Teknomekanik, Vol. 5, No. 2, pp. 80-89, December 2022
e-ISSN: 2621-8720 p-ISSN: 2621-9980

Numerical analysis of flow characteristics of the oil-water mixture in stratified-annular horizontal pipe

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Received Aug 31st, 2022; Revised Sep 27th, 2022; Accepted Oct 13rd, 2022
DOI: https://doi.org/10.24036/teknomekanik.v5i2.14572

ABSTRACT

The loss of oil fluid flow in the piping system in the petroleum industry due to friction is the cause of low efficiency. To reduce friction loss, the viscosity of petroleum can be lowered by adding water as a mixture. Actually, the flow loss in a piping system is influenced by several factors including flow pattern, fluid type, flow velocity, flow pressure and pipe diameter. This study aims to determine the effect of flow patterns on changes in velocity in the two-phase flow of oil and water in a piping system. This numerical analysis research was carried out using Fluent 6.2 software with variations in the velocity of the oil-water mixture: 0.2, 0.4 and 0.6 m/s. The simulation results show that the greatest pressure loss occurs at a fluid velocity of 0.6 m/s where the flow is stratified mixed. While the smallest pressure loss at a mixture velocity of 0.2 m/s when the flow is stratified smooth. From the results of the study, it can be concluded that the increase in fluid flow velocity has a positive correlation with the increase in the value of flow losses in the pipe.

Keywords: Numerical analysis; Fluid-mixture velocity; Pressure drop; Horizontal pipe.

How to Cite:

N. Erizon, J. Jasman, I. Irzal, M. F. Aldio, A. Saputra, and C. T. Tin, "Numerical analysis of flow characteristics of the oil-water mixture in stratified-annular horizontal pipe", *Teknomekanik*, vol. 5, no. 2, pp. 80-89, Dec. 2022. https://doi.org/10.24036/teknomekanik.v5i2.14572

1. INTRODUCTION

In the world of the petroleum industry, many piping systems are found that carry fluids through the plumbing system from the mining area to the production site and users [1], [2]. Piping systems are widely used because they are easy to move and low operating costs [3]. In addition, the piping system maintenance process is quite simple and easy to manage [4], [5]. However, due to the long distance traveled, the transportation of oil through the piping system causes considerable pressure losses [6], [7]. This pressure loss is strongly influenced by the volume of oil to be moved and the distance from the mining area to the processing site. In addition, pressure losses during the transportation process in the piping system are also influenced by several factors, including: the type of oil being transported, flow rate, dimensions and characteristics of the piping, distance traveled, etc [8], [9].

Several studies can be found in the literature, related to efforts to reduce the value of flow losses in the piping system. Various methods have been proposed in reducing pressure loss such as; speed setting [10], pipe dimension setting [11], long pipe [12], type of pipe material [13], flow direction setting [14], injection of water into the pipe to reduce the density [15]. One method that is quite good for reducing flow losses is, injection of water into the pipe to reduce friction [15]. Water injected into the pipe will reduce the density of the oil so that the viscosity will be lower [16]. With low viscosity, the frictional force that occurs between the fluid and the inner surface of the pipe can be minimized [17]. The decrease in pressure loss in the pipeline can directly reduce the energy / power required for the pump used as the driving force [18]. An experimental study related to pressure loss in oil-water flow in a horizontal pipe. The results of their research show that the type of oil-water flow pattern and water cut input have a significant effect on the velocity and distribution of turbulence in the stratified and dispersed patterns [19].

Another study by the CFD method using Fluent 6.2 software, showed that the oil-water flow pattern had an effect on stratified flow pattern, smoothness, and the type of oil and water flow interface. In a numerical study using the K-epsilon model, it was found that the distribution pattern of oil-water in a horizontal pipe (inside diameter = 0.0024 m) is in turbulence on the continuous phase [20]. In addition, they also show that there is a significant effect of changes in mixed flow velocity on the flow pattern and pressure loss. Another study using the oil-water mixture simulation method in a horizontal pipe by varying the velocity and the amount of mass fraction (balanced oil and water ratio, 50:50), showed that the flow conditions became unsteady with friction losses occurring against the pipe walls in the flow being negligible [20]. This study aims at analyzing numerically the effect of two-phase flow velocity (oil-water mixture) on friction losses. The fluid velocity is varied from 0.2 to 0.6 m/s in a pipe with a diameter of 0.0254 m. The results of this study will describe the benefits for engineers in designing a working mechanism on a piping system by minimizing flow losses that occur due to friction.

2. MATERIAL AND METHODS

2.1 Fluid flow in piping systems

Every fluid flow in the pipe will run into a pressure drop as a result of fluid friction with the pipe wall. This pressure drop causes a decrease in the head which results in the bee's thrust that occurs. The loss of fluid flow head contained in the pipe due to friction can be calculated using the Darcy Weisbach equation (Eq. 1).

$$hf = f.\frac{l}{D}.\frac{v^2}{2.g} \tag{1}$$

Where *L* is the length of the pipe (m), *D* is the diameter of the pipe (m), *v* is the average flow velocity (m/s), *g* is the gravitational force (m/s^2) and *f* is the coefficient of friction. The value of f (friction factor) is highly dependent on the type of flow: laminar or turbulent. If the flow is laminar then the value off = 64/NR, while for turbulent flow, value of:

$$f = \frac{0.314}{R^{1/4}} \tag{2}$$

For horizontal flow in pipes, the flow pattern will depend on the phase ratio, mixed flow rate, density ratio, viscosity ratio, wetting properties, surface tension and pipe geometry. The ratio of the water and oil fractions in the pipeline can be calculated using the equations $Co\frac{Qo}{Qo+Qw}$ (oil fraction) and Cw = $\frac{Qw}{Qo+Qw}$ (water fraction). While the velocity at the superficial level for the two fluids is calculated using the Uso $= \frac{Qo}{A}$ (for oil) and Usw $= \frac{Qw}{A}$ (for water) equations. Based on these four equations, an equation for the relationship between superficial velocity and fluid fraction can be written in the equation 3.

$$\frac{U\,so}{U\,sw} = \frac{Co}{Cw} \tag{3}$$

$$Uo = \frac{Qo}{Ao} \tag{4}$$

$$U\,W = \frac{Qw}{Aw} \tag{5}$$

$$\varepsilon\frac{Ao}{A} \tag{6}$$

$$\varepsilon\frac{Aw}{A} \tag{7}$$

In calculation, it is assumed that each separate phase in a two-phase flow occupies a different part of the cross section. The actual velocity of each phase, the in-situ velocity, becomes different from the superficial velocity because it is calculated from the volumetric flow passing through an area smaller than the cross-sectional area. If the dividing parts occupied by oil and water are Ao and Aw respectively, then the velocity for each fluid is calculated using equation 3 and equation 4. Where *U* is velocity (m/s), *Q* is discharge (m^3/s)

Teknomekanik, Vol. 5, No. 2, pp. 80-89, December 2022
e-ISSN: 2621-8720 p-ISSN: 2621-9980

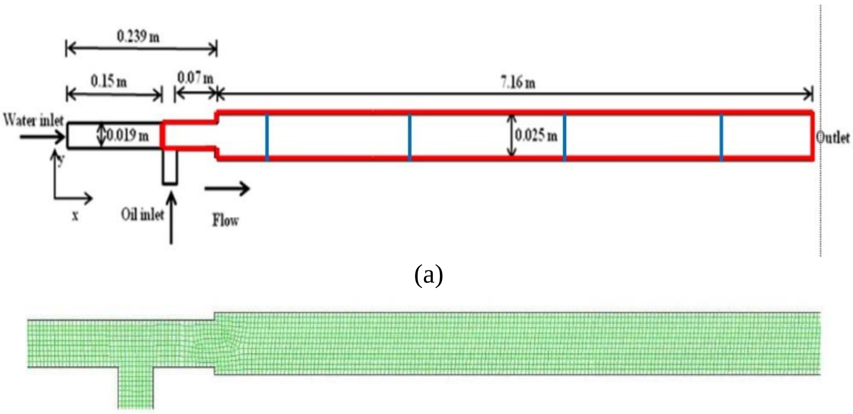
and A is the cross-sectional area (m^2), ε is the actual fraction, while the subscript O is oil and W is water. Based on Equations 3 and 4, it can be said that the actual velocity always exceeds the superficial velocity for each phase. The actual fraction or in-situ area of oil and water is defined by equations 5 and 6. Finally, the velocity of the mixture defined by dividing the total volumetric flow by the cross-sectional area of the pipe can be calculated according to equation 8. The velocity of the mixture is equal to the sum of the superficial velocities as in equation 9.

$$U\,m = \frac{(Qo + Qw)}{A} \tag{8}$$

$$Um \;= Uso + Usw \tag{9}$$

2.2 Oil and water mixture flow modeling

In this study, the flow of the oil-water mixture was simulated on a horizontal pipe with a test area length of 7.25 m. The dimensions of the pipe as a test specimen refer to the dimensions of the previous study [21]. Observation of the oil-water flow pattern was observed at a distance of 5 m from the end of the test area. The level of oil-water mixing was observed at the four observation sample points indicated by the blue line (Figure 1(a)), while the observed pressure distribution was observed in the red lined area which is 7.25 m long, as shown in Figure 1.a. In this study, discretization is done by dividing the pipe into small pipe, it is called cells which amount to 47,000 cells. The shape of the pipe that has been discretized into 47,000 cells can be seen in Figure 1(b).



(a)

(b)

Figure 1 : (a) Simulated horizontal pipe geometry, (b) Horizontal pipe geometry with meshing of 47,000 cells

The observation on the mixing of oil and water was carried out in the test area with varied mixture speeds and the mass fraction value of oil and water in the test area was 0.5. The length of the test area is 7.25 m which is divided into four observation sample points vertically, with a pipe diameter of 0.0254 m. Four observational sample points were selected taking into account the rate of change on flow oil and water along the test area. Observation point 1 is located 2.02 m from the end of the test area, observation point 2 is 3.82 m from the end of the test area, observation point 3 is located 5 m from the end of the test area, and observation point 4 is located 6.2 m from the end of the test area.

2.3 Simulation model with speed variation of oil-water mixture

The flow condition in this study is unsteady and the calculation model used is Volume of Fluid (VOF) [22], [23]. The choice of the VOF method is used according to the flow in this case, namely the liquid-liquid two-phase flow. In this study, 3 experiments were carried out with variations in the velocity of the mixture, namely with values of 0.2 m/s, 0.4 m/s, and 0.6 m/s.The fluids characteristics used in this study can be seen in Table 1. While, the oil-water inlet velocity as listed in Table 2, was calculated by equation 9 and equation 10. The experiment was carried out at an interfacial tension condition of 0.032 N.

$$Uw \;= Umix/[1 + \left(\frac{\alpha_o}{\alpha_w}\right)] \tag{9}$$

$$Uo \;= Uw.[\left(\frac{\alpha_o}{\alpha_w}\right)]$$

Where, $\alpha_o = 1 - \alpha_w$, Uw is the water inlet velocity (m/s), Uo is the oil inlet velocity (m/s), α_o is the mass fraction of the oil in the mixture and α_w is the mass fraction of the mixed calm water. In this study, the mass fraction between oil and water was set at 50:50.

Table 1 : Characteristics of fluids in the experiment

Fluid Type	**Viscosity (*Pa.s*)**	**Density (*kg/m*^{3})**
Water	0.001	1000
Lube Oil	0.107	890

Table 2 : Oil and water mixture input variables on fluent 6.2 software

Mixture speed (*m/s*)	**Inlet speed (*m/s*)**
0.2	0.1
0.4	0.2
0.6	0.3

The effect of the mixture velocity on the flow pattern and the distribution of the mixing level of oil and water will be analyzed at four test sample points in the test area vertically. The results of the numerical simulation will be plotted graphically the relationship between the volume of the water fraction and each observation sample point. In addition, the pressure distribution along the pipeline will also be analyzed.

3. RESULTS AND ANALYSIS

3.1. Flow pattern analysis

In this study, a two-phase flow of oil and water flowing in a horizontal pipe was carried out using Fluent 6.2. The results of numerical simulations in the test area, with a mixture velocity of 0.2 m/s, 0.4 m/s, and 0.6 m/s. The blue color in the graph indicates the oil phase and the red color indicates the water phase. The shape of the flow pattern at a mixture velocity of 0.2 m/s can be seen in Figure 2.a. In this condition, a Stratified Smooth (SS) flow is formed, which is a flow type with a smooth interface, without droplets and only in the small waves. Meanwhile, for a higher mixture velocity of 0.4 m/s the flow pattern formed is Stratified Wavy (SW) as shown in Figure 2(b). In this flow pattern, waves are formed in the interface area with a more larger amplitude waves than Stratified Smooth (SS). Oil droplets in water and water in oil occur in Stratified Wavy (SW) flow. When the mixture velocity is increased to 0.6 m/s the flow pattern formed is Stratified Mixed (SM) where there are water droplets in the oil and oil droplets in the water as shown in Figure 2.c. In this flow pattern, the interface becomes more wavy than Stratified Wavy (SW). The water phase forms droplets in the oil phase by large numbers, and the oil phase also forms droplets in the water phase by large numbers.

Based on Figure 2, it can be seen that the flow velocity of the mixture greatly affects the shape of the oil and water flow pattern in the horizontal pipe. Based on the simulation, it is found that the mixture velocity is low with the formed flow patterns are Stratified Smooth (SS) and Stratified Wavy (SW), while at a higher mixture velocity, the formed flow is Stratified Mixed (SM). This is thought to be related to the level of mixed flow turbulence at the Reynolds number where the higher velocity can effect to the higher flow turbulence level. This simulation is in agreement with research that has been carried out by several researchers experimentally [24].

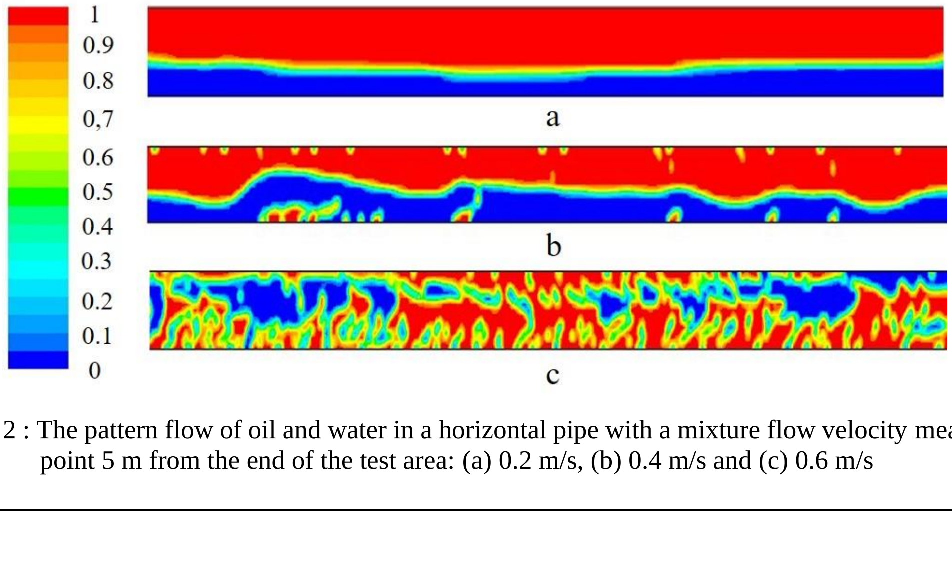


Figure 2 : The pattern flow of oil and water in a horizontal pipe with a mixture flow velocity measured at a point 5 m from the end of the test area: (a) 0.2 m/s, (b) 0.4 m/s and (c) 0.6 m/s

3.2. Oil and water mixing rate analysis

The analysis of the oil and water mixing rate aims at seeing the distribution of water in the oil pipe. So, it can observe the effect of injecting water into the oil flow which will be useful for consideration of pumping costs. At a mixture velocity of 0.2 m/s at observation points 1 and 2, it is seen that there is a flow turbulence. While at observation point 3 and observation point 4 the flow looks like Stratified Smooth (SS). This Stratified Smooth (SS) condition is considered as the actual characteristic of the flow at this velocity while the turbulence at the two observation points (1 and 2) occurs due to the mixing of oil and water in the input region and at the velocity of this mixture. It causes turbulence processes and fast flow patterns to be formed. The simulation results can be seen in Figure 3. (a-d) and Figure 4. (a-d).

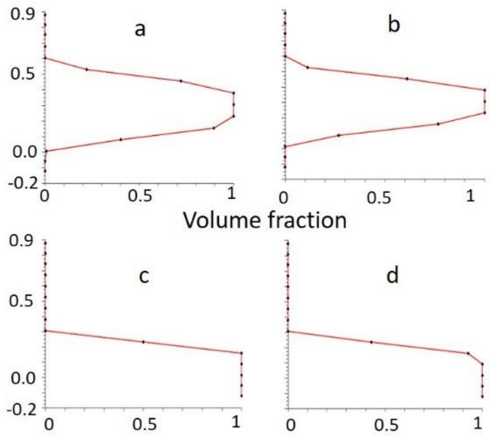


Figure 3 : The volume of the water mixture fraction at the point (a) 2.02 m, (b) 3.82 m, (c) 5 m and (d) 6.2 from the end of the test area

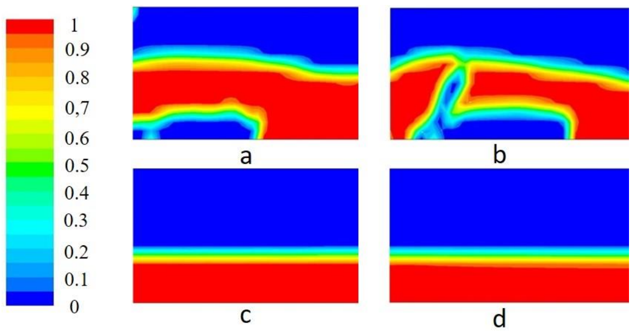


Figure 4: The flow pattern of the mixture velocity at the point (a) 2.02 m, (b) 3.82 m, (c) 5 m and (d) 6.2 from the end of the test area

At a mixture velocity of 0.4 m/s at observation points 1 and 2, it is seen that there is a larger turbulent flow than the flow pattern at a mixture velocity of 0.2 m/s at the same point. Meanwhile, at observation point 3 there is a flow transition as shown in Figure 5. (c). At the observation point, the 4 flow patterns have completely become Stratified Wavy (SW). This Stratified Wavy condition is a true characteristic of the flow at a mixture velocity of 0.4 m/s. The large flow turbulence at the first two observation points occurred because the mixing speed of oil and water at the input area was higher than the study with a mixture velocity of 0.2 m/s. While the transitional flow pattern (starting to wavy) at observation point 3 occurs due to the same thing as the first two observation points. The simulation results can be seen in Figure 5. (a-d) and Figure 6. (a-d).

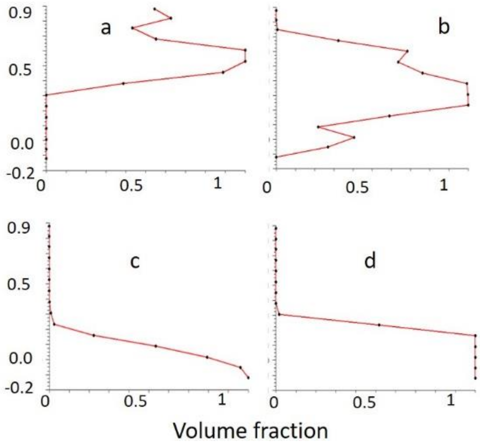


Figure 5 : (a) The volume of the water mixture fraction is 0.4 m/s at point; (a) 2.02 m, (b) 3.82 m, (c) 5 m (d) 6.2 m from the end of the test area

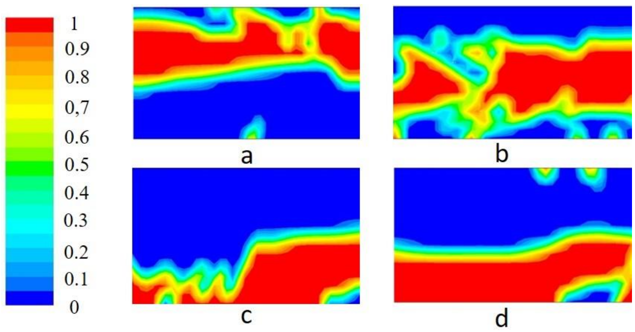


Figure 6 : (a) 0.4 m/s mixture velocity flow pattern at point; (a) 2.02 m, (b) 3.82 m, (c) 5 m (d) 6.2 m from the end of the test area

When the mixture velocity is increased to 0.6 m/s at observation point 1 there is no turbulence, but the oil is still at the bottom of the pipe. At the point observation 2, turbulence have started to occur in quite large numbers. Meanwhile, at observation point 3 and observation point 4, the flow pattern has become Stratified Mixed (SM) where there are water droplets in the oil and oil droplets in the water. This Stratified Mixed (SM) condition is a true characteristic of the flow at a speed of 0.6 m/s. At observation point 1, the oil is still at the bottom of the pipe, this happens due to the influence of the high mixture velocity. So, the actual formation process of the flow pattern at this mixture velocity takes a long time. The simulation results can be seen in Figure 7. (a-d) and Figure 8. (a-d).

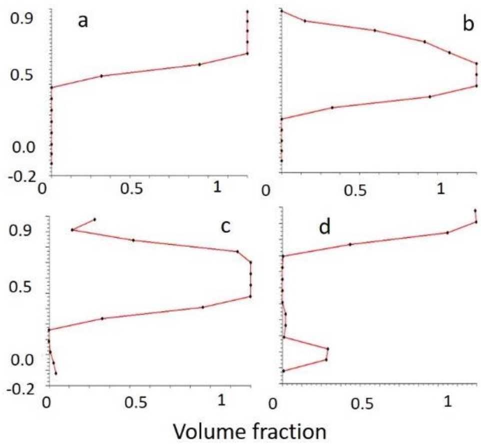


Figure 7 : (a) Volume of mixture fraction 0.6 m/s at point; (a) 2.02 m, (b) 3.82 m, (c) 5 m (d) 6.2 m from the end of the test area

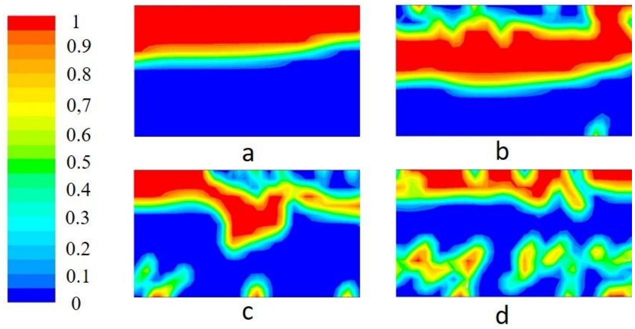


Figure 8 : (a) 0.6 m/s mixture flow pattern at point; (a) 2.02 m, (b) 3.82 m, (c) 5 m (d) 6.2 m from the end of the test area

Based on the simulation results, the higher speed of the mixture can effect to the higher level of oil-water mixing. Likewise with the flow pattern, the higher velocity of the mixture can effect to the formation of the oil-water flow pattern, it can takes a long time formation, while at the low velocity of the mixture, the formation of the oil and water flow pattern takes a relatively short time. Figure 7(a-d) and Figure 8(a-d), are the combined curves of the local water volume fraction for each observation sample point.

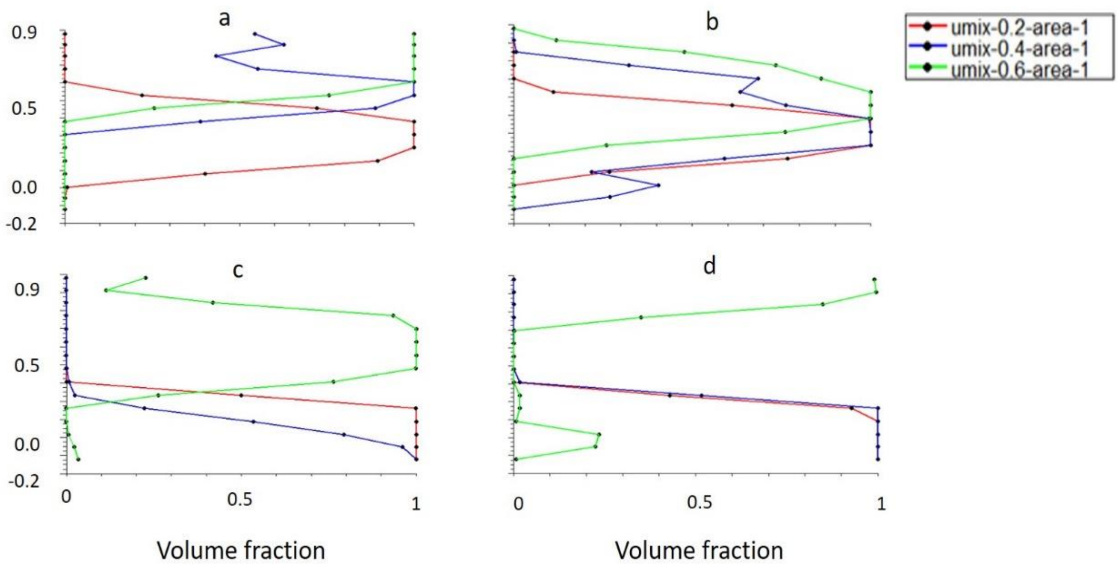


Figure 9 : Combined local water volume fraction with variations in the velocity of the mixture at (a) sample point 1, (b) sample point 2, (c) sample point 3 and (d) sample point 4.

3.3. Pressure distribution analysis

The pressure distribution along the test area is shown in Figure 10. Based on the figure, it can be seen that to obtain an outlet pressure equal to atmospheric pressure at a lower mixture velocity, a lower inlet pressure is also required. This is thought to be influenced by the increasing level of flow turbulence at high mixture speeds. So, the friction loss that occurs is also high even though the friction coefficient does not change much. Friction loss in this case is influenced by high flow rates and high mixing rates.

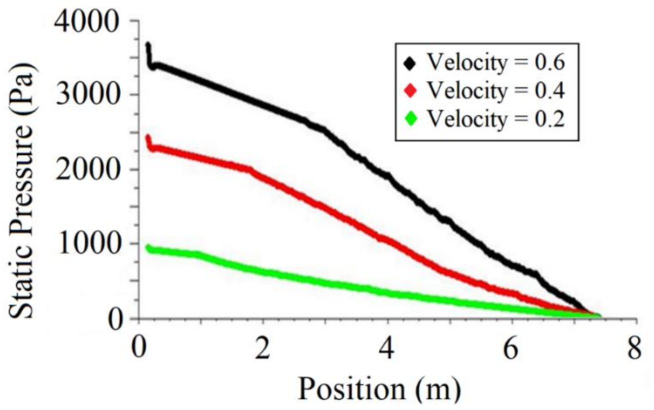


Figure 10 : Pressure distribution at different speeds: mixture 0.2 m/s (green line), 0.4 m/s (red line) and 0.6 m/s (black line)

4. CONCLUSION

Research on the effect of changes in velocity on the flow pattern and pressure distribution on the flow of the oil and water mixture that has been carried out with variations in the velocity of the mixture has yielded significant results. When the mixture velocity is 0.2 m/s, the flow pattern formed is Stratified Smooth (SS) which has a smooth interface with the characteristics of no droplets and only wave-shaped. At a higher mixture velocity of 0.4 m/s the flow pattern that appears is Stratified Wavy (SW) with a characteristic flow pattern, waves are formed at the interface area with more large waves amplitude than Stratified Smooth (SS) and droplets begin to appear. Meanwhile, when the mixture speed is increased to 0. The higher speed of the mixture will effect to the higher level of oil and water mixing. Likewise with the flow pattern formation process, the higher velocity of the mixture will effect to the formation of the oil and water flow pattern, it can takes a long time formation, while at the low velocity of the mixture, the formation of the oil and water flow pattern takes a relatively short time. What affects the pressure distribution is the relationship between the turbulence level of the mixed flow, the higher speed of the mixture will effect to the higher frictional loss occured. Friction loss in this case is influenced by high flow rates and high mixing rates.

ACKNOWLEDGEMENTS

We are grateful to Manufacturing Laboratory, Universitas Negeri Padang for the equipment used in this work.

DECLARATIONS

Author contribution

Nelvi Erizon: Writing - Original Draft, Writing -Review & Editing, Conceptualization, Investigation, Resources, Visualization. Jasman and Irzal: Conceptualization, Investigation, Supervision. Muhmammad Fikhri Aldio and Aprizal Saputra: Writing - Review & Editing, Resources, Visualization, Supervision. Chau Trung Tin: Data curation, Resources, Formal analysis

Funding statement

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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