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Dispersion characteristics of ionic microbubble suspension in continuous plant prototype developed for mineral beneficiation

Rajeev Parmar, Subrata Kumar Majumder *

Chemical Engineering Department, Indian Institute of Technology Guwahati, Guwahati 781039, Assam, India

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ABSTRACT

Microbubbles offer a larger gas–liquid interfacial area and high mass transfer coefficient compared to conventional bubbles. They are being proposed for process intensification in various unit operations. This study investigates the dispersion characteristic of ionic microbubble suspension in continuous plant prototype developed for mineral beneficiation. The effects of different operating variables and physiochemical properties of liquid on the dispersion of ionic microbubble suspension are examined. A phenomenological model with consideration of liquid circulation is developed to analyze the dispersion coefficient of the microbubble suspension due to circulation. Generalized correlations for dispersion coefficient and the time to reach uniform dispersion are also developed based on the physicochemical properties of microbubble suspension. The present work may be useful for further study of microbubble aided mineral separation for industrial applications.

1. Introduction

As we are leading towards our future, technology is changing day by day to more advancement than last few decades. Technologies are getting much deeper and smaller, thereby enhancing the efficiency and capacity. In every field, research has gone to higher level by exploring new areas. In chemical engineering, bubbles play an important role in various unit operations. Microbubbles are useful often when there is a need of large interfacial area. For reactions involving more than one phase, sufficient interfacial area must be availed to make it economically successful. In recent studies it has been reported that smaller bubbles give rise to larger interfacial area, which motivate the introduction of processes aided with microbubbles [1]. In general bubbles are considered to be microbubbles, if they have diameter in the range of 1–100 μm [2]. In the present scenario microbubble has got much popularity as they are being used in many chemical, biochemical, metallurgical and petrochemical industries to increase the efficiency of the process. Microbubble offers high surface area per unit volume than the conventional bubbles which helps to intensify the mass transfer processes at low cost [3]. The charge on surface of microbubble is very useful to separate the opposite charge particles [4]. Microbubble also finds uses in medical science. They have been used as diagnostic aids to scan the various organs of body and they are being proposed to be used as a drug or gene carriers and treatment in cancer therapy [5]. The microbubble-aided extraction process is becoming a highly promising direction in chemical engineering [6]. In the recent years a lot of research has been done to explore the physiochemical characteristics of microbubble. Yoon and Yardan [7] measured the zeta potential of microbubble by microelectrophoresis method. Han and Dockko [8] also made an attempt to measure the charge on the surface of microbubble. Hasegawa et al. [9] further extended the work to investigate the effect of pH on zeta potential of microbubble. Oliveira and Rubio [10] examined the effect of coating on the zeta potential of microbubble. Numerous experiments has revealed that microbubble provides high mass transfer rate than the conventional bubbles. Kaster et al. [11] reported that microbubbles can enhance oxygen transfer. Bredwell and Worden [3] claimed that the mass transfer characteristics of microbubbles is 6 fold higher than conventional bubbles. Devatine et al. [12] also reported the enhancement of oxygen transfer rate by microbubbles. The use of microbubble is not limited to oxygen transfer, it is also used to improve the ozonation in various liquid medium [13–15]. The disinfectant activity of microbubbles provides an alternate way to use them against phytopathogens in infected plant roots in hydroponic culture solutions [16]. The hydrodynamic characteristics of microbubble also remains a subject of interest. Madavan et al. [17] reported that microbubble can be used for reduction of friction during fluid flow. The influence of the type of gas on the reduction of skin friction by microbubble injection has

* Corresponding author. Tel.: +91 361 2582265x4265.
E-mail addresses: skmaju@iitg.ernet.in,
http://www.iitg.ernet.in/chemeng/SKM.html (S.K. Majumder).

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Nomenclature

Notation

A_c	Column cross-sectional area (m^2)
C	Tracer concentration (Kg/m^3)
C_u	Tracer concentration in upstream suspension (Kg/m^3)
C_d	Tracer concentration in downstream suspension (Kg/m^3)
$\overline{C}$	Average concentration (Kg/m^3)
C_s	Concentration of surfactant (ppm)
C_c	Concentration of SCMC (kg/m^3)
C_{sc}	Concentration of salt (kg/m^3)
C_∞	Equilibrium tracer concentration (Kg/m^3)
D_c	Column diameter (m)
d_b	Microbubble diameter (m)
E_z	Overall liquid dispersion coefficient (m^2/s)
E	Dispersion coefficient due to turbulence (m^2/s)
E_c	Dispersion coefficient due to circulation (m^2/s)
g	Acceleration due to gravity (m^2/s)
K	Consistency of fluid ($Pa\,s^n$)
K'	Parameter defined in Eq. (4)
K_c	Conductivity ($mS\,m^{-1}$)
L	Characteristic length (m)
L_p	Length of pipe (m)
n	Flow behavior index (−)
ΔP	Pressure drop (N/m^2)
p	Parameter defined in Eq. (28)
Q	Microbubble suspension flow rate (m^3/s)
Q_t	Amount of tracer injected (kg)
q	Constant in Eq. (27)
RF	Relative frequency (−)
S	Circumference between upstream and downstream microbubble flow (m)
U_c	Suspension circulation velocity (m/s)
t	Time (s)
t_m	Mixing time (s)
Z	Location in vertical axis (m)

Greek letters

μ_e	Effective viscosity (kg/m.s)
ρ_m	Density of suspension (kg/m^3)
λ	Liquid exchange factor (m/s)
δ	Parameter defined in Eq. (25)
α	Parameter defined in Eq. (30)
θ	Dimensionless time (−)
τ	Wall shear stress (N/m^2)
γ_a	Apparent shear rate (s^{-1})
σ	Surface tension (N/m)

Dimensionless groups

Bo	Bodenstein number ($(U_c L/E_Z)$ (−)
Fr	Froude number (U_c^2/gL) (−)
Re_n	Non-Newtonian liquid Reynolds number ($\frac{D_c^n U_c^{2-n}\rho}{8^{n-1}K}\left(\frac{4n}{3n+1}\right)^n$) (−)
We	Weber number $\rho_m U_c^2 L/\sigma$ (−)

Subscripts

e	Effective
d	Downstream flow
m	Mixture
p	Pipe
t	Tracer
u	Upstream flow

also been studied, however similar reduction of skin friction for all the gases were reported [18]. The skin friction can be reduced up to 40% with microbubbles [19]. The rheology of microbubble suspension has been studied by many authors. The microbubble suspension has found to behave as non-Newtonian [20,21]. In the past few years, a lot of attention has been given to the potential applications of the microbubbles for water treatment due to their capability to generate highly reactive free radicals [22]. The adsorption ability of microbubble is utilised to purify water [23]. The COD removal efficiency of microbubble system is 20% higher than the conventional bubble column [24].

1.1. Lacuna and objective of the work

Dispersion is very essential operation in chemical processes like heat transfer, mass transfer, mineral separation etc. The transport characteristics of a reactor are significantly affected by the dispersion phenomena inside the reactor. Even though the mass transfer and hydrodynamics properties of microbubbles have been discussed in the literature, still there is a significant knowledge gap on dispersion mechanism of flow of microbubble suspension. To achieve technical feasibility of microbubble suspension flow and microbubble aided mineral separation by flotation, a detailed study on the dispersion characteristics of microbubble suspension are required. To the best of our knowledge, a single study by Bredwell and Worden [3] is available in literature in which a brief description of liquid axial dispersion coefficient of microbubble is illustrated. Thus in the present work an attempt has been made to explore the dispersion characteristic and mixing time of microbubble suspension of recirculation system in a continuous plant prototype, which has not been reported till date. The aim of this communication is to study the phenomenon of dispersion associated with microbubble-suspension flow to aid in mineral beneficiation. The results of this dispersion phenomenon will be incorporated to the degree of separation of fine particle by microbubble flotation in the next scope of our study which will be published in future.

2. Experimental setup and procedure

The schematic of the plant prototype in which the experiments were carried out is shown in Fig. 1. It consists of a microbubble generator, a gas compressor and other accessories such as rotameters, control valves, conductivity meter, thermometer and test tubes for collecting samples. The column was 0.60 m high and having internal diameter 0.20 m. Both inlet and outlet of the column were at the lower end through which microbubble generator was connected. The air used to create microbubbles was supplied from a compressor controlled by a valve. The liquid flow rate was measured using rotameters from which the flow was maintained by using control valves. Pressurized dissolution is considered as one of the most significant method to produce microbubble [25]. Therefore in the present study the pressurized dissolution method is opted to produce microbubble. The schematic representation of pressurized dissolution technique is shown in Fig. 2. In this method, mixture of gas and liquid are mixed in a mixer and transported to pressure vessel. By adjusting the outlet flow rate to 4–10 L/min, pressure of about 3–4 atm was built in the pressure vessel. Gas was allowed to dissolve in a liquid. The water with oversaturated air is then released to low atmospheric pressure to form the microbubble. The size and population of the microbubbles can be controlled by regulating the pressure in the pressure vessel. A typical size distribution of the microbubble produced in the present method is shown in Fig. 3. In the present study the mixing characteristics of microbubble suspension is estimated by stimulus-response technique. This method involves