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A conductometric method for determining of the upward gas-liquid-liquid three-phase flow

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Abstract This paper reports the results of research involving observations of flow patterns during air-oil-water three-phase flow through a vertical pipe with an internal diameter of 0.03 m and a length of 3 m. The conductometric method based on the measurement of electrical conductivity of the gas-liquid-liquid system was used to evaluate the flow patterns. In the studies, a set of eight probes spaced concentrically in two tube sections (four probes per each) with a spacing of 0.015 m were used. The paper presents a theoretical description of the test method and the analysis of the measurement results for air-oil-water multiphase flow system. Results of this study indicate that the developed method of characterizing the voltage of the gas-liquid-liquid system can be an important tool supporting other methods to identify flow patterns, including visual observation.

Keywords: Conductometric method; Three-phase flow; Flow patterns

Nomenclature

A	–	cross-section area of pipe, m^2
d	–	internal diameter of pipe, m^3
j	–	superficial velocity, m/s
Q	–	volumetric flow rate, m^3/s

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Greek symbols

η – dynamic viscosity, Pa s
ρ – density, kg/m^3

Subscripts

a – air
i – i-phase
o – oil
w – water

1 Introduction

Upward oil-air-water flow is common in the processes of transport and processing of petroleum. The crude oil often has a high water content or water is purposely added to the oil to promote its transfer through the pipeline. The transport of petroleum is also promoted by the use of compressed gas, which is fed into a pipeline. The awareness of the phenomena which accompany the co-current flow of air, water and oil plays an important role in engineering calculations and forms an interdisciplinary problem for research conducted in the petrochemical industry. Due to the mutual interaction of phases with different properties (interaction on the phase boundaries) during the flow in a pipeline, there are liquid turbulences and local disturbance in the flow. As a consequence, three-phase gas-liquid-liquid flow is very irregular, random and the flow patterns are often unstable. For this reason, the insight into the dynamic parameters during such flows forms a key issue. The identification of flow patterns during three-phase gas-liquid-liquid flow plays a principal role in the design of pipelines and transport equipment, especially when considering the techniques of calculating void fraction and pressure drop. It is important to have objective methods for forecasting the conditions for the formation and assessment of flow patterns in three-phase flow.

Most studies concerned with oil-air-water three-phase flow focus primarily on the visual observation and classification of flow patterns. Shean [1] conducted a study into air-water-mineral oil three-phase flow (ρ_o = 889 kg/m^3, η_o = 0.0718 Pa s at 20 °C) in a pipe with the internal diameter of 0.019 m. Pleshko and Sharma [2] report the results of experimental study into identification of flow patterns during air-water-Exxon Isopar-V oil flow (ρ_o = 814 kg/m^3, η_o = 0.00748 Pa s) in a vertical column with an internal diameter of 0.051 m. Woods *et al.* [3] presented a detailed analysis of air-water Finavestan A50B oil mixture flow (ρ_o = 829 kg/m^3,

$\eta_o = 0.012$ Pa s) in a pipeline with an internal diameter of 0.026 m. Oddie *et al.* [4] describe the results regarding three-phase mixture flow composed of kerosene, water and nitrogen as well as two-phase one involving water-nitrogen and kerosene-water mixture in a vertical pipe with an internal diameter of 0.152 m.

Descamps *et al.* in [5] determined the effect of the manner in which gas is fed into a two-phase liquid-liquid mixture on phase inversion phenomenon. They performed a comparative studies with regard to two-phase salty water-oil and three-phase air-water-oil mixture flow in a vertical channel with an internal diameter of 0.0828 m. The three-phase mixture consisted of air, salty water ($\rho_w = 1060$ kg/m^3, $\eta_w = 0.00085$ Pa s) and Vitrea 10 oil ($\rho_o = 830$ kg/m^3, $\eta_o = 0.0075$ Pa s).

The conductometric method is based on measurement of electrical conductivity, i.e., the ability of a liquid to conduct electricity for technical and scientific research applications. The area of interest of a conductometric study is very extensive and primarily involves: scientific study (electrochemical methods of analysis and electrochemical methods for determining the physico-chemical constant values), industry (measurement of concentration levels, control of washing and rinsing processes, automatic control applications), water and waste management, agriculture processing and associated services, environment conservation, medical sciences, etc.

One of the means of performing flow diagnostics which has not gained a great popularity involves the application of conductivity phenomenon for the assessment of the characteristics of multiphase mixture flow. In this type of mixture, each of the components has distinct physical and chemical properties and this characteristic can find application in the assessment of the dispersion of specific phases due to the application of the phenomenon of conductivity. In addition, only a small number of research works refers to the application of the conductivity method as a potential tool useful for identifying flow patterns during upward three-phase air-oil-water flow. In this respect, a study were conducted by Wang *et al.* [6], as well as Gao and Jin [7] with regard to upward three-phase air-water-oil flow through a pipe with an internal diameter of 0.0125 m. Such studies were also performed with regard to oil applied in industrial conditions, whose density was $\rho_o = 856$ kg/m^3 and $\eta_o = 0.011984$ Pa s, respectively, at the temperature of 40 °C. These authors used multiwire sensors and a system of miniprobes to characterize the flow of gas-liquid mixture formed during the flow. Wang *et al.* [6] based on two kinds of signals measured from miniconductance probe array and vertical multielectrode array conductance sensor studied oil-gas-water three-phase flow. In this regard, the nonlinear analysis of conductance fluctuating signals can give an effective indicator to understand and identify the gas-oil-water three-phase flow pattern characteristics. Gao and Jin [7] carried out experiment for measuring the time series of flow signals, which was studied in terms of the mapping from time series to complex networks. Two network mapping methods were proposed for the analysis and identification of air-water-oil flow pattern dynamics.

Jin *et al.* [8] presented the design and geometry optimization of a conductivity probe with a vertical multiple electrode array, which can be used to measure the volume fraction and axial velocity of two-phase flow. The designed system can be used to predict volume fraction in vertical upward gas-water two-phase flow with satisfactory accuracy. Brandt *et al.* [9,10] reported the results of experimental study into identification of flow patterns during water-oil and air-water-oil flow in vertical pipe with an internal diameter of 0.0125 m and a length of 2.5 m by used conductance probe. The proposed method can be useful in identification of water-oil two-phase flow in vertical downward flow.

Du *et al.* [11] conducted an experimental study of oil-water two-phase vertical upward flow in a 0.02 m internal diameter pipe. They used vertical multiple electrode array conductance sensor to measure the water holdup and miniconductance probes define observed flow patterns. They presented a flow pattern map with oil and water superficial velocity ranging from 0.258 m/s to 3.684 m/s and 0.184 m/s to 1.474 m/s, respectively. Finally, they proposed an effective quadric time-frequency representation, i.e., the adaptive optimal kernel time-frequency representation to investigate the complex behavior underlying vertical upward oil-water flow in pipe.

In present study, the conductometric method which to this time has found little application in three-phase flow studies, was used to evaluate the flow patterns in co-current upward air-oil-water flow.

2 The air-oil-water three-phase flow experiment

The experiments were carried out on the experimental installation, whose diagram is presented in Fig. 1. The research was conducted in a transparent vertical pipe (1) made of plexiglass, with an internal diameter of 0.030 m and a length of 3 m. The fluids were fed from separately supplying systems into a flow regulation and measurement system (2). Then, they were trans-

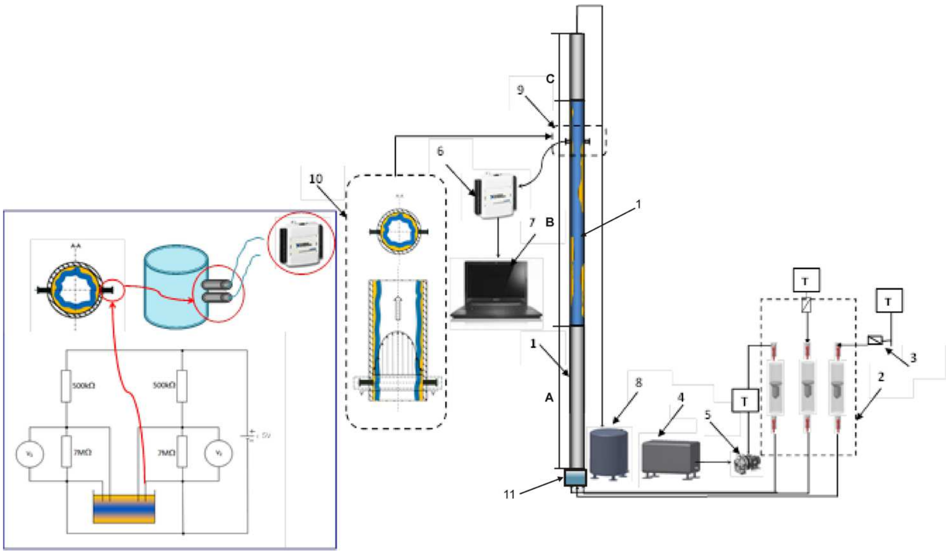
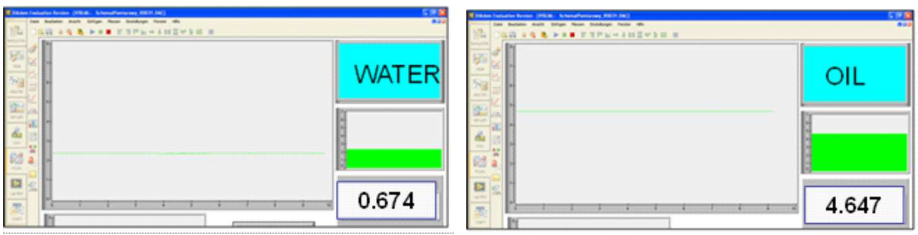


Figure 1: Diagram of the experimental set-up: 1 – measurement channel, 2 – flow meters, 3 – reduction valve, 4 – oil tank, 5 – oil pump, 6 – NI USB-6210 module, 7 – data acquisition device, 8 – separator, 9 – conductance probes (details of the construction and principles of measurement by the conductometric method are shown in the drawing in the magnification seen on the left side of the diagram), 10 – cross-section of the measurement channel, 11 – mixing chamber, A – stabilisation section, B – test section, C – exit section, T – thermocouples.

ported to the mixing chamber (11), where multiphase mixture was formed. Oil was pumped from a tank (4) into the installation by gear pump (5). At the inlet of the supply system, the temperature (T) of circulating fluid was measuredby the thermocouple. Water and air was provided from the water supply and pneumatic network respectively and fed to an array of rotameters (2), whose role was to regulate and measure their flow rates. Afterwards the working fluids were pumped into to the mixing chamber (11) where three-phase mixture was produced. The multi-phase mixture which left the mixing chamber passed through a section of flow stabilization (A) (i.e. distance between air-water-oil mixture distributor and test section) where the parameters of the flow stabilized and specific flow patterns were formed. Average pressure values of three-phase mixture (at the outlet of mixing chamber) ranged from 111.3 kPa to 141.3 kPa. Observation and identification of the flow patterns was performed in the vertical test section (B) of the installation that followed the flow stabilization section. An exit length of measurement channel (C) was 0.5 m. The length of this channel section was sufficient to eliminate the impact of the outlet effect on the flow patterns. After leaving the measurement channel the three-phase mixture flows into the separator (8), where oil-water mixture was separated by gravity. Both water (tap water) and oil were kept in the same large separator with a capacity of about 3 m^3 for several days. After gravity separation resulting from differences in the densities of the mixture components, oil occupied the top part of the vessel while the water remained in the lower part, the water was removed from the separator while gear pump was used to transport pure oil into the oil storage tank. More detailed information on the conditions and measurement data is given in [12].

In the study, the method of measuring electrical conductivity of liquids was applied with an aim of determination of liquid dominant phase on the pipe wall. In the analyzed case, in the liquid mixture the role of the insulator was provided by L-AN 15 oil ($\rho_o = 859.81$ kg/m^3 and $\eta_o = 0.029$ Pa s at the temperature of 20 °C) while tap water played the role of the conductor. When the conductor came into contact with the measuring probe, low-voltage was generated as the output signal (Fig. 2a). In contrast, when the insulating phase was in contact with the measuring probe, the output signal took the form of high-voltage signals (Fig. 2b). A system of eight measuring probes situated concentrically at a distance of 0.015 m along the pipe wall plane was applied in this research. The output signal from the electrical probes was registered by a computer with an 16-channel NI USB-6210 analog-digital measurement card manufactured by National Instruments (6), which was operated by use of DIAdem Evaluation Version software. The registration range of this card was (0-5)V.



a) b)

Figure 2: Voltage characteristics of pure liquids: a) water, b) oil L-AN 15.

3 Results

The research confirmed the existence of a large number of varied flow patterns. The diversity of these patterns was associated with the occurrence of a wide range of variability in the volume flow rate of the phases (Q_i), which were equal to: 0.005–0.33 m^3/h, 0.13–13.5 m^3/h, 0.1–0.88 m^3/h for oil, air and water, respectively. Since there was considerable dynamic characteristics of flow patterns, visual observations and registration of flow patterns was performed along with the measurements of conductivity. Observations were performed on the basis of registration of videos and pictures using Canon 300D camera with a shutter speed of 1/4000 s. The flow patterns were registered under stabilized flow conditions, which was initiated in the pipeline for a constant superficial velocity of the liquids (water and oil) and variable superficial velocity of the air. The sampling frequency of the conductometric system was equal to 100 Hz, while the registration time of the samples for a single measurement point (i.e., for given volume flow rate of the phases) was between 5 and 10 s. The electrical signals from the probes indicated the type of the dominant liquid phase along the pipe wall in the three-phase air-water oil mixture flow. This, in turn, provided grounds for the statement about the occurrence of an inversion point of the liquid phases in a given mixture. Table 1 contains the photos of air-oil-water three-phase flow patterns registered during the experiments. The flow patterns were subsequently classified into two main groups; water dominant (O/W) and oil dominant flow patterns (W/O). Tables 2 and 3 contain a detail characteristic of the identified flow patterns.

Table 4 shows actual examples of the characteristics of the fluctuation in electrical voltage relative to the particular three-phase patterns, duration of the measurement time and the conditions of their occurrence. Since conductometric method was used to determine the dominance of the liquid components in the three-phase mixture, these characteristics correspond to the respective flow with the dominant water phase – Tab. 4a and b, and dominant oil phase – Tab. 4d, and the dispersion (emulsion) of the both phases – Tab. 4c. The charts containing the actual courses of voltage for the three-phase mixture also present their mean values for single-phase water, oil and air flow. The superficial velocity of air, j_a, water, j_w, and oil, j_o, listed in the Tab. 4 were calculated according to relation

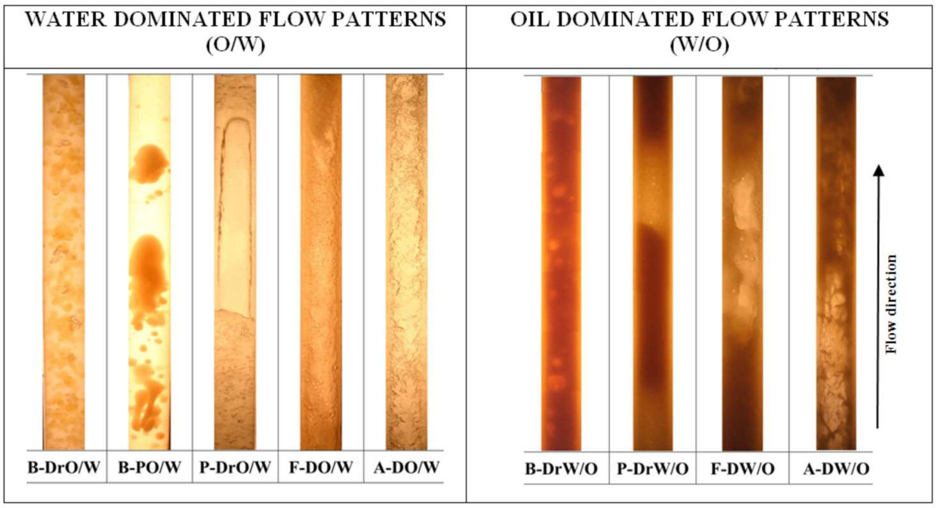
$$j_i = \frac{Q_i}{A} = \frac{4Q_i}{\pi d^2} \tag{1}$$

where: Q – volumetric flow rate, A – cross section area of pipe, d – internal diameter of pipe.

The course of the voltage characteristics in Tab. 4 confirms that the three-phase oil-water-air flow is characterized with considerable degree of stochasticity. At the instance when water is the dominant phase in the flow, for a small superficial velocity of air, j_a, and oil, j_o, (Tab. 4a), the value of voltage is in the range of 2–3 V. From the course of the variation in voltage we can conclude that small oil droplets remain in contact with the channel wall, as they do not lead to considerable variations in the voltage value.

For the case when the superficial velocity of air increases, and small bubbles and plugs of gas combine to form large agglomerates, carrying oil film, the value of the voltage increases to around 4.5 V (Tab. 4b). When the superficial velocities of the gas, j_a, are very high while the ones for oil, j_o, and water, j_w, are considerably smaller (Tab. 4c), we have to do with the liquid phase dispersion in the three-phase flow. In this case air flows in the form of semi-slugs, carrying the emulsion with it.

Table 1: Flow patterns observed during co-current air-oil-water three-phase flow in a vertical pipe.



The flow rate of the emulsion is so high that during the contact with the channel wall, the voltage reaches its extreme values, i.e., around 4.64 V. The occurrence of voltage dips (i.e., when voltage decrease to around 4V)

Table 2: Characteristics of air-water-oil three-phase flow in vertical pipe, water dominated flow.

WATER AS DOMINANT PHASE (O/W)	
Symbol	Name and description of flow pattern
B-DrO/W	oil in water type, droplet-bubble flow
The water phase occupies the entire channel and constantly remains in contact with the pipe wall, while the gas phase flows in the continuous water phase in the form of single gas bubbles or their aggregations with varied sizes relative to the void fraction of the gas phase and concentration of the oil phase. For a small concentration of the oil phase in liquid and relatively small water velocities, oil flows in the form of single droplets, while an increase of the fraction of the oil phase leads to the decrease in droplet size and their denser aggregation. An air bubble flowing through the liquid mixture results in turbulence of oil droplets in water.	
B-PO/W	oil in water type, plug-bubble flow
This flow pattern originates in the conditions of relatively small velocities of the continuous water phase flow and a small void fraction of the gas phase, which takes the form of small bubbles. An increase in the flow rate of the oil phase leads to accumulation of oil droplets to form larger aggregation and formation of oil plugs with a length of 2 diameters of the channel, which are additionally followed by smaller oil droplets. Due to their small sizes the air bubbles are not capable of breaking oil plugs, however, they only cause their slight disturbances.	
P-DrO/W	oil in water type, droplet-plug flow
An increase in the flow rate of the gas phase leads to the breaking up of plugs and larger oil droplets flowing in the continuous water phase. The gas phase takes the form of cylindrically shaped plugs with a rounded front section which periodically displace towards the top of the channel, thus leading to the mixing and aeration of the liquid phases. This type of flow can also be accompanied by the dynamic displacement of small oil droplets dispersed in liquid in the form of semi-slugs. Liquid flows along the surface of gas plugs in the opposite direction to its motion. Along with the increase of void fraction of oil in the liquid, the size of the liquid slugs decreases and the liquid film flowing on the wall increases in thickness.	
F-DO/W	oil in water type, disperse-froth flow
Water is still the dominant phase in the flow along the channel although there are small oil droplets suspended in the mixture, whose concentration is relative to the void fraction of the oil phase in the flow. The breaking and forming gas bubbles with an irregular shape pass the channel with a considerable velocity and contribute to the formation of multiphase mixture with the characteristics similar to froth due to oscillatory nature of the flow. The liquid film forming along the channel wall reminds marble and the gas phase is largely mixed with the liquid.	
A-DO/W	oil in water type, disperse-annular flow
The gas occupies the core of the channel (flowing with a velocity of a dozen meters per second), which leads to the displacement of dispersed oil and water mixture on the channel wall. The oscillatory nature of the liquid mixture declines. The liquid mixture forms an annulus on the channel wall with a varied thickness and forms waves with characteristics relative to the velocities of the gas and liquid phases.	

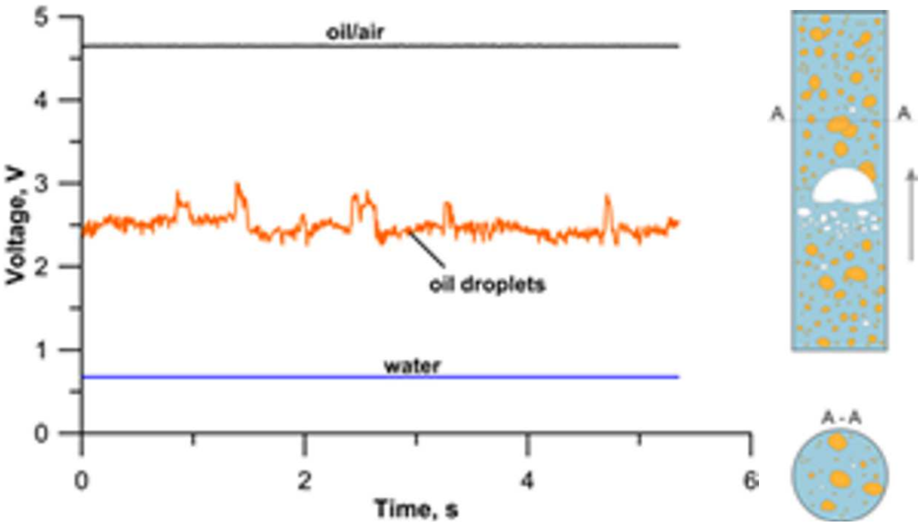
Table 3: Characteristics of air-water-oil three-phase flow in vertical pipe (oil dominated flow).

OIL AS DOMINANT PHASE (W/O)	
Symbol	Name and description of flow pattern
B-DrW/O	water in oil type, droplet-bubble flow
Oil occupies the entire measurement channel and constantly remains in contact with the pipe wall – it flows upwards carrying water drops with varied sizes. The gas phase flows in the continuous oil phase in the form of single gas droplets with a small size.	
P-DrW/O	water in oil type, droplet-plug flow
An increase in the flow rate of the gas phase gives rise to cylindrically-shaped plugs; however, their front section is more flattened than for the case of the pattern with the dominant water phase. Gas plugs are displaced periodically upwards the channel leading to the mixing of the liquid phases. This type of flow can also be accompanied by dynamic displacement of small water droplets in mixture in the form of semi-slugs. In such a case the liquid flows along the surface of gas plugs in the opposite direction to the direction of a gas plug.	
F-DW/O	water in oil type, disperse-froth flow
Oil is dominant liquid in the flow. It contains small water droplets with the concentration that the relative to the void fraction of water phase in the liquid, which in this case is relatively small. The breaking and forming gas bubbles have an irregular shape and move with a large velocity. As they are accompanied by oscillatory liquid flow, they contribute to the formation of multiphase mixture which reminds froth. The liquid film on the channel wall reminds of marble, while the gas phase is considerably mixed with liquid.	
A-DW/O	water in oil type, disperse-annular flow
Air flows in the middle of the channel with a high velocity, thus displacing highly dispersed liquid mixture of small water droplets in oil phase on the channel wall. The mixture is considerably dispersed and reminds milk in color. Due to the strong dispersion of the liquid phases, we can observe a prolonged time necessary for the draining of the channel from the liquid mixture.	

indicates the occurrence of non-homogenous emulsion with variations in the local volume fractions of oil and water in the dispersed mixture. During the dominance of oil in the flow (Tab. 4d), voltage fluctuates in the range of 3–4.64 V.

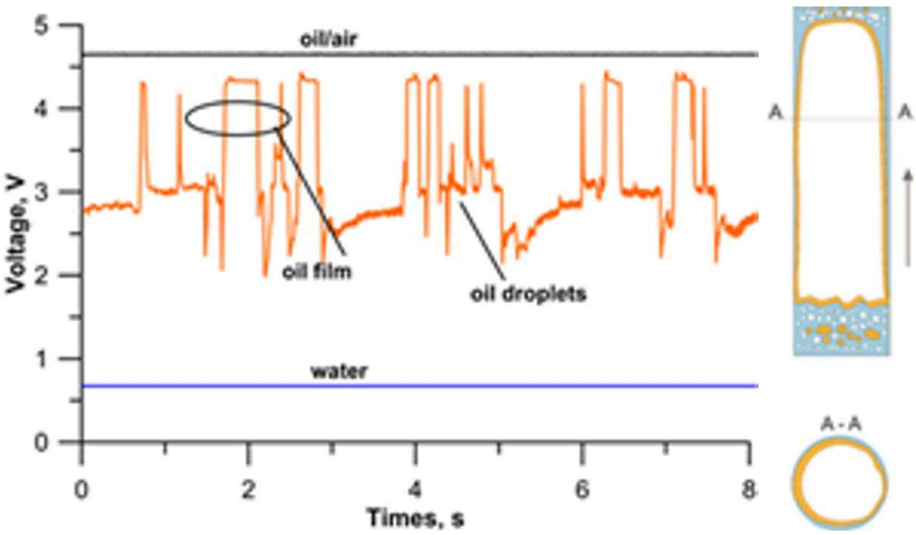
Table 4: Actual courses of fluctuation of voltage for various three-phase flow patterns.

a) oil in water type, droplet-bubble-plug flow



$j_o = 0.0021$ m/s, $j_a = 0.05$ m/s, $j_w = 0.17$ m/s

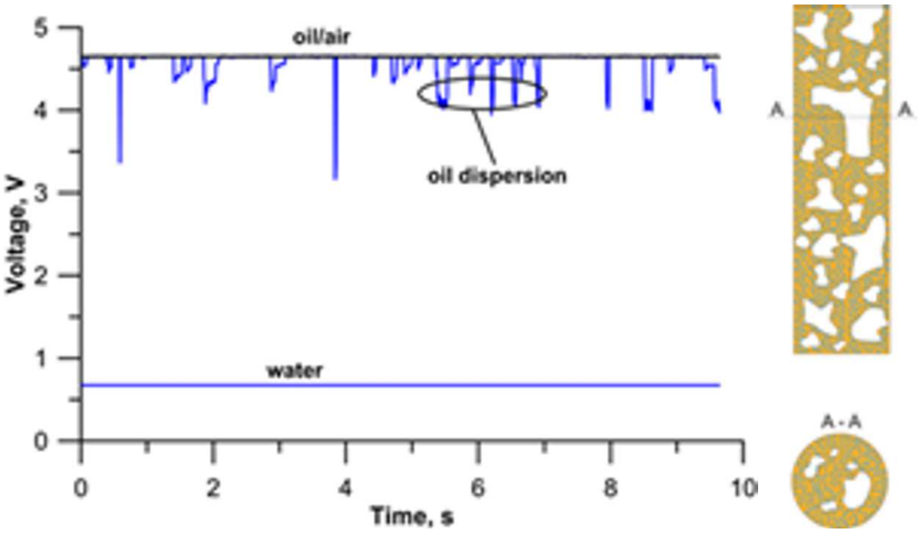
b) oil in water type, droplet-large bubble-large plug flow



$j_o = 0.0021$ m/s, $j_a = 0.14$ m/s, $j_w = 0.17$ m/s

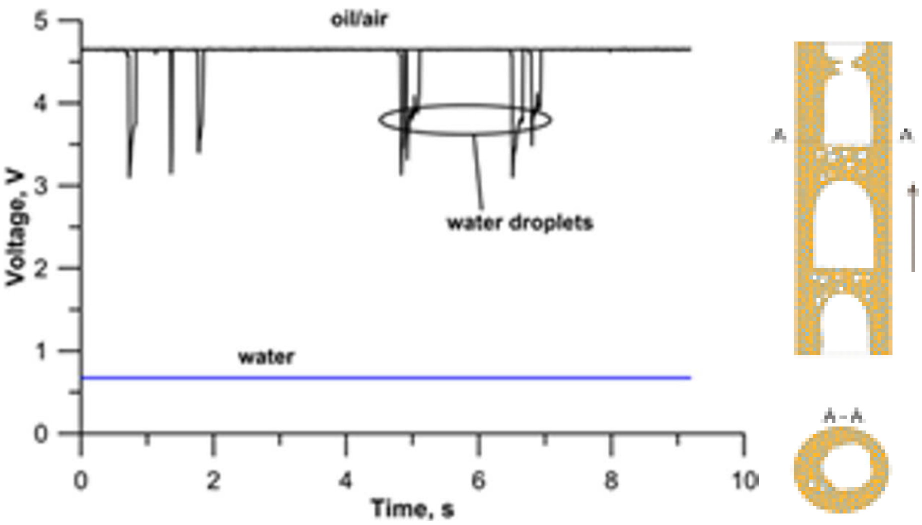
Tab.4 continue

c) water in oil type, disperse (emulsion)-slug flow



$j_o = 0.0021$ m/s, $j_a = 5.31$ m/s, $j_w = 0.04$ m/s

d) water in oil type, droplet-plug flow



$j_o = 0.03$ m/s, $j_a = 0.14$ m/s, $j_w = 0.17$ m/s

The reason for such fluctuations can be associated with the formation of water drops in oil, which generate changes in the voltage, as it reaches its maximum value during their contact with the channel wall. For the case when water drops accumulate on the channel wall, the voltage decreases to around 3V.

4 Conclusions

The reason for such fluctuations can be associated with the formation of water drops in oil, which generate changes in the voltage, as it reaches its maximum value during their contact with the channel wall. For the case when water drops accumulate on the channel wall, the voltage decreases to around 3V.

The results of research indicate that conductometric method with measuring the value of voltage in a gas-liquid-liquid system can offer a practical tool in assisting visual identification of flow patterns during upward air-water-oil three-phase flow. This method enables qualitative assessment of multi-phase flow patterns and can offer aid in the determination of the conditions for the dominance of the specific liquid phases in the flows of two immiscible liquids. Non-linear analysis of the electrical conductance of liquids can be applied as a successful tools for getting insight and characteristic of three-phase air-water-oil flow patterns.

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