Abstract: The objective of this paper is to investigate the flow regimes of three phase flow, emerged to be as two phase flow. These two phases are air phase and oil dispersed in water phase, in other words the latter phase can be termed as water–oil emulsion phase or simply emulsion phase. Pipeline emulsions flow is inescapable for upstream oil production system in transporting mixtures of crude oil and water. The mixing, turbulence as well as agitation through wellbores, expansion or contraction, valves, pumps, etc. will emulsify either the oil phase or water phase, depending on the volumetric amount of the phases. This is executed in a flow loop system with varying air and liquid-emulsion velocities. The oil percentages to create the water–oil emulsion are varied from 0% to 24%. Flow pattern maps are developed at low range of fluid velocities (0.01–0.1 m s\(^{-1}\)) and it is compared with established maps. Stratified smooth (SS), stratified to stratified-wavy (SSW), stratified wavy (SW) and stratified wavy with ripples (SWR) are the flow patterns, observed in the experiment. The stratified smooth and stratified to stratified-wavy flow regimes are found to be the most dominant. Oil dispersed in the water (emulsion) phase results a clear distinction of the stratified and the stratified-wavy regimes. An increase in flow regime area occupied by stratified/stratified-wavy in the flow pattern map is evident with increasing oil percent in the dispersed liquid phase. The addition of oil to the liquid phase causes a dampening effect on the flow regime transition, most considerably from stratified to nearly non-stratified flow. This might be attributed to the increase in viscosity at high oil percentages. The pressure drop is not significant in the whole flow phenomena and is found to
increase with increasing liquid velocity for all oil percentages as the velocity range of the experiment is very low (0.01–0.1 ms\(^{-1}\)). Pressure drop and liquid hold up are compared with previous theories and our prediction. Experimental data are predicted with approximately ±10% deviation.

**Subjects:** Fluid Mechanics; Chemical Engineering; Industrial Chemistry; Chemical Processing & Design

**Keywords:** three phase flow; emulsion; viscous; horizontal pipe; stratified; PVC pipe

1. **Introduction**

Multiphase flow is the general term used to describe the simultaneous flow of two or more phases. Research of three phase flow in pipes is an important study as it is being encountered in many industries. Therefore, knowledge of the hydrodynamics of flow is a required field. Emulsions or the dispersion of one immiscible phase into other, are found in oil production and processing facilities where crude oil can be found to be mixed with water in the presence of naturally occurring emulsifiers. Oil will always be produced together with water from the reservoir and towards the end of the reservoir life, the amount of produced water will increase, especially if the reservoir is driven by natural water aquifer. This scenario will induce the formation of water-in-oil emulsions. Treating stable water-in-oil emulsions can be expensive as well difficult and some major oil producers are reported to reduce the selling price of their oil for not meeting the required oil quality. Additionally, at certain liquid flow rates, one liquid phase will be dispersed in the other phase so that emulsions may form in the line.

Researchers Neogi, Lee, and Jepson (1994) investigated the stratified three phase flow of oil (Mineral oil, LVT-200), water and gas through a horizontal Plexiglas pipe that was 10 cm in diameter and 10 m in length. The oil had a density of 820 kg/m\(^3\) and viscosity of 2cP at 30°C. They compared their results with that of the mechanistic model which yielded a good prediction of the water and oil film thickness in the pipe. They also said that an increase in the liquid phase velocity led to a more significant increase in water layer thickness compared to the increase in the oil layer thickness. There was an experiment performed by Aswad, Hamad-Allah, and Alzubaidi (2006) with water, kerosene and air flowing through a 0.051 m inner diameter, 4 m long horizontal pipe where the effect of liquid flow rates and water ratios were observed for stratified flow. It was observed that the pressure drop increased with increasing liquid phase velocity. They also found that the results showed good similarity with that obtained from the three phase model of Taitel et al. (1995) for liquid and water thicknesses, as well as system pressure drop in the pipe.

Al-Hadhrami et al. (2014) used low viscosity Safrasol D80 oil in their experimentation that was conducted at 20°C in a 2.25 cm inner diameter horizontal pipe. They used superficial velocities of water and oil in the range of 0.3–3 ms\(^{-1}\), in addition to gas superficial velocities in the range of 0.29–52.5 ms\(^{-1}\). The water cuts investigated were in the range of 10–90%. The resulting experimentation yielded a variety of flow patterns including stratified smooth and wavy which changed with water fraction and gas and liquid velocities. They also saw that pressure gradients increased with both gas and liquid superficial velocities, which was also the findings observed in Aswad et al. (2006). Oddie et al. (2003) studied both two and three phase flow in large diameter pipes, using kerosene, tap water and nitrogen gas as the three phases and conducted a total of 444 tests using an 11 m long, 15 cm diameter transparent pipe in inclines of 0° (vertical pipe) to 92°. They said that stratified (smooth and wavy) along with other flow patterns were observed for the three phase flow. For the oil–water two phase flow, they saw dispersed, mixed, semi-mixed, segregated and semi-segregated flows. They concluded that the results for flow pattern and shut-in holdup closely matched that predicted by the mechanistic model by Petalas and Aziz (2000). Eight out of the 10 experiments conducted for three phase flow in the horizontal pipe matched the model. In terms of stratification, two phase flow also behaves similarly to three phase flow. Brauner, Moalem Maron, & Rovinsky (1998) modeled liquid–liquid flow systems through pipes. She said that the flow pattern depended on the liquid velocities, tube diameter and inclination as in gas-liquid conditions.
systems. For stratified flow of oil and water (Chakrabarti, Pilgrim, Sastry, & Das, 2011; Shirley, Chakrabarti, & Das, 2012; Trallero, 1995; Nadler & Mewes, 1995, 1997), a curved interface would be expected due to surface tension forces, wall wetting properties and the diminished gravity effect.

Açikgöz, França, and Lahey (1992) studied the three phase oil–water–gas system in 0.748 in ID horizontal tubes. Different flow regimes were obtained with flow patterns that were classified based on the liquid phase that wetted the pipe wall, the separated or dispersed liquid–liquid flow pattern and the flow pattern between the gas and bulk liquid phase.

Research into three phase flow characteristics is limited and relies on an adjusted two phase model to account for the physical properties of the liquid phases. Generally, the pressure gradient increases in proportion to increasing gas and liquid flow rates. More specifically, the pressure gradient is dependent on the flow regime. Low gas and liquid superficial velocities such as to cause stratified and partially mixed oil and water flow, causes slight increases in pressure gradient. Increasing the superficial gas velocity over 1 ms\(^{-1}\) to the slug or continuous oil–water flow results in a strong increase in pressure drop. Moreover, for dispersed liquid systems, the pressure gradient was found to be higher for oil dominated as compared to water dominated due to the change in the continuous phase (Sarica & Zhang, 2006). Furthermore, a two-fluid model has been used by treating the dispersed phase as a continuous phase that interacts with the actual continuous phase (Brennen, 2005). The two liquid phases are reduced to a single phase, a pseudo-liquid, allowing it to be modelled as two phase flow. Three phase pressure drop was examined by Pan (1996) in which the two immiscible liquid phases were treated as a single phase, enabling two phase correlations to be used to model the pressure gradient. In the present study, it has been tried to explore air and emulsion phase flow patterns and their transitions. This is the novel part of the study.

2. Experimental procedure
A schematic representation of the experimental flow loop is shown in Figure 1. Two taps of the manometer with CCl\(_4\) as manometer-fluid are attached to the pipe and placed 1.5 m apart. This pressure reading is generated by the bottom liquid phase. The stirrer/mixer is kicked off to begin the mixing of oil (at 32°C and 1 atm. pressure, \(\rho = 907.78\) kg/m\(^3\), \(\mu = 52\) cP, surface tension = 31 dynes/cm) and water in the tank. The oil is chosen as soybean oil to avoid any environmental hazard of petroleum oil. Simultaneously high viscosity like crude oil is observed during flow. The entire pipe section (5 m) with 50 mm internal diameter, is made of PVC except for the transparent visual section (1 m). The control valve, V1, after the pump
and the bypass recycle valve, V2, are adjusted to control the flow through the rotameter. The pumped liquid is allowed to circulate and make its way back into the tank. The liquid is allowed to pass through a rotameter and the gas is circulated from the compressor via a rotameter. Both the rotameters are calibrated prior to experiment. The system is allowed to reach a steady state before initiate any reading.

Flow patterns are observed in the transparent section. Visual observation and Sony HDR-CX240 camera is used to record the flow pattern. The air flow rate is varied between 0.01 to 0.12 ms$^{-1}$. The runs are then repeated for liquid flow rate up to 0.1 ms$^{-1}$. This entire procedure is repeated for various oil percentages ranging from 0% to 24%. Viscosities of different mixtures are estimated by the Brookfield DV-E viscometer. At these percentages of oil, water always remains as the continuous phase with oil droplets dispersed into it. Figure 2 describes the cross-sectional view of (a) three phases and (b) two phases with oil–water emulsion as one phase.

3. Results and discussion

3.1. Flow regime maps

The flow regimes identified for all the variations of oil content are stratified smooth (SS), Stratified to stratified-wavy (SSW) small, stratified wavy (SW), stratified wavy with ripples (SWR) (Figure 3). The stratified smooth classification is given to flow of liquid with low frequency interracial surface...
disturbances and a relatively stable air-liquid interface. The transition region from SSW is classified by rare to frequent sinusoidal and surge waves with a smooth interface between the waves. SW flow is categorized as surging or cresting waves followed by a sinusoidal interface. The final flow regime, stratified wavy with ripples (SWR) is a high surging wave that reached near the top of the pipe. Slug flow is characterized by liquid encompassing the entire tube with intervals of long bubbles contacting the top of the glass tube, however in our range of velocities, this pattern is absent. Flow regimes such as the annular, mist, dispersed bubble are not observed due to the velocity limits of both the air and emulsion.

Figure 4, which represents 100% water cut, shows mainly SSW and SW. Stratified smooth (SS) is seen for low liquid superficial liquid velocity and the entire range of superficial gas velocity. At intermediate to high superficial liquid velocity and low superficial gas velocity or at low superficial liquid velocity and high superficial gas velocity, stratified-wavy is dominant. Wavy flow with ripples is paramount only at high liquid and gas superficial velocities.

For 93% water cut, the transition to SW flow case occurs at 0.04 ms\(^{-1}\) liquid velocity (Figure 5), but for the 100% water cut, this transition occurred at 0.03 ms\(^{-1}\). Additionally, when compared to...
100% water cut, the stratified-wavy flow occurred at higher air velocities and the wavy-slug transition began at a lower air velocity. This may be attributed to the increased effective liquid viscosity upon addition of the oil. The fact is again extended to Figures 6 and 7. These phenomena could be realized by seeing Figure 8. This increased viscosity is said to have dampened the flow instability. The applied flow instability, i.e., the air flow, is not enough to allow the shear effects of the air to overcome the gravitational and viscous effects of the liquid, which would have been required to achieve fully wavy flow. At 86% water cut, there is no significant change except SW which is extended more in comparison to 93% water cut (Figure 6). At 76% water cut, SS flow is recorded to encroach more to the right of the map at a liquid velocity of 0.023 ms$^{-1}$ and air flow at 0.078 ms$^{-1}$ (Figure 7). Also, SSW flow appeared at liquid velocity 0.054 ms$^{-1}$ and gas velocity 0.026 m/s, further narrowing the stratified-wavy region. This can again be explained due to the increase in liquid viscosity due to the addition of oil.

These flow regime phenomena can be attributed to the fact that the oil and water are mixed into an emulsion with the oil being dispersed into the water as fine drops that coalesced only at rest. The emulsion/dispersion appeared to be in equilibrium since the oil did not fully separate from the dispersed phase. This might be due to the intensive mixing in the sump that prevents coalescence of the oil.

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**Figure 6. Flow regime map for 86% water cut.**

**Figure 7. Flow regime map for 76% water cut.**
droplets after being fed to the test section. Therefore, the flow patterns such as stratified—stratified, stratified-dual continuous, stratified-oil continuous, stratified-water continuous are not observed. It can be said that the system behaves like a gas—liquid two phase flow, which can justify the use of the weighted average liquid properties. However, the variation of viscosity in Figure 8 is not an expression of additive property. Moreover, the viscosities at different water cut has been applied to the Blasius equation (Taitel & Dukler, 1976) for completion of momentum balance equation as described (Equations (1)–(11)) by Taitel and Dukler (1976). No better result is obtained by doing so, to justify the change in flow regime with different oil percentage. The change in velocity gradient with respect to viscosity is needed to be looked further analytically. To estimate liquid holdup or pressure drop, Taitel and Dukler (1976) theory is extended for calculation.

Referring to Figure 2a and b, the flow of three fluids, water, oil and gas, is considered. The water is heavier than the oil and occupies the bottom of the pipe. The oil flows in the middle and the gas at the top. A momentum balance for each phase can be written as follows:

\[
-A_W \frac{dp}{dx} - \tau_w S_w + \tau_i S_i - \rho_w A_w g \sin\beta = 0 \tag{1}
\]

\[
-A_O \frac{dp}{dx} - \tau_O S_O - \tau_i S_i + \rho_O A_O g \sin\beta = 0 \tag{2}
\]

\[
-A_G \frac{dp}{dx} - \tau_G S_G + \tau_i S_i - \rho_G A_G g \sin\beta = 0 \tag{3}
\]

In this present case as oil is dispersed into water, the dispersed phase is considered as a single liquid phase (Figure 2b). Physical properties of liquid are taken as additive properties of oil and water except viscosity, depending on their fraction. Viscosity is calculated based on Figure 8. Momentum balance for the liquid phase will be

\[
-A_L \frac{dp}{dx} - \tau_L S_L + \tau_i S_i - \rho_L A_L g \sin\beta = 0 \tag{4}
\]

\[
\tau_L = f_L \left( \frac{\rho_L U_L^2}{2} \right), \tag{5}
\]
\[ \tau_G = f_G \left( \frac{\rho_G U_G^2}{2} \right), \]  
\[ \tau_i = f_i \left( \frac{\rho_G (U_G - U_L)^2}{2} \right), \]  
\[ f = C \text{Re}^{-n} \]  

where \( A \) is a cross sectional area, \( \rho \) is density, \( P \) is pressure and \( \beta \) is the inclination angle, positive for upward inclination. The subscripts are: \( W \) for water, \( O \) for oil, \( G \) for gas and \( L \) for oil in water emulsion. For the present case, three shear stresses are needed to be solved: \( \tau_G \), the shear stress acting on the wall wetted by the gas \( S_G \); \( \tau_L \), the shear stress acting on the wall wetted by the liquid phase \( S_L \); \( \tau_i \), the shear stress acting on the liquid and gas interface \( S_{GI} \).

For the shear stresses \( (\tau) \) between the liquids or gas and the pipe surface, the friction factors, \( f_L \), \( f_W \) and \( f_i \) can be approximated by the correlation, where \( C = 0.046 \), \( n = 0.2 \) for turbulent flow, and \( C = 16 \), \( n = 1 \) for laminar flow. The Reynolds number with the concept of hydraulic diameter is defined as

\[ \text{Re}_L = \frac{4 A_L \rho_L U_L}{\mu_L} \]  
\[ \text{Re}_G = \frac{4 A_G \rho_G U_G}{(S_G + S_i) \mu_G} \]  
\[ \mu_L = 2.55 x - 0.057 x^2 \text{ in cP (Figure 8)} \]  

where \( x = \text{oil}\% \).

For the interfacial gas–liquid shear stress we used a constant value of \( f_i = 0.014 \), (Cohen & Hanratty, 1968) but if the value of \( f_i \) is larger than \( f_i \), then \( f_i = f_a \) is used.

Pressure drop can be eliminated from Equations (3) and (4) to yield

\[ \frac{\tau_L S_L}{A_L} + \frac{\tau_G S_G}{A_G} + \tau_i S_G \left( \frac{1}{A_G} + \frac{1}{A_L} \right) - (\rho_L - \rho_G) g \sin \beta = 0 \]  

Equation (12) is solved to get holdup and pressure drop.

Three kind of flow transitions are predicted, for air–water flow by Taitel & Dukler (1976), for oil water flow by Trallero (1995) and for oil–water again by Brauner and Maalem Maron (1993) respectively. These transitions are appended in the flow pattern map of Figures 4–7 and new figures (Figures 9–12) are emerged. It is evident from these figures that the experimental stratified range (including all wavy forms) is within the confinement of other researchers’ stratified region. However, in actual practice transition within stratification changes with oil percentage in water.

In Figures 9–12, experimental flow patterns are compared with the theories of several scientists who derived equations for separated flow. In the present study oil–water together behaves as a single phase and as a result it resembles a two phase system.

All studies and theories are inferred based on two phases, liquid and gas. However, if the liquid phase is a mixed phase, effect on stratification is not clarified in preceding research. With the change of oil percentage or in other words with the change in viscosity in the liquid phase, different flow regime emerges in the stratified pattern. This can be strongly said as the novel part of the work.
At this range of velocity, the prediction of pressure drop (Figures 13 and 14) and liquid holdup (Figures 15 and 16) are not as perfect as smooth stratified flow for an air–water flow situation. The reason may again be due to flow pattern variations with oil percentage. In some cases, prediction exceeded ±10% and may be due to the sudden change in viscosity of the liquid phase. At low oil percentage, the liquid property resembles water, therefore the prediction is better. However, at low liquid velocities prediction is poor. This can be attributed to the change in residence time of liquid in the pipe due to changing viscosity.

The next section describes the instrument uncertainties. Despite the fact that instrument errors are within 5% (max), the prediction for pressure drop or hold up goes up to 10% (some cases more) deviation. Conventional stratified flow models where one pure liquid taken into account, are not a
good basis for prediction in the present study. The way viscosity handled for prediction might not be totally correct and interfacial tension to consider “minimum stable energy state” is not regarded in the current research.

3.1.1. Uncertainty and repeatability
For uncertainty analysis the procedure described by Holman (1989) has been followed. If $P$ is the parameter function of the independent variables $p_1, p_2, p_3 \ldots \ldots \ldots p_n$, then

$$P = P(p_1, p_2, p_3 \ldots \ldots \ldots p_n)$$  \hspace{1cm} (13)
Figure 13. Experimental and predicted pressure drop at 93% water cut.

Figure 14. Experimental and predicted pressure drop at 76% water cut.

Figure 15. Experimental and predicted liquid holdup at 93% water cut.
Let the error associated with these independent variables be $e_1, e_2, e_3 \ldots e_n$, and the resulting uncertainty in $P$ be $e$, then

$$e = \left[ \left( \frac{\partial P}{\partial p_1} e_1 \right)^2 + \left( \frac{\partial P}{\partial p_2} e_2 \right)^2 + \cdots + \left( \frac{\partial P}{\partial p_n} e_n \right)^2 \right]^\frac{1}{2}$$

The liquid flow rates have been measured with rotameters of different ranges. The rotameter for the liquids range from 0 to 25 l per minute (lpm) with a least count of 1 lpm have an average uncertainty of ±2.3%. At low velocities the uncertainty goes up to 5%. To measure the pressure drop, two pressure tapings have been provided at distances of 1.5 m in the test section. The manometer has an uncertainty of ±2.4% and the viscometer has an uncertainty of ±2% (supplied by the manufacturer).

Reproducibility of data has been checked during experimentation. The measurements have been carried out for several times for a particular inlet emulsion velocity and composition of both the fluids to obtain consistent results and the accuracy of measurements. The results agree within ±1.5%.

4. Conclusions

Earlier it is said that oil is produced together with water from the reservoir and towards the end of the reservoir life. As the water amount continues to be increased, the water-in-oil emulsions reach phase inversion point. This is the point where crude oil becomes the dispersed phase, while water becomes the continuous phase, i.e., oil-in-water emulsions, similar to our study, where focus is given to low velocity ranges. Four flow patterns are identified over this low range of superficial gas and liquid velocities, for the flow through horizontal PVC pipeline. In the present study, the liquid is a dispersion of oil in water. Flow patterns observed are stratified smooth, stratified to stratified-wavy, stratified wavy and stratified wavy with ripples. The addition of oil to the liquid phase causes a dampening effect on the flow regime transition, most considerably from stratified to non-stratified flow. Addition of oil in water increases the region of flow pattern in the flow regime map that is occupied by stratified and stratified-wavy. Nevertheless, this phenomenon is not following any consistent pattern. The shift is more significant for the largest oil percentage used (24%). The flow pattern maps that resulted from different oil percentages are compared with the regime-transition of previous research. In addition to the flow regime, pressure drop and liquid hold up are also compared with previous theory and our predictions. Experimental data are lying within a deviation band of approximately ±10%.
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