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Experimental study on the drag coefficient of single bubbles rising in static non-Newtonian fluids in wellbore

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ABSTRACT

Using an empirical drag coefficient model to investigate the laws of bubble rising in non-Newtonian fluids is important for calculating the safe cycle time in avoiding typhoon, tripping operation in offshore drilling engineering. Herein, the drag coefficient for a single bubble rising steadily in a static non-Newtonian fluid within a wellbore was experimentally investigated using a vertical, cylindrical wellbore mimic. The effects of viscosity, density and surface tension of the fluids, as well as bubble diameters on the drag coefficient were studied. The experimental results indicate that the drag coefficient increases with the increase of the fluid viscosity, surface tension and bubble diameters, while the solution density has little effect on the drag coefficient. Meanwhile, the relationship between Reynolds number (Re) and drag coefficient and that between Re and Eötvös numbers (*Eo*) were analyzed, respectively. The result suggests that surface motion leads to a transition of drag coefficient. A new correctional model for the drag coefficient of single bubbles rising in static non-Newtonian fluids in a wellbore was obtained, which showed a good agreement with the experimental data.

1. Introduction

Gas invasions are hazardous during offshore oil and gas well drilling processes. Gas invasion occurs if gasses formed when drilling is stopped for hostile weather diffuse through the mud cake into the wellbore under either balanced or overbalanced conditions. It also occurs if gases formed when drilling natural fractures or cave formations are replaced with drilling fluids. Gas invasion may lead overflows, well kicks, blowouts and other operational accidents (Stewart and Schouten, 1988; Zhang, 1987). Therefore, it is crucial to study bubble rising in a wellbore for drilling design, operation and wellbore pressure control. It is also important for calculating the safe cycle time in avoiding typhoon, tripping operation in offshore drilling engineering.

Due to the complicated rheological characteristics of drilling fluids, empirical drag coefficient models are normally used to calculate the terminal velocity of rising bubbles (Kitagawaa et al., 2004; Loth, 2008; Simonnet et al., 2007; Guan et al., 2014). A rising bubble reaches a terminal velocity in static liquids when the lift and resistance forces get balanced, and relationship between drag coefficient and bubble terminal velocity can be described as follows (Fan, 2008):

$$C_D = \frac{4g(\rho_l - \rho_g)d_e}{3\rho_l u_B^2} \tag{1}$$

where C_D is the drag coefficient for the bubble; d_e is the equivalent bubble diameter, m; u_B is the terminal velocity for the bubble, m/s; ρ_l and ρ_g are the liquid and gas densities, respectively, kg/m^3; g is the local gravitational acceleration, m/s^2. If the drag coefficient is obtained, the bubble terminal velocity can be directly calculated by Eq. (1). Therefore, it is a typical method for investigating the laws governing bubbles rising in non-Newtonian fluids using an empirical drag coefficient model. Chhabra (1988) correlated the drag coefficient in power-law fluids with the drag factor described by a flow index polynomial and proposed the following model:

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$$C_D = \frac{24}{\mathrm{Re}_B}\frac{2+3X_E}{3+3X_E}X \tag{2}$$

where X is the drag factor, and Re_B is the terminal Reynolds number. The power-law model, having wide applicability due to its simplicity (Chhabra, 1993), has been used for the rheological description of non-Newtonian fluids in Eq. (2) and is also used in this work. Shapiro (1961) made certain assumptions and stated the resistance curve for solid particles rising in a liquid can be described simply using the laws of solid particles settling. However, Karamanev and Nikolov (1992) noted the defects in Shapiro's theory. Their experimental results showed that the trajectories of solid particles rising and settling in Newtonian fluids were completely different. Karamanev (1996) suggested the drag coefficient for rising particles to be a constant when the Reynolds number exceeds a critical value. To determine the critical Reynolds number, they proposed a segmentation model based on experimental results:

$$C_D = \frac{24}{\mathrm{Re}_B}\left(1+0.173\mathrm{Re}_B^{0.657}\right)+\frac{0.413}{1+16300\mathrm{Re}_B^{-1.09}} \tag{3a}$$

for $Re_B < 135$, and

$$C_D = 0.95 \tag{3b}$$

for $Re_B > 135$. To determine the mass transfer rate of oxygen from a rising air bubble to the liquid phase, Margaritis (1999) established a relationship between the drag coefficient and Reynolds number based on the experimental data and Turton model (1986). In contrast to Karamanev's model, the critical Reynolds number for Margaritis's model is 60, as follows:

$$C_D = \frac{16}{\mathrm{Re}_B}\left(1+0.173\mathrm{Re}_B^{0.657}\right)+\frac{0.413}{1+16300\mathrm{Re}_B^{-1.09}} \tag{4a}$$

for $Re_B < 60$, and

$$C_D = 0.95 \tag{4b}$$

for $Re_B > 60$. To obtain an approximate expression for the history force on a spherical bubble for finite Reynolds number, Mei et al. (1994) proposed the following empirical drag coefficient model from numerical results:

$$C_D = \frac{24}{\mathrm{Re}_B}\left\{\frac{2}{3}+\left[\frac{12}{\mathrm{Re}_B}+0.75\left(1+\frac{3.315}{\mathrm{Re}_B^{1/2}}\right)\right]^{-1}\right\} \tag{5}$$

Rodrigue et al. (1998) proposed a relatively simpler drag coefficient model for bubbles rising in non-Newtonian fluids to determine a possible existence of a jump discontinuity of bubble velocities:

$$C_D = \frac{16}{\mathrm{Re}_B}Y_{(n)} = \frac{16}{\mathrm{Re}_B}\left[2^{n-1}3^{(n-1)/2}\frac{1+7n-5n^2}{n(n+2)}\right] \tag{6}$$

where n is the liquidity index; $Y_{(n)}$, derived using a perturbation method, is a correction function dependent on the power-law index. Dewsbury et al. (2000) applied Karamanev's model in their experimental study on the dynamics of solid particles rising in non-Newtonian fluids. While studying the movement of a single bubble rising along a slightly inclined surface, Perron et al. (2006) took the C_D value as a constant at 0.95 when $\mathrm{Re}_B > 135$, which was consistent with the actual results. Li Zhang et al. (2008) measured bubbles rising in fluids with high viscosity using a Lucite column, which was a 0.6 m high square cross section (side length 0.21 m) to minimize the wall effect, and developed the following correlation from experimental data:

$$C_D = B_1\mathrm{Re}^{B_2}Ar^{B_3}Eo^{B_4}\left(1+B_5Ac^{B_6}\right) \tag{7}$$

where Re, Ar, Eo and Ac are the Reynolds number, Archimedes number, Eötvös number and acceleration number, respectively; B_i (i = 1, 2, 3, 4, 5, and 6) are constants measured experimentally. Hayashi and Tomiyama (2012) successfully validated the empirical model proposed by Mei et al. (1994) for low Reynolds numbers while studying app:addword:regularityTaylor bubbles rising in a vertical tube.

In Karamanev's model C_D is a constant (0.95) when $\mathrm{Re}_B > 135$, while in Margaritis' model C_D is a constant (0.95) when $\mathrm{Re}_B > 60$. Both Mei's and Rodrigue's models only agree with experimental data for low Reynolds numbers. Therefore, verifying or determining the critical Reynolds number is necessary for more general applications. On the other hand, most of these empirical models only correlate to Reynolds number without considering the bubble characteristics and other liquid physical parameters. Moreover, few studies performed further research on the drag coefficient for bubbles rising in a wellbore. In this work, the drag coefficient of single bubbles rising in static non-Newtonian fluids was experimentally investigated using a vertical cylindrical wellbore mimic. The effects of viscosity, density and surface tension of aqueous solutions, as well as bubble diameters on the drag coefficient were systematically investigated. The relationship between Reynolds number (Re) and drag coefficient and that between Re and Eötvös numbers (Eo) were analyzed, respectively. A novel correlation for the drag coefficient of single bubbles rising in static non-Newtonian fluids in a wellbore was proposed. Compared to previous works, the proposed correlation agrees well with experimental data under wellbore conditions.

2. Experiment and methods

2.1. Setup

Fig. 1 shows a schematic for the experimental setup. The setup consisted of three parts: a wellbore circulation system, a gas injection control system and a data acquisition system. The wellbore circulation system and the gas injection control system were designed and manufactured by China University of Petroleum, with a maximum working pressure of 0.6 MPa.

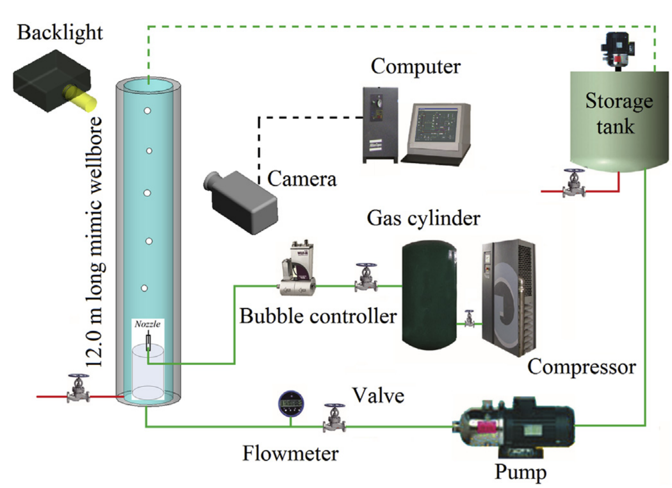

Fig. 1. Schematic for the experimental setup.