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Gas-liquid two-phase flow in a square microchannel with chemical mass transfer: Flow pattern, void fraction and frictional pressure drop

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ABSTRACT

The dynamics of the gas-liquid two-phase flow are of great significance for the heat and mass transfer performance in a microreactor. In this paper, the flow pattern, void fraction and frictional pressure drop of gas-liquid two-phase flow of CO_2 and MEA/[Bmim][BF_4] aqueous solution accompanied by the chemical reaction in a 400 μm square microchannel were investigated experimentally by a high-speed camera and pressure sensor. Three kinds of flow regimes were observed: slug-bubbly flow, slug flow and slug-annular flow. The void fraction and frictional pressure drop in the slug flow regime were mainly investigated, and the applicability of models without consideration of the mass transfer proposed in the literature was assessed. Considering the effect of chemical absorption, two correlations were proposed with the Hatta number for predicting the two-phase void fraction and Chisholm parameter *C*, which showed good prediction performance.

1. Introduction

The microreactor has numerous advantages over the macroscale equipment, such as large surface area, low energy consumption, and high reaction heat flux. It accordingly receives increasing attention in various gas-liquid two-phase flow applications, including the heat exchange, catalytic reaction, air conditioning and refrigeration, nuclear power system, the heat and mass transfer systems [1–4], etc.

Flow pattern, void fraction and pressure drop are important characteristic parameters for pipe design and process control, which could provide essential information for judgment and prediction of the mass transfer and heat transfer coefficients, refrigerant capacity and evaporation capacity in the gas-liquid two-phase flow and heat/mass transfer process. Qu and Mudawar [5] investigated the saturated boiling flow in a microchannel heat exchange tank, and estimated the heat transfer coefficient based on the annular flow model. Lee and Mudawar [2] studied the heat transfer performance of R134a boiling flow in a microchannel heat exchange pool. They found that the thermal alteration depends dramatically on the flow mechanism at different vapor quantity ranges. The void fraction is closely related to the accelerational and gravitational terms from the total experimental pressure drop [6]. Xing et al. [7] pointed out that void fraction had significant influence on gravitational pressure drop of slug flow, churn flow and annular flow in vertical mini rectangular duct. Therefore, the accurate prediction of void fraction is of key importance for the calculation of pressure drop. In order to obtain large heat transfer coefficient, many condensing devices relied on reducing the channel diameter to attain large steam flow rates and surface shear forces. However, the small channel diameter would lead to large pressure drop in the channel and thereby bring about the reduction of overall efficiency of the equipment or system. Therefore, it is necessary to accurately predict the pressure drop for the design of high efficient heat transfer equipments. Yue et al. [8] correlated the liquid-side volumetric mass transfer coefficients of CO_2 in deionized water in microchannel with the gas-liquid two-phase frictional pressure drop, and obtained a good prediction result with the mean absolute error (MAE) of 18.9%. Niu et al. [9] studied the mass transfer performance of CO_2 into polyethylene glycol in a microchannel, and the liquid-side volumetric mass transfer coefficient had also been well predicted by using the Yue et al.'s [8] model.

In comparison with the two-phase flow in conventional sized channel, the gas-liquid two-phase flow in microchannels is more relative to the surface tension and viscous force rather than the gravity force and inertia [10]. The change of the relative importance of the forces leads to a great difference in the dynamics of the gas-liquid two-phase flow between the microchannel and the

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Nomenclature

Bo	Bond number (dimensionless), $Bo = (\rho_l - \rho_g)gD_h^2/\sigma$
C	Chisholm parameter (dimensionless)
c	mass concentration (wt%)
Ca	Capillary number (dimensionless), $Ca = U_{tp}\mu_l/\sigma$
D	diffusion coefficient ($m^2\ s^{-1}$)
D_h	hydraulic diameter (m)
f	friction factor (dimensionless)
G	mass flux ($kg\ m^{-2}\ s^{-1}$)
g	gravitational acceleration ($m\ s^{-2}$)
Ha	Hatta number (dimensionless), $Ha = \sqrt{Dk_{ov}/k_l^2}$
K	loss coefficient (dimensionless)
k_l	liquid-side physical mass transfer coefficient ($m\ s^{-1}$)
k_{ov}	constant of overall reaction rate (s^{-1})
L	length (m)
La	Laplace number (dimensionless), $La = [\sigma/(g(\rho_l - \rho_g))]^{0.5}/D_h$
P	pressure (Pa)
Q	flow rate ($ml\ h^{-1}$)
Re	Reynolds number (dimensionless), $Re = D_hU\rho/\mu$
U	superficial velocity ($m\ s^{-1}$)
V	volume (m^3)
w	width (m)
x	gas mass fraction (dimensionless)

Greek symbols

Δ	difference
α	void fraction (dimensionless)
β	volumetic quality (dimensionless)
θ	angle (°)
μ	dynamic viscosity (Pa s)
ρ	density ($kg\ m^{-3}$)
σ	surface tension ($N\ m^{-1}$)
ϕ_l^2	two-phase friction multiplier (dimensionless)
X	Lockhart and Martinelli parameter (dimensionless)

Subscripts

Ac	accelerational
B	bubble
C	microchannel
F	frictional
Fl	local term
g	gas phase
go	only-gas phase
Gr	gravity
l	liquid phase
lo	only-liquid phase
tp	two-phase

traditional equipment. The bubble flow, slug flow (Taylor flow), slug annular flow and annular flow, churn flow and other flows and corresponding flow patterns map in microchannels have been obtained in the literature in terms of the liquid property, channel diameter, operating condition and the entrance geometry, etc. [11–13]. However, the widely accepted flow transition models or correlations in large pipes were found unsuitable in microchannels [14]. Akbar et al. [15] proposed a model based on Weber number to describe the flow pattern transition of air-water flow from the surface tension to the inertial force control region in a microchannel. The inapplicability could also be seen from the analysis of void fraction and frictional pressure drop in microchannels. For example, for void fraction, Armand [16] proposed a linear model with volumetric quality, while Chung and Kawaji [12] proposed a nonlinear correlation to volumetric quality, as they found that the Armand-type linear model deviated from the data in the 100 μm and 50 μm diameters for the N_2-H_2O two-phase flow in circular microchannels. Subsequently, Kawahara et al. [17], Xiong and Chung [18] and Choi et al. [19] modified the constant term in the Chung and Kawaji [12] model for the N_2-H_2O two-phase flow in microchannels with different diameters. For the two-phase frictional pressure drop, the model is divided into homogeneous model correlated by choosing the suitable two-phase viscosity, and separated flow model according to the Lockhart and Martinelli theory [20]. Nevertheless, most frictional pressure drop correlations focused on the separated flow model, especially on the correlation of Chisholm parameter C [21–25]. It has been noticed that the channel size and mass flux had important influences on the two-phase friction multiplier, and many efforts have been devoted to improve the Chisholm [21] parameter C to apply in microchannels [9,24,26]. The reason that the correlations in conventional size are inapplicable for microchannel could be mainly attributed to the complicated gas-liquid two-phase flow behavior occurring in the microscale. Furthermore, the previous models or correlations for microchannels are primarily based on the air-water, nitrogen-water, refrigerant gas-liquid two phase flow systems in which the interfacial mass transfer was negligible. However, for the gas-liquid two-phase flow with chemical absorption, the flow process would become more complicated. The size of bubble continuously decreased along the flow direction in the microchannel during chemical reaction [27]. Chemical absorption could remarkably affect the gas-liquid two-phase distribution, bubble shape and velocity, and accordingly influence the flow pattern, void fraction and pressure drop. However, few studies could be found on the dynamics of gas-liquid two-phase flow with chemical reactions in a microchannel. This motivates us to implement a systematic study.

The global warming stemming from the emissions of greenhouse gases especially carbon dioxide has become a serious concern all over the world. The CO_2 capture method widely used in industry is chemical absorption by organic amine aqueous solution, particularly monoethanolamine (MEA) aqueous solution due to its rapid absorption and good selectivity for CO_2. However, owing to the easy degradation, oxidation, and high energy consumption, MEA absorption has restrictions for the applications [28]. In recent years, using mixed solution to achieve high CO_2 capture performance is a common design idea. In many absorbents, ionic liquids (ILs) are considered as potential solvents due to their relatively high thermal stability, negligible low vapor pressure and adjustable physicochemical properties [29]. Furthermore, it has been found that the addition of 1-butyl-3-methylimidazolium tetrafluoroborate ([Bmim][BF_4]) into MEA solution showed higher antioxidant activity, lower amine loss rate, easier regeneration performance, and enhanced absorption capacity than the MEA solution [28]. Thus, the study of CO_2 absorption into MEA/[Bmim][BF_4] aqueous solution has received extensive attention.

Therefore, in view of this research background, in this paper, the gas-liquid two-phase flow pattern, void fraction and frictional pressure drop in a 400 μm square microchannel were investigated experimentally. Pure CO_2 was employed as gas phase, and the MEA/[Bmim][BF_4] aqueous solution was used as the liquid phase. The influences of the operating condition and chemical reaction rate on flow pattern, void fraction and frictional pressure drop were explored. Two prediction correlations for void fraction and