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## CHARACTERIZATION OF AIR-WATER-OIL THREE-PHASE HORIZONTAL FLOWS

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**Abstract.** For the oil industry, it is of utmost importance to obtain knowledge about three-phase flow characteristics, such as flow patterns and pressure drop. This paper will investigate and classify three-phase flow patterns, based on visual methods through high-speed camera and pressure drop comparison. The procedure was performed in a horizontal steel tube with 15 meters length, with 51.1 mm and 82.1 mm i.d., with a mineral oil with a viscosity of 68.4 mPa.s. The experiment consists in fixing the superficial velocities of oil and water, in order to keep the water cut of the flow at 33% and 60%, and increasing the gas superficial velocity, to obtain different flow patterns. The identified flow patterns were captured using a high-speed camera, and those that were not visually differentiable, a method based on pressure drop analysis was used. The last method was based on comparing the three-phase pressure drop with single-phase pressure drop of oil and water, thus allowing to determine which phase is predominant and whether there was emulsion generated. The patterns identified were intermittent-stratified (INT-ST), intermittent-water continuous (INT-WC), intermittent-oil continuous (INT-OC) and intermittent-dual continuous (INT-DC). The flow patterns presented in 33% water cut showed an emulsion with the predominance of the oil phase, the analysis of pressure drop was necessary. Oppositely, in the flow patterns for 60% of water cut, the analysis made through the images of the high-speed camera were enough. However, the method used in this work for the classification of flow patterns based on videos and the analysis of the pressure drop proved to be accurate and useful for three-phase flow.

**Keywords:** three-phase flow, multi-phase, flow pattern, horizontal flow, pressure drop

### 1. INTRODUCTION

Three-phase flow occurs when three distinct phases flow concurrently. Since this type of flow is recurrent in the oil industry, due to the decompression of oil along the production line, leading to the formation of gas bubbles or production below the bubble point Keskin *et al.* (2007). In addition, an injection of water as a recovery method, as well as the presence of a water cone or aquifer, causes the water to drain into the ducts. Thus, a certain amount of water will flow together with oil and gas, resulting in a three-phase system.

In the flow assurance perspective, it is extremely important to understand the phase distribution topology, known as flow pattern, and the slip of one component in relation to another, for the pressure gradient and phases volume fraction prediction. These phenomenological conditions are of economic importance, because of the operational and safety costs involved in the design and operation of extraction and production facilities for the oil industry Al-Safran and Brill (2017).

When we are talking about three-phase flow, few studies in the literature were developed. Researchers such as Malinowsky (1975) and Laflin and Oglesby (1976) classified three-phase flows in only two phases: oil-water as a single mixture and air as another component, thus classifying them as gas-liquid flows and not seeing the need to make an exclusive classification for the three-phase. Sobocinski (1955), a pioneer in this type of classification, defined nine flow patterns for the three-phase, taking into account the interfaces between liquid-air and oil-water, namely: Stratified-No liquid mixing, Ripple-No liquid mixing, Surface waves - Interception of oil and water mixing, Light waves- Incipient emulsion, Waves-Incipient emulsion, Waves-Partial emulsion, Heavy waves - Partial emulsion, Light crests - Emulsion and Semi annular-Emulsion. The classification made by the author consists of naming in the first part the interface between the oil-water and in the second the liquid-air interface. Despite considering all component interfaces, the liquid-liquid classification did not make it clear which phase was predominant, thus, far from being a complete nomenclature for the three-phase.

Açikgöz *et al.* (1992) presented a more complete nomenclature, dividing it into three parts, where the first part classifies the liquid-wall relationship of the duct, in the second the relation between liquid-liquid, and in the third part the relation of the liquid-air. Thus, it classified the patterns into 10 types: Oil based-Dispersed-Plug flow, Oil based- Dispersed-Slug flow, Oil-Based — Dispersed-Stratified wavy flow, Oil based-Separated-Wavy flow, Oil based-Separated-Stratified annular wavy flow, Oil based- Separated dispersed-Stratifying-annular flow, Water based-Dispersed- Slug flow, Water based-Dispersed-Stratified wavy flow, Water based-Separated-Incipient stratifying annular flow, Water based- Dispersed-Stratifying annular flow. Even with a more detailed classification, the third part of the classification makes it impractical for a general application.

Taking these aspects into account, Keskin *et al.* (2007) performed their experiments and classified the flow patterns in two parts, the first caused by gas-liquid components, and in the second part, through Trallero (1997) classification of oil-water flows. They managed to identify the flow patterns for the three-phase, namely: stratified-stratified (ST-ST), stratified-dual continuous (ST-DC), stratified-oil continuous (ST-OC), stratified-water continuous (ST-WC), intermittent-stratified (INT-ST), intermittent-dual continuous (INT-DC), intermittent-oil continuous (INT-OC), intermittent-water continuous (INT-WC), annular-oil continuous (AN-OC), annular-water continuous (AN-WC), dispersed bubbles-oil continuous (DB-OC) and dispersed bubbles-water continuous (DB-WC). The present work considered Keskin *et al.* (2007) nomenclature to classify the flow patterns that were found.

In general, the flow patterns were classified by the authors visually using a high-speed camera. However, a difficulty was encountered in classifying the patterns when the liquid phases are found dispersed among themselves. Thus, the same analysis applied by Yusuf *et al.* (2012) was used, which found the same difficulty, however for liquid-liquid flows. These authors classified the flow patterns based on the pressure drop and visually. The classification based on pressure drop, was made by a comparison with the single-phase pressure drop of water. If they are of the same magnitude the flow would be dominated by the water phase. If the pressure drop gradient is approximate or higher than single-phase flow of oil, under the same flow conditions, the regime would be predominant of the oil phase.

This article describes flow patterns in the three-phase flow by visual identification by high-speed camera and pressure drop, in different water cuts ranges, in different diameters. The water cut was fixed at 33% and 60%, with the purpose of verifying the flow with predominance of oil and water respectively, and after setting a percentage of water injection, the values of superficial velocities of oil and gas varied. The experiments were carried out in 2" and 3" pipes. Analysis of holdup and slip will be subject of further articles.

## 2. EXPERIMENTAL SETUP

The experiments were conducted at the facilities of LabPetro - Experimental Laboratory of Petroleum, located at the Center for Petroleum Studies - CEPETRO, at the University of Campinas - UNICAMP. A structure of experimental facilities at LabPetro consists of a storage tank for storage and gravitational separation of oil and water. Pumps for water and oil with volumetric flow rate, controlled by frequency variable drivers. Coriolis mass flow meters for oil, water and gas are present. A compressed air injection system, controlled by a valve system, control the pressure in the line and also the flow rate. The heat exchangers for water and oil, Pt-100 RTD, water cut meter, transducers for differential pressure and quick-closing pneumatically valves are present. Flow control and collection of experimental data are performed by the LabVIEW® software which, through an integrated panel, controls the actions of the line's electronic and electromechanical system. The test section consists of a horizontal line of 15 m length with 2" and 3" in diameter, made of galvanized steel. To obtain the visualization of the flow, a high-speed camera was attached to the line in front of a visualization section made of acrylic. Flow movies were essential to identify the flow patterns, mainly for the interface between oil and water. In Table 1 follows the brands and models of the equipment used in the experimental setup

Table 1. models of the equipment used in the experimental setup.

Equipment	Manufacturer	Model / Characteristics
Oil pump	IMBIL	Centrifugal pump
Water pump	NETZSCH	Two spindle pump
Storage tank	Interfibra industrial	12000 liters
Coriolis mass flow meter-gas	MicroMotion	CMFS050M
Coriolis mass flow meter-oil	MicroMotion	F300S
Coriolis mass flow meter-water	MicroMotion	F300S
Heat exchanger	FYTERM	T – 3480 shell and tube
Chiller	Carrier	30 RA/RH
Valve system	FESTO	3S7PLLCTYQM
Choke	Fischer	choke657
Water cut meter	ROXAR	Nemko 05 ATEX 1121
Frequency variable driver – oil pump	CFW - 700	WEQ
Frequency variable driver – water pump	CFW - 700	WEQ
Differential pressure transducer	Rosemount	2088
Temperature sensor	ECIL	PT 100 1/10 DIN
Pneumatically valves	MGA	VET 3” + AT DA

## 2.1 Experimental Fluids and Test Matrix

The fluids used in the experiment were mineral oil, tap water and compressed air. The mineral oil of the brand Luchetti 600® showed a density of approximately 853.977 kg/m<sup>3</sup> at 43.76 °C, and viscosity of 68.4 mPa.s, whereas the water has a density of 998.278 kg/m<sup>3</sup> at the same temperature of the system, and its viscosity remains around 0.662 mPa.s. Another important measurement is the water fraction in oil that the limit imposed was up to 10% and this factor did not change the flow pattern neither does not influence the predominant phase when the water injection was varied between 33% and 60%. Following the operational limits of the line, the superficial velocities tested were:

- Water superficial velocity: 0.2 m/s - 1.5 m/s
- Oil superficial velocity: 0.1 m/s - 1.0 m/s
- Air superficial velocity: 0.3 m/s - 2.5 m/s
- Water cut fraction: 33% and 60%

An important parameter used to carry out the tests and to define the test matrix, was necessary to understand the phenomenon of phase inversion. According to Descamps *et al.* (2006), Descamps *et al.* (2007), Spedding *et al.* (2000), Xu *et al.* (2012), Rocha *et al.* (2017), the gas injection in the flow does not significantly influence the inversion point of the three-phase flow. Through the correlation of Arirachakaran *et al.* (1989), in which it was validated by Rocha *et al.* (2017) for use in the three-phase, we were able to determine the fraction of water injection, so that the phase inversion occurs, which is represented in Eq. (1). The water cut was defined as in Colmanetti *et al.* (2018) Eq. (2).

$$C_{w,inv} = 0,5 - 0,1108 \log \left( \frac{\mu_o}{\mu_w} \right) \quad (1)$$

$$C_w = \frac{J_w}{J_w + J_o} \quad (2)$$

The results obtained through Arirachakaran *et al.* (1989) was 27.68%, but due to the operational limitations of the line, the minimum amount of water fraction that was injected in the experiment was around 33% which is the closest water cut zone in order to try to reproduce a continuous phase of oil. The 60% Water Cut value was set to obtain a phase with predominance of water.

## 3. EXPERIMENTAL RESULTS

The flow patterns found, follow the classification of Keskin *et al.* (2007) which are: Intermittent-Stratified (INT-ST), Intermittent- Dual continuous (INT-DC), Intermittent-Oil continuous (INT-OC), Intermittent-Water continuous (INT - WC). Fig 1 presents the observed flow patterns after classification through visual observation and pressure drop for 3”. The same is done for 2” pipe in Fig. 2.

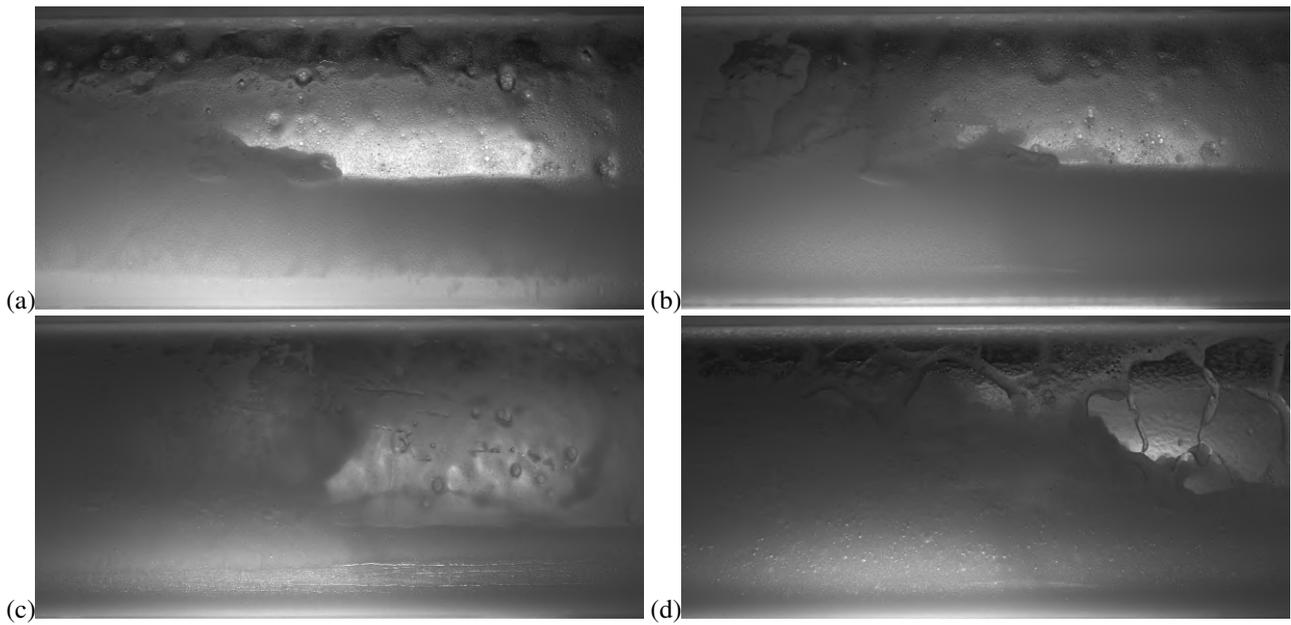


Figure 1. Flow patterns observed for 3'' horizontal flow, according to the Keskin *et al.* (2007) classification (a) INT-ST (b) INT-OC (c) INT-DC (d) INT-WC.

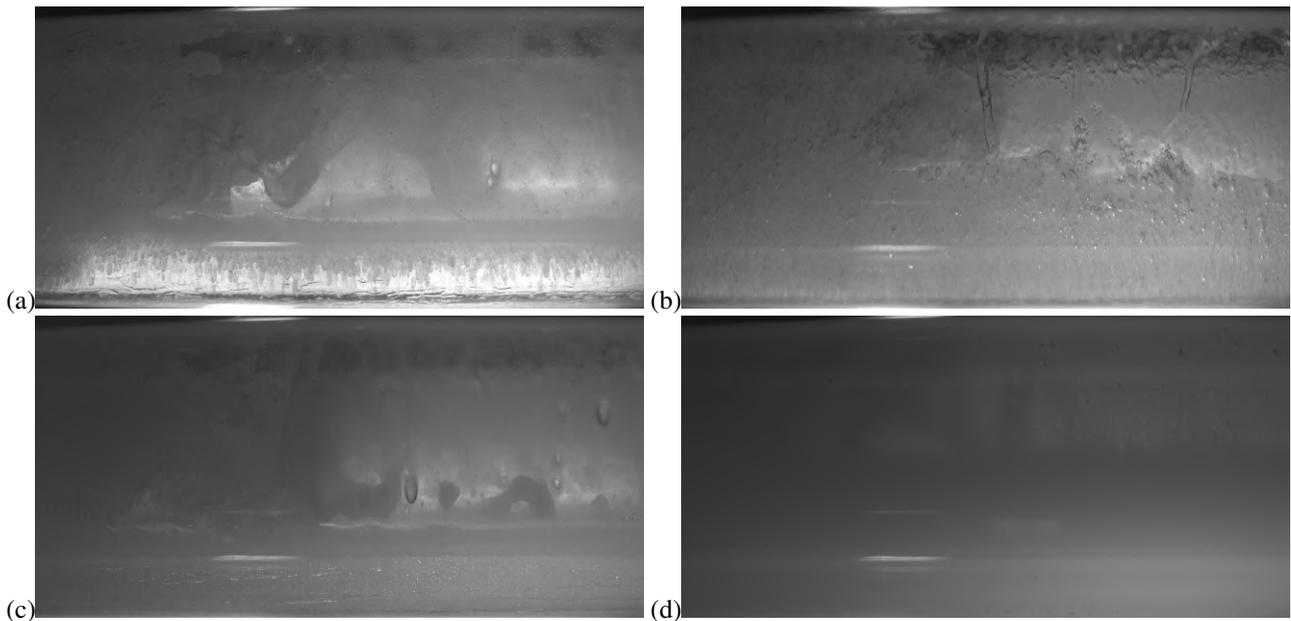


Figure 2. Flow patterns observed for 2'' horizontal flow, according to the Keskin *et al.* (2007) classification (a) INT-ST (b) INT-WC (c) INT-DC (d) INT-OC.

Based on the flow patterns shown in the figures above flow pattern maps were built and are presented in Figures 3 and 4, divided by water cut and pipe diameter.

Figures 3 (a) and 4 (a) presents the flow maps with water cut at 33% for 3'' and 2'' pipes, respectively. Three flow patterns were identified, classified by both visual observation and pressure drop, which are: INT-ST: Gas-liquid flow pattern with elongated bubble formation in low gas flow rates. The oil and water are completely separated with the possibility of a few drops occurring at the interface between oil and water. The other flow patterns were classified by the pressure drop, due to the high superficial velocities of liquids and gas, the liquid phases do not separate clearly, usually always forming an emulsion of difficult visual classification.

Therefore, the INT-OC flow pattern is observed in low water fractions with relatively high liquid flow rates. Gas-liquid flow pattern is intermittent. The only continuous liquid phase is oil, the water is completely dispersed in the oil, forming a water in oil emulsion.

The INT-DC flow pattern, presents both  $D_{w/o}$  - dispersion of water in oil and  $D_{o/w}$  - dispersion of oil in water flow pattern in the liquid-liquid flow. To determine which would be the dominant phase and the dispersion in this type of

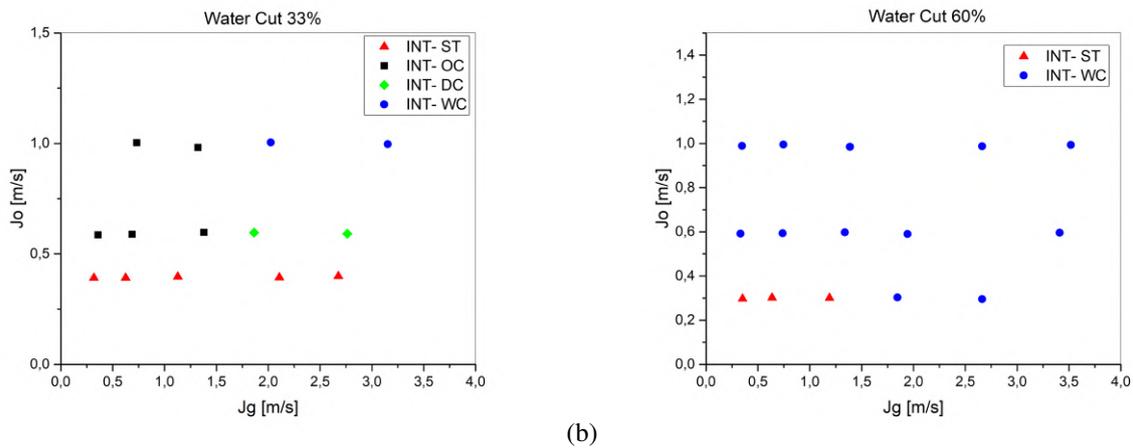


Figure 3. Flow pattern map for 3'' with water cut (a) 33% (b) 66%.

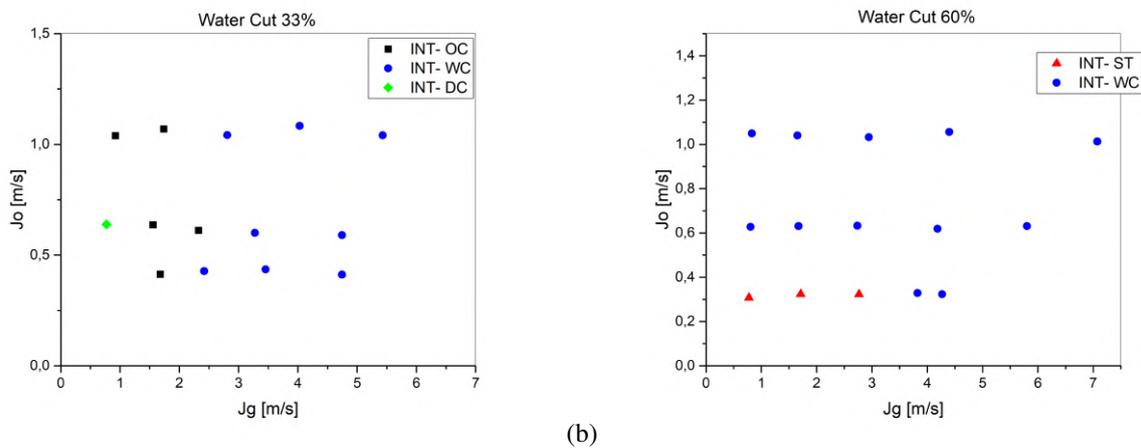


Figure 4. Flow pattern map for 2'' with water cut (a) 33% (b) 66%.

pattern, the comparison of pressure drop was performed. In which we compared the pressure drop with single-phase flow of water or oil.

Table 2. Classification the flow patterns by pressure drop.

$\frac{dP}{dz} \frac{3P}{dP} / \frac{dP}{dz} \frac{SO}{dP}$	Flow Pattern
< 0.6	Water Continuous
0.6 - 0.9	Dual Continuous
> 0.9	Oil Continuous

The patterns defined in table 2 above, through pressure drop, were made from the ratio of the maximum mean value of the pressure gradient of the three-phase flow ( $\frac{dP}{dz} \frac{3P}{dP}$ ) oscillation over time and the oil single-phase flow at mixture velocity pressure gradient ( $\frac{dP}{dz} \frac{SO}{dP}$ ). Factors such as increased superficial velocity and no distinction of the interfaces between oil and water, made this type of classification efficient. If these factors are considered, an emulsion generated has a higher viscosity than oil, because of which its pressure drop will be higher.

In the second flow pattern map in the Fig. 3 (b) where the water fraction is 60%, the flow patterns identified were all classified by the visual method determined by Keskin *et al.* (2007). Due to the predominant high water fraction, the flow patterns presented were: (INT-ST) already classified, and (IN-WC) : which is formed due to the high water fraction, the oil is completely dispersed in the continuous water phase. In the case of gas-liquid, the occurrence of slug flow was the characteristic observed. So water is the predominant phase, and the flow patterns observed was (INT-ST), it causes the water layer to present a more stratified interface with the oil, and this pattern is observed only in two different air velocities. In the flow pattern (INT-WC) the emulsion generated was due to the high superficial velocities, it causes the oil present in the flow to be dispersed in the continuous phase which is water, because the emulsion viscosity is higher than oil, the resulting pressure drop is greater than that of single-phase oil flow. Although these flow patterns were classified

visually, the pressure drop data served to confirm that the visual classification was correct, corroborating with validation of this method as well.

Due to the limitation of the experimental apparatus, it was not possible to reach other gas superficial velocities, for both water cuts. The gas did not influence significantly, generating only one pattern between the gas-liquid interface, which was the intermittent pattern. However, in regions where it presented a higher superficial velocity, it generated some instability in the liquid-liquid interface, almost always generating an emulsion.

In Fig. 4 (b) for water cut of 66%, all flow pattern classified in accordance with the classification by Keskin *et al.* (2007). As they have a greater predominance of water in this case the visualization by the high-speed camera was enough to classify, and the comparison of its pressure drop gradients was analyzed in order to corroborate with validation of the results obtained visually. The flow patterns identified were: INT-ST and INT-WC.

#### 4. CONCLUSION

The present study characterizes horizontal air-water-oil three-phase flow through two different pipe diameters (2" and 3"). Flow patterns were investigated through flow visualization studies and pressure drop analysis. The general conclusions about this experimental work are listed as following.

- An inconclusive classification for three-phase flow was observed.
- Comparison with visual method and pressure drop gradient was essential for the validation of flow pattern classification.
- For 33% water cut in 3" pipe it was observed INT-OC, INT-DC, INT-ST and INT-WC flow patterns.
- For some reason, to be studied, the INT-ST pattern was not observed in 33% water cut for the 2" pipe, all other flow patterns observed for 3" were present in the 2".
- Flow patterns with a predominance of water were easier to identify by the high-speed camera.
- For 60% water cut in both 2" and 3" pipes, the INT-ST and INT-WC were the only observed flow patterns.
- The patterns that have a predominance of oil presented some difficulty in classifying by high-speed camera, so it was necessary to analyze the respective pressure drop.
- Gas flow change, in general, did not influence the flow patterns in this study, only the intermittent flow pattern at the interface between gas-liquid was observed.

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