water Holdup

A detailed study of oil-water distribution across the cross section from the top to the bottom of the pipe was carried out for input water percentages of 20, 40, 60 and 80%. The ratio of the height at which measurement is made to the diameter of the pipeline, h/D is plotted against the *in situ* water percentage.

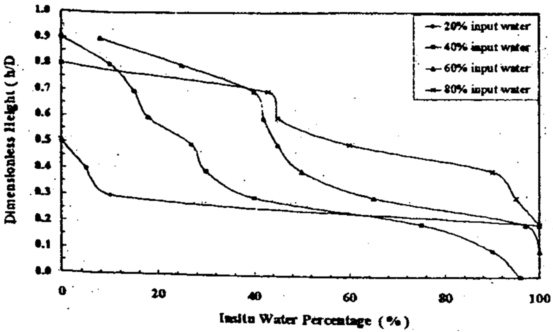


Figure 5 Variation of Water Percentage with Vertical Position
(1.2 m/s, 0 ppm surfactant)

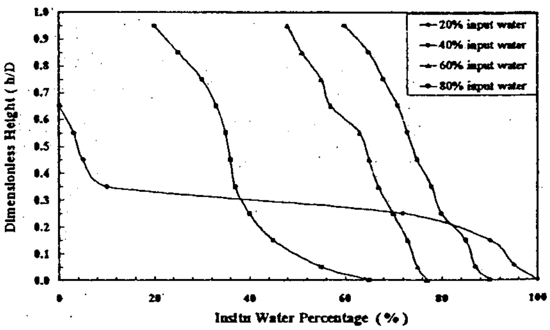


Figure 6 Variation of Water Percentage with Vertical Position
(1.2 m/s, 15ppm surfactant)

The results for a mixture velocity of 1.2 m/s at surfactant concentrations of 0 and 15 ppm are shown in Figures 5 and 6 respectively. Figure 5 shows that, for the input water cut of 20%, no water appears above h/D of 0.5. A thin layer is seen between the h/D of 0.3 and 0.5 with less than 10% of water in it. This depicts layers in which the oil-water mixture is similar to the semi-segregated flow shown in Figure 1. At a h/D of 0.2, the percentage of water increased rapidly to 100%, and the water dominant layer is here. At higher input water cuts of 40% and 60%, there is much more mixing at the oil/water interface. The mixed layer occupies almost the entire cross section from a h/D of 0 up to 0.9 and a free thin oil layer exists at the top of the pipe and a small amount of oil reaches the bottom for 40%. At an input water cut of 60%, there is a water layer below h/D of 0.1 and some water is seen above h/D of 0.9. For the input composition of 80% water cut, no water is encountered above an h/D of 0.8 and no oil is below 0.2. In between, the mixed layer presents. It is seen that the *in situ* water distribution line is almost vertical between 0.6 and 0.7. This signifies the presence of a relatively well mixed oil-water interface. These kind of well mixed layers were also observed at the h/D between 0.5 and 0.7 for 60% input water cut and between 0.4 and 0.5 for 40%.

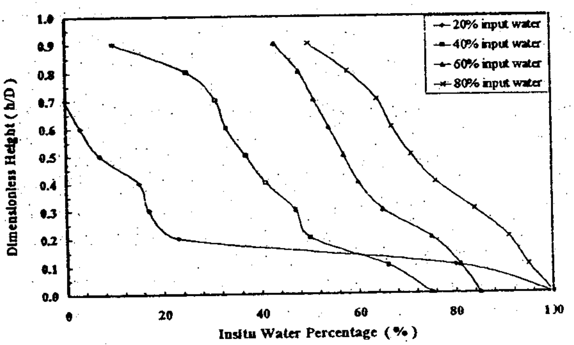


**Figure 7 Variation of Water Percentage with Vertical Position
(1.6 m/s, 0 ppm surfactant)**

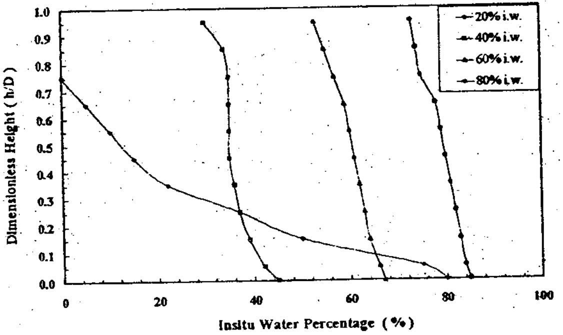


**Figure 8 Variation of Water Percentage with Vertical Position
(1.6 m/s, 15ppm surfactant)**

Figure 6 gives the effect of the addition of 15 ppm surfactant. There is little change on 20% input water cut. For the other three input cuts, oil and water are relatively well mixed across the pipe diameter. More water gets to the top and much more oil has been entrained to the bottom of the pipe. For example, 20% water is seen at a h/D of 0.95 and 35% oil reaches the bottom for an input water percentage of 40%. For the 60% and 80% input water cuts, the variation in the composition does not change much with vertical position and the oil/water composition changes almost linearly with vertical position between the top and the bottom of the pipe. A well-mixed oil/water layer is present here. As it can be seen, 80% water cut has the most conspicuous change. Half of the input oil (10%) overcomes the buoyancy and reaches the pipe bottom and almost 60% water appears at the top of the pipe.

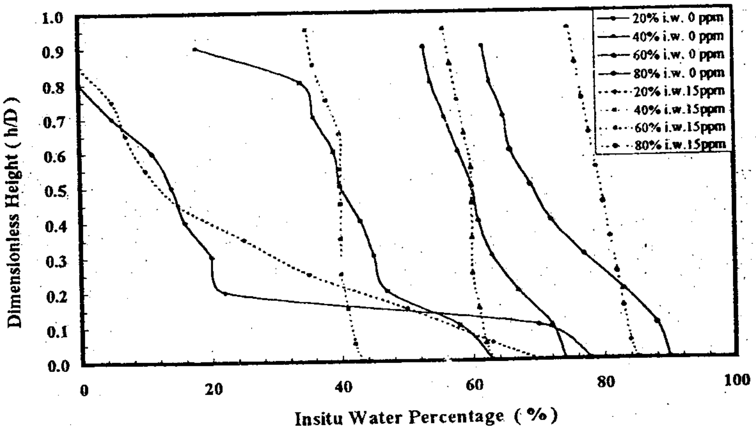


**Figure 9 The Effect of surfactant on *in situ* Water Percentage
(2.0 m/s)**

As the mixture velocity is increased to 1.6 m/s, Figure 7, 8 show similar trends as shown in Figures 5 and 6. Compared with the 1.2 m/s, it is seen that the thickness of the mixed layer increases with increase in the mixture velocity. When surfactant is present, Figure 8 shows that the water distribution curves for the 40, 60, and 80% water cuts become uniform across the pipe.

The effect of surfactant is clearly shown in Figure 9 at a higher mixture velocity of 2.0 m/s. Without surfactant, the oil/water flow are not homogenous for any input water cut. The three almost vertical dot lines of 40, 60 80% indicate that, at this velocity, the flow becomes homogenous for these three input water cuts. The results of 20% input water cut have little change when surfactant was added. Here, because of the thin water layer, the velocity of water is very low. Water can not mix into the oil.

3.2 Oil-Water Distribution and Velocity Profile

Figures 10 and 11 give the *in situ* velocity profile and oil-water distribution at two input water cuts of 20% and 60%. The corresponding results with surfactant are shown in the Figures 12 and 13. The oil-water distribution curves are shown for 75% *in situ* water and oil percentage respectively for 40 and 60% input water cuts; 85% is set as this point for 20 and 80% input water cuts.

From Figure 10, it is seen that for an input water cut of 20%, the distribution curves for 0.4m/s and 0.8 m/s are almost same. A segregated flow pattern was observed at these two velocities. Only water layer is seen at the bottom while oil layer is above it and no mixed layer exists. It is seen that the oil moves faster than the water. As the velocity is increased to 1.2 m/s, a small layer of dispersion is observed between a height of 0.3 to 0.5. Below this layer, there is a sharp increase in the water percentage as can be seen from

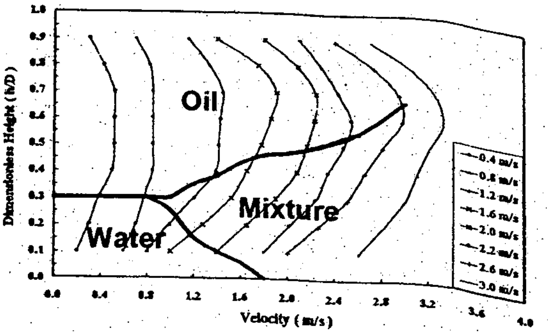


Figure 10 Oil-Water Distribution (20%, 0 ppm surfactant)

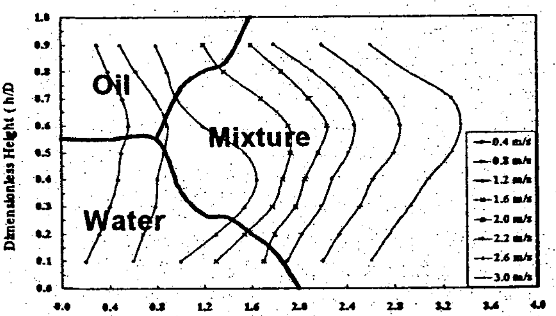


Figure 11 Oil-Water Distribution (60%, 0 ppm surfactant)

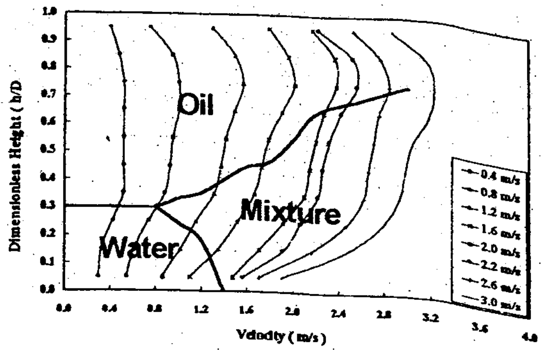


Figure 12 Oil-Water Distribution (20%, 15 ppm surfactant)

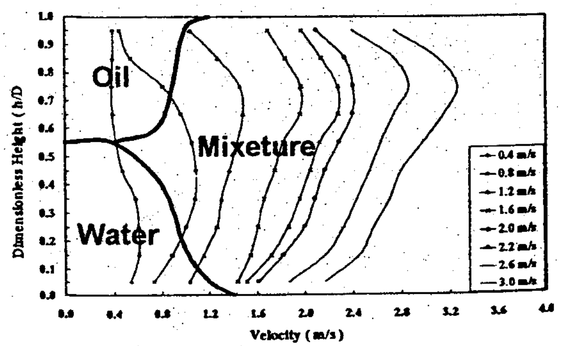


Figure 13 Oil-Water Distribution (60%, 15 ppm surfactant)

Figure 5. The mixed layer moves faster than the water layer. Increasing the velocity from 1.2 to 1.6 m/s, it is noticed that the velocity profile changes substantially. From Figure 7, it is seen that water reaches a h/D of 0.7 and an oil/water mixture is observed between 0.2 and 0.7. Now, the velocity of the mixed layer is the highest. The velocity profile of 2.0 m/s is very similar to that of 1.6 m/s. An oil-water dispersion is seen to occupy most of the cross section from the bottom to h/D of 0.8 with an oil layer existing above 0.8. With increase in mixture velocity from 2.2 to 3.0 m/s, the whole cross section of pipe is full of oil-water dispersion.

The thicker lines give the oil-water distribution. The "water" layer, which actually contains 85% and above water, flows at and below h/D of 0.3 from 0 to 0.8 m/s, and then slowly becomes thinner to 1.0 m/s. From 1.0 m/s to 1.4 m/s, it disappears faster and then gradually losses about 1.8 m/. For the "oil" layer (which has more than 85% oil), it moves above water layer until 0.8 m/s, then starts to mix with the water. From 0.8 m/s to 3 m/s, the oil layer gradually decreases from an h/D of 0.3 to 0.7.

Figure 11 shows the results for input water cut of 60%. Again, a segregated flow pattern is obtained for velocity of 0.4 and 0.8 m/s. There is no significant difference between the velocities of oil and water. As the mixture velocity is increased to 1.2 m/s, the in situ velocity curve changes sharply. From an h/D of 0.3 to 0.7, the oil and water are becoming mixed and the mixture velocity is now greatest. The water layer is now moving faster than the oil layers. With increase in velocity to 1.6 m/s, the oil-water dispersion occupies the whole cross section of the pipe. The velocity profiles for 2.0 m/s and above are very similar to that of 1.6 m/s. For 60% input water cut, as with 20%, the mixing process starts at above 0.8 m/s. However, this time the mixing zone is enlarged from the beginning of the mixing. It shows that a large amount of water helps the mixing. The oil and the water layers both disappear very quickly. Free oil layer no longer exists at 1.6 m/s and free water layer disappears at 2.0 m/s.

From Figure 12 and 13, it is seen that when 15 ppm surfactant is added, the velocity profile changes drastically. This is corresponding to the different water distribution curves shown in Figure 5, 6, 7 and 8 and indicates that addition of surfactant enhances the mixing to a large degree.

We see that in Figure 12, the velocity profile of 0.4 m/s is more like that of 0.8 m/s in Figure 10, and the velocity profiles of 0.8 and 1.2 m/s in Figure 12 are very similar to those of 1.2 and 1.6 m/s in Figure 10. It is seen also that water layer decreases quickly and it no longer exist above 1.4 m/s. Meanwhile, the oil layer become thinner and thinner from 0.7 cm to 0.15 cm at 3 m/s. Therefore, the mixed layer is much bigger than that without surfactant. From Figure 10 and 12, to prevent the existence of separated water layer, a mixture velocity of greater than 1.8 m/s is needed without surfactant, with surfactant, the minimum velocity is 1.4 m/s.

At the input water cut of 60%, Figure 13 shows that the velocity distribution curves are totally different from those in Figure 11. It is clearly seen that at 0.4 m/s, the water layer moves faster than the oil layer. For 0.8 m/s, a semi-segregated flow pattern was observed and the mixture layer flows at highest velocity. Oil and water are totally mixed at 1.2 m/s as shown in Figure 6. Also, the velocity for water and oil now begin to mix is reduced to 0.4 m/s with the help of surfactant. Below 0.8 m/s, there is a very thin mixture layer exist. Similarly, much bigger mixing zone is shown in Figure 13. Here the oil and water layers no longer exist at relatively lower velocities of 1.2 and 1.4 m/s respectively.

From these figures, it is also seen that at low water cut of 20%, water layer disappears much quicker than oil layer does while at high water cut of 60%, oil layer lost quicker. Oil and water are easier mixed at 60% input water cut.

4. CONCLUSION

The flow of oil-water mixture in horizontal pipeline was experimentally investigated in this study. From the experimental data, flowing conclusions can be obtained:

1. *in situ* water percentage changes with the mixture velocity and input water cut.

2. The mixture velocity profile is a function of input water cut, mixture velocity.

3. Existence of surfactant has great influence on holdup, velocity profile and oil-water distribution. Addition of surfactant enhances the mixing of oil and water to a large degree. With the help of surfactant, corrosion could be prevented at lower mixture velocity.

5. REFERENCES

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