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Study on the mass transfer of bubble swarms in three different rheological fluids

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ABSTRACT

The mass transfer of the absorption of carbon dioxide bubble swarms into three different rheological fluids (Newtonian fluids, shear thinning fluids and viscoelastic fluids) were investigated experimentally. The volumetric liquid-phase mass transfer coefficients under different operating conditions were determined by using a carbon dioxide probe. The influences of gas flow rate and liquid properties on volumetric liquid-phase mass transfer coefficient were studied. Results indicated that the volumetric liquid-phase mass transfer coefficient increased with gas flow rate but decreased with increasing liquid apparent viscosity. Moreover, the viscoelasticity of liquid resulted in a decrease of mass transfer rate. A semi-empirical model was developed, the prediction by this model showed a satisfactory agreement with the experimental data in all three types of liquids studied.

1. Introduction

Mass transfer between dispersed bubble swarms and continuous liquid phase is widely encountered in many industrial processes such as chemical, biochemical, environmental and metallurgical processes. Extensive efforts have been devoted to the study of the gas–liquid mass transfer process in gas–liquid two phases system [1–3]. It is well known that the mass transfer coefficient is one of the most important parameters for designing and optimizing the gas–liquid mass transfer equipment. However, up to now, accurately obtaining the volumetric liquid-phase mass transfer coefficient is still a very difficult task due to the diversity of gas liquid mass transfer devices.

Generally, there are two most widely used methods obtaining the volumetric liquid-phase mass transfer coefficient: experimental determination and prediction by mathematical models. The experimental determination of the volumetric liquid-phase mass transfer coefficients involves monitoring the liquid-phase gas concentration as a function of time at a fixed position for dynamic experiments [4,5]. Although the experimental measurement of the mass transfer coefficient is relatively accurate, it would usually create considerable deviation in scale-up industrial equipment and has very limited operating condition. Therefore, lots of mathematical models were successively developed to predict the mass transfer coefficient of gas–liquid two phases flow process. Furthermore, those mathematical models could be classified into two kinds: theoretical model and empirical correlation. Classical theoretical models include two-film theory [6], penetration theory [7], surface renewal theory [8] and many improved models based on those classical theories [9–11]. As a matter of fact, due to the inherent complexity of mass transfer in gas–liquid two phases flow, gas–liquid mass transfer in two-phase flow system is usually influenced by many various factors, such as the geometrical characteristics of equipment, the operating conditions and the physical properties of fluids etc. [12]. Therefore, in order to facilitate establishing precisely mathematical model, some assumptions and simplifications were generally needed for attaining strictly theoretical equation to predict mass transfer coefficient. In addition, a number of empirical correlations have been proposed [13–18] by fitting experimental data. These correlations usually show considerably useful and effective in practical processes, although they also have the disadvantage with limited application range in which the operating conditions and systems must similar to that used in experiments.

Due to the complexity of rheological property of non-Newtonian fluids, especially mass transfer of bubble swarms in non-Newtonian fluids compared to Newtonian fluids, most of studies have naturally been focused on Newtonian fluids, few studies concerned non-Newtonian fluids. Gómez-Díaz et al. [19,20] studied the mass transfer process of carbon dioxide in shear-thinning fluids and analyzed the effect of gas flow rate and solution concentration on mass transfer. They also proposed a correlation to predict the interfacial area and gas hold up of carbon dioxide bubble swarms rising in non-Newtonian fluids. Garcia-Ochoa and Gomez [21] investigated the mass transfer phenomenon of oxygen bubble rising in xanthan gum solutions, and proposed a correlation of volumetric

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Nomenclature

A	parameter of liquid (Pa s^b)
a	gas–liquid interfacial area per unit liquid (m^2 m^{-3})
b	parameter of liquid
C	concentration of carbon dioxide in liquid (mol L^{-1})
C^*	saturation concentration of carbon dioxide in liquid (mol L^{-1})
D	diffusivity of carbon dioxide in the liquids (m^2 s^{-1})
D_C	column diameter (m)
De	Deborah number
d_s	Sauter diameter (m)
f_c	correction factor
Fr	Froude number
g	gravitational acceleration (m s^{-2})
H	liquid height of ungassed (m)
H_L	liquid height of gassed (m)
K	consistency index in a power-law model (Pa s^n)
k_L	liquid-side mass transfer coefficient (m s^{-1})
l	length scale of eddy (m)
N_1	first normal stress difference (Pa)
n	flow index in a power-law model
Q	volumetric gas flow rate (m^3 s^{-1})
t_c	contact time (s)
u	fluctuation velocity of liquid (m s^{-1})
U_G	superficial gas velocity (m s^{-1})

Greek symbols

ε	turbulent energy dissipation of per unit mass (m^{-2} s^{-3})
ϕ	gas holdup
$\dot{\gamma}$	shear rate (s^{-1})
μ	viscosity of liquid (Pa s)
ρ	liquid density (kg m^{-3})

Subscripts

c	contact
G	gas phase
L	liquid phase
W	water

liquid-phase mass transfer coefficients by introducing shear viscosity. They concluded that the mass transfer process of shear thinning fluid is analogous to that of Newtonian fluids as its viscosity could be expressed as shear viscosity. However, in many practical processes, the rheological properties of liquids usually vary with the transformations of liquid composition, such as in biochemical process, with the progressing of fermentation, the rheological properties of fermentation liquor change from Newtonian fluids to shear-thinning fluids, and even to viscoelastic fluids. It has been found that viscoelasticity of liquid could create a negative influence on mass transfer rate [22,23]. Although several mass transfer correlations have been reported by introducing Deborah number (De) to describe the influence of the viscoelasticity of liquids [24–26], the available academic information about the effect of viscoelasticity on mass transfer in gas–liquid two-phase flow remains still insufficient.

In this study, the mass transfer from carbon dioxide bubbles swarms into Newtonian fluids, shear thinning fluids and viscoelastic fluids were investigated experimentally. Furthermore, the effects of the fluid properties and operating conditions on the mass transfer were also studied. Based on the Higbie's penetration theory and Kolmogorov's theory of isotropic turbulence, a semi-empirical model for predicting volumetric liquid-phase mass transfer in Newtonian fluids, shear-thinning fluids and viscoelastic fluids was proposed. Experiments were carried out to validate the present model.

2. Experimental

2.1. Experimental set-up

The experimental set up was shown in Fig. 1. The experiments were carried out in an open rectangular Plexiglas bubble column with 0.1 m × 0.1 m cross-section and 1 m height. The bubble column comprised with two 0.002 m diameter air holes in the center of the column bottom, one is nitrogen (N_2) inlet and the other is carbon dioxide (CO_2) inlet. At first N_2 was fed into bubble column for desorbing CO_2 from liquids. Meanwhile, the dissolved concentration of CO_2 was measured by a calibrated CO_2 sensor (FC-100: ASR Co., Ltd.) which was located at above 0.6 m from the nozzle. Due to the disturbance of rising bubble on liquids, the homogeneous distribution of CO_2 concentration were observed for several seconds, i.e. the reading of CO_2 sensor could be considered as the real CO_2 concentration of the bulk liquid. The ventilated process of N_2 was stopped when the CO_2 sensor indicated dissolved CO_2 in the column was zero. After a short interval, the CO_2 was fed in to the liquid through a calibrated rotameter with desired gas flow rate (4×10^{-6} m^3 s^{-1}, 8×10^{-6} m^3 s^{-1}, 12×10^{-6} m^3 s^{-1}, 16×10^{-6} m^3 s^{-1} and 20×10^{-6} m^3 s^{-1}). The increases of the dissolved CO_2 at different times were monitored with the calibrated CO_2 sensor. The sampling frequency was 1/30 Hz. All the experiments were carried out under room temperature (298.15 K) and atmospherical pressure.

2.2. Experimental materials

In this work, tap water and glycerin aqueous solutions (25 wt%, 50 wt% and 75 wt%) were used as reference Newtonian fluids. Carboxymethyl cellulose (CMC) aqueous solutions (0.2 wt%, 0.4 wt%, 0.6 wt%, 0.8 wt% and 1.0 wt%) were used as reference shear thinning fluids. And polyacrylamide (PAA) aqueous solutions (0.3 wt%, 0.6 wt%, 1.0 wt% and 1.2 wt%) were used as reference viscoelastic fluids.

The densities of liquids were measured using a densitymeter (AntonPaar, DMA4500M, Austria) with an accuracy of $\pm 5 \times 10^{-5}$ g cm^{-3}. And the rheological measurements were carried out by a programmatic rheometer (Reologica, Instruments AB, Sweden) with shear rate ranging from 0.1 to 1000 s^{-1}. The measured results were shown Fig. 2, it could be observed that both CMC solution and PAA solution exhibited shear thinning behavior.

The variation of the apparent viscosity μ with shear rate $\dot{\gamma}$ could be described by power law model [27]:

$$\mu = K\dot{\gamma}^{n-1} \tag{1}$$

where K is the consistency index and n is the flow index of the fluid.

Because PAA solution showed markedly viscoelastic behavior, and the variation of the first normal stress difference N_1 with shear rate could be expressed as:

$$N_1 = A\dot{\gamma}^{b} \tag{2}$$

where A, b are material viscoelastic parameters.

Liquid physical properties and fitted parameters of K, n, A, b are summarized in Table 1.