Effects of shape oscillation on mass transfer from a Taylor bubble

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ABSTRACT

Interface tracking simulations of mass transfer from Taylor bubbles were carried out to investigate effects of shape oscillation on the mass transfer. Mass transfer from carbon dioxide Taylor bubbles in a glycerol-water solution was also measured to obtain experimental data for the validation of the numerical method. A high spatial resolution was used to resolve thin concentration boundary layers on the bubble interface, which enabled us to capture the agitation of boundary layer due to interfacial waves. The predicted mass transfer coefficients were in good agreements with the experimental data, provided that the spatial resolution was high enough to capture thin concentration boundary layers of high Schmidt number Taylor bubbles. The simulations have made it clear that the effect of agitation of concentration boundary layer due to interfacial waves on the total mass transfer rate is small and a fluctuation of the Sherwood number is caused by a fluctuation of the bubble surface area. This result implies that interface tracking methods using boundary layer approximations can give accurate predictions for mass transfer from bubbles even when the flow field is not fully resolved when the wave effect on the net mass transfer is negligible.

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1. Introduction

A large bubble flowing through liquid in a circular pipe is bullet-shaped and is called the Taylor bubble. Since Taylor bubbles are often encountered in various practical systems such as heat pipes, chemical and nuclear reactors and so on, many theoretical, experimental and numerical studies on Taylor bubbles have been carried out, e.g. Dumitrescu (1943), Davies and Taylor (1950), Bretherton (1961), Wallis (1969), Nicklin et al. (1962), Barnea (1990), Polonsky et al. (1999a, 1999b), Funada et al. (2005), Onea et al. (2009), Hayashi et al. (2010) and Hayashi and Tomiyama (2012). Especially Taylor bubbles have played an important role in recent advances of small-scale chemical reactors due to its desirable characteristics in heat and mass transfer such as low axial dispersion of a train of Taylor bubbles, efficient heat transfer in a liquid film between the bubble and heated wall, and efficient mixing in the wake region of bubbles (van Baten and Krishna, 2004; Vandu et al., 2005; Kececi et al., 2009; Worner, 2012; Hassanvand and Hashemabadi, 2012).

The total amount of mass transfer or the mass transfer coefficient is of primal interest in most of the literature on mass transfer from Taylor bubbles, and the effect of unsteady motion of bubble interface on an interfacial mass flux has not been investigated in detail. As is well known for bubbles in an infinite liquid, shape oscillation enhances mass transfer from bubbles (Beek and Kramers, 1962; Angelo et al., 1966; Clift et al., 1978), and therefore, shape oscillation of a Taylor bubble may also play some role in mass transfer.

The nose of a Taylor bubble is almost steady, whereas its tail oscillates with time in low and moderate viscosity systems (e.g. Polonsky et al., 1999a, 1999b). Polonsky et al. (1999a) measured oscillation of the tail region of Taylor air bubbles in vertical pipes filled with water. They paid attention to non-axisymmetric oscillation of the tail and showed that a linear potential flow model well describes the first mode of the non-axisymmetric oscillation. Liberzon et al. (2006) also investigated shape oscillation of Taylor air bubbles rising through water in vertical pipes. They pointed out that interfacial waves are excited by the tail oscillation and propagate upward along the bubble side and proposed a model, in which the wavelength of the waves propagating in the bubble side is a function of the frequency of tail oscillation and the velocity of the liquid film. The model reasonably agrees with their experimental data.

Tsuchiya et al. (2001) measured single carbon dioxide (CO_2) bubbles dissolving into water in a vertical pipe. The bubbles were initially larger than the pipe diameter, i.e. Taylor bubbles. They suggested that interfacial waves propagating from the bubble tail toward the nose promote mass transfer (wave effect). Szeri (1997) proposed a theoretical model for interfacial wave-enhanced gas absorption at a gas-sea surface. Tsuchiya et al. (2003) took into account the wave effect into their mass transfer correlation

(Tsuchiya et al., 2001) for oscillating bubbles based on Higbie's penetration model (Higbie, 1935).

Aboulhasanzadeh et al. (2012) and Bothe and Fleckenstein (2013) proposed interface tracking methods, in which an analytical concentration profile for boundary layer is used for evaluating the interfacial mass flux in computational cells larger than the boundary layer thickness, to efficiently simulate the mass transfer from high Schmidt number bubbles. There might be a possibility that this approach may cause some errors in regions where concentration boundary layers are agitated due to interfacial waves. Aboulhasanzadeh et al. (2013) however showed that their interface tracking method with the boundary layer approximation can give good predictions of the mass transfer coefficient of Taylor bubbles, which implies that the wave effects on the mass transfer are not significant.

The variation in bubble interfacial area due to shape oscillation is also known as one of the causes of mass transfer enhancement (Beek and Kramers, 1962; Angelo et al., 1966; Clift et al., 1978). The effects of interfacial area variation on mass transfer enhancement for Taylor bubbles were however not discussed in Tsuchiya et al. (2001). To obtain some insight into the underlying physics in enhancement of mass transfer from a Taylor bubble by shape oscillation, i.e. by interfacial wave and/or interfacial area variation, the interaction between the interface motion and the interfacial mass flux should be investigated.

The effects of shape oscillation on mass transfer from single Taylor bubbles in a vertical pipe are investigated in this study. An interface tracking method (Hayashi and Tomiyama, 2011) is used as a numerical tool to investigate the interfacial mass flux and the behavior of dissolved chemical species in the vicinity of the bubble interface. Mass transfer from single CO_2 Taylor bubbles rising through the vertical pipe filled with a glycerol-water solution is also measured for validation of the numerical method.

2. Experimental method and condition

The rear of a Taylor bubble in a low Morton number system, e.g. in an air–water system of $\log M = -11$, is known to strongly fluctuate (Polonsky et al., 1999a) and have three-dimensional structure. Here the Morton number M is defined by

$$M = \frac{\mu_L^4 \Delta \rho g}{\rho_L^2 \sigma^3} \tag{1}$$

where μ is the viscosity, ρ the density, g the magnitude of the acceleration of gravity, σ the surface tension, $\Delta \rho$ the density difference $\Delta \rho = \rho_L - \rho_G$, and the subscripts L and G denote the liquid and gas phases, respectively. It is not easy to analyze fluctuation of bubble interface with time-dependent three-dimensional structure and to investigate a relation between the interface motion and

Table 1
Physical properties of 50.0 wt% glycerol-water solution at 298 K.

Morton number $\log M$		−7.78
Schmidt number Sc		8260
Liquid viscosity μ_L (Pa s)		5.07×10^{-3}
Liquid density ρ_L (kg/m^3)		1124
Surface tension σ (N/m)		0.0695
Henry constant H (GPa)	CO_2	0.21
	N_2	21.7
	O_2	7.52
Solubility C_S (mol/m^3)	CO_2	18.4
	N_2	0.174
	O_2	0.503
Diffusion coefficient α_L (m^2/s)	CO_2	0.546×10^{-9}
	N_2	1.09×10^{-9}
	O_2	1.25×10^{-9}

interfacial mass transfer. To the contrary, in a high Morton number system, e.g. $\log M = 0.032$ used in Almatroushi and Borhan (2004), the shapes of Taylor bubbles are stationary and no interfacial waves are formed. Therefore a moderate Morton number system was utilized in this study. A glycerol-water solution of 50.0 wt.% and CO_2 of 99.9 vol.% purity were used for the liquid and gas phases, respectively, which formed a moderate Morton number system of $\log M = -7.8$. The physical properties of the liquid and gas phases are summarized in Table 1 (Washburn, 1928; von Kiss et al., 1937; Jordan et al., 1956; Sekino et al., 1972). The Sc in the table is the Schmidt number defined by

$$Sc = \frac{\mu_L}{\rho_L \alpha_L} \tag{2}$$

It should be noted that the concentration boundary layer can be very thin compared to the velocity boundary layer due to the high Sc, $Sc = 8260$.

Fig. 1 shows the experimental setup. The test section is a vertical pipe made of transparent fluorinated-ethylene-propylene (FEP) resin, the length and inner diameter, D, of which were 2000 mm and 12.5 mm, respectively. The reference elevation ($z = 0$ mm) in measurements was located 1950 mm below the water surface in the upper tank. The pipe was installed in the acrylic duct. Water was filled in the gap between the duct and the pipe to reduce optical refraction at the pipe surface. The temperature was kept at 298 ± 0.5 K. The liquid in the vertical pipe was refreshed before each run by circulating the liquid using a pump, and was replaced with a new liquid after about 10 runs.

CO_2 gas was stored in the hemispherical cup by using the gastight syringe and released as a single bubble by rotating the cup. Taylor bubbles of $\lambda > 0.7$ were dealt with, where the diameter ratio λ is defined by
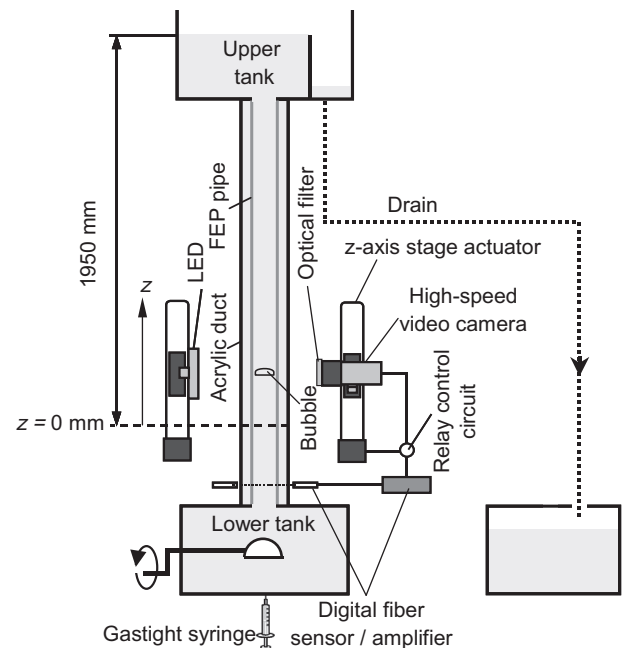
$$\lambda = \frac{d}{D} \tag{3}$$

where d is the sphere-volume equivalent bubble diameter.

Front and side images of a bubble were recorded by using the two synchronized video cameras (Integrated Design Tools, M3, frame rate: 180 frame/s, exposure time: 1.0 ms, spatial resolution:

Fig. 1. Experimental setup.