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Unified drift velocity closure relationship for large bubbles rising in stagnant viscous fluids in pipes

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ABSTRACT

This study investigates the effects of oil viscosity, pipe diameter, and pipe inclination angle on drift velocity. Experiments were conducted for medium viscosity oils using a 0.0508-m ID pipe for inclination angles between 0° and 90°. In these experiments, it was observed that as the liquid viscosity increased, the drift velocity decreased. Drift velocity displayed a convex parabolic behavior with respect to the inclination angle. For all liquid viscosities, a maximum velocity value was observed between 30° and 50° inclinations from horizontal. A unified dimensionless closure relationship for drift velocity is proposed. It was developed using data acquired in this study and available data from literature with a pipe diameter range of 0.0373–0.178 m.

1. Introduction

Lately, the oil and gas industry turned its focus toward the production of heavier oil, due to the increase and improvement in exploration and drilling technologies, as well as a higher price per barrel of oil and depletion of light oil reserves. In the past, heavy oil reserves were neglected due to the high cost associated with their production, and the lack of proper technology. High density and high viscosity hydrocarbons currently constitute nearly 70% of the available reserves in the world, increasing the need to gain and improve the knowledge of the flow behavior of these fluids.

Most of the multiphase flow models were developed for low viscosity oils. Therefore, these models do not properly consider the effects of viscosity on the flow characteristics and behavior of multiphase flow. Consequently, more comprehensive research to understand the effects of viscosity on multiphase flow is required in order to develop a model that considers liquid viscosity effects.

Gokcal (2005) experimentally studied the effects of high viscosity oil–gas flow. He observed a marked difference between the experimental results for low and high viscosity oils. Additionally, a considerable discrepancy between experimental data and model predictions was reported. Intermittent slug and elongated bubble flow were observed to be the dominant flow pattern. Later, Gokcal et al. (2008) conducted experiments and developed correlations for slug flow characteristics, taking into account the effects of viscosity. The considered parameters correspond to pressure gradient, drift velocity, transitional velocity, and slug length and frequency. All tests were conducted for horizontal flow and oil viscosities range from 0.121 Pa s to 1.0 Pa s. Kora (2010) conducted experiments and developed correlations for slug liquid holdup in horizontal high viscosity oil–gas flow. Jeyachandra (2011) studied the effect of the inclination angle for horizontal and near-horizontal flow.

In general, all the previous studies in high viscosity oils (0.121 Pa s $< \mu_O <$ 1.0 Pa s) demonstrated large differences in two-phase flow behavior as compared to low viscosity oils. In order to clarify the transition between low and high viscosity two-phase flow of hydrocarbons, Brito (2012) conducted an experimental study to analyze the medium viscosity oil (0.39 Pa s $< \mu_O <$ 0.166 Pa s) effect on two-phase flow behavior. She analyzed the change in pressure drop, flow pattern, liquid holdup and flow characteristics in a 0.0508-m ID horizontal pipe.

This study aims to understand the medium oil viscosity effect on the drift velocity for medium oil viscosities (0.039 Pa s $< \mu_O <$ 0.166 Pa s) in horizontal and upward inclined pipes. Gokcal et al. (2008) conducted drift velocity experiments for high viscosity oils in 0.0508-in. ID pipes and observed that viscosity has a major impact on drift velocity. Later, Jeyachandra (2011) carried out an experimental program considering the same viscosity range as Gokcal et al. (2008) in 0.0762-m and 0.1524-m ID pipes. The previous studies are further expanded to include medium oil viscosities and propose a new drift model. The new closure relationship is valid for a broad range of viscosities, inclination angles (0°–90° from horizontal), and pipe diameters.

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1.1. Translational velocity

Translational velocity is defined as the velocity of a slug unit. The expression for translational velocity, v_t, was proposed by Nicklin et al. (1962) as the summation of the total mixture velocity, v_M, multiplied by the flow coefficient, C_o, and the drift velocity, v_d. This is expressed as

$$v_T = C_o v_M + v_d. \tag{1}$$

The flow coefficient, C_o, is an approximate ratio of the maximum to the average velocity of a fully developed velocity profile. For turbulent and laminar flows, C_o is 1.2 and 2.0, respectively (Wallis, 1969). The product of the flow coefficient and the mixture velocity corresponds to the maximum mixture velocity of the slug unit. Based on this expression, the drift velocity is an important parameter of translational velocity, in particular when the mixture velocity is small.

1.2. Drift velocity

Four dimensionless numbers have been identified by previous studies (Wallis, 1969; Weber, 1981; Joseph, 2003) as important terms to characterize drift velocity, namely, Froude, Fr, Eotvos, E_o, Viscosity, N_{vis}, and Reynolds, Re, numbers. Since the viscosity number is obtained by dividing the Froude number by the Reynolds number, only two of them can be used simultaneously.

$$Fr = v_d {\rho_L}^{0.5} \left(gD(\rho_L - \rho_G)\right)^{-0.5}. \tag{2}$$

$$E_O = gD^2(\rho_L - \rho_G)\sigma^{-1}. \tag{3}$$

$$N_{vis} = \mu\left(gD^3(\rho_L - \rho_G)\rho_L\right)^{-0.5}. \tag{4}$$

$$Re = v_d \rho_L D {\mu_L}^{-1}. \tag{5}$$

Dumitrescu (1943) and Davies and Taylor (1950) proposed a potential flow solution for the drift velocity determination in vertical flow. Potential flow theory inherently neglects the effects of surface tension and viscosity, yielding a drift velocity model that is only a function of gravitational effects and pipe geometry. The equation proposed was

$$v_d^v = 0.351\sqrt{gD} \tag{6}$$

Benjamin (1968) followed the potential flow analysis to determine the drift velocity for horizontal flow. He proposed an experimental procedure where the drift velocity for horizontal flow is the same as the velocity of the gas penetration when the liquid is drained out of a horizontal pipe. His experiments provided the following expression for drift velocity.

$$v_d^h = 0.542\sqrt{gD} \tag{7}$$

Wallis (1969) and Dukler and Hubbard (1975) claimed that drift velocity cannot possibly occur in a horizontal pipe since gravity cannot act in the horizontal direction. However, Nicholson et al. (1978), Weber (1981), and Bendiksen (1984) demonstrated that drift velocity in horizontal flow can be the result of a gravitational potential from the difference in pressure between the top and bottom of the bubble nose. Bendiksen (1984) proposed the correlation of drift velocity for inclined flow as follows:

$$v_d = v_d^h \cos\theta + v_d^v \sin\theta. \tag{8}$$

Zukoski (1966) conducted an experimental program to determine the influence of liquid viscosity, pipe diameter, and surface tension over the drift velocity. The author suggested that, for vertical flow, the drift velocity is independent of surface tension effects if $E_o > 40$. Additionally, for $Re > 100$, the effect of the viscosity over the bubble rise velocity is negligible. For low Reynolds numbers, $Re < 4$, the drift velocity is inversely proportional to the liquid viscosity. No analysis of the liquid viscosity effect is presented for horizontal or inclined flow. Zukoski (1966) also suggests that as the pipe diameter increases, drift velocity also increases. Finally, the drift velocity describes a convex curve with respect to the inclination angle, reaching a maximum around 45° from the horizontal.

Wallis (1969) suggested that drift velocity in long gas bubbles is governed by Froude, Viscosity, and Eotvos numbers. He mentioned the existence of the dominance of three effects, namely, inertia ($N_{vis} < 0.003$ and $E_o > 100$), viscosity ($N_{vis} > 0.5$ and $E_o > 100$) and surface tension ($E_o = 3.37$). In summary, if the E_o is larger than 100, the effect of surface tension over drift velocity is negligible for vertical flow.

Weber et al. (1986) presented an experimental study to analyze the effect of liquid viscosity on drift velocity for inclined tubes. His data reveals that depending on liquid viscosity, the drift velocity for horizontal flow, v_d^H, can be either smaller or larger than the drift velocity for vertical conditions, v_d^V. In a 0.0373-m ID pipe, $\Delta v_d = v_d^V - v_d^H$ is negative for low viscosities ($\mu_L < 0.0511$ Pa s) and positive for high viscosities ($\mu_L > 0.194$ Pa s). The authors also proposed a correction to Bendiksen (1984) to account for the case of $\Delta v_d < 0$ as follows:

$$v_d = v_d^h \cos\theta + v_d^v \sin\theta + 1.37(\Delta v_d)^{2/3} \sin(\theta)(1 - \sin(\theta)). \tag{9}$$

2. Experimental program

An experimental study to determine drift velocity in medium viscosity oils for different pipe diameters and inclination angles was conducted. This section includes a detailed description of the experimental facility, fluid properties of the test fluids, experimental procedure, instrumentation, the experimental matrix, as well as the uncertainty analysis that was followed for this study.

2.1. Experimental facility

The experimental facility consists of an oil storage tank, a 20 HP screw pump, a 3.05-m (10-ft) long acrylic pipe with 0.0508-m (2-in.) ID, heating and cooling loops, transfer hoses, two transfer tanks, a diaphragm pump, and instrumentation. The heating and cooling loops are used to maintain the desired temperature and thereby control the viscosity of the oil. The acrylic pipe is located close to the storage tank. The inclination of the pipe can be varied from 0° to 90° using a pulley arrangement.

2.2. Properties of test fluids

Compressed air was used as the gas phase and typical properties of the DN-20 mineral oil used in these tests are as follows: (1) gravity: 30.5°API; (2) viscosity: 0.166 Pa s at 21.1 °C; (3) density: 873 kg/m^3 at 15.6 °C; and (4) surface tension: 0.0275 N/m at 40 °C.

2.3. Experimental procedure

2.3.1. Inclined pipe

After heating the oil to the required temperature for the desired viscosity, the oil pump is turned on to supply oil to the pipe. Then, the main inlet valve and the auxiliary inlet valve are closed. The drainage valve is opened to drain the residual oil captured and thus to create a gas pocket in the inlet chamber. The pulley arrangement is used to set the pipe at the desired inclination. Next, the drainage valve is closed and the main inlet valve is opened to release the gas bubble into the stagnant oil column.