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Hydrodynamic and mass transfer characteristics of slug flow in a vertical pipe with and without dispersed small bubbles

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ABSTRACT

In this work, we present a numerical study to investigate the hydrodynamic characteristics of slug flow and the mechanism of slug flow induced CO_2 corrosion with and without dispersed small bubbles. The simulations are performed using the coupled model put forward by the authors in previous paper, which can deal with the multiphase flow with the gas–liquid interfaces of different length scales. A quasi slug flow, where two hypotheses are imposed, is built to approximate real slug flow. In the region ahead of the Taylor bubble and the liquid film region, the presence of dispersed small bubbles has less impacts on velocity field, because there are no non-regular intensive disturbance forces or centrifugal forces breaking the balance of the liquid and the dispersed small bubbles. In the liquid slug region, the strong centrifugal forces generated by the recirculation below the Taylor bubble lead to the effect of heterogeneity, which makes the profile of the radial liquid velocity component sharper with higher volume fraction of dispersed small bubbles. The volume fraction has a maximum value in the range of $r/R = 0.5–0.6$. Meanwhile, it is usually higher than 0.35, which means that larger dispersed bubbles can be formed by coalescences in this region. These calculated results are in good agreement with experimental results. The wall shear stress and the mass transfer coefficient with dispersed small bubbles are higher than those without dispersed small bubbles due to enhanced fluctuations. For short Taylor bubble length, the average mass transfer coefficient is increased when the gas or liquid superficial velocity is increased. However, there may be an inflection point at low mixture superficial velocities. For the slug with dispersed small bubbles, the product scales still cannot be damaged directly despite higher wall shear stress. In fact, the alternate wall shear stress and the pressure fluctuations perpendicular to the pipe wall with high frequency are the main cause for breaking the product scales.

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1. Introduction

Slug flow, one of the most frequently encountered patterns of two-phase flow, usually occurs in the chemical process, nuclear and petroleum industries, such as production and transportation of hydrocarbons, boiling and condensation processes in thermal power plants and emergency cooling of nuclear reactors.

In real slug flow, the Taylor bubble is separated by the liquid slugs that may or may not contain dispersed smaller bubbles. The real slug flow is characterized by its random intermittence and inherent instability. One of the main characteristics is the pseudo-periodical alternation of Taylor bubble with an annular liquid film around it and liquid slug. The two regions constitute "slug unit" and slug flow consists of a sequence of slug units. In order to understand the complex characteristics of slug flow, various experiments has been conducted to study the Taylor bubble, the liquid film and the liquid slug in stagnant and flowing liquids for various inclination angles. In this paper, the upward slug flow in a vertical pipe is emphasized.

The rising velocity of the Taylor bubble in a stagnant liquid is influenced by the forces including the viscous, inertial and interfacial forces. White and Beardmore (1962) described a wide spectrum of experimental results on this problem in vertical tubes and presented a graphical map where the relative magnitudes of all the three kinds of forces for vertical pipes were shown.

In a fully developed slug flow, the rising velocity of the Taylor bubble can be regarded as steady. A great number of experiments have shown that the rising velocity of the Taylor bubble in a flowing liquid depends to a great extent on the mixture velocity and the rising velocity in stagnant liquid. Nicklin et al. (1962) suggested an empirical correlation for the rising velocity of the Taylor bubble V_{TB} in a flowing liquid as follows:

$$V_{TB} = CV_S + V_{TB0}, \tag{1}$$

where V_{TB0} is the rising velocity of the Taylor bubble, C is the coefficient and V_S is the mixture velocity. The term CV_S is interpreted as the fluid velocity at the centerline of the pipe just upstream of the

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nose of the Taylor bubble or the maximum local superficial liquid velocity (Nicklin et al., 1962). For fully developed turbulent flows, $C \simeq 1.2$, which is close to the ratio of the maximum centerline velocity, V_C, to the averaged mixture velocity, V_S, when the one seventh power velocity profile is assumed; for fully developed laminar flows, $C \simeq 2$, which is close to the ratio of $V_C/V_S = 2$ when the parabolic profile for the velocity is assumed (Collins et al., 1978; Nicklin et al., 1962). The flow characteristics of slug flow especially around the Taylor bubble have been measured by many investigators because of its importance regarding the influences on the trailing bubble and mass transfer. Ahmad et al. (1998) obtained the velocity profiles in the liquid film and in the wake for the near-wall region surrounding single Taylor bubbles and pairs of Taylor bubbles, respectively, using the photochromic dye activation (PDA) method. This method was also used by DeJesus et al. (1995) and Kawaji et al. (1997). The velocity distribution in horizontal slug flow was measured by Kvernvold et al. (1984) using the laser doppler velocimetry (LDV) technique. Polonsky et al. (1999) determined the velocity field in front of a Taylor bubble rising in stagnant and upward flowing water using particle image velocimetry (PIV). Van Hout et al. (2002) also applied PIV to measure the velocity characteristics of the flow field around a Taylor bubble rising in stagnant water in a vertical pipe. The study was extended by Shemer et al. (2005) to include Taylor bubbles rising in laminar and turbulent background flows. PIV measurements of the velocity field in the wake of an elongated Taylor bubble were performed by Shemer et al. (2007) for different pipe diameters and various Reynolds numbers.

Recently, more and more attention has been paid to the two-phase flow induced internal corrosion of pipelines, in which the gas–liquid mixture of CO_2, H_2S, oil and water is transported (Liu, 1997; Maley and Jepson, 2000; Wang et al., 2001; Wang and Nesic, 2003). In the process of corrosion, what is happening near the tube wall has a great influence on the corrosion (Efird, 2000). It can be deduced and experiences have also shown that both mass transfer coefficient and wall shear stress, which are enhanced by multiphase flow, are the crucial parameters governing the multiphase flow induced corrosion, especially in the vertical upward slug flow.

Up to now, the measurements of wall shear stress and mass transfer coefficient are still a difficult problem. Kaul (1996) and Sun (1991) studied the wall shear stress of horizontal slug flow by hot film probes. Liu (1997) studied the wall shear stress in vertical bubbly flow by the hot film probes. Cognet et al. (1984), Hanratty (1991) and Mao and Dukler (1989) studied the wall shear stress in vertical slug flow by limiting diffusion current probes. Limiting diffusion current technique has also been widely employed over the past several decades to measure the mass transfer coefficients under a large variety of flow conditions. Wang et al. (2001) studied the mass transfer coefficient in water–oil–gas multiphase flow in horizontal pipelines. Zheng and Che (2007) also used this technique for the mass transfer coefficients. Besides, a thoroughly experimental investigation on the hydrodynamic characteristics of gas–liquid vertical upward slug flow was achieved in their paper.

Obviously, studying the flow and the wall transfer characteristics is essential in order to understand the intrinsically complicated natures of slug flow and slug flow induced corrosion. For further understanding on the mechanisms of slug flow and slug flow induced CO_2 corrosion, there is an urgent need for a better insight into the details of slug flow. Fortunately, computational fluid dynamics (CFD) technology is a good tool to achieve the objective. There have been several papers performing numerical simulations of the slug flow in a vertical pipe. Mao and Dukler (1990, 1991) developed a method for determining the shape and rise velocity of a single Taylor bubble rising in stagnant or flowing liquid. The gas-free liquid flowing was solved only for the regions ahead and around the Taylor bubble up to its bottom and the flow behind the bottom of the Taylor bubble was excluded from the calculation. Turbulence was incorporated into the model through the low-Reynolds-number k–ε model of Nagano and Hishida (1987), where a damping factor was employed to adjust the turbulent viscosity between the pipe wall and the Taylor bubble interface. In the paper of Clarke and Issa (1997), the proposed method was based on the ensemble averaged transport equations governing the flow of the liquid around the Taylor bubble and in the slug, which together comprise one slug unit. Turbulence was accounted for by the standard k–ε model. An iterative scheme was used to determine the shape of the bubble and its rise velocity from the conditions of constant pressure within the bubble and smoothness of the bubble nose at the axis. The equations were solved on a block structured, non-orthogonal mesh which conforms to the flow domain boundary. The method also incorporated cyclic boundary conditions at inlet and outlet for periodic slug flow and the presence of dispersed gas in the liquid slug was accounted for approximately by assuming homogeneous flow within the liquid slug. Bugg et al. (1998) extended the numerical model of Mao and Dukler (1990, 1991) to simulate a single Taylor bubble rising in stagnant liquid over a large range of conditions. In their extended model, the solution domain was extended behind the Taylor bubble, allowing field information to be obtained in the wake region. The volume of fluid (VOF) method was implemented by Taha and Cui (2006). Turbulence was accounted for by the RNG k–ε model. The shape and rising velocity of a single Taylor bubble was calculated in stagnant and in moving liquid in vertical tubes. The velocity field in a slug unit and the wall shear stress were also calculated. Zheng et al. (2007), also employing the VOF method, simulated almost the same properties of slug flow as Taha and Cui (2006). Besides, the near wall mass transfer, the slug flow induced CO_2 corrosion rate, the formation and the damage mechanism of corrosion product scale are included, too. Turbulence is simulated through the low Reynolds number k–ε model.

In the published numerical simulations for slug flow over the past several decades, the great endeavor has been devoted to the Taylor bubble shape and the flow characteristics around the Taylor bubble. It is usually assumed that the fluid around the Taylor bubble is liquid, a single phase fluid, and the dispersed small bubbles around the Taylor bubble are out of consideration (sometimes some large bubbles shedding off from the Taylor bubble can be captured by the VOF method. However, they are not the dispersed small bubbles). However, plenty of the dispersed small bubbles exist in real slug flow, especially in the liquid slug region, where intensive mass transfer and momentum transfer happen. It is expected that the consideration of the dispersed small bubbles can lead to more reasonable results. Only the work of Clarke and Issa (1997) has referred to the dispersed small bubble. Nevertheless, the assumption of homogeneous flow within the liquid slug determines that the effect of heterogeneity due to the presence of dispersed small bubbles cannot be reflected. Thus, the main purpose of the present paper is to develop a new model to simulate the slug flow with dispersed small bubbles. In addition, the investigations of the near wall mass transfer and the slug flow induced CO_2 corrosion in this situation are also the concern of this paper.

In this paper, the coupled model developed by the authors (Yan and Che, 2010), which can deal with the multiphase flow with the gas–liquid interfaces of different length scales, are used to simulate a single Taylor bubble flowing in a vertical pipe with and without dispersed small bubbles. In the present model, a two-phase turbulence model with the modified wall shear stress is employed to account for turbulence. For approximating real slug flow, a quasi slug flow, where two hypotheses are imposed, is built to avoid some physical phenomena difficult to deal with using the reported numerical models. The flow characteristics, the volume fraction distribution of the dispersed small bubbles, the wall shear stress

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