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Study of hysteresis effects and emulsion properties in watercut measurement using high speed multi-frequency impedance sensor

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ABSTRACT

Oil and water mixtures are present in many applications, specifically in upstream oil production. To investigate oil–water mixture properties and to measure phase fractions, a watercut meter was developed that utilizes an electrical impedance measurement method. In this method, watercut is measured by using a newly developed algorithm that uses multiple frequencies to enhance the accuracy of the watercut measurements and to identify the mixture dispersion type. Electrical characteristics of the mixture were investigated by studying the effect of two factors, the emulsion properties and hysteresis effect. The dependency of the watercut meter response to the influencing factors was reduced by implementing the developed novel method. Using this method, the uncertainty in watercut measurement from 0% to 100% was obtained to be about $\pm 3\%$ regardless of phase distribution and droplet size.

1. Introduction

Multiphase flow meters have been in use in different industries such as chemical and petroleum for many years. In the petroleum industry, two-phase flow has significant importance in production wells and pipelines. Among different two-phase flow types, liquid–liquid dispersion is commonly found in different applications and due to its importance it has been investigated by many researchers.

In two-phase water–oil flow, two types of dispersion occurs which are oil-in-water (o/w) and water-in-oil (w/o). In oil-in-water (water-in-oil) dispersion, water (oil) is the continuous phase and oil (water) is the dispersed phase which means that oil (water) droplets are in the water (oil). By changing the water volume fraction (watercut) and by energy input [1], during a specific phenomenon, the dispersed phase switches to the continuous phase and the continuous phase inverts to the dispersed phase. This phenomenon is called *phase inversion*. After phase inversion, oil droplets in water invert to water droplets in oil and vice versa.

The phase inversion was observed to occur for a specific range of watercut values. Water is the continuous phase for higher watercuts and oil is the continuous phase for lower watercuts. Between these two limits there is a range that either phase can be stably continuous. This region is called *ambivalent range* [2]. The ambivalent range shows the hysteresis effect presence [3]. Phase inversion from oil-in-water to water-in-oil dispersion and water-in-oil to oil-in-water dispersion represents the hysteresis phenomenon [4,1]. The procedure at the beginning of the dispersion determines which phase will be continuous [2]. The ambivalent range width depends on how the dispersion is produced [5].

Various parameters which affect the phase inversion and ambivalent range have been investigated in an agitated tank by different researchers [1,2,4,5,6,7]. The impeller size [4,7], tank impeller diameter ratio [4], and density difference of liquids [4,6,7] do not have important effect on the ambivalent range. Ambivalent range narrows by increasing the agitation speed [5,1]. According to Norato et al. interfacial tension has a significant effect on ambivalent range [4]. The ambivalent range is a function of viscosity ratio which has significant effect on ambivalent range and phase inversion [2,4,6,7].

Phase inversion is defined by coalescence and breakup imbalance [8,7]. It is found that the coalescence rate is higher than breakup rate at the phase inversion region [7]. Therefore, droplet size increases significantly before the phase inversion because of the high coalescence rate [8,1]. Also, it is found that the phase inversion process occurs gradually and locally within the mixture [1].

Although viscosity and density of two dispersion types in an oil–water mixture are identical, dielectric constant of oil-in-water and water-in-oil are different [9].

In the watercut meter industry, different methods have been in use such as near-infrared technique (NIR) [12], microwave method [13–15], gamma tomography [16], and impedance measurements [17]. The impedance measurement method uses the impedance

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Nomenclature

A_{ci}	closed loop gain for ideal op-amp
A_{or}	open loop gain for ideal op-amp
C_f	feedback capacitance
C_s	stray capacitances due to the effect of the cable
C_x	equivalent mixture electrical capacitance
f	frequency
$Phase_T$	threshold phase
R_f	feedback resistance
R_x	equivalent mixture electrical resistance
V_i	input voltage of sensor
V_o	output voltage of sensor
β	feedback factor
w	angular frequency
w_c	-3 dB cut off angular frequency
w_u	op-amp unity gain bandwidth

variation of the oil–water mixture for different water contents to obtain the watercut. There are different types of sensors and configurations that are in use for impedance measurements such as stripe, ring [18], cylindrical [17] and 6 electrodes configuration [19].

The impedance method is applicable for gas–liquid mixture and liquid–liquid emulsion [20,21]. In the Turbomachinery Laboratory at Texas A&M University, the impedance measurement method was used for gas volume fraction measurement in the gas–liquid (air–water) mixture employing two impedance electrodes and a slotted orifice plate as the flow conditioner and homogenizer [22]. In the current study, a similar sensor but with higher frequencies was implemented to measure the watercut in oil–water emulsions in an agitated vessel.

The accuracy of watercut meters is typically reported for well homogenized conditions. In two-phase oil pipelines, due to the presence of pumps, valves, bends, flow conditioners and flow homogenizers, the level of flow heterogeneity and emulsion properties of the oil–water mixture changes. The level of flow heterogeneity and emulsion properties affects the accuracy of the watercut meters, specifically in the ambivalent range.

To reduce the dependency of electrical response of the watercut sensor to the upstream flow conditions, the electrical characteristic of the mixture for different emulsion properties and heterogeneity levels was investigated in this study.

In the real-world watercut meter applications, the emulsion properties vary with changing the volume fraction of the mixture, agitation or applying shear forces to the mixture. In this study, to investigate the effects of emulsion properties and the level of mixture heterogeneity to the sensor response, the mixture at specific watercut was agitated for different durations of time. The electrical response of the sensor to the variation of emulsion properties by time was recorded.

By using the response of a multi-frequency impedance sensor along with a newly developed algorithm detailed mixture characterization were performed. Also, resistance and capacitance of the mixture were calculated. In addition, hysteresis effects were studied in order to investigate their influence on the accuracy and performance of the watercut meter.

2. Experiments

In this section, experimental setup, procedure, and mixture resistance and capacitance calculation are provided.

2.1. Experimental setup

The test section is shown in Fig. 1. In this test section, a 48.6 mm diameter agitated vessel was used to mix two immiscible liquids. The liquids were chosen to be tap water and vegetable oil. The selection was made based on availability and ease of disposal. The agitated vessel includes an impeller with four blades that are 24 mm long. Liquids were mixed in a 30.5 cm long vertical clear PVC pipe. Two ultra-machinable brass impedance electrodes were flush mounted to the pipe across from each other. The sensors at their contact points with the fluid mixture have the diameter of 17 mm.

The electrodes were connected to the circuit by using RG 58/U type coaxial cables. The circuit is shown in Fig. 2. In the circuit, 'Texas Instrument – LM7171' op-amp was used in the shown configuration. Dual power supply was used to apply 15 VDC to the op-amp. In the circuit, R_x and C_x represent the resistance and capacitance of the mixture, respectively. R_f and C_f are the feedback resistance and capacitance. C_{s1} and C_{s2} are the stray capacitances due to the effect of the cables. The lengths of the cables were kept as short as possible to decrease the stray capacitance effect on the circuit performance.

Twelve sinusoidal signals with different frequencies ranging from 0.2 to 10 MHz and similar amplitude were combined and applied as the input signal to the circuit. A Picoscope-5242B was used as a signal generator and data acquisition system. The Picoscope, which is shown as DAS in Fig. 1, has two input channels and one output channel. The output channel was connected to input of the circuit and one of the inputs of the Picoscope. Other input channel of the DAS was connected to the output of the circuit. The Labview interface was used to display and record the input and output waveforms.

2.2. Experimental procedure

In this section, detail descriptions about the experiments are provided. Two types of studies were performed. First, emulsion properties of the mixtures were investigated. Emulsion properties were varied by agitating and applying shear forces to the oil–water mixture. This process changes the droplet size, the dispersed phase distribution and electrical mixture properties. To study the effect of emulsion properties on the sensor response, water–oil mixture for different watercut values was mixed in a 48.6 mm diameter agitated vessel for different durations of time. The duration of mixing process varies the droplet size and the distribution of the dispersed phase. To initiate the experiments,

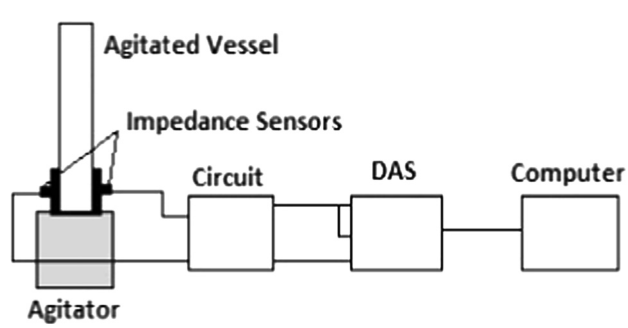

Fig. 1. Schematic representation of the experimental setup.