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Simulating the impacts of internals on gas–liquid hydrodynamics of bubble column

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HIGHLIGHTS

- A generic TFM-PBM model is constructed for bubble columns with internals.
- The bubble size distribution and its variation are validated against literature data.
- Impacts of internals and configurations on gas–liquid hydrodynamics are investigated.

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ABSTRACT

Impacts of vertical internals on gas–liquid hydrodynamic of bubble columns were simulated using an Eulerian two fluid model coupled with a population balance method (TFM-PBM). The interfacial drag force, the shear induced lift force, and the radial wall lubrication force exerted on bubbles were included in the model. The effects of wall boundary conditions were investigated numerically. The numerical results showed the radial wall lubrication force greatly impacts the radial distribution of time-averaged gas holdup, especially in the internals affecting region. When the internals were present, the turbulent dissipation rates increased significantly in the gaps between the internal walls, and more bubbles with smaller bubble size were predicted in the bubble column. Meanwhile, the gas holdup increased with dense internals insertion, especially in r/R equal to 0.6–0.9 region. The internals and the configurations influence the overall liquid circulation. When 31 thin internals are inserted in column at a low superficial gas velocity, large scale liquid circulations are replaced by small local vortex. However, the variations of liquid circulations are different at a high superficial gas velocity, when the large scale liquid circulations are always present in the column regardless of inserting 31 thin internals or 8 thick internals.

1. Introduction

Bubble columns are important reactors for a variety of chemical processes (Chen and Fan, 2004). Many industrial applications include exothermic reactions; hence, internal heat exchangers are used to remove the excess reaction heats. In a process of liquid methanol synthesis, heat-exchanging internals covering 5% of the cross-sectional area (CSA) are equipped to maintain an isothermal operation. In a highly exothermic process of Fischer-Tropsch (F-T) synthesis, the internals occupying about 22–25% of the CSA of the column are required. The presence of dense internals will influence the heat and mass transfer coefficients significantly, resulting in changes of the reactor performance and the desired product (Krishna et al., 2001). Therefore, it is important to understand the impacts of internals on the gas–liquid hydrodynamics in a bubble column.

Over the years, various invasive and non-invasive techniques have been used in the experimental studies of empty bubble columns, but only limited studies have been focused on the effects of heat-exchanging internals on the gas–liquid hydrodynamics. Chen et al. (1999) measured gas holdup profiles, liquid recirculation, and turbulent stresses for a 0.44 m diameter bubble column with vertical internals covering 5% of column's CSA at superficial gas velocities up to 0.1 m/s. A slight increase (about 10%) in gas holdup and a significant decrease in turbulent stresses and the eddy diffusivities were reported due to decreasing length scales of turbulence. No significant difference was observed on liquid recirculation under the condition of 5% occluded CSA in their large scale bubble column. Forret et al. (2003) investigated liquid dispersions in a 1 m diameter bubble column with 56 vertical internal tubes (22% CSA), and found that the presence of internals significantly influenced large scale liquid recirculation. Zhang et al.

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Nomenclature

Roman letters

A	bubble cross-sectional area, m^2
A_{ij}	bubble impact area, m^2
A_{nsa}	net sectional area of bubble column, m^2
$b(v_i : v_j)$	breakup frequency, s^{-1}
B_B	production of bubble by breakup, $kg^{-1}\ m^{-3}\ s^{-1}$
B_D	destruction of bubble by breakup, $kg^{-1}\ m^{-3}\ s^{-1}$
c_f	surface area increase coefficient
$c(v_i, v_j)$	coalescence rate, $m^3\ s^{-1}$
$C_{1\varepsilon}, C_{2\varepsilon}, C_{3\varepsilon}, C_\mu$	constants for turbulence closure model
C_B	production of bubble by coalescence, $kg^{-1}\ m^{-3}\ s^{-1}$
C_D	destruction of bubble by coalescence, $kg^{-1}\ m^{-3}\ s^{-1}$
C_d	drag coefficient
C_{lift}	lift coefficient
C_w	function for deformable bubbles
C_{w1}, C_{w2}	wall force coefficients
C_{wc}	cut-off coefficient
C_{wd}	damping coefficient
C_{wl}	wall lubrication coefficient
d	bubble diameter, m
d_b	sauter mean bubble diameter, m
d_{eq}	equivalent hydraulic diameter, m
d_t	internal tube diameter, m
D_C	bubble column diameter, m
Eo	Eötvös number
f_{bv}	bubble breakup volume fraction
$\mathbf{F}$	interfacial momentum exchange term, $kg\ m^{-2}\ s^{-2}$
g	acceleration due to gravity, 9.81 $m\ s^{-2}$
G_k	production of turbulent kinetic energy, $kg\ m^{-1}\ s^{-3}$
h_0, h_f	liquid film thickness, m
H	liquid height, m
k	turbulent kinetic energy, $m^2\ s^{-2}$
K_{lg}	inter-phase momentum exchange coefficient, $kg\ m^{-3}\ s^{-1}$
L_{wp}	wetted perimeter, m
$\dot{n}_\lambda$	number of eddies per unit volume, m^{-4}
n_w	wall normal vector
N	number of tubes or bubble bins
$p_c(d_i, d_j)$	coalescence efficiency
$p_b(d_i : d_{j,k})$	breakup efficiency
r_{ij}	equivalent radius, m^{-1}
Re	Reynolds number
R_ε	strain rate, $kg\ m^{-1}\ s^{-4}$
S_i	Source term of i-th bubble group, $m^{-3}\ s^{-1}$
t	time, s
$t_{contact}, t_{drainage}$	contact/drainage time between bubbles, s
$\mathbf{u}$	velocity vector, $m\ s^{-1}$
u_b	bubble rise velocity, $m\ s^{-1}$
u_t	turbulent velocity, $m\ s^{-1}$
u_v	liquid velocity gradient, $m\ s^{-1}$
u_w	wake entrainment velocity, $m\ s^{-1}$
$\bar{u}_\lambda$	eddies turbulent velocity, $m\ s^{-1}$
U_g	superficial gas velocity, $m\ s^{-1}$
u, v, w	velocity component, $m\ s^{-1}$
v, V	bubble volume, m^3
w	collision frequency, $m^{-3}\ s^{-1}$
y_w	cell distance to the nearest wall, m

Greek letters

α	void fraction
ε	turbulent dissipation rate, $m^2\ s^{-3}$
γ	shear strain rate, s^{-1}
λ	eddy size, m
μ	dynamic viscosity, $kg\ m^{-1}\ s^{-1}$
π	≈ 3.1415926
ρ	density, $kg\ m^{-3}$
σ	surface tension, $kg\ m^{-2}$
$\sigma_k, \sigma_\varepsilon$	turbulent Prandtl number
τ	stress, $kg\ m^{-3}$
ξ	eddy size divided by parent bubble size
$\Pi_{k,l}$	bubble-induced turbulence term, $m^2\ s^{-3}$
$\Pi_{\varepsilon,l}$	bubble-induced turbulence term, $m^2\ s^{-4}$
Θ	coefficient for wake entraining

Subscripts

b	bubble index
g	gas index
l	liquid index
i, j	phase index, number index

(2009) measured the profiles of gas holdup and liquid velocity in a 0.5 m diameter bubble column with internals of up to 11% CSA, increased gas holdup and enhanced liquid circulation were observed. Recently, Al-Dahhan's group conducted a series of experimental studies aimed at clarifying the impacts of vertical internals on the hydrodynamics of bubble columns. Among the works, Youssef and Al-Dahhan (2009) tested an air-water system with superficial gas velocities up to 0.2 m/s in a 0.19 m diameter column with internals that mimic the process used in methanol synthesis (5% covered CSA) and that of the Fischer-Tropsch (F-T) process (22% covered CSA). The impacts of internals on the local gas holdup, gas–liquid interfacial area, bubble chord length, and bubble velocity distributions were examined. Increases in gas holdup and interfacial area were obtained with insertion of the internals and the bubble chord length decreased significantly for the case of dense internals. However, the impacts of the sparse internals on the gas holdup and the bubble size were insignificant, which was in agreement with Chen et al. (1999). Subsequently, Youssef et al. (2012) extended the investigation on the bubble sizes and overall gas holdup, with a 0.45 m diameter bubble column equipped with internals covering 0–25% CSA and at superficial gas velocities in a wide range 0.03–0.45 m/s covering pseudo-homogeneous to heterogeneous flow regimes. Their experimental results confirmed that dense internals led to an increase of gas holdup and a decrease in the bubble chord length due to enhanced bubble breakup. A vigorous recirculation was observed as a result of the insertion of the internals. Recently, Kagumba and Al-Dahhan (2015) investigated the impact of internals size on bubble dynamics of a 0.14 m diameter bubble column. Two different configurations, namely, 30 thin tubes and 8 thick tubes equally covering 25% CSA, were tested, respectively. The results showed that thin internals gave consistently higher overall and local gas holdup than that of the thick internals or empty column. However, the effect of the internals diameter was insignificant in the churn-turbulent flow regime. Using gamma ray CT, Al Mesfer et al. (2016) further examined the impact of dense internals on gas holdup distribution for the 0.14 m diameter bubble column, and at superficial gas velocities in range of 0.05–0.45 m/s covering bubbly through churn-turbulent flow regimes. Significant increases in overall and local gas holdup were obtained with insertion of dense internals. At a high superficial velocity, the influence of dense internals became insignificant. Comparing to the case without internals,