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Measurement of gas phase characteristics in bubbly oil-gas-water flows using bi-optical fiber and high-resolution conductance probes

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ABSTRACT

In the present study, experiments are carried out to investigate local gas phase characteristics of bubbly oil-gas-water flows in a vertical upward pipe with small inner diameter (ID). Bi-optical fiber probe signals at different radial positions and leading and rear half-ring conductance sensor fluctuation signals are collected in a 20 mm ID test pipe. Then flow parameters, including local gas volume fraction, gas velocity and bubble size distribution are extracted according to optical probe signals. The results show that the gas phase superficial velocity, mixture superficial velocity of oil and water as well as mixing ratio of oil and water all have significant impacts on the distribution of gas phase flow parameters. Additionally, in order to validate the results obtained from optical probe signals, multi-scale cross entropy (MSCE) algorithm is applied to analyze signals of high-resolution half-ring conductance sensor to uncover the dynamical instability of oil-gas-water bubbly flows under different flow conditions.

1. Introduction

Oil-gas-water three-phase flows are frequently encountered in petroleum exploitation and transportation in industrial processes. The flow structures are more complicated compared with gas-liquid or oil-water two phase flow due to significant differences in physical property and mutual interactions among phases, which makes it a great challenge to measure local flow parameters. Bubbly flow is a fundamental structure in three-phase flows and a comprehensive knowledge on its local gas phase characteristics is of significant importance to design and optimize the structure of sensor as well as to develop oil-gas-water three-phase flow models.

Probe technology has been widely used in local flow parameters measurement in multi-phase flow. In early researches, Neal and Bankoff [1] proposed that conductance probe can be used to measure local concentration in gas-liquid flow on the basis of conductivity contrast between continuous and dispersed phases. Miller and Mitchie [2] acquired void fraction with optical fiber probe due to refractive index distinction and found that the angle and structure of probe were key factors to affect the results. Lucas et al. [3] optimized conductance probe with six electrodes using finite element analysis and obtained profiles of concentration and velocity in liquid-solid flows. Abauf et al. [4] theoretically deduced the cone angle of optical probe and found that the bubble rising velocity was related to piercing time, i.e. when the velocity is greater than 0.4 m/s, it would be a constant multiplied by the time. Afterwards, Cartellier et al. [5,6] made a comparison among three optical probes with different structures and found that sharp cone probe was the most suitable shape in phase distinctions and velocity measurement. More parameters would be acquired and the accuracy of sensors could be verified with combination measurement using optical probe, conductance probe and other sensors [7–9]. Related researches show that measurement error is significantly caused by complex interaction between optical probe and bubble. Julia et al. [10] recorded the piercing process with high speed camera and concluded that blinding effect, crawling effect and drifting effect were main error sources. Vejrazak et al. [11] utilized three non-dimensional parameters to characterize the interaction and found the interaction position had great influence on the measurement precision.

Local flow parameters, such as gas volume fraction, gas velocity and bubble size distribution can be calculated from signals of probe. Researches show that a more accurate concentration distribution of dispersed phase can be obtained with a proper threshold [12–15]. The velocity can be extracted by dual-probe technology and cross-correlation method [16–19]. Utilizing a single optical probe can also measure velocity because of its special structure [20]. Recently, four-sensor probes are developed to measure the velocity vectors of dispersed phase [21–23]. An array of probes can be used to acquire parameters at different positions, from which we can acquire more detailed flowing information compared with single probe [24–26].

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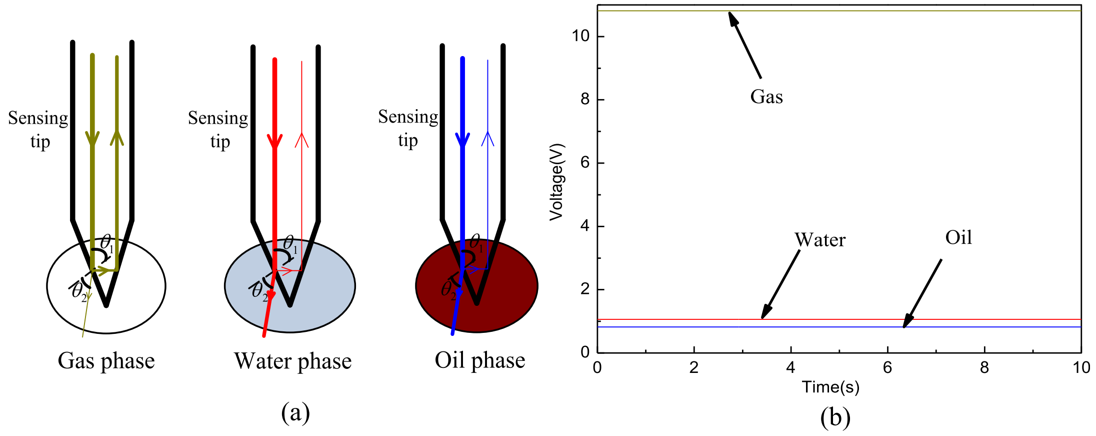

Fig. 1. Measurement principle and result of optical fiber probe.

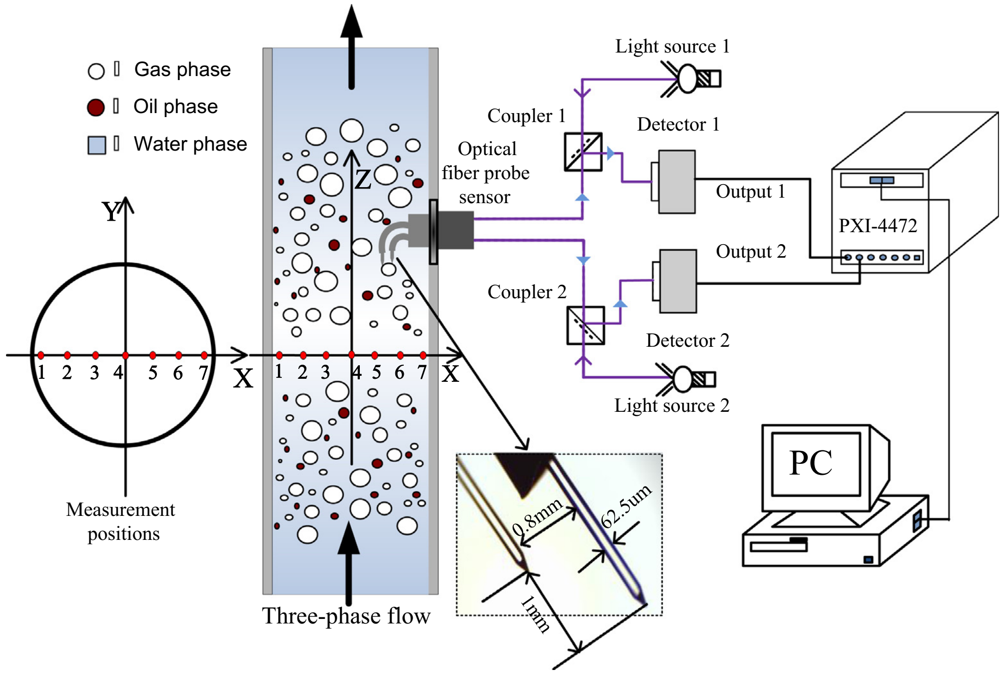

Fig. 2. Measurement system of traversing bi-optical fiber probe sensor.

As oil phase and gas phase are both non-conductive media, measurement of gas phase characteristics in bubbly oil-gas-water flows cannot be realized by conductance probe. Considering the unique advantage of optical probe in high sensitivity to detect gas, a traversing bi-optical fiber probe sensor is designed to acquire gas phase characteristics at seven positions in a 20 mm ID test pipe in this study. The profiles of local gas volume fraction, gas velocity along with bubble size distribution are obtained from the optical probes signals. In order to validate the results derived from optical probe signals, we collected the fluctuation signals of high-resolution leading and rear half-ring conductance sensor simultaneously and uncover dynamic instability in bubbly flows with MSCE analysis.

2. Measurement system and experiment facility

2.1. Measurement system of traversing bi-optical fiber probe sensor

Measurement of gas volume fraction using optical fiber probe is based on the refraction and reflection law. Phases can be discriminated by detecting the intensity of reflected light due to the contrast in refractive index. When light reaches the interface between probe and media, refraction and reflection will occur based on Snell refraction law:

$$n_1 \mathrm{Sin}\,\theta_1 = n_2 \mathrm{Sin}\,\theta_2 \tag{1}$$

and Fresnel reflection law [27]:

$$\begin{aligned} r_s &= \frac{n_1 \cos\theta_1 - n_2 \cos\theta_2}{n_1 \cos\theta_1 + n_2 \cos\theta_2} \\ r_p &= \frac{n_2 \cos\theta_1 - n_1 \cos\theta_2}{n_2 \cos\theta_1 + n_1 \cos\theta_2} \end{aligned} \tag{2}$$

where n_1 and n_2 represent refractive indexes of two media, θ_1 and θ_2 indicate incident and refraction angles, r_s and r_p denote reflectivity of *s*-wave and *p*-wave. As shown in Fig. 1(a), most of the light will be reflected back and return to measuring terminal through the fiber when the tip of probe makes contact with gas phase. On the contrary, most of the light will be refracted out and little light will return back when the tip is immersed in liquid phase. An optical probe with 35° cone angle is adopted in this study, which is differ-