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Estimation of bubble column hydrodynamics: Image-based measurement method

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ABSTRACT

Bubble column reactors (BCRs) have proven their worth in the chemicals industry by achieving high heat and mass transfer rates at relatively low cost. Limiting the design and scale-up, however, are the complex hydrodynamics that they exhibit, whose influence on transport characteristics are not fully understood to date. In addition, most studies in the literature focus on single phase system, whereas typical industry systems are multiphase.

In this paper, a better understanding of the BCR hydrodynamics is obtained through investigating the coupling of Electrical Resistance Tomography (ERT) and Dynamic Gas Disengagement (DGD) technique. The increase in a Population Balance Model (PBM) simulation accuracy is achieved by allowing for the inference of bubble population property distributions such as bubble size and axial position. However, using a PBM to simulate bubble swarm phenomena under the influence of bubble coalescence and breakage requires accurately known boundary conditions. These are gas void fractions, the bubble size profile and the bubble number density distribution (BNDD).

Electrical Resistance Tomography (ERT) is a non-invasive imaging technique suitable for creating images of changing gas void fractions in BCRs. In this work, a steady-state two-phase air-water system was set-up in a BCR. The ERT data for analysis of the local disengaging gas volume were captured over four rings of electrodes on a column of height 1.545 m and diameter 0.29 m. To facilitate measurements of bubble population distributions, a Dynamic Gas Disengagement (DGD) approach was used to induce transient gas holdup fractions which were captured by the ERT apparatus.

The time profiles for the disengagement of gas void fractions locally were calculated for superficial gas velocities ($u_g s$) in the range 5.0×10^{-3} to 1.0×10^{-2} ms^{-1} (bubbly flow regime). From the known time profiles and height of the column sections, the bubble population properties were calculated. At u_g of 1.0×10^{-2} ms^{-1}; the local average bubble rise velocities were found to range from 2.0×10^{-1} to 6.5×10^{-1} ms^{-1}; the local Sauter Mean Bubble Diameters (SMBD) were found to range from $2.3\times10^{-3}$to 2.5×10^{-2} m; and the axially averaged BNDD of bubble sizes were found to range from 3.6×10^{-3} to 7.6×10^{-6} m^{-1}.

The smallest bubble size classes were found to be 2.3×10^{-3} m at u_g in the range 7.0×10^{-3} to 1.0×10^{-2} ms^{-1} with relative error of 4% compared to the theoretical prediction of 2.2×10^{-3} m . At u_g in the range of 5.0×10^{-3} to 6.0×10^{-3} ms^{-1}, the smallest bubble size classes were determined to be 1.65×10^{-3} m yielding the relative error of 37% compared to the theoretical prediction. The determined BNDDs were log-normal distributions and are consistent with both theoretical predictions and experimental findings. The low error values of the obtained results indicates the method is suitable for the development of PBM boundary conditions as well as the BCRs design and scale-up.

1. Introduction

High mass transfer rates and effective product yields are usually obtained from reactions set-up in an accurately designed and scaled-up bubble column reactors (BCRs) [1]. The performance of BCRs is often evaluated by the analysis of hydrodynamic parameters measured by experimental methods or predicted by simulation methods [2]. The bubble sizes and their number density distribution (BNDD) are essential bubble population parameters for column hydrodynamic parameter predictions [1]. The Dynamic Gas Disengagement (DGD) technique is proposed to be coupled to a measurement technique that allows for determining the

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Nomenclature

A_L	cross-sectional area, [m^2]
A	area or elemental area of a column cross-section, [m^2]
A_s	cross-sectional area occupied by small bubbles, [m^2]
A_L	cross-sectional area occupied by large bubbles, [m^2]
A_x	cross-sectional area of the column, [m^2]
B	parameter constant for the mean of the lognormal distribution
C	parameterization constant
D	parameter constant for the offset of the lognormal distribution from the abscissas axis
d_{32}	Sauter mean bubble diameter, [m]
d_b	bubble diameter, [m]
F	sensitivity matrix of the forward model operator
f	index of captured ERT data frame for image reconstruction
$f(d_b)dd_b$	volume fraction of bubbles with size between d_b and d_b+dd_b
g	acceleration due to gravity, [m s^{-2}]
h_{LM}	iterative step change in the conductivity distribution obtained by the Levenberg–Marquardt method
H	height, [m]
I	identity matrix
L	height of a column section, [m]
ΔL	elevated liquid height due to aeration of the liquid, [m]
m	time index of the period of a bubble size class disengagement
N	largest bubble size or total number of bubble sizes
n_z	axially averaged bubble number density distribution, [m^{-1}]
n	bubble number density distribution, [m^{-1}]
p	pressure [kg (ms^2)$^{-1}$]
ΔP	differential pressure between the unaerated and aerated liquid, [kg (ms^2)$^{-1}$]
R^2	regression statistic
R	radius of column reactor, [m]
r	radius of a bubble size class, [m]
S	slope of graph of H against t, [m s^{-1}]
S^2	residual mean squares
t	time, [s]
t_{min}	initial or stating time of the dynamic gas disengagement process, [s]
Δt	differential time step between successive disengagement periods, [s]
U_g'	local superficial gas velocity, [m s^{-1}]
U_b	bubble rise velocity, [m s^{-1}]
$U(d_b)$	the rise velocity of bubble size d_b, [m s^{-1}]
U_{bs}	the rise velocity of the small bubble size class, [m s^{-1}]
U_{bL}	the rise velocity of the large bubble size class, [m s^{-1}]
u_g	superficial gas velocity, [m s^{-1}]
V_L'	local superimposed liquid velocity, [m s^{-1}]
vol	volume of disengaging gas, [m^3]
V	measured voltage data, [V]
X^2	least squares regression
z	column axial length or column vertical axis, [m]

Greek letters

ε	local gas holdup
ξ	conductivity distribution vector, [S/m]
ξ_k	conductivity distribution vector at k iteration, [S m^{-1}]
μ	mean of the lognormal distribution
σ	standard deviation of the lognormal distribution
λ	Tikhonov regularization parameter

Abbreviations

AC	alternating current
ACD	area average of conductivity distribution
BCR	bubble column reactor
BNDD	bubble number density distribution
CFD	computational fluid dynamics
DGD	dynamic gas disengagement
DP	differential pressure
ERT	electrical resistance tomography
FEM	finite element method
Fps	frame per second
PBM	population balance model
SMBD	Sauter mean bubble diameter
TACD	time and area average of conductivity distribution

disengaging bubble rise velocities. The coupling approach is envisaged to be useful for calculating the global bubble size profile [3]. The gas hold-up and bubble size profile computed during the DGD process can be analyzed to predict hydrodynamic parameters in a BCR. Typical examples of the column hydrodynamic parameters are the gas holdup profile, specific interfacial area, mass transfer coefficient, residence time distribution and level of liquid circulation or mixing [4].

In addition, the time profile of disengagement of bubble sizes locally or globally in a column can be analyzed given the known height of column sections for the calculation of the average bubble rise velocity values. The bubble sizes can be determined from the bubble rise velocities using empirically developed correlations that map these bubble population parameters [5].

A coupling of Electrical Resistance Tomography (ERT) to the DGD process technique was explored for the estimation of bubble rise velocities and bubble population sizes in a column [6]. The profile of time-dependent gas hold-up during the DGD process imaged at column sections by the ERT technique was divided into 5 regions to obtain 5 bubble sizes by Haibo et al. [6,7]. The bubble size classes were broadly categorized into small and large bubble sizes by [6,8] when validated with large and small bubble classes obtained by the pressure measurement method. The division of the time-variant gas holdup profile captured by the ERT technique in the work in determining the times for bubble sizes disengagement reduces the resolution of bubble sizes. Thus, a new analysis technique of the high temporal ERT estimates of the local gas void fractions during DGD is proposed in the current work to obtain higher bubble size resolution.

In the present work, a higher accuracy of interpretation of a gas holdup profile is proposed based on an integration of ERT and the DGD process. The new interpretation technique improves the resolution of bubble size distribution having been tested for varied gas flow rates. The new method is low in capital cost, non-intrusive, non-radioactive and requires less computation. Therefore, it allows for accurate determination of the global bubble size classes, the bubble number density distribution (BNDD) and the Sauter Mean Bubble Diameter (SMBD). Many alternative techniques, such as conductivity probes [5,9], optical probes and cameras [10,30] and bubble size analyzers are either intrusive or costly or

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