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Investigating the influence of the configuration of the bundle of heat exchanging tubes and column size on the gas holdup distributions in bubble columns via gamma-ray computed tomography

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ABSTRACT

The impact of dense vertical internal tubes and their configurations on the gas holdup distributions and their diametrical profiles in pilot-scale bubble column is visualized and quantified for the first time ever using an advanced gamma-ray computed tomography (CT) technique. Two arrangements of vertical internals (circular and hexagonal configurations) occupying the same cross-sectional area (CSA) of the column (about 25% of the total cross-sectional area to represent the heat exchanging tubes that are used in the Fischer-Tropsch synthesis), were examined in addition to the measurement in the bubble column without vertical internals. Moreover, the gas holdup distribution results of the 18-inch (0.46 m in outer diameter, O.D.) bubble column are compared with an available data of 6-inch (0.15 m in O.D.) bubble columns with and without vertical internals. CT scans have been conducted for 18-inch bubble columns with and without vertical internals for the air-water system under a wide range of superficial gas velocity (0.05–0.45 m/s). The experimental results indicate that an improvement in the gas holdup distribution over the column's cross-sectional area is obtained when the vertical internal tubes (arranged in either a circular or a hexagonal configuration) were used. However, better cross-sectional gas holdup distribution was achieved in the bubble column with vertical internals arranged in a hexagonal configuration as compared to the bubble column without and with vertical internals arranged in a circular arrangement. Additionally, the averages of the cross-sectional gas holdup and their profiles for bubble column with and without vertical internals are close to each other when the bubble column with vertical internals is operating at a high superficial gas velocity, which is calculated based on the free cross-sectional area for the flow. Furthermore, the gas holdup distributions are further improved when the larger bubble column with vertical internals was used as compared to the 6-inch bubble columns with and without vertical internals.

1. Introduction

Bubble/slurry bubble columns equipped with a bundle of heat-exchanging tubes are well-fitted reactors for conducting highly exothermic reactions, such as Fischer-Tropsch (FT) synthesis, acetic acid production, cyclohexanol manufacturing, and many others [1–5]. The reason these reactors were selected for wide applications in industry is that they possess superior advantages in facilitating sufficient heat removal and temperature control (close to isothermal condition), which allow for a secure and high reactor performance [6–12].

Despite the wide variety of applications of bubble/slurry bubble columns (e.g., in industry), the design and scale-up of these reactors is a difficult engineering task due to the complex behavior of multiphase flow patterns and the absence of a phenomenological model that can reliably predict the flow patterns for these columns [13–16]. Additionally, the presence of the dense geometry of vertical tubes inside these reactors further alters the flow structure and the intensity of the mixing [17–21]. As a result, these vertical internal tubes make the design and scale-up even more challenging and complicated. Therefore, a comprehensive understanding of the impacts of vertical tubes on the hydrodynamics of these reactors is much needed to the successful design, scale-up, and optimize the performance of a bubble/slurry bubble column equipped with a bundle of the intense heat exchanging tubes.

One of the most critical hydrodynamic parameters for the design, scale-up, and modeling of bubble/slurry bubble columns is the gas holdup because of its impacts on the momentum, heat, and mass

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Nomenclature

Acronyms

CT	gamma-ray computed tomography
FT	Fischer-Tropsch synthesis
mReal	multiphase reactors engineering and applications laboratory
DSCT	dual-source gamma-ray computed tomography
NaI	sodium iodide scintillation detectors
AM	alternating minimization algorithm
EM	expectation maximization algorithm
GRD	gamma-ray densitometry technique
ARE	absolute relative error

Symbols

CSA	cross-sectional area (m^2)
D	column diameter (m)
O.D.	outer column diameter (m)
I.D.	inner column diameter (m)
H	column height (m)
μ	linear attenuation coefficients (cm^{-1})
ε	local gas holdup (–)
⟨ε⟩	mean of the gas holdup values along the diametrical profiles (–)
SD	standard deviation (–)
N	number of data points along the diameter of the column (–)
$\overline{\varepsilon_g}$	cross-sectional average of the gas holdup (–)
R	column radius (m)
$\varepsilon_{g,ij}$	gas holdup value in each pixel (–)
ε_{avg}	average of the cross-sectional gas holdup (–)
F	maldistribution factor of the gas holdup distribution (–)

transfer rates between phases; hence, it characterizes the performance of these reactors [22–26]. Also, local gas holdup distribution has a significant effect on the reactor's performance. For example, the high degree of non-uniform gas holdup distribution inside these columns causes a significant reduction in the specific interfacial area between the gas-liquid or gas-slurry phases, thereby reducing the mass transfer rate. Moreover, this uneven distribution could increase the liquid back-mixing and thus may promote a temperature gradient that could lead to a greater chance that local hot spots will form [27–29]. Furthermore, improving the gas holdup distribution by presenting different designs or arrangements of heat-exchanging tubes will increase the contact area between the gas-liquid phases in a bubble column or the gas-catalyst-liquid phases in a slurry bubble column; this allows for a high mass transfer rate, which consequently enhances the reaction rate.

The proper arrangement of the heat-exchanging tubes is crucial to maintaining the uniformity of the gas-liquid distribution over the column's cross-sectional area. This will provide better contact and interaction between phases, which enhances the productivity of these reactors. Eventually, understanding the influence of vertical tubes on gas-liquid distribution inside bubble columns is vital for the safe operation and efficient design of these reactors. Unfortunately, up-to-date, information of gas-liquid distribution for large-scale bubble column with intense vertical internals is not available in the literature.

So far, much research has focused extensively on the hydrodynamics of bubble columns without vertical internal tubes to achieve high performance in these reactors. However, few studies have investigated the effects of vertical internal tubes on the hydrodynamics of these reactors, while many of the industrial applications for the bubble/slurry bubble columns involve inserting bundle of vertical tubes to (1) remove the released heat of the reaction, (2) enhance the breakup of bubbles, or (3) reduce a degree of back-mixing of a liquid phase [30–34]. As pointed out earlier, the existence of the bundle of vertical tubes significantly affects the fluid dynamics of these reactors, and quantifying and predicting these impacts is difficult without experimental work. Therefore, the current investigation focuses on bubble columns equipped with dense vertical internal tubes.

To the best of the authors' knowledge, the local gas holdup distribution over the entire cross-sectional area of the bubble column equipped with vertical internal tubes has been measured using gamma-ray computed tomography (CT) in no more than two studies in the literature. One of these studies was performed by Chen et al. [35], where the authors measured for the first time the gas holdup distribution and related radial profiles in a pilot-scale bubble column (44 cm in inner diameter, I.D.) with and without vertical internals for air-water and air-drakeoil systems operated under a range of superficial gas velocities from 0.02 to 0.1 m/s. To simulate the heat-exchanging tubes used in industrial methanol synthesis, the 1-inch (0.0254 m in O.D.) aluminum vertical internals in their work were designed and arranged sparsely in a circular configuration that blocked only 5% of the column's cross-sectional area. Their experimental results revealed that the gas holdup distributions at the highest superficial gas velocity (i.e., 10 cm/s) were axisymmetric at the fully developed region for both systems in the bubble columns with and without vertical internals. Additionally, the gas holdup values obtained in the bubble column without vertical internals for the air-drakeoil system were lower than those measured in the same column for the air-water system. Furthermore, the authors pointed out that the effects of the vertical internals were not significant on the gas holdup for both systems.

The second of the two studies was recently conducted by Al Mesfer et al. [36]. They imaged and quantified the gas holdup distributions in bubble columns (14 cm in I.D.) with and without vertical internals for the air-water system under a wide range of superficial gas velocity (5–45 cm/s) calculated based on the free and the total cross-sectional area (CSA) of the column. The authors used 0.5-inch (0.0127 m in O.D.) Plexiglas® vertical internals that were arranged densely in a hexagonal shape over the CSA of the column. These vertical internals were designed to cover 25% of the column's CSA to represent the heat-exchanging tubes that were used in Fischer-Tropsch (FT) synthesis. The CT images revealed that the gas holdup distributions were almost axisymmetric in the bubble columns with and without vertical internals for all studied superficial gas velocities except for the high superficial gas velocities of 30 and 45 cm/s, where distributions exhibited asymmetrically. Moreover, the authors found that the overall and local gas holdups rose significantly with increasing superficial gas velocities when the gas velocity was calculated based on the total CSA of the bubble column. Furthermore, they reported that the overall and local gas holdup profiles that were achieved in the bubble column without vertical internals operated under high superficial gas velocity could be extrapolated to the columns with vertical internals if these columns worked under the same superficial gas velocity if it was calculated based on the free CSA of the column. However, the intensity of mixing and local liquid/slurry velocity and turbulent parameters cannot be similarly extrapolated [5].

According to the prior discussion, it is evident that the characteristics of gas holdup distributions in a large-scale bubble column equipped with dense (covering 25% of the total CSA) vertical internal tubes have not yet been visualized and quantified. Therefore, the goal of this study to visualize and quantify for the first time the influence of the presence dense vertical internals and their configurations on the gas-liquid distribution over the entire CSA of large-scale bubble