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Measurement of oil bubble size distribution in oil-in-water emulsions using a distributed dual-sensor probe array

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ABSTRACT

The scope of the present study is to experimentally investigate the oil bubble size distribution in oil-in-water emulsions. The geometry parameter of a dual-sensor probe is firstly optimized through examining its electrical field distribution and sensitivity. Afterward, an eight-channel distributed dual-sensor probe array is designed for a pipe with 20 mm inner diameter (ID) to measure the local holdup, bubble velocity as well as bubble size of the dispersed oil phase in oil-in-water emulsions under low mixture velocity and high water-cut. The results indicate that the changes in mixture velocity and water-cut substantially affect the oil bubble size distribution on different positions at the pipe cross section. With the extraction of the increasing rate regarding multi-scale cross entropy (MSCE) from the fluctuating signals from the leading and rear sensor of the dual-sensor probe, the dynamic instability in the motion of oil bubbles is analyzed. It proves that the multi-scale cross entropy can be an effective indicator on globally characterizing the nonlinear dynamics in oil-in-water emulsions at the pipe cross section.

1. Introduction

For the sake of enhancing oil recovery, alkali-surfactant-polymer (ASP) flooding has been widely applied in oilfields. The injection of surfactant can significantly reduce the interfacial tension and further lead to the obvious enhancement in oil displacement efficiency [1–3]. However, emulsions arise with the surfactant added to the oil wells, where the remarkable change in the rheology brings about great difficulties in the accurate measurement of flow parameters. Therefore, a correct understanding on the local flow characteristics in the pipeline flow of emulsions will be beneficial for uncovering the underlying coalescence and breakup mechanism in oil bubbles during the process of emulsification.

The research results have shown that the addition of surfactant can grossly affect the pressure drop and flow pattern in gas-liquid two-phase flow. Duangprasert et al. [4] investigated the effect of sodium dodecyl sulfate (SDS) on the flow characteristics in vertical upward gas-liquid flows and reported the decrease in gas Reynolds number at which flow pattern changes from slug flow to slug-bubble transition flow. They also found a significant reduction in pressure drop gradient in slug flow as well as slug-churn transition flow. Xia et al. [5] implemented a gas-liquid two-phase flow experiment in a 59 mm ID inclined upward pipe with 100 ppm SDS and addressed that SDS plays an important role in reducing pressure drop gradient in slug and annular flow. A 88.6% drag reduction in vertical upward gas-liquid two-phase flow with the addition of HY-3 surfactant derives from the study of Liu et al. [6]. van Nimwegen et al. [7,8] placed their research emphasis on the effect of inclination angle on the surfactant-added gas-liquid flows. The results indicate that the inclination angle seldom affects the flow characteristics under high gas velocities, while surfactant presents an obvious impact on the minimum in pressure drop and flow pattern with low gas velocities. Additionally, the interface morphology in gas-liquid flows with the addition of surfactant has also received attention [9].

An obvious change of effective viscosity and turbulent pressure drop in oil-water two-phase flow has been reported with the presence of surfactant [10–12], and drag reduction phenomenon in the pipeline of emulsions is demonstrated to be associated with the dispersed phase concentration [11], oil viscosity [12] as well as pipe ID [13,14]. With the intention to further uncover the mechanism in drag reduction, laminar and turbulent behaviour in the pipeline flow of emulsions has also been a research focus [15–19]. Besides, the addition of surfactant can significantly reduce the interfacial tension, leading to the oil droplets distributing in the pipe with micrometer sizes. Hence, intensive attention has been paid on the stability as well as the size of dispersed phase in emulsions. Krebs et al. [20] studied the dynamic coalescence phenomenon of oil droplets in emulsions in a micro channel. Static light scattering technology was applied by Malassagne-Bulgarelli

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et al. [21] to analyze the relationship between oil bubble size distribution and oil mass fraction in emulsions. It was concluded that the oil bubble size at which the peak of probability in oil bubble size distribution shifts to a higher value with the increasing oil mass fraction. Using in situ rheo-optical measurements, Covis et al. [22] suggested that the size of oil droplets barely changes when oil void fraction locates between 20% and 60%. Kowalska [23] proposed that oil droplet sizes in oil-in-water emulsions measured from laser scattering method show a good agreement to the results simulated with Kleeman's method. The effectiveness of by-line Nuclear Magnetic Resonance (NMR) emulsion droplet sizing was elucidated by Ling et al. [24]. Considering the physical property discrepancies in emulsions under different water conductivities, the variation in salinity is proved to have a profound influence on the parameters including viscosity and dispersed phase size [25–27].

To date, the measurement of oil droplet sizes in emulsions is mainly restricted to static image observation. However, the investigation on the local flow characteristics in the pipeline flow of emulsions is deficient. As reported, oil bubble size in emulsions is generally micrometers and is particularly difficult to be detected. With the advantages of high sensitivity and quick response, probe technique including optical probe [28–30] and impedance probe [31–39], is widely utilized in local flow parameters measurement. Therefore, investigating the potential of mini-probe technique is conducive to develop novel methods for measuring oil bubble size distribution in oil-in-water flows with surfactant addition.

On the basis of optimizing a dual-sensor probe, we set up the measurement system for a distributed dual-sensor probe array and implement an experiment of pipeline flow of oil-in-water emulsions with low mixture velocity and high water-cut, where the local oil bubble velocity, oil holdup as well as oil bubble size distribution are extracted on different positions at the pipe cross section. The oil bubble size distribution through probe technique is compared with the results obtained from the images using an optical microscope. Furthermore, multi-scale cross entropy algorithm is applied to investigate the dynamic instability in the motion of oil bubbles.

2. Optimization of the distributed dual-sensor probe array

The schematic diagram of the distributed dual-sensor probe array is shown in Fig. 1, where it can be seen that the probe array is composed of eight identical dual-sensor probes. The coordinates of the centers of eight dual-sensor probes are tabulated as Table 1. Probe 1 is located at the center of the pipe, while Probe 2 to Probe 4 all locate at the position with a distance of 3.75 mm from the center. As for Probe 5 to Probe 8, the distance from which to the center are all equal to 7.5 mm. The dual-sensor probe consists of a leading and a rear sensor respectively with a diameter of 0.15 mm, as well as a 2.5 mm ID stainless steel sleeve. Both of the two sensors are coated with Teflon for insulation. Afterward, the insulation layer at the sensor tip is gently removed with abrasive paper. Insulating compound is injected to the space between sensor and sleeve to fix the probe. During the experimental process, the tips of leading and rear sensors are both stimulated by +15 V excitation voltages, while the sleeve is connected to the ground. Thus an equivalent circuit where a current flows through the sensor tip and sleeve forms. When the probe is immersed in oil phase, the equivalent resistance formed by sensor tip and sleeve significantly rises due to the high resistivity, and the output voltage correspondingly presents a low value. Conversely, the output voltage increases to a high value when the probe is surrounded by water phase because of its better electrical conductivity. The electrical field distribution of the dual-sensor probe can be described with the Laplace equation:

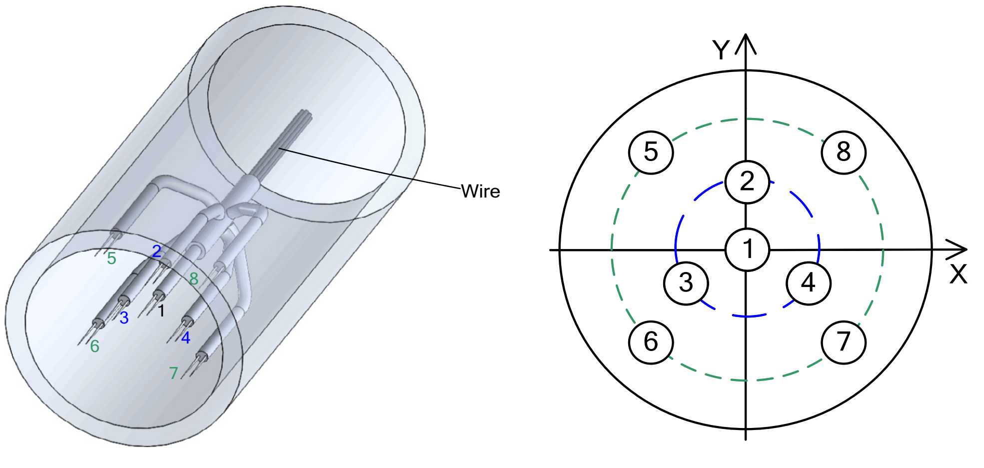
$$\nabla^2 U = \frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} + \frac{\partial^2 u}{\partial z^2} = 0 \tag{1}$$

The geometry parameters of the dual-sensor probe to be optimized include the lengths of the leading and rear sensor stretching from the bottom of the sleeve l_1 and l_2, as well as the radial distance between the two sensors labeled as s [see Fig. 2(a)]. Wu et al. [40] formulated the relationship between the size of dispersed phase d_B and the axial distance from the leading to the rear sensor d ($d = l_1 - l_2$) as:

$$0.5 d_B \leqslant d \leqslant d_B \tag{2}$$

Table 1
Central coordinates of the distributed dual-sensors probes.

Probe no.	X (mm)	Y (mm)
Probe1	0	0
Probe2	0	3.75
Probe3	−3.2476	−1.875
Probe4	3.2476	−1.875
Probe5	−5.3033	5.3033
Probe6	−5.3033	−5.3033
Probe7	5.3033	−5.3033
Probe8	5.3033	5.3033



(a) 3D structure of distributed dual-sensor probe array (b) Distribution of dual-sensor probes

Fig. 1. Distributed dual-sensor probe array.