Iran. J. Chem. Chem. Eng. Research Article Vol. 41, No. 2, 2022

Experimental Investigation on Super High Viscosity Oil-Water Two-Phase Flow in a Horizontal Pipe

Hasanzadeh, Yasha; Alavi Fazel, Seyed Ali*+; Azizi, Zoha;
Peyghambarzadeh, Seyed Mohsen; Azimi, Alireza
Department of Chemical Engineering, Mahshahr Branch, Islamic Azad University, Mahshahr, I.R. IRAN

ABSTRACT: *The flow patterns and pressure gradient of a two-phase mixture of water/super high viscous oil in a horizontal pipe were experimentally investigated. The mixture containing oil with a viscosity of 67 cP and density of 0.872 g/cm^3, and pure water flows through an acrylic pipe with a length of 6m and a diameter of 20 mm. Superficial velocities of water and oil were in the range between 0.18–1.2 m/s and 0.18–0.95 m/s, respectively. Six flow patterns were identified. The stratified flow became visible at low velocities of oil (<0.42 m/s) and water (<0.26 m/s) and bubbly flow patterns happened at low superficial oil velocities (Uso = 0.18–0.22 m/s). The dispersion of oil in water (DO/W) occurred at high superficial water velocity (Usw =0.79 – 1.2 m/s) at low or moderate superficial oil velocities (Uso = 0.18 –0.53 m/s). Dispersion of water in oil (DW/O) appeared from superficial oil velocity of higher than 0.69 m/s. The effect of oil viscosity on flow structure was assessed by comparing the present work with the available data and this revealed that the extent of dual continuous patterns reported by other systems containing low viscosity oil is 5% higher than the results of the present study. The effect of oil viscosity on the pressure gradient was also investigated. The pressure gradient values obtained in this study were 80% greater than other studies at similar superficial oil and water velocities. The experimental pressure gradient was also compared with the values predicted by the Al-Wahaibi correlation and two-fluid model. The Al-Wahaibi correlation agreed reasonably with the experimental results, with an average absolute error of less than 9%, while the error of the two-fluid model was 30%. Based on the results, a clear overview of the flow patterns and pressure drop with detailed information was presented.*

KEYWORDS: *Oil-water flow; Flow pattern map; Pressure gradient; Super high viscous oil.*

INTRODUCTION

There has been little investigation of horizontal two-phase liquid-liquid flows compared with vertical flows in the literature [1]. During their co-current flow in a pipe, the deformable interfaces of two fluids can acquire a variety of characteristic distributions, which are called flow regimes or flow patterns. These flow patterns can affect the pressure gradient in the pipe, thus, identification of flow patterns in two-phase flow is very significant for predicting pressure loss and optimization in pipeline design. In petroleum industries, it is very important to predict the type of flow pattern at some critical points like valves or other equipment. In a valve, much attempt is exerted to avoid

---

***** *To whom correspondence should be addressed.*
+ *E-mail: alavifazel@gmail.com*

1021-9986/2022/2/635-651 17/$/6.07

slug or bubbly flow because such flow patterns can damage the valve due to their uncontrolled impulse or cavitation. Therefore, it is better if the valve is placed in a position in which the stratified flow has occurred. Also, for oil transfer from the source to the refinery, it is better to reduce pressure loss in the pipeline. One way to reduce pressure loss in the pipeline is transferring oil in such conditions so that the flow patterns with low-pressure loss occur in the pipe. The best flow pattern with the lowest pressure loss is stratified flow, so it is desirable to transfer oil in some conditions in which the stratified flow is dominant. The global heavy oil reserve is approximately 2 trillion barrels, more than twice the conventional light crude oil. As conventional oil recourses are being depleted worldwide, vast heavy oil reserves available in various parts of the world become more and more important as a future energy source. Accurate prediction of super high-viscosity oil multiphase flow behavior is needed to produce and transport super high-viscosity oil economically and safely.

There is currently no work available in the literature on super high oil viscosity affecting such flow patterns and pressure gradients for horizontal oil-water flow with this condition. Investigating the effect of fluid properties, pipe geometries, and materials under different operating conditions will help us to obtain a clear picture and understand the liquid-liquid behavior. Such studies can be linked at the end to obtain a generalized flow pattern map and pressure gradient for the liquid-liquid flow. The use of super-high viscosity oil and its effects on pressure gradients and flow patterns at different speeds are the most important innovations in this work.

Angeli et al. [2] studied the pressure gradient in horizontal liquid-liquid flows. They reported that the material of the tube wall can strongly affect the pressure gradient during two-phase liquid-liquid flow. Pressure gradients under all conditions were higher in the steel than in the acrylic tube for the same mixture velocities and flow volume fractions. *Angeli et al.* [3] studied flow structure in horizontal oil-water flow. There are substantial differences in the flow pattern and phase distribution occurring in the acrylic resin (TranspaliteTM) and the stainless steel tubes. *Oddie et al.* [4] conducted an experimental study of two- and three-phase flows in large-diameter inclined pipes. In this investigation, the effects of the flow rates of different phases and also pipe deviation on the holdup were evaluated. Detailed flow pattern maps were generated over the entire range of flow rates and pipe inclinations for all of the fluid systems. *Rodriguez et al.* [5] studied experimentally oil-water flow in horizontal and slightly inclined pipes. Extensive results of holdup and two-phase pressure gradient as a function of superficial velocities, flow patterns, and inclinations were reported. The seven observed oil-water flow patterns for horizontal, upward, and downward inclined flow are reasonably well described by Traveller's flow pattern map. *Mandal et al.* [6] studied oil-water flow through different diameter pipes, they reported similarities and differences among different conditions. A new flow pattern namely rivulet flow has appeared in the 0.012 m pipe. The design of the mixer section was also found to affect the downstream distribution of the two liquids. The flow pattern map may change its appearance remarkably merely by changing the way of introducing the two fluids in the test rig. *Xu*. [7] worked on oil-water two-phase flow in horizontal pipelines. Their aim was to give a brief review of oil-water pipe flows from the literature. *Bannwart et al.* [8] have performed an experimental investigation on liquid–liquid-gas flow; flow patterns and pressure gradient were studied. An important observation in this study was the occurrence of core-annular flow in all pipe sizes and inclinations due to its practical importance in the production and transportation of heavy oil. In the experiments reported herein, water was always in contact with the pipe wall (hydrophilic-oil phobic pipe material), which guarantees the lubrication process and keeps the oil from sticking to the pipe wall. *Hanafizadeh et al.* [9] considered the influence of the flow regimes on the performance of an airlift pump experimentally. The data was obtained for air-water two-phase flow in a vertical pipe. The three main flow regimes namely slug, churn and annular were visually detected in their works. *Hanafizadeh et al.* [10] have performed an experimental investigation of the oil-water two-phase flow regime in inclined pipes. Various flow patterns have been reported comprising: bubbly, slug, smooth stratified, wavy stratified, churn, annular and dual continuous flow. From the obtained results, it can be inferred that non-stratified flows such as bubbly and slug flows are dominant flow patterns in the upward flows and stratified flows are dominant flow patterns in the downward flows. *Ahmad ShamsulIzwan Ismail et al.* [11] have performed an experimental investigation on pressure losses, liquid holdup, and flow patterns of oil-water two-phase flow in horizontal pipes. In general, five flow patterns were observed during this experimental work. A new flow pattern map was established for the Malaysian waxy crude oil-water flow in a horizontal pipe at ambient conditions (30°C). *Jagan et al.* [12] the results of experimental studies on two-phase flow patterns of the air-water mixture in a pipe with different orientations were reported. The results show that the stratified flow is observable in the horizontal pipe but not in the titled pipe. They reported for same velocities of water and air. *Zhuoran Dang et al.* [13] experimental studied vertical and horizontal two-phase pipe flow through double 90-degree elbows. The results show that in the upper and lower horizontal test sections, bubbly flow, plug flow, slug flow, pseudo slug flow, and stratified flow are observable. As they reported, the existence of the elbow breaks up the plug from the top horizontal test section into small bubbles at the inlet of the vertical downward test section. Most of the area with averaged void fraction development in the vertical downward section shows an ‘‘increasing-decreasing” void fraction trend due to the change of liquid velocity. *Sadra Azizi et al.* [14] have performed flow patterns and oil holdup prediction in vertical oil-water two-phase flow using pressure fluctuation signals. They worked experimentally on the feasibility of flow pattern and oil holdup prediction for vertical upward oil-water two-phase flow using pressure fluctuation signals. The flow pattern and the oil holdup were predicted successfully from the pressure fluctuation signals using wavelet transformation and an artificial neural network. For this purpose, the PNN and MLP networks were trained to predict the flow patterns and oil holdup, respectively. Water and diesel fuel were selected as immiscible liquids. The observed flow patterns were Dispersed Oil in Water (DO/W), Dispersed Water in Oil (DW/O), Transition Flow (TF), Very Fine Dispersed Oil in Water (VFD O/W), and a new flow pattern called Dispersed Oil Slug & Water in Water (D OS& W/W). The results indicated that the proposed method can be a useful tool for characterizing the different vertical upward oil-water flow patterns (accuracy=95.8% for testing data) and determining the oil holdup (AAPE=8.07%, R=0.99 for testing data). Flow patterns and oil holdup can be predicted for vertical oil-water two-phase flow using pressure fluctuation signals obtained by only one pressure sensor and with the help of wavelet transform and artificial neural network. *Tarek Ganat et al.* [15] have performed an experimental investigation of high‐viscosity oil-water flow in vertical pipes: flow patterns and pressure gradient. Flow experiments have been conducted for two-phase flow in a vertical pipe. The experiments were made for highly viscous oil-water in a stainless pipe at 250 psig pressure through the laboratory-scale flow test equipment. The test section used is a vertical transparent tube of 50 cm in length and 40 mm ID. The test fluid utilized in this experiment is synthetic oil (viscosity = 35 mPas, density = 860 kg/m^3) and filtered tap water (interfacial tension 31 mN/m at 20 °C, viscosity 0.95 mPas at 25 °C). The measurements of superficial velocities of oil and water varied between 0.01 to 3 m/s. Six typical flow patterns were categorized and mapped under two groups, the oil-dominant region, and the water-dominant region, and were then categorized based on the variations of oil and water superficial velocities, and mixture fluid velocity, at different amounts of water holdup in the vertical tubing. The results concluded that the pressure gradient is significantly influenced by flow patterns and flow rates. The pressure gradients increase with rising mixture fluid velocity and water cut with a similar trend. The experiment shows that for a mixture of fluid velocity below 1 m/s, the pressure gradient shows a gravity-dominated behavior with a linear rise from pure oil to a pure water pressure gradient. Besides, the oil viscosity has a high effect on the pressure gradients; however, it is observed that in similar water and oil superficial velocities, there is a subsequent increase in the pressure gradient due to the increase in oil viscosity. This influence is because of the frictional pressure gradient which is negligible. *Lusheng Zhai et al.* [16] worked on Complex Admittance Detection of Horizontal, Oil-Water Two-Phase Flows Using a Capacitance Sensor. An equivalent circuit model of the horizontal oil-water two-phase flow is established based on a concave capacitance sensor, during which an infinitesimal dividing method is proposed to calculate the equivalent complex admittance of the fluid. A measurement system for the concave capacitance sensor is designed to realize the simultaneous detection of the real and imaginary parts of oil-water flows. Through carrying out the flow loop test of horizontal oil-water flows, the response characteristics of the real and imaginary parts in different flow patterns, i.e., ST, ST&MI, DO/W&w, and DW/O&DO/W, are collected. *Lusheng Zhai et al.* [17] have performed a prediction of pressure drop for segregated oil-water flows in small diameter pipes using the modified two-fluid model. An important observation in this study by introducing dynamic contact angle, they calculate the oil-water interface shape by solving the young-la place equation. The oil-water interface shapes and the wave characteristics are considered to modify the closure relations of the Two-Fluid Model (TFM), and consequently, the pressure drop of horizontal oil-water flows is predicted using the modified TFM. In addition, they predict the pressure drop of horizontal oil-water flows using the TFM with the flat interface. The results show that the TFM, modified with dynamic contact angle, allows for higher accuracy in pressure drop prediction, and it is not dependent on the flow pattern discrimination. Generally, the two-fluid model modified with dynamic angle is independent of the flow pattern discrimination, thus, it exhibits obvious advantages in predicting the pressure drop in liquid-liquid pipe flows. *Jiaqiang Jing et al.* [18] experimentally studied the highly viscous oil-water annular flow in a horizontal pipe with 90° elbow. The selected test fluids are mineral oil and tap water with a viscosity ratio of approximately 1000 and a density ratio of 0.9. Measurements are recorded for the flow rates of oil and water from 10.60 to 28.26 L/min and 3.83 to 14.13 L/min, respectively, with the water volume fraction ranging from 0.13 to 0.50. For oil-water flow in the upstream section, only stable core-annular flow is observed; while in the downstream section, generally, three flow patterns, including incomplete annular flow, complete annular flow, and stable annular flow, appear successively with the increase of water input fraction. Results show that the drag reduction factor and oil transport efficiency at the up and downstream section reveals the adverse impact of the elbow on downstream parameters, which results in the increase of the frictional pressure gradient and the decrease of the reduction factor and oil transport efficiency. Therefore, in order to guarantee high oil transportation efficiency in transportation practice, the water input fraction had better be held at the critical threshold, and the oil flow rate should be increased to the uttermost. A stable water ring efficiently lowers heavy oil flow resistance in a horizontal pipe with a 90° elbow. *S. Ahmad et al.* [19] worked on a numerical simulation of viscous dissipation in a micropolar fluid flow through a porous medium. A laminar flow of a micropolar fluid through a resistive porous medium in a channel with plane walls is considered with allowance for viscous dissipation. It is found that the effect of viscous dissipation is to increase the heat and mass transfer rate at both the lower and upper walls of the channel. By using suitable similarity variables, the system of nonlinear partial differential equations is reduced to coupled ordinary differential equations, which are solved numerically by means of quasi-linearization. In a previous work [20] the prediction of the pressure drop in water-high viscosity oil flows was performed using an artificial neural network, and the ability of the improved artificial neural network to calculate the pressure drop in two-phase flows (water-high-viscosity oil) in the horizontal tube was investigated.

In the present article, pressure drop and flow pattern have been studied as the major flow characteristics under different flow conditions in a horizontal pipe. Flow patterns and pressure gradients of oil-water two-phase flows are investigated experimentally at various superficial velocities. The goal of this study is to promote a better understanding of flow patterns and pressure gradients of liquid-liquid two-phase pipe flow, introduce the best available correlation to calculate pressure gradient, and show the effect of oil viscosity on flow structure and pressure gradient in horizontal oil-water flow. This is achieved by combining the obtained results of this study with those reported by *Vale* and *Kvandal.* [21], *Angeli* and *Hewit.* [2], *Yusuf* [22] and *Chakrabarti et al.* [23]. It is noted that the pipe material in the mentioned references was the same as that in the present work. The experimental pressure gradient database was also compared with the *Al-Wahaibi* correlation and two-fluid model [24].

EXPERIMENTAL SECTION

Experimental set-up

The experimental studies on flow patterns and pressure drop were carried out in the liquid-liquid flow facility shown schematically in Fig. 1,2. Pure water and oil (Density of 0.872g/cm^3 and Viscosity of 67 cP) were used as test fluids. The separation and storage of the two fluids take place in three separator tanks. Each fluid was transferred from its storage tank with a pump to the test section made up of 20 mm acrylic pipe. Oil and water are led by centrifugal pumps from the bottom of the storage tank respectively into the test section. Flow rates of the oil and water are controlled just before entering the test section. The two fluids entered the test section from two pipes *via* a Y-like-junction which ensures a low degree of mixing. The water phase was allowed to enter from the bottom

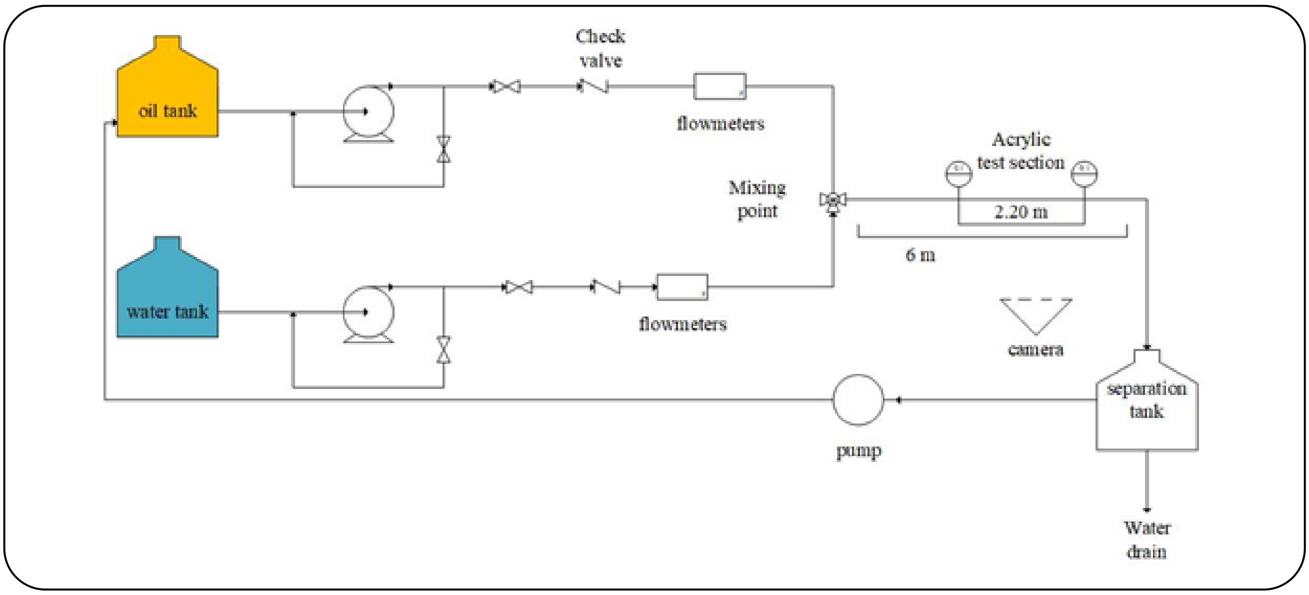


Fig. 1: Schematic diagram of the experimental facility with the acrylic test section.

Fig. 2: test section.

while the oil joined from the top to reduce the effect of mixing. Two flow meters with a maximum capacity of 60 l/min were attached to each of the flow lines (water and oil). Thus, the maximum uncertainty of the flow meters measurement was ± 0.06 L/min %. The measurement uncertainties are listed in the form of standard deviation in Table 1. The mixture returns *via* a PVC pipe to a separator tank which allows the two phases to separate and hence return to their respective storage tanks. The test section was set to horizontal. Pressure drop was measured in the acrylic horizontal pipe at 380cm from the inlet and the pressure ports were placed over a distance of 220 cm. The pressure drop was measured with a Differential Pressure Transmitter. The temperature was controlled at 25°C with temperature controllers. The uncertainties of the data being collected from pressure, transmitters were up to 0.2%. A high-speed camera and visual observation were used to identify the different flow patterns and the transition from one pattern to another. In this work, 350 fps was selected and the images were then transferred and analyzed using ImageJ bundled (1.8.0-112). Experiments have been repeated twice at the same flow conditions; more than 99% reproducibility has been observed in pressure drop values. The camera was located 4 m from the inlet test section. In this work, laminar and turbulent flows are investigated. Details of the experimental rig and details of operating conditions are listed in the form (Tables 2, 3).

Table 1: Maximum uncertainty of the measurements.

Measured parameter	Uncertainty
Pressure	± 0.2 %
Pipe diameter	± 0.2 mm
Oil and water density	± 0.3 kg/m^3
Temperature	± 0.1 C^0

Table 2: Components of the experimental equipment.

Device	model
Temperature controllers	Samwon - SU-105DA-N
Differential Pressure Transmitter	Smart Line ST700 (Honeywell)
High-speed camera	Canon -EOS 5D Mark IV and lens 24-105mm f/4L
Flow meters	Model:lzm-25g
Centrifugal pumps	VID-001008004
kinematic viscometer	SVM3001

Table 3: Details of operating condition.

Parameter	Operating condition
Superficial oil velocity (m/s)	0.18-0.95
Superficial water velocity (m/s)	0.18-1.2
Reynolds number range	40 - 24,000
Temperature (°C)	25

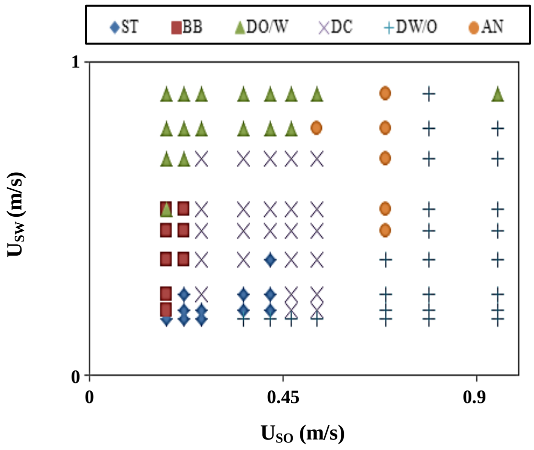


Fig. 3: Flow pattern map constructed for this study (stratified (stratified smooth, SS, and Stratified Wavy, SW), bubbly (BB), Dual Continuous (DC), annular (AN), Dispersed Water in Oil (DW/O), and Dispersed Oil in Water (DO/W))

Assumptions in this paper: (1) The temperature is assumed to be constant along with the bed-steady state conditions. (2) The slope of the pipe is considered a zero-Horizontal pipe. (3) The pressure gradient due to altitude changes is considered zero. (4) Since the slope in the horizontal tube is zero, there is no need to correct the volume fraction of the liquid.

RESULTS AND DISCUSSION

Flow pattern map

The flow patterns identified in this work are presented in Fig. 3. They are classified into six patterns namely; stratified (stratified smooth, SS, and Stratified Wavy, SW), bubbly (BB), Dual Continuous (DC), annular (AN), Dispersed Water in Oil (DW/O), and Dispersed Oil in Water (DO/W). They are defined as follows:

Stratified (stratified smooth, SS, and stratified wavy, SW): where the two fluids flow in separate layers at the top and bottom of the pipe according to their densities. Dual Continuous (DC): where both oil and water form continuous layers at the top and bottom of the pipe, respectively, but drops of one phase appear into the continuum of the other phase. Annular (AN): where water forms an annular film at the wall and oil flows in the pipe core. Bubbly (BB): where the oil appears in the form of elongated drops (slightly longer than the pipe diameter) within the water continuum. Dispersed Oil in Water (DO/W): where the pipe cross-sectional area is occupied by water containing dispersed oil droplets. Dispersed Water in Oil (DW/O): where oil is the continuous phase and water is presented as droplets across the pipe cross-sectional area.

Stratified flow transitions to dual continuous and bubbly flows. When water velocity increases transition to bubbly flow occurred. This is largely due to the increase in the turbulence of the water phase at a high water velocity and because the layer of the oil phase is thin at these oil velocities. When oil velocity increased, a transition to dual continuous flow occurred. This is attributed to the fact that at these flow conditions, the oil layer was thick enough to resist the turbulence of the water phase from breaking its continuous flow. Bubbly flows transition to DC flow. As the increase in superficial water velocity, the length of the bubbles decreased. At this condition, the oil layer was thick enough to withstand the effect of turbulence caused by the water layer. Dual Continuous (DC) flow transition to DO/W and DW/O flow. As the water velocity increased, more of the oil was dispersed into the water phase. Further increase in water velocity caused the DC flow to transform into the annular flow and then to Dispersion of Oil in Water flow (DO/W). The water phase did not disperse into the oil phase at low oil superficial velocity. This is possible because the region near the wall had relatively higher shear stress due to high-velocity gradients. As the oil superficial velocity increased, more water dispersed into the oil phase while the thickness of the water layer was found to decrease until the whole water dispersed in the oil phase. This is likely due to the increase in instability as a result of the combined effect of the turbulence force caused by the velocities and the viscosity resistance due to the thick oil layer in the pipe. Annular flow transition to DO/W flow. Further increase in water velocity changed the annular pattern to dual continuous flow. The increase in superficial oil velocity was observed to be transformed into DW/O flow. At low superficial oil velocities, DO/W was transformed from bubbly flow, while at moderate oil superficial velocities, it is a dual continuous flow that changed to DO/W. At higher oil superficial velocities, DO/W was inverted from the dispersion of water in oil. DW/O flow transition to DO/W pattern and dual continuous flow.

Visual observation

Stratified flow

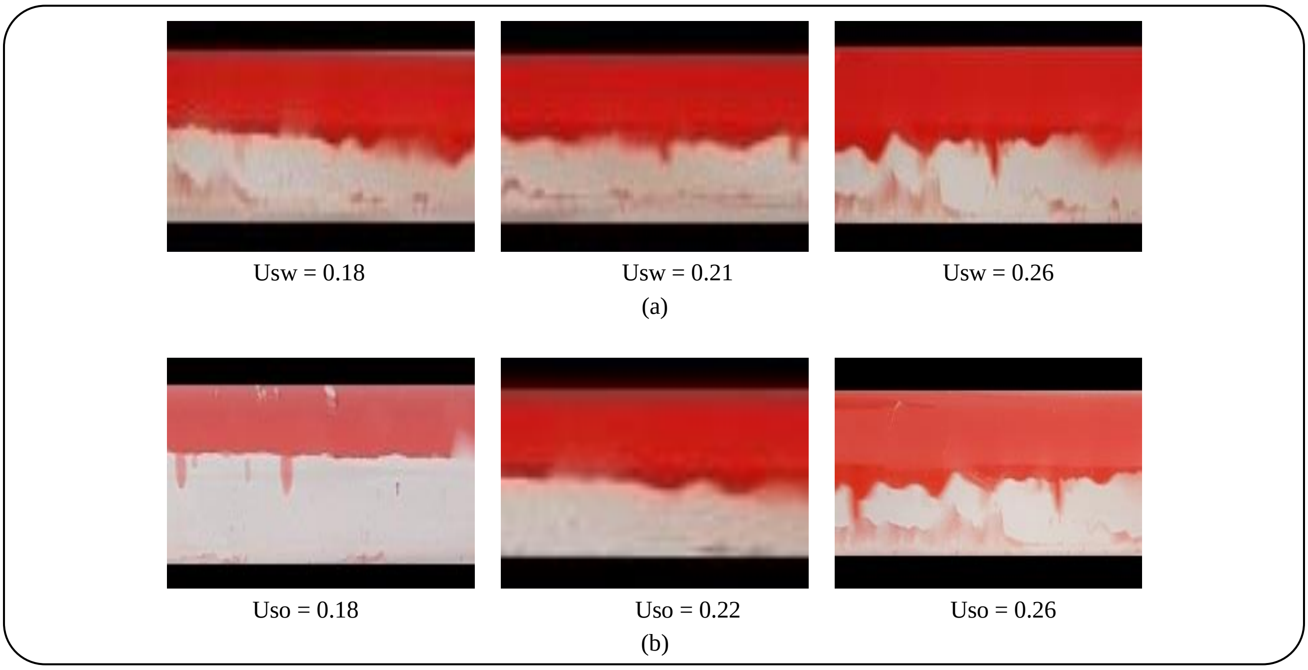
The stratified flow became visible at low oil and water velocities because at these velocities gravity force overcame while momentum fluctuation was minimal. The stratified flow was observed to transform into two types of flow patterns as superficial water velocity increased. These are transitions to dual continuous and bubbly flows. Stratified flow changed to bubbly flow at superficial velocity (Uso) less than 0.22 m/s. This is largely due to the increase in the turbulence of the water phase at high water velocity, and because the layer of the oil phase is thin at these oil velocities, the prospect of the waves at the interface breaking the thin layer of oil is very high, thereby, creating a continuous water phase with the oil phase dispersed non-uniform as a bubble. The transition from stratified to dual continuous flow occurred at superficial velocity Uso > 0.22 m/s. This is attributed to the fact that under these flow conditions, the oil layer was thick enough to resist the turbulence of the water phase from breaking its continuous flow. The stratified flow was observed within the range of superficial oil and water velocity respectively 0.18–0.42 m/s and 0.18–0.26 m/s. The flow changed to stratified wavy flow as superficial water velocity increased. For example, at a superficial velocity Uso = 0.22 m/s and Usw = 0.18 to Usw = 0.26 m/s, the wave amplitudes increased in size as superficial water velocity increased as shown in Fig. 4a. For the effect of superficial oil velocity on stratified flow, the area of the pipe occupied by the oil phase increased and stratified flow extended to higher superficial oil velocities at lower superficial water velocities (see Fig. 4b).

Bubbly flow

Bubbly flow pattern happened at low superficial oil velocities (Uso = 0.18–0.26 m/s) and moderate superficial water velocities (Usw = 0.21–0.53 m/s) (see Fig. 5a). The increase in superficial water velocity caused a decrease in the bubble length. The elongated bubbles were initially slightly longer than the pipe diameter. On the other hand, as superficial oil velocity increased, the bubble length increased due to the increase in the bubbles' coalescence rate. Further increase in the oil velocity made the oil layer to preserve its continuity. Low oil velocity made the thin oil layer form and the turbulence of the water layer increased. This created instability at the interface and broke the thin oil layer, therefore, droplets of oil were in the water continuum. As the increase in superficial water velocity, the length of the bubbles decreased. Hence, a transition to either DC flow occurred depending on the superficial velocity of the water. On the other hand, as superficial oil velocity increased at Uso=0.26 m/s, Usw=0.37 m/s, was observed to be transformed to DC flow (see Fig. 5b).

Dual Continuous (DC) flow

Dual continuous flow happened within the range of superficial oil and water velocities respectively 0.26–0.53 m/s and 0.26–0.69 m/s. Dual continuous flow is a function of the relative velocity of the two phases. As the increase in superficial water velocity occurred, more of the oil dispersed into the water phase. Transition to either AN and then DO/W flow occurred depending on the superficial velocity of water (see Fig. 6a). As the increase in superficial oil velocity occurred, the transform to DW/O flow was observed (see Fig. 6b). The water phase was not dispersed into the oil phase



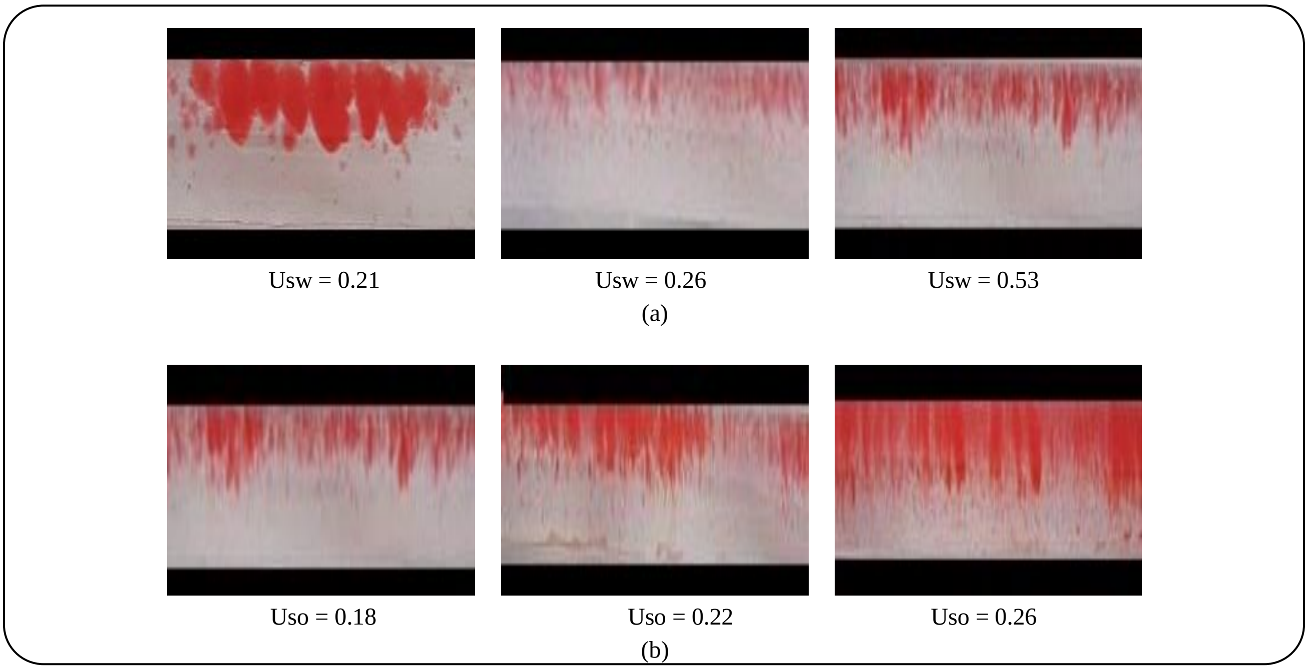
Usw = 0.18 Usw = 0.21 Usw = 0.26

(a)

Uso = 0.18 Uso = 0.22 Uso = 0.26

(b)

Fig. 4: Effect of increasing water and oil superficial velocity at (a) Uso = 0.22 m/s, (b) Usw = 0.18 m/s.



Usw = 0.21 Usw = 0.26 Usw = 0.53

(a)

Uso = 0.18 Uso = 0.22 Uso = 0.26

(b)

Fig. 5: Effect of increasing superficial water and oil velocity on bubbly flow at (a)Uso = 0.18 m/s and (b) Usw = 0.37m/s.

at low oil superficial velocity. This may be due to the relatively higher shear stress as a result of high-velocity gradients at the region near the wall. As the oil superficial velocity increased, more water dispersed into the oil phase while the thickness of the water layer was found to decrease until the whole water dispersed in the oil phase. This is considered the transition from DC flow to the dispersion of water in oil (DW/O). Thus, it can be concluded that as the superficial water velocity increased, the superficial oil velocity at which the transition from dual continuous to the dispersion of water in oil appeared also increased.

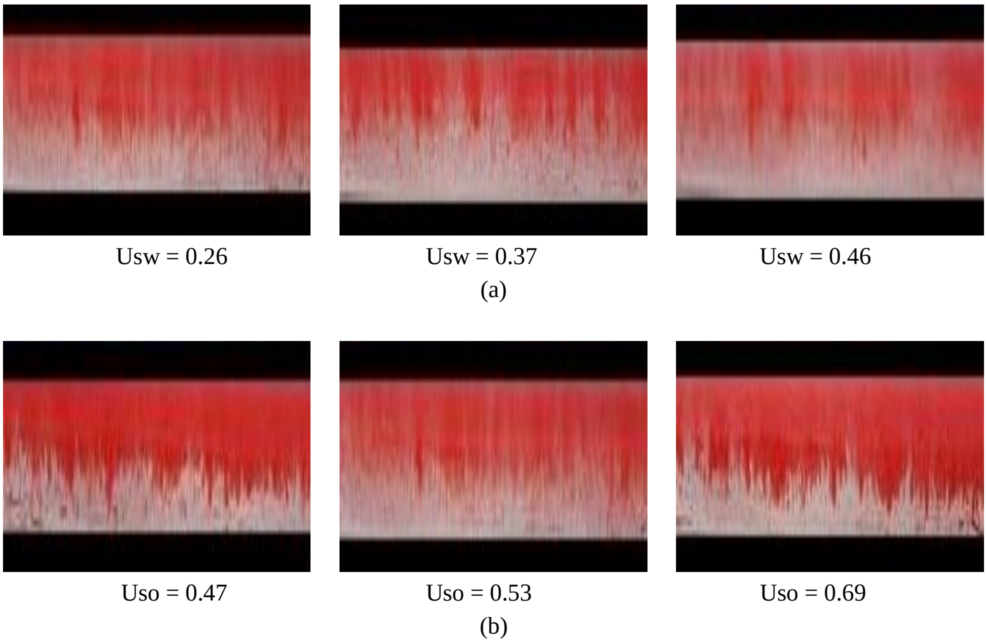


Fig. 6: Effect of increasing superficial water and oil velocity on DC flow at (a) Uso = 0.47 m/s and (b) Usw = 0.26 m/s.

Annular flow

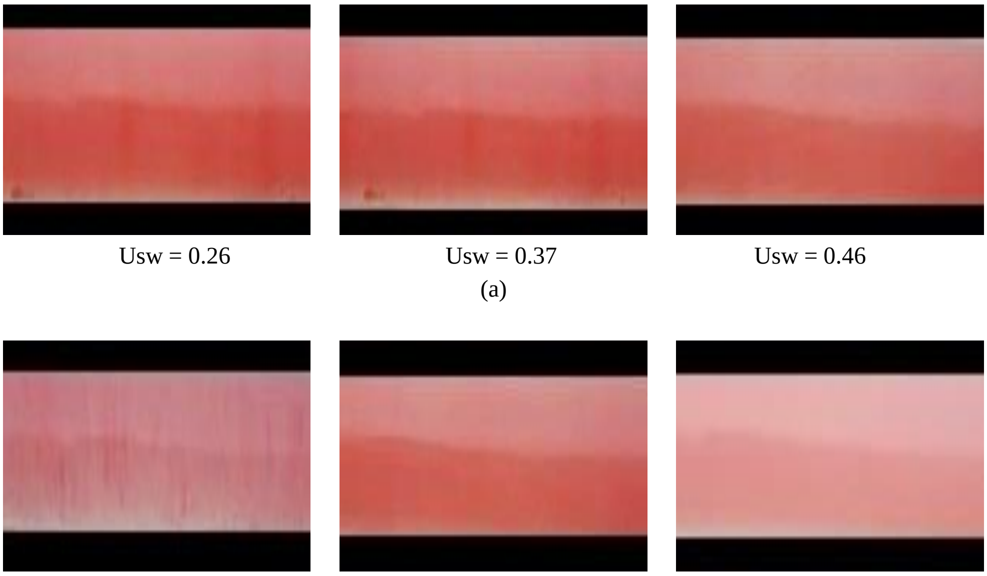
In this study, this pattern occurred within the range of superficial oil and water velocities respectively, 0.53 –0.69 m/s and 0.79 – 0. 9 m/s. A thin layer of water was seen at the top of the pipe and the interface was disturbed with oil drops seen within the water. As the water superficial velocity increased, the disturbance at the interface also increased. Therefore, more of the oil flowing in the core of the pipe was seen to disperse into the water phase until the whole oil collapsed into droplets. This is attributed to the increase in turbulence due to the increase in water velocity. For the effect of superficial oil velocity on annular flow, the thickness of the core oil layer increased while the thin water layer at the top decreased as the superficial oil velocity increased. An annular flow where oil is in the wall-wetting phase did not occur. As the increase in superficial oil velocity occurred, the transform to DW/O pattern was observed (see Fig. 7a). As the increase in superficial water velocity occurred, the transform to DO/W pattern was observed (see Fig. 7b).

Dispersion of Oil in Water (DO/W)

Dispersion of oil in water occurred at high superficial water velocity at low or moderate superficial oil velocities. This pattern occurred within the range of superficial oil and water velocities respectively 0.18 –0.53 m/s and 0.79 – 1.2 m/s. However, at higher water superficial velocities (Usw = 1.2 m/s), an increase in superficial oil velocity did not have a significant effect on the dispersion (see Fig. 8a). Fig. 8a shows that at low and moderate oil superficial velocities (Uso = 0.47 m/s), the oil was initially dispersed in the water continuum at the top of the pipe with a continuous layer of water flowing at the bottom. As the water velocity increased, the area occupied by the dispersed oil extended to the entire pipe cross-sectional area. In this study, (DO/W) pattern transformed from bubbly and DC flow (see Fig. 8b). At low superficial oil velocities, DO/W was transformed from bubbly flow while moderate oil superficial velocities is a dual continuous flow that changed to DO/W. At higher oil superficial velocities, DO/W was inverted from the dispersion of water in oil.

Dispersion of Water in Oil (DW/O)

Unlike the dispersion of oil in water that was observed throughout the oil superficial velocities investigated, the Dispersion of Water in Oil (DW/O) appeared from a superficial oil velocity of 0.69 m/s to the top. This pattern occurred within the range of superficial oil and water velocities respectively 0.69 –0.95 m/s and 0.18 – 0.69 m/s. As the increase in superficial water velocity>0.69 m/s,

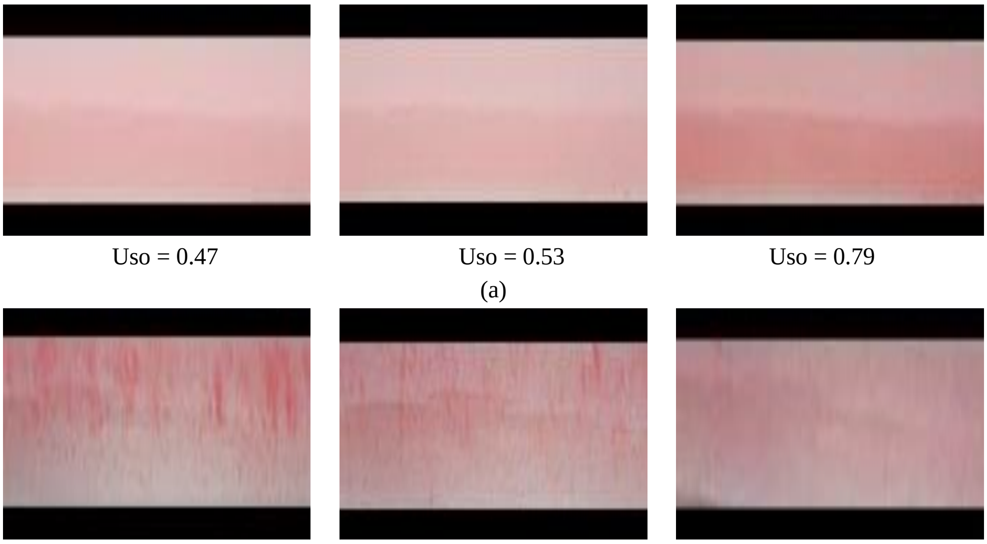

Usw = 0.26 Usw = 0.37 Usw = 0.46

(a)

Uso = 0.53 Uso = 0.69 Uso = 0.79

(b)

***Fig. 7:* Effect of increasing superficial water and oil velocity on annular flow at (a) Uso = 0.69 m/s and (b) Usw = 0.79 m/s.**


Uso = 0.47 Uso = 0.53 Uso = 0.79

(a)

Usw = 0.79 Usw = 0.9 Usw = 1.2

(b)

Fig. 8: Effect of increasing superficial oil and water velocity on (DO/W) flow at (a) Usw = 1.2 m/s and (b) Uso = 0.22 m/s.

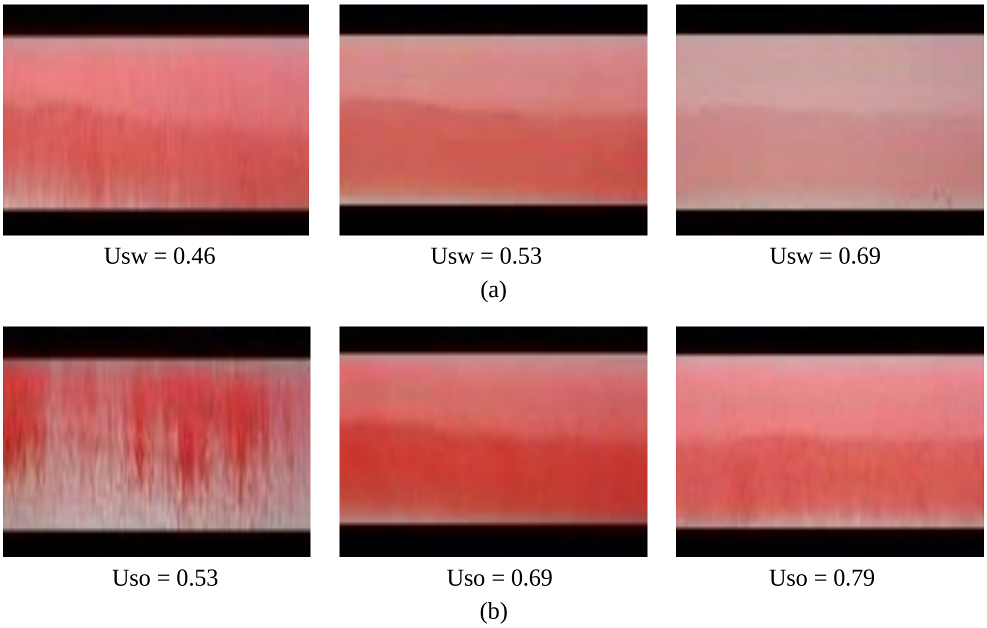
transform to DO/W pattern was observed (see Fig. 9a). At moderate superficial oil velocities (>0.79 m/s), as water velocity increased, the ratio of oil to water in the pipe decreased until the water layer was thick enough to form a continuous phase at the bottom of the pipe with the water dispersed in the oil continuum at the top. Therefore, dual continuous flow occurred. At high oil velocities, the turbulence of the flow was high enough to keep the two phases dispersed in one another. (See Fig. 9b).

Flow pattern comparison between the current study and other work

Comparing the current experimental results at 67 cp with those reported in the literature for viscosities between 1 and 12 cP (see Table 4).

Table 4: Data used for comparting flow pattern.

Parameters	P. Hanafizadeh[10]	N. Yusuf [22]	present work
Pipe diameter (mm)	20	25	20
Viscosity (cP)	1	12	67


Usw = 0.46 Usw = 0.53 Usw = 0.69

(a)

Uso = 0.53 Uso = 0.69 Uso = 0.79

(b)

Fig. 9: Effect of increasing superficial water and oil velocity on (DW/O) flow at (a) Uso = 0.79 m/s and (b) Usw = 0.37 m/s.

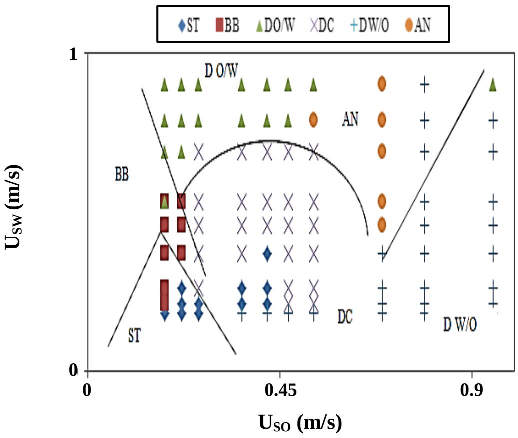


Fig. 10: Comparison of flow pattern map between this study and N. Yusuf et al [22]. Flow pattern map constructed (stratified (Stratified Smooth, SS, and Stratified Wavy, SW), Bubbly (BB), Dual Continuous (DC), Annular (AN), Dispersed Water in Oil (DW/O), and Dispersed Oil in Water (DO/W)).

The obtained flow patterns map of horizontal flow was compared with the work of *N. Yusuf et al.* [22]. Transition boundaries between flow regimes in Yusuf's work have been depicted with lines in Fig. 10.

There is acceptable compatibility between the experimental results of this study and the work of *N. Yusuf et al.* [22]. As seen in Fig.15, there are some differences in the transition boundary of ST to DC flow and AN to DW/O flow between this experimental study and the work of Yusuf. These differences may be due to the difference between the pipe diameters and oil properties used in Yusuf's work and this experimental study. These differences between this study and Yusuf's work show that pipe diameter and viscosity are two important parameters in the flow pattern. Moreover, the obtained flow patterns map of horizontal flow was compared with the work of *P. Hanafizadeh et al.* [10]. Transition boundaries between flow regimes in Hanafizadeh’s work have been depicted with lines in Fig. 11.

There are some differences in the transition boundary of ST to DC flow and AN to DO/W between this experimental study and the work of *Hanafizadeh et al.* [10]. These differences may be due to the difference between the oil properties used in Hanafizadeh’s work and this experimental study.

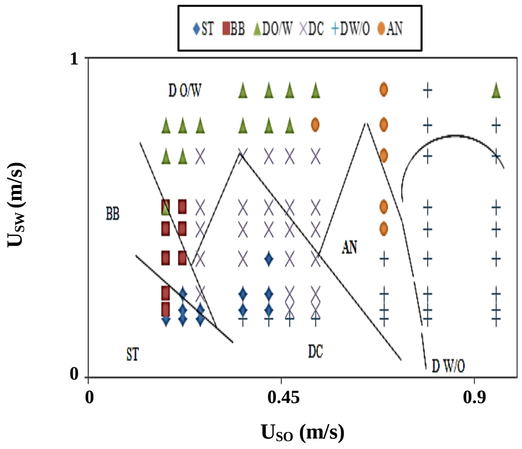


Fig.11: Comparison of flow pattern map between this study and P. Hanafizadeh et al [10]. Flow pattern map constructed (stratified (Stratified Smooth, SS, and Stratified Wavy, SW), Bubbly (BB), Dual Continuous (DC), Annular (AN), Dispersed Water in Oil (DW/O), and Dispersed Oil in Water (DO/W)).

Effect of oil viscosity on the flow pattern

Stratified flow: The only difference is the extent to which the flow pattern extends. Bubbly flow: the oil-water viscosity ratio is high which increased the interface inconstancy and as a result, a bubble formed at low oil flow rates so that systems of oil-water flow with high viscosity ratio and high interfacial forces will have a higher chance for intermittent flows to form. The bubbly flow pattern this work has a wide range because of the high viscosity ratio. Annular flow: *Yusuf et al.* [22] and *Hanafizadeh et al.* [10] due to the high viscosity of the oil used in their studies reported annular flow. High oil viscosity favors the formation of an annular flow pattern. Thus, as the oil viscosity increases, the probability to have an annular flow increases too. The high viscosity in this work has contributed to the formation of an annular flow pattern. Dual continuous flow: Compared with the results of this study, at low oil velocities, *Hanafizadeh et al.* [10] and *Yusuf et al.* [22] reported the early formation of DC flow as superficial water velocity increased. The extent of the dual continuous pattern reported by those systems (lower oil viscosity system) is smaller when compared to the present study results. This could be related to the higher oil-water viscosity ratio used in this study.

Dispersion of Oil in Water and Water in Oil (DO/W and DW/O) flows: The extent of DO/W and DW/O pattern reported by *Hanafizadeh et al.* [10] and *Yusuf et al.* [22] system (lower oil viscosity system) is smaller when compared to the present study results. This could be related to the higher viscosity used in this study.

Pressure gradient results

The flows with oil film on pipe walls tend to have higher pressure gradients. Corresponding to the same superficial oil velocity, shear stress near the pipe wall increases as the superficial water velocity increases. This causes a higher pressure gradient. On the other hand, high shear stress helps thin oil film at the pipe wall and breaks up the oil into droplets so that water becomes more dominant near the pipe wall. Pressure gradient due to friction was measured in this study, superficial water and oil velocities ranged from 0.18 to 1.2 m/s and 0.18 to 0.95 m/s respectively. The results are presented in Fig. 12. At low superficial oil velocities with increasing superficial water velocity, pressure gradient didn't increase much. Also, at moderate superficial oil velocities (Uso = 0.36 m/s), where the flow transformed from dual continuous to dispersed flow the pressure gradient increased more than the low superficial oil velocities as superficial water velocity increased. Nevertheless, at high superficial oil velocities, where the transition from dispersion of water in oil to the dispersion of oil in water occurred with an increase in superficial water velocity (Uso = 0.69 and 0.95 m/s), the pressure gradient was observed to initially increase gradually before a sharp increase occurred. The peak of the pressure gradient occurred close to the superficial water and oil velocity where the transition to annular flow appeared.

Comparing pressure gradient experimental data with a two-fluid model and al-Wahaibi correlation

The experimental pressure gradient was also compared with the Al-Wahaibi correlation (Eq. (1)) and two-fluid model (Eq. (2)) as shown in Figs. 13-17. This reveals that the Al-Wahaibi correlation is able to predict better the experimental results in comparison with the two-fluid model.

$$\frac{dp}{dx} = 2.4\left(\frac{f_m \rho_m U_m^2}{2D}\right)^{0.8} \qquad (1)$$

$$\frac{dp}{dx} = 2.4\left(\frac{f_m \rho_m U_m^2}{2D}\right) \qquad (2)$$

Where *dp/dx* is the pressure gradient, f_m is the two-phase friction factor, ρ_m is the mixture density, *Um* is

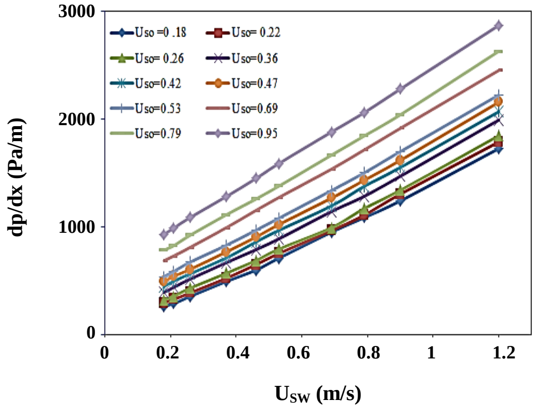


Fig. 12: Effect of increasing superficial water velocity on pressure gradient at different superficial oil velocities.

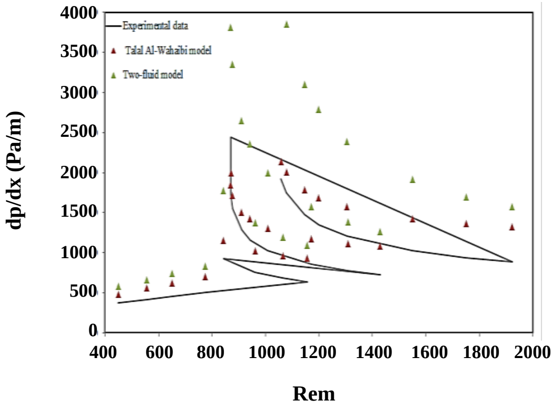


Fig. 15: Comparing experimental data with Al-Wahaibi correlation and two-fluid model [24] in D W/O flow regime.

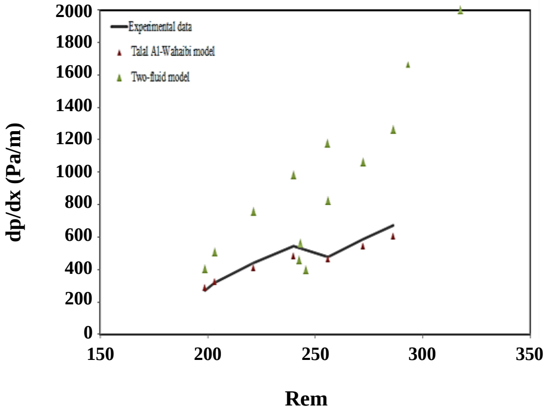


Fig. 13: Comparing experimental data with Al-Wahaibi correlation and two-fluid [24] model in BB flow regime.

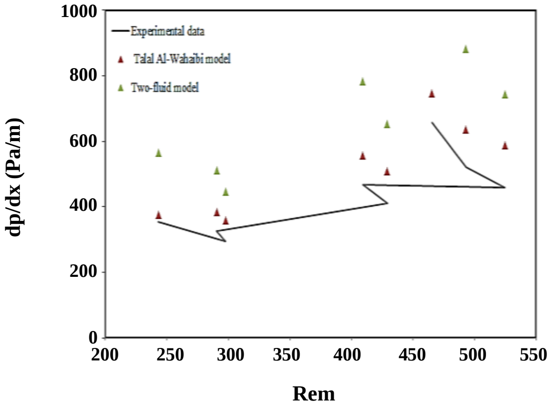


Fig. 16: Comparing experimental data with Al-Wahaibi correlation and two-fluid model [24] in SW flow regime.

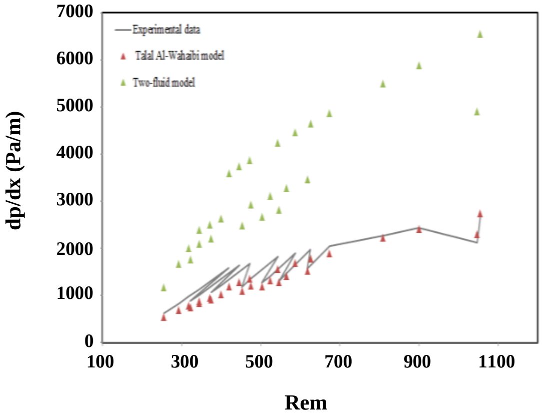


Fig. 14: Comparing experimental data with Al-Wahaibi correlation and two-fluid model [24]in D O/W flow regime.

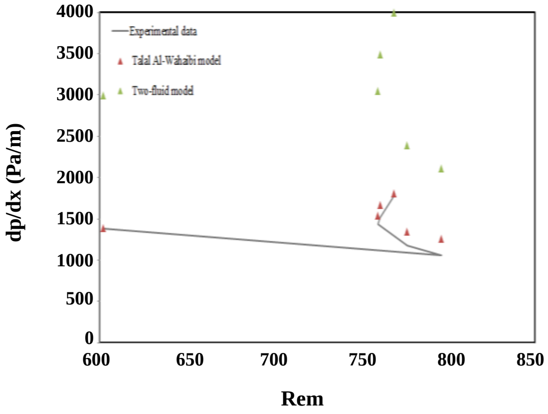


Fig. 17: Comparing experimental data with Al-Wahaibi correlation and two-fluid model [24]in AN flow regime.

Table 5: Comparing of the accuracy of pressure gradient prediction two-fluid model& Al-Wahaibi correlation [24] against published data.

Source	% AAPE
Two-fluid model [24]	30
Al-Wahaibi correlation [24]	9

Table 6: Data used to investigate the effect of oil viscosity on the pressure gradient.

Parameters	Vale and Kvandal[21]	Angeli and Hewitt[2]	Chakrabarti[23]	N. Yusuf[22]	Present work
Pipe diameter(mm)	37	25	25	25	20
Viscosity (cP)	2.3	1.6	1.3	12	67

the oil-water mixture velocity and D is the pipe diameter. The Average Absolute Percent Error (AAPE) is calculated to evaluate the prediction capability of the correlation. Unlike the Average Percent Error (APE), the absolute errors are considered so the positive errors and the negative errors are not canceled. The equation is given by :

$$\mathrm{AAPE}=\left[\frac{1}{n}\sum_{k=1}^{n}\left|\frac{\left(\frac{dp}{dx}\right)_{pred}-\left(\frac{dp}{dx}\right)_{exp}}{\left(\frac{dp}{dx}\right)_{exp}}\right|\right]\times 100 \tag{3}$$

The accuracy of the predictions was measured by calculating the Average Absolute Percent Error (AAPE) which can be seen in Table 5.

From the existing models in predicting the pressure gradient of two-phase flow in horizontal pipes, two models Al-Wahaibi and two-fluid were selected to compare with experimental data. The Al-Wahaibi correlation is in good agreement with the experimental data and can be used for high viscosity two-phase flow. The results, particularly in Figs 13-17, indicate that the Al-Wahaibi correlation is more accurate in comparison with the two-fluid correlation. The experimental pressure gradient database was also compared with the two-fluid model. The model was found to highly underpredict the experimental data, especially those working with a steel pipe. This could be probably attributed to the wetting phenomena which are not taken into account in the two-fluid model. This reveals that the Al-Wahaibi correlation (Eq. (1)) is able to better predict the experimental results in comparison with the two-fluid model. In a recent work [25], we developed a new correlation for estimating the pressure gradient of oil-water two-phase flow in a horizontal pipe (Eq. (4)), which agreed reasonably well with the experimental results.

$$\frac{dp}{dx}=\left(\frac{f\rho_m U_m^2}{2D}\right)^{g6} \tag{4}$$

Where *f* is a function of roughness and *Re* number and includes some parameters that were determined by genetic algorithm

Effect of oil viscosity on the pressure gradient

The effect of oil viscosity and pipe diameter on pressure gradient were compared with the data of *Vale* and *Kvandal* [21], *Angeli* and *Hewitt* [2], *Chakrabarti et al.* [23], and *Yusuf* [22] as shown in Figs. 18–21. The pressure gradient values obtained in this study are greater than in their studies at similar superficial oil and water velocities. This is because the viscosity of the oil used in their studies is lower than that used in this work (see Table. 6). The viscosity of the small diameter pipes appears to have a greater impact on the pressure drop. One of the important points in this article is the high viscosity of the oil and its effects on pressure drop.

Since the oil is in direct contact with the pipe wall especially during stratified, dual continuous, and dispersion of water in oil flow regimes, the system with higher oil viscosity is expected to have higher drag, hence greater pressure drop. From the figures, it is clear that the differences in pressure gradient results become bigger with higher oil velocities. The largest difference in pressure values was observed in the flow region where oil is in the continuous phase. On the other hand, in flow patterns where water forms the continuous phase (DO/W), the pressure gradient values observed at similar conditions are approximately the same.

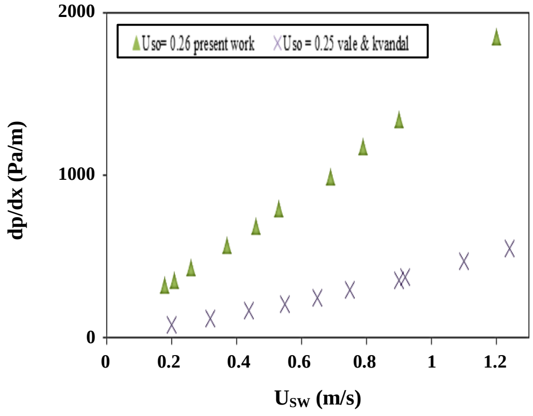


Fig. 18: Effect of oil viscosity on pressure gradient: comparison between present study and vale and kvandal[21].

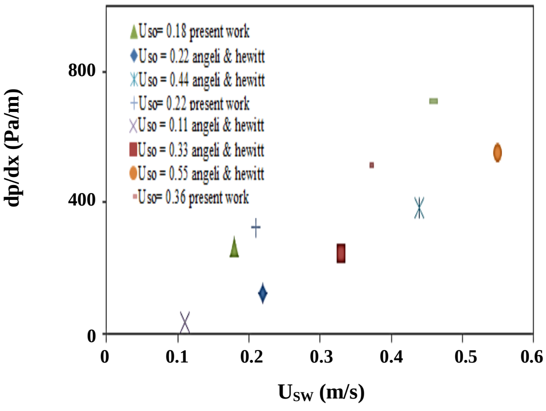


Fig. 19: Effect of oil viscosity on pressure gradient: comparison between the present study and Angeli and Hewitt [2].

According to Fig 18 -21, it is clear that the closer the viscosity of the two fluids are to each other, and the closer the pressure drops are to each other. However, in general, the pressure gradient in a flow with higher viscosity is always greater.

CONCLUSIONS

Flow pattern and pressure gradient were obtained using a combination of oil-water properties in a 20 mm acrylic horizontal pipe. The effect of oil viscosity on pressure gradient and flow pattern was compared with the data of *Valle* and *Kvandal* [21], *Angeli* and *Hewitt* [2], *Chakrabarti et al.* [23], Yusuf [22], and *Hanafizadeh et al.* [10]. Three forces affect the dispersed phase in two-phase liquid-liquid flow, namely buoyancy, gravity, and inertia force.

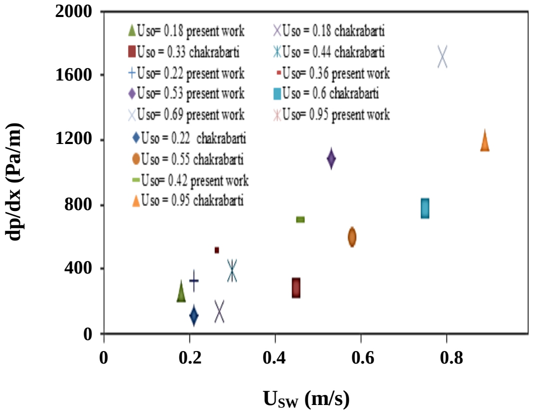


Fig. 20: Effect of oil viscosity on pressure gradient: comparison between present study and Chakrabarti et al[23].

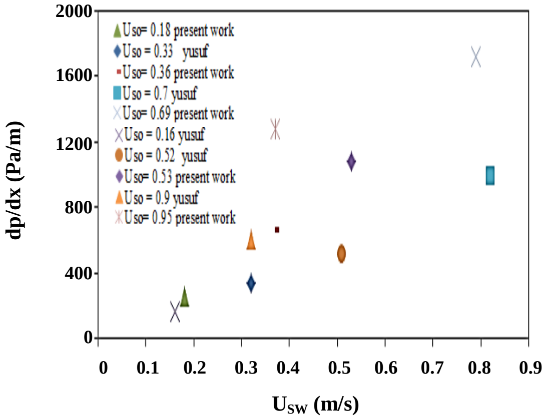


Fig. 21: Effect of oil viscosity on pressure gradient: comparison between the present study and Yusuf [22].

Six flow patterns were identified, namely stratified, bubbly, dual continuous, annular, dispersion of oil in water, and dispersion of water in oil flow.

The stratified flow became visible at low velocities of oil (<0.42 m/s) and water(<0.26 m/s). The flow changed to stratified wavy flow as superficial water velocity increased (>0.18 m/s). Stratified flow changed to bubbly flow at superficial velocity (Uso) less than 0.22 m/s. The transition from stratified to dual continuous flow occurred at superficial velocity (Uso) > 0.22 m/s.

Bubbly flow pattern happened at low superficial oil velocities (Uso = 0.18–0.26 m/s) and moderate superficial water velocities (Usw = 0.21–0.53 m/s). Low oil velocity led to the formation of the thin oil layer and the turbulence of the water layer increased. Dual continuous flow is a function of the relative velocity of the two phases. As the increase in superficial water velocity, more of the oil was dispersed into the water phase. Annular flow occurred within the range of superficial oil and water velocities 0.53 –0.69 m/s and 0.79 – 0. 9 m/s, respectively. As the superficial oil velocity increased, it was observed to transform into DW/O pattern but no annular flow where oil is in the wall-wetting phase occurred.

Dispersion of oil in water (DO/W) occurred at high superficial water velocity (Usw =0.79 – 1.2 m/s) at low or moderate superficial oil velocities (Uso = 0.18 –0.53 m/s). Dispersion of water in oil (DW/O) appeared from a superficial oil velocity of 0.69 m/s to the top. As the increase in superficial water velocity>0.69 m/s, a transform to (D O/W) pattern was observed.

The obtained flow patterns map of horizontal flow was compared with available data in the literature. There is acceptable compatibility between the experimental results of this study and available data in the literature. There are some differences in the transition boundary of ST to DC flow and AN to DW/O between this experimental study and the other work, the most important of which maybe due to the difference between the oil properties used in this work.

Pressure gradient strongly depends on flow rates and flow patterns. Oil viscosity also plays an important role in pressure gradients. At the same superficial water and oil velocities, the pressure increases with an increase in oil viscosity. The pressure drop behavior is evaluated in terms of the oil-water interface shape and its modifications caused by variations in the flow rates. Large difference in pressure gradient data was obtained. The differences in the results become larger as the oil viscosities and velocities increased. The largest difference in pressure values was observed in the flow region where oil is in the continuous phase. The pressure gradient values obtained in this study are greater than those in their studies at similar superficial oil and water velocities (over 80%). This is because the viscosity of the oil used in their studies is lower than the one used in this work.

The experimental pressure gradient was also compared with the Al-Wahaibi correlation and two-fluid model. The absolute average percentage error (%AAPE) in the two-fluid model was 30% and in Al-Wahaibi correlation was 9%. The Al-Wahaibi correlation agreed reasonably (9% AAPE) well with the experimental results and it can be used for high viscosity two-phase flow.

Nomenclatures

D	Pipe Diameter, mm
dp/dx	Pressure Gradient, Pa/m
fm	Two-Phase Friction Factor
Hw–Ho	Water and Oil Hold-Up
Qw–Qo	Water and Oil Volumetric Flow Rate, m^3/s
Rem	Reynolds Noumber Oil and Water Mixture
Uso	Oil Superficial Velocity, m/s
Usw	Water Superficial Velocity, m/s
Um	Oil-Water MixtureVelocity, m/s

Greek symbols

ε	Wall Roughness, N/M
ρ_m	Mixture Density, kg/m^3
μ_m	Average Mixture Viscosity, Cp

Subscripts

exp	Experimental
m	Mixture
o	Oil
pred	Prediction
s	Superficial
w	Water

Abbreviation

AAPE	Average Absolute Percent Error
AN	Annular
BB	Bubbly
DC	Dual continuous
DW/O	Dispersed water in oil
DO/W	Dispersed oil in water
Equ	Equation
SS	Stratified smooth
SW	Stratified wavy

Received : Mar. 7, 2020 ; Accepted : Feb. 14, 2022

REFERENCES

[1] Kong R., Kim S., Characterization of Horizontal Air-Water Two-Phase Flow, *Nucl. Eng. Des.*, **312**: 266-276(2017).

[2] Angeli P., Hewitt G.F., Pressure Gradient in Horizontal Liquid-Liquid Flows, *Int. J. Multiphase Flow*,**24(7)**: 1183–1203(1998).

[3] Angeli P., Hewitt G.F., Flow Structure in Horizontal Oil-Water Flow, *Int. J. Multiphase Flow*, **26(7)**: 1117–1140 (2000).

[4] Oddie G., Shi H., Durlofsky L.J., Aziz K., Pfeffer B., Holmes J.A., Experimental Study of Two and Three Phase Flows in Large Diameter Inclined Pipes, *Int. J. Multiphase Flow*, **29(4)**: 527–558 (2003).

[5] Rodriguez O.M.H., Oliemans R.V.A., Experimental Study on Oil-Water Flow In Horizontal and Slightly Inclined Pipes, *Int. J. Multiphase Flow*, **32(3)**: 323–343 (2006).

[6] Mandal T.K., Chakrabarti D.P., Das G., Oil Water Flow Through Different Diameter Pipes–Similarities and Differences, *Trans. IChem E. Part A. Chem. Eng. Res. Des*, **85(8)**: 1123–1128 (2007).

[7] Xu X., Study on Oil-Water Two-Phase Flow in Horizontal Pipelines, *J. Pet. Sci. Eng*, **59(1)**: 43-58 (2007).

[8] Bannwart A.C., Rodriguez O.M.H., Trevisan F.E., Vieira F.F.,de Carvalho C.H.M., Experimental Investigation on Liquid–Liquid–Gas Flow: Flow Patterns and Pressure-Gradient, *J. Pet. Sci. Eng.*, **65(1-2)**: 1–13(2009).

[9] Hanafizadeh P., Ghanbarzadeh S., Saidi M., Visual Technique For Detection of Gas-Liquid Two-Phase Flow Regime in the Airlift Pump, *J. Pet. Sci. Eng.*, **75(3-4)**: 327–335 (2011).

[10] Hanafizadeh P., Hojati A., Karimi A., Experimental Investigation of Oil- Water Two Phase Flow Regime in an Inclined Pipe, *J. Pet. Sci. Eng.*, **136**: 12-22 (2015).

[11] ShamsulIzwan Ismail A., Experimental Investigation of Oil-Water Two-Phase Flow in Horizontal Pipes: Pressure Losses, Liquid Holdup and Flow Patterns, *J. Pet. Sci. Eng.*, **127**: 409-420 (2015).

[12] Jagan V., Experimental Studies on Two Phase Flow Patterns of Air–Water Mixture in a Pipe with Different Orientations, *Flow Meas.Instrum*, **52**: 170–179 (2016).

[13] Zhuoran D., ZijiangY., Xiaohong Y., Mamoru I., Experimental Study on Void Fraction, Pressure Drop and Flow Regime Analysis in a Large ID Piping System, *Int. J. Multiphas. Flow*, **111**: 31-419 (2019).

[14] Azizi S., Karimi H., Darvishi P., Flow Pattern and Oil Holdup Prediction in Vertical Oil-Water Two-Phase Flow Using Pressure Fluctuation Signal, *Iran. J. Chem. Chem. Eng. (IJCCE)*, **36(2)**: 125–141(2017).

[15] Ganat T., Ridha S., Hairir M., Arisa J., Gholami R., Experimental Investigation of High‐ Viscosity Oil-Water Flow in Vertical Pipes: Flow Patterns and Pressure Gradient, *J. Petrol. Explor. Prod. Technol*, **9**: 2911–2918 (2019).

[16] Zhai L., Liu R., Zhang H., Jin N., Complex Admittance Detection of Horizontal Oil-Water Two-Phase Flows Using a Capacitance Sensor, *IEEE Sensors Journal*, **19(17)**: 7489-7498 (2019).

[17] Zhai L., Liu R., Zhang H., Jin N., Prediction of Pressure Drop for Segregated Oil-Water Flows in Small Diameter Pipe Using Modified Two-Fluid Model, *Exp. Therm. Fluid Sci*,**114**:110078 (2020).

[18] Jing J., Yin X., Mastobaev B., Valeev A., Sun J., Wang S., Liu H., Zhuang L., Experimental Study on Highly Viscous Oil-Water Annular Flow in a Horizontal Pipe with 90° Elbow, *Int. J. Multiph. Flow*, **135**: 103499 (2021).

[19] Ahmad S., Ashraf M., Ali K., Numerical Simulation of Viscous Dissipation in a Micropolar Fluid Flow through a Porous Medium, *J. Appl. Mech. Tech. Phy.*, **60**: 996-1004 (2019).

[20] Hasanzadeh Y., Alavifazel S.A., Azizi Z., Peyghambarzadeh S.M., Azimi A., Prediction of the Pressure Drop in Water-High Viscosity Oil Flows Using Artificial Neural Network, *Solid State Technology*, **64(2)**: 7167-7186 (2021).

[21] Valle A., Kvandal H., Pressure Drop and Dispersion Characteristics of Separated Oil/Water Flow, *Two-Phase Flow Modelling and Experimentation*, *Int. Symposium*, **1**: 583–592 (1995).

[22] Yusuf N., Effect of Oil Viscosity on the Flow Structure and Pressure Gradient in Horizontal Oil-Water Flow, *Chem. Eng. Res. Des.*, **90(8)**: 1019–1030 (2012).

[23] Chakrabarti D.P., Das G., Ray S., Pressure Drop in Liquid-Liquid Two Phase Horizontal Flow: Experiments and Prediction, *Chem. Eng. Technol.*, **28**: 1003–1009 (2005).

[24] Al-Wahaibi T., Pressure Gradient Correlation for Oil–Water Separated Flow in Horizontal Pipes, *Exp. Therm. Fluid Sci.*, **42**: 196–203(2012).

[25] Hasanzadeh Y., Alavifazel S.A., Azizi Z., Peyghambarzadeh S.M., Azimi A., Development of A New Correlation for Estimating Pressure Gradient of Oil- Water Two Phase Flow in a Horizontal Pipe, *Int. J. ADMT*, **14(4)**: 51-58 (2021).