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CFD simulations of a bubble column with and without internals by using OpenFOAM

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HIGHLIGHTS

- Euler-Euler CFD model in OpenFOAM for bubble column with vertical internals.
- Experimental validation with liquid velocity field with Radioactive Particle Tracking (RPT).
- Good agreement with the experimental data for both bubble columns with and without internals.

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ABSTRACT

Bubble column reactors are widely employed in various applications. Nowadays computational fluid dynamics (CFD) provides the state-of-the-art capabilities of simulating the hydrodynamics in these reactors. In the present work, bubble column is numerically simulated by using open source CFD tool, OpenFOAM 2.3.1. Euler-Euler two-fluid model is used for the simulations. In the first part, OpenFOAM simulations are validated with experimental data from the literature over a column diameter range of 138–600 mm and the superficial gas velocity in the range of 19–169 mm/s. The velocity and holdup patterns as well as circulation patterns in the bubble column are compared. In addition, Fluent® simulations are performed for the same conditions in order to compare the accuracy of OpenFOAM solvers. In the second part of the work, the validated OpenFOAM solver is applied to simulate the flow field in the 120 mm ID bubble column with and without internals. The internals consisted of (a) one vertical central rod of 36 mm diameter, (b) one central rod of (a) and four vertical additional rods of 12 mm diameter, (c) one central rod of (a) and fourteen vertical additional rods of 12 mm diameter. The OpenFOAM simulations are found to be in good agreement with the experimental data for both bubble columns with and without internals. As regards to experiments, radial profiles of gas hold-up and the liquid velocity were measured by using the radioactive particle technique (RPT). Such measurements were made at four axial locations.

1. Introduction

The understanding of turbulent two-phase bubbly flows is important due to the wide spread occurrence of this phenomenon in natural and engineering systems. In the latter case, bubble columns are widely used in chemical process industry. Experiments, empirical correlations, one-dimensional convection-dispersion models and compartment models usually form the basis for the design of industrial scale bubble columns. However, such approach remains somewhat restricted when one aims on the efficient and reliable design and performance. In this perspective, three-dimensional computational fluid dynamic (CFD) simulations have proven to be useful. CFD helps to understand the complex two-phase fluid dynamics in the bubble column through details of mean flows (fields of three components of mean velocities and mean gas hold-up), interphase rates of mass, energy and momentum transfer and turbulence parameters (such as turbulent kinetic energy, energy dissipation rate, Reynolds stresses, etc.). This technique has considerably grown in importance and interest during

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Nomenclature

A	anti-diffusive flux
C	courant number
$C_{\varepsilon1}$, $C_{\varepsilon2}$, $C_{\varepsilon3}$	Constants in epsilon equation [Eq. (13)]
C_D	drag coefficient
C_L	lift coefficient
C_t	turbulence parameter
C_{VM}	virtual mass coefficient
C_{TD}	turbulent dispersion coefficient
D	column diameter, m
d_B	bubble diameter, m
F_I	interphase forces
F_L	lift force
Fr_G	Froude number for gas phase
F_X	face flux or mass flux through the cell face
f	Flux
g	acceleration due to gravity, ms^{-2}
H_D	height of gas-liquid dispersion, m
I	turbulence intensity
k	turbulent kinetic energy, $m^2\ s^{-2}$
k_m	mixture turbulent kinetic energy, $m^2\ s^{-2}$
l	turbulence length scale, m
Mo_L	Mortin number for liquid phase
P	pressure, Pa
Q_G	net volumetric flow rate of gas, $m^3\ s^{-1}$
Q_L	net volumetric flow rate of liquid, $m^3\ s^{-1}$
R	radius of column, m
r	radial distance from the centerline, m
Re	Reynolds number
Re_G	Reynolds number for gas phase
S_k	source term in the conservation equation for k_m, $m^{-1}\ s^{-2}$
s	surface area, m^2
U'	fluctuating velocity component, ms^{-1}
u_G	gas velocity, ms^{-1}
u_L	liquid velocity, ms^{-1}
u_i, u_j	three components of velocity, ms^{-1}
u_m	three components of mixture velocity, ms^{-1}
V	volume, m^3
V_G	superficial gas velocity, ms^{-1}
x	distance to first node from the wall, m

Greek letters

ε	turbulent energy dissipation rate, $m^2\ s^{-3}$
ε_m	mixture turbulent energy dissipation rate, $m^2\ s^{-3}$
$\in_G$	fractional gas hold-up
$\in_L$	fractional liquid hold-up
$\in_W$	fractional gas hold-up at wall
$\overline{\in}_G$	mean gas hold-up
$\overline{\in}_L$	mean liquid hold-up
κ	kappa
λ	parameter in Eq. (15)
μ	molecular viscosity, $kg\ m^{-1}\ s^{-1}$
μ_t	turbulent viscosity, $kg\ m^{-1}\ s^{-1}$
μ_m^t	mixture turbulent viscosity, $kg\ m^{-1}\ s^{-1}$
μ_L^t	liquid turbulent viscosity, $kg\ m^{-1}\ s^{-1}$
μ_G^t	gas turbulent viscosity, $kg\ m^{-1}\ s^{-1}$
ν	kinematic viscosity, $m^2\ s^{-1}$
ν_t	eddy or turbulent diffusivity, $m^2\ s^{-1}$
ρ_G	gas density, $kg\ m^{-3}$
ρ_L	liquid density, $kg\ m^{-3}$
ρ_m	mixture density, $kg\ m^{-3}$
σ_L	surface tension of the liquid, $N\ m^{-1}$
σ_m	turbulence parameter in k_m and ε_m equation
τ_{ij}	Reynolds stress, Pa
τ_P	characteristic time for bubble generated turbulence in Eq. (20)
ϕ	instantaneous properties such as $u_i, u_j, u_m, \in_L, \in_G$, P
∇^2	Laplacian operator
Δt	time step, s
Δx	single grid size, m

Subscripts

B	bubble
c	continuous phase
d	dispersed phase
fc	cell face
G	gas
L	liquid
m	mixture

Superscripts

$'$	fluctuating variable
m	mixture
t	turbulent

Abbreviations

FCT	flux corrected transport
MULES	multidimensional universal limiter with explicit solution
PISO	Pressure Implicit with Splitting of Operator
RNG	re-normalization group
SIMPLE	Semi-Implicit Method for Pressure Linked Equations
VTK	visualization toolkit

the past two decades following exponential developments of computing resources and abilities of numerical techniques. Nevertheless, the path of CFD modeling and simulations of bubble columns still faces many challenges.

In this work, we have mainly focused on understanding the behavior of two-phase bubbly flow in bubble columns with internals. The hydrodynamic studies related to the presence of internals in bubble columns have not been sufficiently carried out and addressed in the open literature. Larachi et al. [1] carried out useful studies in internals-containing bubble columns by performing two-fluid Euler continuum transient 3-D simulations by using FLUENT. They simulated five pilot-scale configurations: vessels of uniform filling (dense and sparse), vessels of non-uniform filling with large core and wall clearances, and equal cross-sectional hollow vessels. Almost similar qualitative flow pattern (an upflowing region was in the center and downflowing one nearby the wall as that of for open bubble column) was obtained for the uniformly arranged internals. On the contrary, non-uniform arrangements of internals resulted into more complex flow patterns with even liquid downward flow in the core region when the number of tubes in the core region was larger than those near the wall. They further found that the magnitude of axial velocities and turbulent kinetic energy were reduced by the presence of internals. In addition, some downward recirculation was revealed in the vicinity of tubes for the sparse arrangement but not for the dense one, which was not observed experimentally. The possible reasons given by authors were (i) they indeed would not exist, or (ii) the spatial scale of scrutiny of the probes was not sufficient for the downflow-