Experimental Investigation of Air-Water-Oil Three-Phase Flow Patterns in Inclined Pipes

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Abstract

Experiments of air-water-oil three-phase flow pattern is investigated in a 20 mm diameter inclined pipe with a length of 6 m using a high speed digital camera. The superficial velocities are in the range of 0.25–3 m/s, 0.25–2.3 m/s, and 0.08–13 m/s for water, low viscosity oil and air, respectively. For describing flow patterns in three-phase flow, two parameters are considered: Interaction of gas and liquids mixture, and interaction of water and oil phases. The flow patterns for different pipe angles are discussed. Observed flow patterns are stratified-oil/water (or water/oil), wavy-stratified-o/w, bubbly-o/w, slug-o/w, plug-o/w, plug-stratified and annular-o/w. Major flow patterns for upward and downward pipe are slug-o/w and wavy-stratified-o/w, respectively. Also the effects of inclination angle varying from -45° to $+45^\circ$ and different oil cuts on flow patterns have been studied. The results show that by increasing the oil cut for different inclination angles, bubbly region extends and plug region becomes smaller.

Keywords: Air-water-oil three-phase flow, Flow patterns, Inclined pipe, Oil cut

Introduction

One of the most applications of three-phase flow is in petrochemical industry in which gas phase usually flows in combination with oil and water phases in transportation pipelines. Also flowing of two non-mixing liquids in which one of them is evaporating leads to a three-phase flow. Flows of two fluids such as oil and water with heating process appears frequently in industrial equipment [1]. Thus, studying flow characteristics such as flow patterns is a necessary issue for designing these equipment. Generally, three-phase flows are more complex than gas-liquid two-phase flows because of an additional phase. In fact, presence of three components due to different physical properties leads to a wide variety of flow patterns. Investigation on three-phase flow is a subject of interest for many researchers in recent years. Acikgoz, et al. [2] studied air-water-oil flow patterns in a horizontal pipe of small diameter (19 mm i.d.). They reported many different flow patterns such as water and oil-based wavy, plug, slug and stratifying-annular flow. Taitel et al. [3] calculated gas-water-oil holdups for stratified flow. They also developed flow pattern maps of air-water-oil three-phase flow for horizontal and inclined upward pipes. Regarding flow patterns, most of experimental

studies have been done for horizontal and vertical flows [1, 4-10]. The effect of injection of second immiscible liquid upon gas-liquid flow is an important issue because of its application in oil recovery. Stapelberg and Mewes [9] studied this injection effect and slug frequency (obtained by a laser) using 23.8 and 59 mm inner diameter pipes. They also extended existing two-phase flow pattern maps to three-phase flow. Chen and Guo [1] used air, water, and oil in a 39 mm inner diameter pipe to investigate three-phase flow. The authors reported front and top view pictures of the flow patterns. They classified the observed flows into more than four flow patterns. Spedding, et al. [8] reported flow regimes for horizontal air-water-oil flow for two different diameters. These test sections were 0.0259-m i.d., 2-m long and 0.0501-m i.d., 4.52-m long Perspex pipes. They developed a flow pattern map which gave flow pattern prediction of the various regimes by using a combination of dimensionless numbers for each phase as the mapping parameters. Bannwart, et al. [4] experimentally studied flow patterns for heavy oil-water-gas three-phase flow in horizontal and vertical 2.84-cm i.d. glass pipes with 5.40 m length. They reported that water flow rate had little effect on flow patterns in comparison to oil and air flow rates. They also concluded that core-annular flow is a very convenient transport method for heavy oil. This is because it increases the fraction of heavy oil transported and also reduces frictional pressure loss. Investigating three-phase flow pattern in different geometries is rarely studied and most of the researches are conducted on straight pipes. Pietrzak and Witczak [7] studied three-phase flow patterns in horizontal U-bends. They developed a new method for calculation of void fractions in the flow. This method can be used for estimating the void fraction of different phases for air-oil, air-water and air-water-oil flows through pipes with different geometries.

Adrian Wegmann, et al. [10] experimentally studied three-phase flows and flow maps in 5.6-mm and 7-mm inner diameter horizontal pipes. The test fluids were low viscosity paraffin, deionized water and air. They determined flow patterns by high speed photography. To illuminate the pipe, they applied laser induced fluorescence (LIF). They concluded that decreasing the pipe diameter changes flow pattern maps and behavior of transition boundaries.

Despite these researches on horizontal and vertical flows, few studies is done on inclined pipes [4, 11, 12]. Bannwart, et al. [4] presented flow patterns of three-phase flow inside an inclined (15°) 1 cm i.d. pipe. Their important observation was the occurrence of core-annular flow in all pipe sizes and inclinations due to its practical importance in transportation of heavy oil. Huang, et al. [11] studied on flow pattern maps of air-water-oil three-phase flow in an inclinable pipe with length of 10 m and inner diameter of 40 mm. They identified different flow patterns for different fluid volume fractions by using a high-speed camera and a single-wire capacitance probe to measure the water layer height in the pipe. They concluded that water fraction is a secondary factor to determine flow patterns in comparison with pipe structures and superficial velocities.

Among these works on horizontal and inclined pipeline, there are some researches on large diameter pipes [5, 12]. Hewitt, et al. [5] conducted experiments using a high

pressure multi-phase flow facility. They used a video camera and a stroboscopic lighting for flow visualization in a test section of 78mm inner diameter and 38m length. They measured hold-up by quick-closing valves and dual energy gamma densitometry. Oddie, et al. [12] experimentally studied three-phase flow in a 11-m long, 15-cm diameter inclinable pipe. They used kerosene, tap water and nitrogen as three phases. The pipe inclination was varied from 0° (vertical) to 92°. Although they studied different inclination angles in their experiments, the flow rates of phases (especially gas phase) were not wide enough to observe different possible flow patterns. They observed bubble, churn, elongated-bubble, slug, and stratified/stratified-wavy flows for water–gas and oil–water–gas flows. Table 1 summarizes the related works on the flow pattern maps of three-phase flow.

Table 1
Air-Water-Oil three-phase flow experimental investigations

Author	Working Fluids	Inclination (deg)	Diameter (mm)	Test section length (m)
Acikgoz, et al. (1992)	Air-Water-Oil	Horizontal	19	1.83
Stapelberg and Mewes (1994)	Air-Water-Oil	Horizontal	23.8, 59	5
Hewitt, et al. (1995)	Air-Water-Oil	Horizontal	78	38
Chen and Guo (1999)	Air-Water-Oil	Horizontal	39	4.32
Nakanishi et al. (1999)	Air-Water-Oil	Horizontal	16	-
Oddie, et al. (2003)	Nitrogen-Tap water-Kerosene	0° (vertical) to 92°	150	10.9
Spedding, et al. (2005)	Air-Water-Oil	Horizontal	25.9, 50.1	2, 4.52
Adrian Wegmann, et al. (2007)	Air-Water-Low viscosity paraffin	Horizontal	5.6, 7	5
Bannwart, et al. (2009)	Air-Water-Heavy oil	Horizontal, Vertical	28.4	5.4
Bannwart, et al. (2009)	Air-Water-Heavy oil	15° from Horizontal	10	1
Pietrzak and Witczak (2013)	Air-Water-Oil	Horizontal U-bends	16, 22, 30	1.5, 3.5, 3.5
Shanfang Huang, et al. (2013)	Air-Water-Oil	2°–30°	40	10

As it is clear in recent publications, previous works mostly investigated horizontal three-phase flow. Thus, there remains a need for a comprehensive experimental work on gas-liquid-liquid three-phase flow patterns, especially in inclined upward and downward pipes. In addition, few researchers have studied effect of liquids volume fraction on flow patterns. In the present study, flow patterns of air-water-oil three-phase flow are investigated experimentally at horizontal, slight and the highly inclined upward and downward pipe. The inclination angles of pipe are in the range of -45° to $+45^\circ$. Three different oil cuts of 25%, 50% and 75% are investigated for each inclination angle. At first the flow pattern maps for different inclination angles are presented. In the second section, the effects of inclination angle and oil cut on flow patterns and transition boundaries are discussed.

Nomenclature		Subscripts	
A	Area, m ²	a	Air
d	Bubble diameter, m	B	Buoyancy
D	Pipe diameter, m	Ba	Axial component of buoyancy force
F	Force, N	Bl	Bubble
L	Length, m	Br	Radial component of buoyancy force
r	Distance to the pipe wall	c	Continuous phase
U	Velocity, m/s	D	Drag force
V	Volume, m ³	l	Liquid
Greek symbols		L	Lift force
α	Fraction of dispersed phase in liquid mixture	m	Mixture
ε	Liquid cut	o	Oil
η	Viscosity, mPa.s	sa	Superficial air
θ	Inclination angle, °	so	Superficial oil
ρ	Density, kg m ⁻³	sw	Superficial water
		w	Water

Theoretical analysis

Different parameters affect three-phase flow pattern that make its analysis much more elaborate than two-phase flow. Main parameters are: fluid properties, fluid flow rates and structure parameters. Therefore, some simplifying assumptions are considered due to complexity of three-phase flow. In the present study working fluids are air, water and oil which their properties are way different. For instance, the oil and water density are relatively a thousand times greater than air density so air-water-oil three-phase flow can be simplified into gas-liquid two-phase flow [13]. Despite this assumption, the simplified flow is still more complex than gas-water two-phase flow. Fluid properties inside the liquid mixture depend on water and oil superficial velocities and fraction of dispersed phase. For instance, viscosity of liquid mixture is defined by [11]:

$$\eta_m = \eta_c(1 + \alpha) \quad (1)$$

Where η_m and η_c are mixture and continuous phase viscosity, respectively and α is the fraction of the dispersed phase. Density of liquid mixture is defined in a same way:

$$\rho_m = \rho_c(1 + \alpha) \quad (2)$$

Where ρ_m and ρ_c are mixture and continuous phase density, respectively and α is the fraction of the dispersed phase. Equations (1) and (2) are applicable for liquid-liquid dispersed flows. Velocity of phases and volume fraction have an effect on both fluid mixture properties and flow patterns of three-phase flow. Generally, when any of the phases reaches to high superficial velocity, the flow pattern tends to act as homogeneous flow. However, at low superficial velocities the flow pattern tends to have the separated flow regime.

Structure parameter like the inclination angle of the pipe is another parameter which has an effect on flow patterns of three-phase flow. It affects both mixing of liquid phases (oil and water) and flow pattern of air-liquid two-phase flow as a simplified model of three-phase flow. Figure 1 shows free body and the force diagram on an oil droplet in the upward inclined pipe. An oil bubble will be lopsided because of buoyancy force. The gravitational acceleration can be divided into two directions, along and across to the pipeline. The component which is along the pipeline causes a buoyancy force on oil droplet, which is calculated as follows:

$$F_B = (\rho_w - \rho_o)Vg \sin \theta \quad (3)$$

Figure 1 Force analysis for an oil drop in an inclined pipe

Due to higher viscosity of oil in comparison with water, following equation can be implied [11]:

$$-\left[\frac{dU}{dr} \right]_o > -\left[\frac{dU}{dr} \right]_w \quad (4)$$

According to these two effects (the buoyancy and the friction), oil droplet and water tend to rotate clockwise and anticlockwise at the interface, respectively. The coupling effect will enhance the mixing of oil and water. As a result, dispersed phase will be dispersed into continuous phase [11]. Dispersion of one phase into another one depends on their flow rates. This means according to water and oil flow rates the dispersed phase and continuous phase are distinguishable from each other. The changing of continuous phase from water to oil or vice versa defines as phase inversion phenomenon. For the oil cuts higher than 0.7 the continuous phase in liquid mixture will change from water to oil [1].

As said before, air-water-oil three-phase flow can be simplified to two-phase flow of air-liquid. By using two-fluid model, buoyancy force F_B , the drag force F_D and the lift force F_L could be considered for air bubbles in inclined pipe (see Fig. 2) [14]. In inclined pipe the buoyancy force can be split into two directions: a radial component normal to the

pipe axis F_{Br} and an axial component parallel to the pipe axis F_{Ba} . Radial component tends to keep the dispersed bubbles at the upper half of the pipe cross-section which enhances the transition to slug flow. On the other hand, the lift force tends to disperse the bubbles and keep the bubbly flow pattern. Generally, for inclined pipe the gas phase is in the upper part of the cross-section except at high superficial velocities of air (greater than 10 m/s) which is defined as annular flow pattern.

$$F_B = \frac{1}{6} \pi d_{Bl}^3 (\rho_l - \rho_g) g$$

$$F_D = C_W \rho_l \frac{W_0^2 \pi}{2} \frac{d_{Bl}^2}{4}$$

$$F_L = C_L \rho_l \frac{(W_0 \sin \theta)^2}{2} A_n$$

$$C_L = 0.4 - 1.2 [14]$$

$$A_n = \frac{\pi}{4} (\gamma d_{Bl})^2 \cos 45^\circ$$

$$\gamma = 1.1 - 1.5 [14]$$

Figure 2 Forces acting on air bubbles in an inclined pipe

To sum up, fluid velocities and their fraction, besides structure parameter like inclination angle, may cause different flow patterns of three-phase flow in inclined and horizontal pipes. Generally, at high superficial velocities of phases (especially gas phase) flow pattern is homogeneous. However, at lower superficial velocity flow regime tends to be separated and volume fraction and structure parameters like inclination angle play an important role to determine air-water-oil three-phase flow pattern.

Experimental setup

1. Test rig

The experiments of this study are carried out in an air-water-oil three-phase flow loop as shown in Fig. 3. The water and oil are transported from their main tank with the centrifugal pumps. There are two shock absorbers which are mounted at the inlet and outlet of the each pump to prevent exerting vibration to the system. The gas phase is injected by a compressor supplied by the local air. The water and oil flow rates are adjusted by two globe valves and are measured by the calibrated rotameters with relative accuracy of 2% RD (accuracy as a percentage of reading). Two bypass lines are used in the test loop to control water and oil flow rates. The compressed air flow rates are controlled and calculated by three rotameters with relative accuracy of 4% RD. The first one is used for low flow rates with a maximum volume flow rate of $1 \text{ m}^3/\text{hr}$. The last one is used for high flow rates with a maximum volume flow rate of $40 \text{ m}^3/\text{hr}$. First, water and air are mixed together via a 45° T junction. Second, oil phase is injected to the

mixture via another 45° T junction placed at the inlet of the pipe (See Fig. 3). The test section has a 6 m long and 20 mm inner diameter transparent acrylic glass pipe in order to visually observe the three-phase flow patterns. The water, oil and air moves forward through the test section and discharged into the separation tank at the end of the main pipe. Air discharged into the atmosphere. Water and oil are stored in a large separation tank with a capacity of 2000 L. because of the difference in density, oil occupied the upper part of the tank while water remains at the lower part. The water is discharged from the separation tank to the sewerage while the oil is pumped to the main oil storage tank with a capacity of 500 L and will be used in the next experiment. The oil and water temperatures maintained constant in each experiment. A swing mechanism is designed for changing the inclination angle of the pipe in the range of -45° to $+45^\circ$. A high speed camera with 1200 fps is used for flow patterns identification at the distance of 4m of inlet of the pipe. The camera is located at the 200D from the entrance of the test section in order to consider steady state flow. Steady flow is defined as flow situation where the pressure drop at different locations remains constant. In this experiment the pressure drop is measured by a pair of calibrated pressure transmitters with an accuracy of 0.3% of full scale.

Figure 3 Schematic of experimental setup

2. Test procedure

To investigate air-water-oil flow in each inclination angle, first the water, oil and air flow rates are adjusted and flow is allowed to reach steady situation. This will happen when the time-averaged measures of pressure transducers remain relatively constant. Secondly the pictures of flow patterns are taken by a high speed camera. The experiments are started with horizontal flow and then three-phase flow is investigated in an upward and downward flows from inclination of -45° to $+45^\circ$. In the present study, the ratio of the oil flow rate to liquid flow rate is defined as oil cut parameter which is shown by ε_o .

$$\varepsilon_o = \frac{Q_o}{Q_o + Q_w} \quad (5)$$

Table 2
Experimental test matrix

$\varepsilon_o = 0.25$	$U_{sa} \left(\frac{m}{s}\right)$	$U_{so} \left(\frac{m}{s}\right)$	0.17	0.26	0.35	0.44	0.53	0.61	0.79	0.88	0.97
		$U_{sw} \left(\frac{m}{s}\right)$	0.53	0.79	1.06	1.32	1.59	1.85	2.38	2.65	2.91
		0.08	✓	✓	✓	✓	✓	✓	✓	✓	✓
		0.70	✓	✓	✓	✓	✓	✓	✓	✓	✓
		0.88	✓	✓	✓	✓	✓	✓	✓	✓	✓
		2.65	✓	✓	✓	✓	✓	✓	✓	✓	✓
		4.42	✓	✓	✓	✓	✓	✓	✓	✓	✓
		7.69	✓	✓	✓	✓	✓	✓	✓	✓	✓
		13.27	✓	✓	✓	✓	✓				
$\varepsilon_o = 0.5$	$U_{sa} \left(\frac{m}{s}\right)$	$U_{so} \left(\frac{m}{s}\right)$	0.26	0.53	0.79	1.06	1.32	1.59	1.85	2.12	2.38
		$U_{sw} \left(\frac{m}{s}\right)$	0.26	0.53	0.79	1.06	1.32	1.59	1.85	2.12	2.38
		0.08	✓	✓	✓	✓	✓	✓	✓	✓	
		0.70	✓	✓	✓	✓	✓	✓	✓	✓	
		0.88	✓	✓	✓	✓	✓	✓	✓	✓	
		2.65	✓	✓	✓	✓	✓	✓	✓	✓	
		4.42	✓	✓	✓	✓	✓	✓	✓	✓	
		7.69	✓	✓	✓	✓	✓	✓	✓	✓	
		13.27	✓	✓	✓	✓	✓				
$\varepsilon_o = 0.75$	$U_{sa} \left(\frac{m}{s}\right)$	$U_{so} \left(\frac{m}{s}\right)$	0.79	1.06	1.32	1.59	1.85				
		$U_{sw} \left(\frac{m}{s}\right)$	0.26	0.35	0.44	0.53	0.61				
		0.08	✓	✓	✓	✓	✓				
		0.70	✓	✓	✓	✓	✓				
		0.88	✓	✓	✓	✓	✓				
		2.65	✓	✓	✓	✓	✓				
		4.42	✓	✓	✓	✓	✓				
		7.69	✓	✓	✓	✓	✓				
		13.27	✓	✓	✓	✓	✓				

One of the main purposes of the present work is to study the effect of oil cut changes on three-phase flow patterns. Tests are conducted in three oil cuts and nine inclination angles to determine flow patterns in various angles and superficial velocities. The

inclination angles are 0° , $\pm 5^\circ$, $\pm 15^\circ$, $\pm 30^\circ$ and $\pm 45^\circ$. To construct the three phase flow maps, in each inclination angle oil cut is changed in three values which are 0.25, 0.5 and 0.75. To observe different flow patterns, oil, water and air superficial velocities varied from 0.17–2.12 m/s, 0.25–3.25 m/s and 0.08–13.27 m/s, respectively. Test sequences for air-water-oil three-phase flow are shown in Table 2. These sequences were repeated for each inclination angle of the pipe.

In the room temperature, fluid properties and flow conditions are given in Table 3.

Table 3

Three-phase flow properties and flow conditions

Property	Range	
Pressure (bar)	1–2	
Temperature ($^\circ\text{C}$)	25	
Inclination (degree)	0, ± 5 , ± 15 , ± 30 , ± 45	
Oil superficial velocity (m/s)	0.17–2.12	
Water superficial velocity (m/s)	0.25–3.25	
Air superficial velocity (m/s)	0.08–13.27	
Phases' properties	Density (kg/m^3)	Viscosity (mPa.s)
Oil	840	4.5
Water	998	1.0
Air	1.2–7.36	0.018

Results and discussion

In this section, the observed air-water-oil three-phase flow patterns in the experiments are described and the related photos are presented. Moreover, flow pattern maps are obtained for oil cut of 25% in different inclination angles. Finally, the effects of inclination angle and oil cut on flow patterns are discussed.

Flow patterns

Flow pattern detection is a significant issue for designing multi-phase flow systems. There are several literatures which used different techniques to determine flow patterns in two-phase flows. In oil-water two-phase flows, Hanafizadeh, et al. [15, 16] e.g. used visual technique to determine flow patterns. They distinguished seven different flow patterns in the same ranges of oil and water superficial velocities as the present work. This technique also has been used for gas-liquid two-phase flow detection in the airlift pump. Three main flow regimes namely slug, churn and annular were visually detected in vertical pipe [17]. In addition, in recent years some studies have been done to develop new methods of distinguishing flow regime maps in gas-liquid two-phase flows which can be developed for flow pattern detection in gas-liquid-liquid three-phase flows. As said before, this needs some simplifying assumptions to be considered. Hanafizadeh, et al. [18] studied a new flow regime map for gas-liquid two-phase flow regime detection in a vertical pipe based on interpretation of transient flow pressure signals and utilizing neural networks.

In the present study, air-water-oil flow patterns have been named corresponding to the method of Hewitt et al. [13] and Huang et al. [11]. To simplify the description of air-

water-oil three-phase flow, at first it is better to consider it as gas-mixture liquid two-phase flow, and then the interaction inside the liquid mixture of oil and water is considered. For instance, stratified-oil in water (ST-O/W) means that gas-liquid is stratified, and oil is completely dispersed into water. This flow regime looks similar to a gas-liquid two-phase stratified flow, except for the dispersed oil droplets. For the case of oil as a continuous phase, describing three-phase flow patterns conform to this rule. However, for describing the interaction inside the liquid mixture of oil and water the second part of the name should change to water in oil (W/O). Seven typical three-phase flow patterns observed in present experiments for horizontal or inclined pipes are shown in Figure 4. In these flow patterns, water is continuous phase and oil phase is completely dispersed in it, i.e. water flow rate to oil flow rate ratio is $\frac{3}{1}$.

The observed flow patterns are: (a) Bubbly-oil in water (Bb-O/W), (b) Stratified-oil in water (ST-O/W), (c) Plug-stratified (PG-ST), (d) Plug-oil in water (PG-O/W), (e) Slug-oil in water (SG-O/W), (f) Wavy stratified-oil in water (WST-O/W), and (g) Annular-oil in water (AN-O/W).

Flow Pattern	Photo
Bubbly – O/W	<p>Oil/Water</p>
Plug – Stratified	<p>Oil Air Water</p>
Plug – Dispersed O/W	<p>Air Oil/Water</p>
Slug – O/W	<p>Air Oil/Water</p>

Figure 4 Photos of different air-water-oil three-phase flow patterns with oil cut of 25% in the 20 mm horizontal and inclined pipe

Horizontal flow

Three oil cuts of 25%, 50% and 75% were investigated for horizontal pipeline and at each oil cut air superficial velocity was in the range of 0.08–13 m/s. Generally, six different flow patterns were observed at horizontal pipe with oil cut of 25%. These flow patterns are: bubbly-o/w, slug-o/w, stratified-o/w, wavy stratified-o/w, plug-dispersed o/w and annular-o/w flow as shown in Fig. 4.

At low oil, water and air superficial velocities plug-o/w flow was observed in horizontal pipe. When air superficial velocity increases, at constant oil and water superficial velocity, plug-o/w flow converts to slug-o/w flow. The further increase in air superficial velocity results in converting slug-o/w flow to stratified-o/w and then wavy stratified-o/w flow. Generally, wavy stratified flow evolves from slug flow by increasing gas flow rate. At high oil and water superficial velocities and low air superficial velocity bubbly-o/w was identified. Also at high air superficial velocities, annular-o/w flow was observed in horizontal pipe. By increasing gas flow rate, annular flow evolves from wavy stratified flow. Generally, annular-o/w flow occurred at air superficial velocities greater than 10 m/s.

The experimental flow patterns map of air-water-oil three-phase flow in a horizontal pipe is shown in Fig. 5. In the present map superficial velocities of water and air (U_{sw} and U_{sa}) correspond to the x and y axis, respectively. Air and water superficial velocities are in the range of 0.08–13 m/s and 0.5–3.25 m/s, respectively. Slug-o/w and wavy-

stratified-o/w flows were observed in a wide range of water and air superficial velocities in horizontal pipeline.

Figure 5 Experimental flow patterns map of air-water-oil three-phase flow with oil cut of 25% in horizontal pipe

Among the experimental studies, listed in Table 1, there is the flow map of Acikgoz et al. [2], which is cited in almost all other literatures. **Figure 6.** shows the comparison of the experimental data of present study with the flow map of Acikgoz et al. [2] for an oil superficial velocity of 0.09 m/s in horizontal pipe. They used a 19 mm inner diameter pipe and defined 10 flow structures. The definitions are given in Table 4.

Figure 6 Comparison of flow patterns map between present study and Ackigoz et al. [2] for horizontal pipe

Table 4 Air-water-oil three-phase flow classification according to Acikgoz et al. [2]

Region	Flow Regime
1	Oil-based dispersed plug flow
2	Oil-based dispersed slug flow
3	Oil-based dispersed stratified/wavy flow
4	Oil-based separated stratified/wavy flow
5	Oil-based separated wavy stratifying-annular flow
6	Oil-based separated/dispersed stratifying-annular flow
7	Water-based dispersed slug
8	Water-based dispersed stratified/wavy flow
9	Water-based separated/dispersed incipient stratifying-annular flow
10	Water-based dispersed stratifying-annular flow

Figure 6 shows that regions 7 and 9 match with the experimental results obtained in present study. That means annular-o/w points are completely in region 9 which represents water-based annular flow according to flow map of Acikgoz et al. [2]. Also stratified-o/w and wavy-stratified-o/w points are in region 8 which refers to water-based dispersed stratified/wavy flow. Some of slug-o/w and plug-o/w points are in region 7 which refers to water-based slug flow. There are some differences between experimental results and flow map of Acikgoz et al. [2] at some points. These disagreements result from different test conditions between the present study and Acikgoz's work, such as difference in oil viscosity or range of superficial velocities.

Inclined upward flows

In present study, four inclination angles of $+5^\circ$, $+15^\circ$, $+30^\circ$ and $+45^\circ$ were considered to investigate air-water-oil flows in upward pipe. At each inclination angle three oil cuts of 25%, 50% and 75% were investigated and at each oil cut air superficial velocity was in the range of 0.08–13 m/s. The flow pattern maps for inclined upward flows with oil cut of 25% are shown in figures 7 – 10.

Figure 7 Experimental flow patterns map of air-water-oil three-phase flow with oil cut of 25% in pipe with inclination angle of $+5^\circ$.

By increasing the inclination angle from horizontal direction to $+5^\circ$, transition boundary between plug-o/w and bubbly-o/w flow moves to the right side of the map a bit. It means that at low air superficial velocities and high water superficial velocities less bubbly-o/w patterns were observed in $+5^\circ$ upward pipe. The transition boundary between slug-o/w and wavy stratified-o/w regimes moves to top side and between slug-o/w and plug-o/w regimes moves to the right side of the map a bit. This phenomenon means that by increasing inclination angle up to $+5^\circ$ slug-o/w regime zone has been expanded.

Increasing the inclination angle up to $+5^\circ$ leads to change of flow pattern type at some points. For instance, plug-o/w flow has been replaced by slug-o/w flow in some points and also at higher air superficial velocities wavy stratified-o/w flow has been replaced by slug-o/w flow in some points. By increasing the inclination angle the transition boundary between annular-o/w and wavy stratified-o/w flow remains almost unchanged.

Figure 8 Experimental flow patterns map of air-water-oil three-phase flow with oil cut of 25% in pipe with inclination angle of $+15^\circ$.

Further increase in inclination angle up to $+15^\circ$ results in movement of transition boundary between bubbly-o/w and plug-o/w flow to the right side more than $+5^\circ$ inclined pipe. It means that some other points which experienced plug-o/w flow in $+5^\circ$ pipe have been replaced by slug-o/w flow in $+15^\circ$ upward pipe. In addition, transition boundary between stratified and non-stratified flow patterns has not moved. However, at one point wavy stratified-o/w flow has been replaced by stratified-o/w flow. This smoothening in stratified flow can be due to a gravitational force, which is considered as a resistant force in upward flows. By further increase in inclination angle of the pipe, the transition boundary between bubbly-o/w and plug-o/w flows and between slug-o/w and plug-o/w flows shift to the left side of the map. Also at some points, in high air superficial velocities, wavy stratified-o/w flow changes to slug-o/w flow. Thus, transition boundary between wavy stratified-o/w and slug-o/w flow moves horizontally and slug-o/w flow regime has occupied most of the upper side areas of the flow map. At this inclination angle, the number of non-stratified flows (slug-o/w and plug-o/w flow patterns) has increased and the number of wavy stratified-o/w flows has decreased.

Figure 9 Experimental flow patterns map of air-water-oil three-phase flow with oil cut of 25% in pipe with inclination angle of $+30^\circ$.

Slug-o/w flow pattern approximately has occupied all parts of the flow pattern map in inclination angle of $+45^\circ$. The transition boundary between wavy stratified-o/w flow and slug-o/w flow has not moved vertically. However, in horizontal direction some points of stratified-o/w flow has been replaced by slug-o/w flow. It is observed that at high liquids superficial velocities some points of plug-o/w flow has been changed to slug-o/w and bubbly-o/w flows. Generally, increasing inclination angle has a little effect on transition boundary between annular-o/w and wavy stratified-o/w flows, i.e. annular flow boundary is approximately fixed in upward flows. Furthermore, for upward flows annular-o/w flow occurs at air superficial velocities greater than 10 m/s.

Figure 10 Experimental flow patterns map of air-water-oil three-phase flow with oil cut of 25% in pipe with inclination angle of +45°.

Inclined downward flows

For investigating air-water-oil three-phase flows in downward pipe four inclination angles of -5°, -15°, -30° and -45° were considered. Like upward flows, at each inclination angle three oil cuts of 25%, 50% and 75% were investigated. **Figures 11-14** show the flow pattern maps of air-water-oil three-phase flow with oil cut of 25% in downward pipelines.

Figure 11 Experimental flow patterns map of air-water-oil three-phase flow with oil cut of 25% in pipe with inclination angle of -5°

The results show that at high superficial velocities of water, some points of slug-o/w flow has been replaced by plug-o/w flow, and vice versa. This is the major change in flow map of -5° downward pipe in comparison with horizontal pipe and other transition boundaries has not changed. For -15° pipe, at low superficial velocities of air and water, plug-o/w flows are converted to stratified-o/w flows at some points. Also at water superficial velocities greater than 2 m/s, some points of plug-o/w flow are replaced by bubbly-o/w flow. These changes results in a smaller region of plug-o/w flow for -15° pipeline in comparison with -5° one.

Major changes in inclination angle of -15° have occurred to wavy stratified-o/w flow region. Generally, stratified region (stratified-o/w and wavy stratified-o/w) has been expanded by decreasing the inclination angle.

Figure 12 Experimental flow patterns map of air-water-oil three-phase flow with oil cut of 25% in pipe with inclination angle of -15°

By decreasing the inclination angle to -30° the transition boundary between wavy stratified-o/w and slug-o/w flow areas moves to the right side of the map. Also at high water superficial velocities the transition boundary between slug-o/w and plug-o/w flow shifts a bit to the left side. These observations results in a small region of slug-o/w flow and bigger region of stratified flow patterns (stratified-o/w and wavy stratified-o/w). The transition boundary between bubbly-o/w and plug-o/w flows remains unchanged comparing to -15° pipeline.

Figure 13 Experimental flow patterns map of air-water-oil three-phase flow with an oil cut of 25% in pipe with inclination angle of -30°

Further decrease in pipe angle to -45° moves the transition boundary between wavy stratified-o/w and slug-o/w flow further to the right side of the map. At low superficial velocities of air and water stratified-o/w flows were observed and flow regime became smoother and the plug-o/w flow was disappeared in this range of superficial velocities. It means that the transition boundary between stratified-o/w and plug-o/w has been disappeared. Also at low superficial velocities of air and high superficial velocities of water bubbly-o/w region has been extended in comparison with -30° . It is concluded from these observations that slug-o/w and plug-o/w regions have occupied small part of the flow map and the major part of the flow pattern map belongs to bubbly-o/w and stratified patterns (stratified-o/w and wavy stratified-o/w). Generally, for downward flows annular-o/w flow occurs at air superficial velocities greater than almost 10 m/s.

Figure 14 Experimental flow patterns map of air-water-oil three-phase flow with an oil cut of 25% in pipe with an inclination angle of -45° .

Effect of inclination angle on flow patterns

In order to investigate the effect of pipe inclination angle on flow patterns, air-water-oil three-phase flow maps in different inclination angles are compared with each other and the movement of transition boundaries is discussed. **Figure 15** shows a comparison between flow pattern maps in inclination angles of 0° , $+15^\circ$ and $+45^\circ$. Increasing the inclination angle of the pipe from 0° to $+15^\circ$ transfers the transition boundary between wavy stratified-o/w and slug-o/w flows to the top side of the map. Also transition boundaries between slug-o/w and plug-o/w flows and between plug-o/w and bubbly-o/w flows shift to the right side of the flow patterns map. Further increase in inclination angle of the pipe results in the movement of the transition boundary between wavy stratified-o/w and slug-o/w flows to the left side and between plug-o/w and bubbly-o/w flows to the lower superficial velocities of water. As a result, the slug-o/w flow region occupies the major part of the flow map.

Figure 15 Comparison of flow pattern maps for air-water-oil three-phase flow with an oil cut of 25% in horizontal, +15° and +45° upward pipe

According to Fig. 16, for superficial velocities of air, by increasing the inclination angle the flow pattern converts from wavy stratified -o/w flow to slug-o/w flow. This proves the idea that by increasing the angle dominant flow tends to slug pattern. Fig. 17 demonstrates that increment in inclination angle of pipeline enhances the chances of developing plug flow from bubbly pattern. In general words, plug flow and slug flow have become dominant patterns due to increase in inclination angle.

Figure 16 change of flow patterns for oil cut of 25 % in downward pipe, $U_o=0.35$ m/s, $U_w=1.06$ m/s, $U_A=4.42$ m/s: (a) horizontal pipe, wavy stratified-o/w (b) +15° pipe, slug-o/w (c) +45° pipe, slug -o/w

Figure 17 change of flow patterns for oil cut of 25 % in downward pipe, $U_o=0.61$ m/s, $U_w=1.85$ m/s, $U_A=0.088$ m/s: (a) horizontal pipe, bubbly-o/w (b) +15° pipe, plug-o/w (c) +45° pipe, plug -o/w

Figure 18 shows a comparison between flow pattern maps in the pipes with inclination angles of 0° , -15° and -45° . The results show that by decreasing the inclination angle to -15° transition boundary between wavy stratified-o/w and slug-o/w flows moves vertically, specifically at lower superficial velocities of water. This movement results in more stratified pattern (wavy stratified-o/w and stratified-o/w) in -15° pipeline. In addition, transition boundaries between plug-o/w and slug-o/w flows and between bubbly-o/w and plug-o/w flows move to the right and left side of the flow map, respectively. Further decreasing of inclination angle shifts transition boundary between stratified pattern and slug-o/w flow to the right side of the map. In addition, the transition boundary between bubbly-o/w and plug-o/w flow moves further to the left side of the flow pattern map. It can be concluded that by decreasing inclination angle stratified patterns (wavy stratified-o/w and stratified-o/w flows) and bubbly-o/w flow have become dominant flows of the flow pattern map.

Figure 18 Comparison of flow pattern maps for air-water-oil three-phase flow with oil cut of 25% in horizontal, -15° and -45° downward pipe

Figures 19 and 20 show the change of flow patterns by the effect of inclination angle for downward pipe. According to the Fig. 19, for a specific oil, water, and air superficial velocity, by decreasing the inclination angle the flow pattern converts from slug-o/w flow to wavy stratified-o/w flow. By decreasing the angle from the horizontal direction to -15° , slug pattern gradually changes to stratified pattern. Finally, at inclination of -45° , wavy stratified pattern occurs. In addition, according to Fig. 20, decreasing the inclination angle converts the plug flow to bubbly flow. In sum, wavy stratified pattern and bubbly pattern extend due to reduction of inclination angle

Figure 19 change of flow patterns for an oil cut of 25 % in downward pipe, $U_o=0.35$ m/s, $U_w=1.06$ m/s, $U_a=0.88$ m/s:
(a) horizontal pipe, slug-o/w (b) -15° pipe, slug/o/w (c) -45° pipe, wavy stratified-o/w

Figure 20 change of flow patterns for an oil cut of 25 % in downward pipe, $U_o=0.79$ m/s, $U_w=2.38$ m/s, $U_A=0.88$ m/s:
 (a) horizontal pipe, plug-o/w (b) -15° pipe, bubbly-o/w (c) -45° pipe, bubbly-o/w

Effect of volume fraction of liquid phases on flow patterns

To investigate the effect of volume fraction on air-water-oil three-phase flow patterns, three oil cuts of 25%, 50% and 75% were studied for each inclination angle. For each oil cut, air superficial velocity was in the range of 0.08 to 13.27 m/s.

Figure 21 shows a comparison between flow pattern maps for oil cuts of 25%, 50% and 75% in horizontal pipe. Increasing the oil cut transfers the transition boundaries between wavy stratified-o/w and slug-o/w flows and between slug-o/w and plug-o/w flows to the left and right side of the flow map, respectively. This phenomenon results in a bigger region of slug-o/w flow. Moreover, increasing the oil cut moves the transition boundary between bubbly-o/w and plug-o/w flows to the left side of the map, i.e. the bubbly-o/w region extends.

A further increase in the oil cut up to 75% moves the transition boundary between wavy stratified-o/w and slug-o/w flows vertically to the top side and between slug-o/w flow and plug-o/w flow to the bottom and a bit right side of the flow map. As said before, this leads to a bigger slug-o/w region. The results also show a bigger bubbly-o/w region and smaller area of plug-o/w flow for higher oil cuts. The transition boundary between annular-o/w and wavy stratified-o/w flows is almost unchanged.

Figure 21 Comparison of flow pattern maps for air-water-oil three-phase flow in 25%, 50% and 75% oil cuts for horizontal pipe

A comparison between flow pattern maps for an oil cut of 25% and 50% in pipe with an inclination angle of -5° is shown in Fig. 22. According to the results, a major change occurs to the transition boundary of bubbly-o/w flow. Increase in the oil cut from 25% to 50%, transfers the transition boundary between bubbly-o/w and plug-o/w flows to the top and left side of the flow map. Finally, in an oil cut of 50%, the transition boundary between bubbly-o/w and plug-o/w flows disappears. The transition boundary between slug-o/w and wavy stratified-o/w flows and between slug-o/w and plug-o/w flows shifts a bit to the left and right side of the flow map, respectively. This results in a bigger region of slug flow. At low superficial velocities of air and water, by increasing the oil cut, slug-o/w flow changes to wavy stratified-o/w flow. Thus, the transition boundary between wavy stratified-o/w and slug-o/w flow shifts vertically and wavy stratified-o/w region extends.

Figure 22 Comparison of flow pattern maps for air-water-oil three-phase flow in 25% and 50% oil cuts in pipe with inclination angle of -5°

Figure 23 shows a comparison between flow pattern maps for oil cuts of 25% and 50% in pipe with an inclination angle of -45°. In this inclination, the same as -5°, the transition boundary between bubbly-o/w and plug-o/w flows disappears in an oil cut of 50%. As a result, the flow map with 50% oil cut has a bigger region of bubbly-o/w flow. According to **Fig. 23**, the transition boundary between slug-o/w and wavy stratified-o/w flows remains unchanged except at lower superficial velocities of air and water, which shifts to the left side and leads to a smaller region of wavy stratified-o/w flow.

Figure 23 Comparison of flow pattern maps for air-water-oil three-phase flow in 25% and 50% oil cuts in pipe with inclination angle of -45°

For upward flows two inclination angles of $+5^\circ$ (low inclination) and $+45^\circ$ (high inclination) were studied, as shown in figures 24 and 25. Contrary to the downward flows, increasing the oil cut from 25% to 50% in $+5^\circ$ pipeline transfers the transition boundaries between wavy stratified-o/w and slug-o/w flows and between plug-o/w and slug-o/w flows to the bottom and top side of the map, respectively. Also, the transition boundary between bubbly-o/w and plug-o/w flows shifts to the left side of the map.

Figure 24 Comparison of flow pattern maps for air-water-oil three-phase flow in 25% and 50% oil cuts in pipe with inclination angle of $+5^\circ$

In $+45^\circ$ pipeline, transition boundary between bubbly-o/w flow and plug-o/w flow shifts to the left side of the map and finally it disappears. As a result, the bubbly-o/w region extends and the plug-o/w region vanishes.

At higher superficial velocities of water, transition boundary between slug-o/w and bubbly-o/w region shifts to top side of the map, the same as $+5^\circ$ pipeline. At lower superficial velocities of water, transition boundary between slug-o/w and plug-o/w regions is unchanged for pipe with inclination angle of $+5^\circ$. However, for $+45^\circ$ pipeline it shifts to bottom side of the flow map.

Generally, it can be concluded that by increasing the oil cut for different inclination angles, bubbly-o/w region has extended and plug-o/w region has become smaller that in most cases the plug-o/w region has been removed.

Figure 25 Comparison of flow pattern maps for air-water-oil three-phase flow in 25% and 50% oil cuts for in pipe with inclination angle of $+45^\circ$

Conclusion

In the present study, the effect of liquid volume fraction and inclination angle on flow patterns of air-water-oil three-phase flow was investigated. The pipe diameter was 20mm and inclination angle was in the range of -45° to $+45^\circ$. The flow pattern maps were extracted in each inclination angle for three oil cuts of 25%, 50% and 75%. Transition boundaries of flow patterns were evaluated in upward and downward flows and dominant flows were identified for both directions of flow and also transition boundaries for different oil cuts were compared. Generally, the below points can be concluded from the experimental results:

1. By increasing the inclination angle to high values, like $+45^\circ$, plug-o/w flow and slug-o/w flow approximately occupy all parts of the flow pattern map, which means non-stratified flow extends. Annular-o/w flow was observed at high superficial velocities of air, generally greater than 10 m/s. Generally, by increasing the inclination angle transition boundary between annular-o/w and wavy stratified-o/w flow remains unchanged and other transition boundaries moves in horizontal direction.
2. By decreasing the inclination angle of the pipe dominant flows tend to be stratified-o/w and wavy stratified-o/w flows. In high downward inclination angles, like -45° , smooth stratified and wavy stratified flows approximately occupy all left side of the flow map. Transition boundary between annular-o/w and wavy stratified-o/w flows is unchanged. In downward flow, unlike upward

flow, transition boundary between wavy stratified-o/w and slug-o/w flow moves in both vertical and horizontal directions.

3. Generally, it can be concluded that by increasing the oil cut for different inclination angles, bubbly region extends and plug region becomes smaller. In most cases the plug region disappeared. In addition, the transition boundary between annular and wavy stratified regions is almost fixed for all conditions.
4. Increase in oil cut for horizontal flow transfers transition boundaries between wavy stratified-o/w and slug-o/w flows vertically to the top and between slug-o/w and plug-o/w flows to the bottom and a bit right side. This means that by increasing the oil cut, slug-o/w region extends for horizontal flow.
5. In general words, in three-phase flows the wavy stratified flow evolves from slug flow and annular flow evolves from the wavy stratified flow by increasing gas flow rate

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