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Correlation of aspect ratio and drag coefficient for hydrate-film-covered methane bubbles in water

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ABSTRACT

Understanding the law of hydrate-film-covered methane bubbles (MHF-bubbles) rise is a prerequisite for predicting the formation and plugging of hydrate formation in deep water wellbore under bubble flow conditions. The aspect ratio and the drag coefficient are two key parameters for predicting the rising velocity of MHF-bubbles. In this work, an experimental facility is built to simulated deep-water wellbore environment. To effectively process the experimental data, a theoretical model for the rising velocity of a single MHF-bubble was established. The motion and deformation of single MHF-bubbles rising were investigated by injecting methane bubbles into water at 6 MPa and 4 °C. Diameters in vertical and horizontal axes of MHF-bubble, bubble size were recorded by high-speed photography. An image processing software was used to measure aspect ratio and terminal rising velocity. The results showed that due to the formation of the hydrate film the MHF-bubble is less likely to deform, and its aspect ratio remains relatively stable during ascent and decreases as the equivalent diameter increases. The drag coefficient decreases in the region where the equivalent diameter of the bubble is less than 1.5 mm and increase along with equivalent diameter in the range 1.5–7 mm. The experimental results of drag coefficient and aspect ratio were compared with correlations available in literature. The comparison showed that these correlations do not give fully satisfactory results in predicting the drag coefficient and aspect ratio of MHF-bubble rising in water. As a result, two new empirical correlations were proposed to correlate the aspect ratio as a function of Eötvös number (*Eo*) and the drag coefficient as a function of Morton number (*Mo*), Eötvös number (*Eo*), Reynolds number (*Re*). It was found that the values predicted by new empirical correlations are generally in good agreement with the experiment results. The results of this study have great significance to research into the problem of natural gas–liquid multiphase flow under high pressure and low temperature.

1. Introduction

With the continuous development of deep-water oil and gas resource exploration. The problem of flow assurance in wellbores caused by the formation or reformation of NGHs has become a hot research topic. Understanding the law of hydrate-film-covered methane bubbles (MHF-bubbles) rise is a prerequisite for predicting the formation and plugging of hydrate formation in deep water wellbore under bubble flow conditions. The aspect ratio (E) and the drag coefficient (Cd) are two key parameters for predicting the rising velocity of MHF-bubbles.

Substantial work on terminal rising velocity models [1–7] and drag coefficient correlation [8–17] has been performed to help us understand the upward motion of methane bubbles in deepwater wellbores. However, the rising of MHF-bubbles is more complicated than that of other bubbles. As early as the 1980s, there were studies on hydrate formation on bubble surfaces. Maini and Bishnoi et al. [18] observed the phenomenon at 3 °C and above 4.826 MPa. Furthermore, they also observed the shedding of small hydrate particles on the edge of bubbles. Topham et al. [19] believed that hydrates would form on bubble surfaces and that gas would transfuse from the inside of the hydrate shell to the outside. Based on experimental observation and theoretical analysis, Gumerov and Chahine et al. [20] concluded that hydrate formation on a bubble surface is subject to the influence of heat transfer rather than mass transfer. Brewer et al. [21] found that the nucleation time for the hydrate on a bubble surface is very short in a

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deepwater field test. However, the influence of a hydrate surface layer on the rising velocity of methane bubbles in deepwater wellbores is significant because the hydrate density is equal to that of water. Existing research results and analysis indicate that, compared with the original bubble, the volume of MHF-bubble changes little, but the weight of the entire bubble and the surface tension between the hydrate and the fluid change [22], which leads to a decrease in the rising velocity of MHF-bubbles.

Luo et al. [23] reported that at 5 °C and 0.15 MPa, bubble surfaces do not form hydrate films, and that their rising velocity is 20.45 ± 0.04 cm/s. However, when the pressure is increased to 0.36 MPa at the same temperature, the bubble surfaces form a thin hydrate film layer, and their rising velocity decreases to 19.11 ± 0.15 cm/s. With further increase in pressure, the hydrate film on the bubble surfaces thicken, and their rising velocity decreases to 16.70 ± 0.34 cm/s. He finally concluded that the decrease in the rising velocity of the MHF-bubble is due to an increase in the bubble weight, and that increasing the pressure promotes hydrate formation on the bubble surface.

Bigalke et al. [16] investigated rising carbon dioxide drops and methane bubbles and observed bubbles with diameters of approximately 1.5 mm at temperatures of 4 and 14 °C and pressures of 16, 24, and 40 MPa. He concluded that changing the surface tension has little influence on the rising velocity of MHF-bubbles, and that the surface tension of a hydrate film is 0.075 Nm^{-1}. Sato et al. [17] described the spatial motion characteristics of rising MHF-bubbles, and observed the rising velocity of MHF-bubbles with diameters of more than 4 mm. Warzinski et al. [24] also observed that the rising velocity of methane bubbles decreases after hydrate formation on the bubble surface, but he did not provide detailed experimental data nor propose a rising velocity model for MHF-bubbles.

In fact, it is very difficult to predict the terminal velocity of bubbles accurately. The rise of a bubble in water is mainly controlled by the bubble characteristics (bubble size, aspect ratio) and properties of gas liquid systems (density, viscosity, surface tension and density difference between gas and liquid, etc.). For MHF-bubbles, the hydrate film thickness can affect the rising velocity, bubble total weight and deformation.

The purpose of this paper is to present the results of studies on MHF-bubble motion in water. To investigate these parameters, an indoor large-scale high-pressure low-temperature system equipped with high-speed high-definition imaging system was built to observe the formation of hydrates on bubble surfaces and the rising of the bubbles simultaneously. To effectively process experimental data, a theoretical model for the rising velocity of MHF-bubbles in water is established in which the equivalent density, influence of hydrate formation on quality distribution, and the thickness of the hydrate film are considered. The experimental results of *Cd* and *E* were obtained by the high-speed high-definition imaging system and compared with correlations available in literature. Finally, two new empirical correlations were proposed to correlate the *E* and the *Cd* of MHF-bubble.

2. Experimental apparatus and procedure

The main experimental apparatus used in this study is shown in Fig. 1, which also shows how the gas is injected into the experimental module and how to control the temperature and pressure of the simulated wellbore.

2.1. Experimental apparatus

The experimental apparatus (Fig. 1) comprises five parts: (1) the temperature control system, (2) the pressure control system, (3) the fluid injection system, (4) the observation module, and (5) the data collection system.

The temperature control system comprises three parts: a refrigeration system, a chilled water circulation system, and a temperature measurement system. These maintain the temperature of the fluid below 4 °C.

The pressure control system comprises two parts: a back-pressure control system and a pressure regulation system. These provide a certain pressure to the experimental system and the gas injection system.

The fluid injection system comprises three parts: a fluid injection system, an additive injection system, and a gas injection

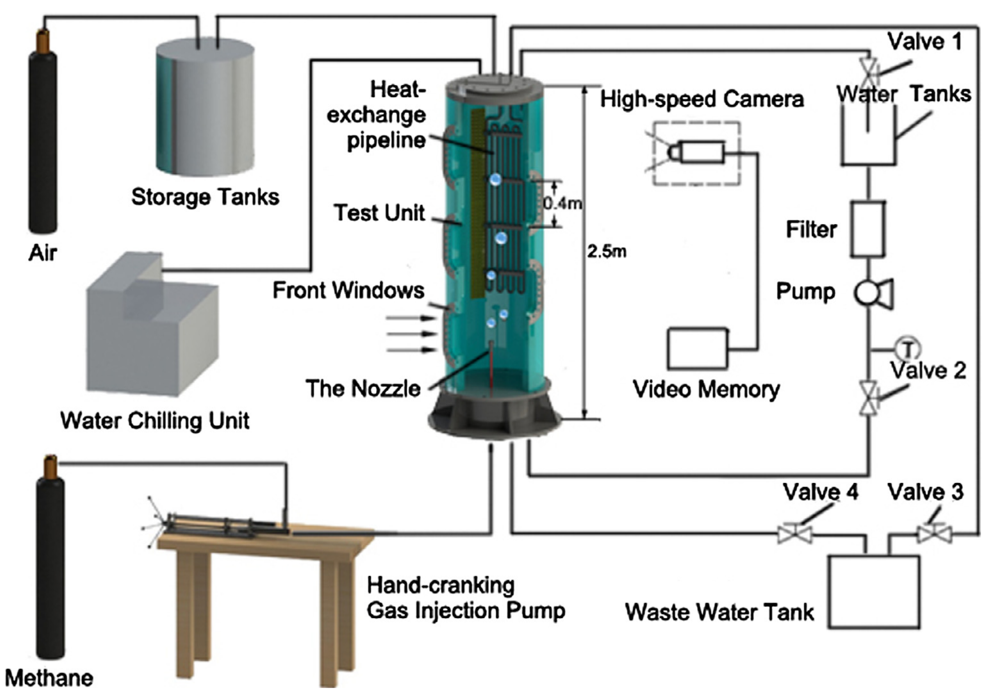

Fig. 1. Experiment process flow diagram for the simulation of oil drop and bubble movement in subsea deep-water.