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Effect of ring sparger diameters on hydrodynamics in bubble column: A numerical investigation

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A B S T R A C T

This paper applies the Eulerian–Eulerian approach to study the effect of ring sparger diameter on the gas and liquid dynamics in a cylindrical bubble column reactor. The distribution of the gas hold-up and liquid flow pattern using different ring sparger diameters (*i.e.,* 0.07, 0.14 and 0.20 m) are investigated. In addition, the influence of different bubble sizes and interfacial force models on the accuracy of numerical results are examined. The results show that the size of ring sparger affects the amount of gas in the column and the position of the liquid phase recirculation (upward and downward liquid flow direction). Furthermore, the appropriate selection of bubble size, and interfacial force models results in accurate liquid velocity and gas hold-up in the bubble column reactor.

1. Introduction

Bubble columns are used as multiphase reactors to produce different types of physical and chemical multiphase reactions in several industries such as chemical, petrochemical, biochemical, wastewater treatment and metallurgical industries [1–14]. Due to simple construction and shape, they contain low maintenance, low operating costs and simple operating (cleaning reactor and running experiment) in industries. They also provide high rate of heat and mass transfer, as well as durability of catalysts [15–17]. They are usually manufactured in cylindrical shape and fitted with a gas distributor (*i.e.,* sparger) at the bottom. The sparger produces bubbles inside the bubble column reactor, having either a liquid phase (water, etc.,) or a liquid–solid suspension [18,19]. Production of small bubbles with spherical shape (having higher interfacial area) without coalescence, particularly near the sparger region results in uniform gas hold-up profile and homogeneous flow regime and eventually higher reactor efficiency [4,5]. Therefore detailed understanding of the macroscopic (gas and liquid flow pattern) and microscopic (bubble coalescence and break-up) interaction between phases, will greatly assists efficient design of reactors and spargers for several industrial applications [19].

There are two main approaches for the modeling of multiphase flows in bubble column that account the interactions between phases; They are Eulerian–Eulerian and the Eulerian–Lagrangian approaches [3]. The former approach is popular and also a suitable option for an industrial bubble column reactor since the volume fraction of dispersed phase is often not small and is distributed using a sparger rather than a single nozzle. In addition, the former approach requires relatively lesser computational effort than that for Eulerian–Lagrangian approach. However, correct selections of interphase forces (*e.g.,* drag force, lift, turbulent dispersion and virtual mass) and its models and turbulence models (*e.g.,* standard k–ε model, Reynolds Stress Model (RSM), Large Eddy Simulation (LES)) are required for an accurate flow prediction in Eulerian–Eulerian model [3,20,21]. Recently, Pourtousi, Sahu [3] reviewed the influence of different interfacial forces and turbulence models on the accuracy of numerical results. They suggested appropriate interfacial forces and turbulence models at different operational conditions for correct modeling of bubble column reactors. Due to complex behavior of multiphase flow in the bubble column reactor, [Pourtousi et al. [3], Pourtousi et al. [4]] recommended

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Nomenclature

C_D	drag force coefficient (dimensionless)
C_{TD}	turbulent dispersion coefficient (dimensionless)
$C_{\varepsilon 1}$	model parameter in turbulent dissipation energy equation (dimensionless)
$C_{\varepsilon 2}$	model parameter in turbulent dissipation energy equation (dimensionless)
C_μ	constant in k-ε model (dimensionless)
$C_{\mu,\,BI}$	constant in bubble induced turbulence model (dimensionless)
d_b	bubble diameter (m)
d_0	sparger hole diameter (m)
E_O	eotvos number ($=\frac{g(\rho_L-\rho_G)d_B{}^2}{\sigma}$) (dimensionless)
D	diameter of the column (m)
g	gravitational constant (m/s^2)
G	generation term (kg/m s^2)
H	height (m)
k	turbulent kinetic energy per unit mass (m^2/s^2)
M_I	total interfacial force acting between two phases (N/m^3)
M_D	drag force (N/m^3)
P	pressure (N/m^2)
r	radial distance (m)
R	column radius (m)
Re_B	reynolds number ($=d_B V_S/\nu$) (dimensionless)
V_G	superficial gas velocity (m/s)
V_T	terminal velocity (m^2/s)
Greek Symbols	
ε	turbulent energy dissipation rate per unit mass (m^2/s^3)
$\in$	fractional phase hold-up (dimensionless)
$\bar{\in}$	average fractional phase hold-up (dimensionless)
μ	molecular viscosity (Pa s)
μ_{BI}	bubble induced viscosity (Pa s)
μ_{eff}	effective viscosity (Pa s)
ρ	density (kg/m^3)
μ_T	turbulent viscosity (Pa s)
σ	surface tension (N/m)
σ_ε	prandtl number for turbulent energy dissipation rate (dimensionless)
σ_k	prandtl number for turbulent kinetic energy (dimensionless)
τ_k	shear stress of phase k (Pa)
Subscripts	
b	bubble
G	gas phase
L	liquid phase

to considered the sensitivity study of different bubble sizes and interfacial force models, as well as information in the literature to find appropriate CFD models for bubble columns.

In addition to CFD modeling, many studies have focused on the influence of operating conditions on the liquid and gas flow pattern and detailed understanding of phase interactions [5,22–27]. The gas and liquid phase flow pattern and the interaction between phases in a bubble column are dependent on bubble column hydrodynamics parameters (*i.e.,* gas hold-up and gas and liquid velocity, etc.). The variation in phase interaction enhances the mixing time, heat and mass transfer rate and this improves the overall efficiency of reactors. Changing of operational conditions, such as bubble column dimensions, inlet velocity (superficial gas velocity), temperature and pressure conditions and sparger specifications, changes the hydrodynamics in a bubble column.

Sparger designs have significant influence on the distribution of the dispersed gas (gas hold-up), bubble size and bubble shape and the distribution of liquid velocity [5,6,21,26]. Various types of gas sparger designs such as perforated plate [15,21], porous plate [28], single point/multipoint sparger [5,22], ring [2,4,27,29] are used in bubble columns. For example, Li et al. [26] studied the effect of number of spargers and their arrangements on the liquid velocity, gas hold-up, mixing characteristics and bubble size distribution in a cylindrical column. The gas holdup rises with the increase of the number of spargers. It was found that the arrangement of sparger positions have influence on the uniformity of gas distribution and liquid flow pattern. Dhotre et al. [22] studied the effect of a single point and multipoint spargers on the distribution of the gas hold-up in bubble column of different heights. For multipoint spargers, the profile of the gas hold-up is relatively flat near the sparger region (at the bottom). In contrast, the single point sparger produces a steep profile of gas hold up adjacent to the sparger region but this profile becomes flatter with the increase of the vertical distance from the bottom. The sparger orifice diameter and position has an effect on the bubble distributions and sizes in bubble column [30]. Sal et al. [15] investigated the effect of the orifice diameter of perforated plate spargers on gas holdup and regime transition in bubble column. Orifice diameter is found to have a significant effect on the total gas hold-up in homogeneous flow regime but not in heterogeneous regime. Bhole et al. [28] compared the gas distribution from a porous plate sparger and from a perforated plate sparger. The former is found to produce smaller bubbles, higher gas holdup and small liquid circulation in the column.

Although few studies have concentrated on the effect of sparger design parameters on the bubble column hydrodynamics [5,6,15,22,23], there are still many aspects on sparger design and configuration that requires further studies. Therefore, the main purpose of the present study is to examine the effect of ring sparger diameter on the gas hold-up and liquid velocity in the cylindrical bubble column. Furthermore, effects of using different bubble sizes and the interfacial force models (such as, drag and turbulent dispersion models) on the accuracy of Euler–Euler method are studied. In this study, the commercial CFD package of ANSYS-CFX is used for all simulation cases.

2. Methodologies

2.1. Governing equations

The two-phase model based on the Eulerian–Eulerian approach is applied to simulate the gas and liquid interaction. Each phase is treated as a continuum in the domain under consideration in this approach. The phases share this domain and interpenetrate as they move within it. The Eulerian modelling framework is based on ensemble-averaged mass and momentum transport equations for each phase and is written as following:

Continuity equation:

$$\frac{\partial}{\partial t}(\rho_k \in_k) + \nabla(\rho k \in_k \mathrm{u}_k) = 0 \tag{1}$$

Momentum transfer equation:

$$\frac{\partial}{\partial t}\left(\rho_k \in_k \mathrm{u}_k\right) + \nabla\left(\rho_k \in_k \mathrm{u}_k \mathrm{u}_k\right) = -\nabla(\in_k \tau_k) - \in_k \nabla \mathrm{p} + \in_k \rho_k g + M_{I,k} \tag{2}$$

The terms on the right hand side of Eq. (2) represents the stress, the pressure gradient, the gravity and the ensemble-averaged momentum exchange between the phases due to