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The impact of heat exchanging internals on hydrodynamics of bubble column reactor

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THE IMPACT OF HEAT EXCHANGING INTERNALS ON HYDRODYNAMICS OF BUBBLE COLUMN REACTOR

By

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ABSTRACT

In this study, the impact of configuration and size of vertical heat exchanging internals in bubble columns on gas holdup, specific gas-liquid interfacial area, bubble chord length, and bubble rise velocity were investigated. Three different configurations of internals, each covering 25% of the column's cross-sectional area, were used to simulate the heat exchanging tubes utilized in the F-T process. The First configuration is a circular-like arrangement of 0.5 inch diameter vertical rods, whereas the second is a hexagonal-like arrangement of 0.5 inch diameter vertical rods. The third configuration is also a circular arrangement but of 1 inch diameter vertical rods used to examine the effect heat exchanging tubes diameter on the hydrodynamics. The experiments were carried out in a 14 cm inner diameter Plexiglas bubble column using air-water system, at superficial gas velocities in the range of 0.02 to 0.45 m/s, measured based on free cross-sectional area of the column available for fluid flow. 4-point optical fiber probe technique was used to collect the diameter profiles of the hydrodynamic parameters. In comparison to bubble column without internals, the obtained result showed that the configuration of the internals significantly affect the hydrodynamics and also the flow resistance inside the column. Steeper gas holdup and specific interfacial area profiles observed when the 0.5 inch circular arrangement internals is used. A distinct asymmetrical radial profiles of gas holdup and specific interfacial area were obtained when the hexagonal arrangement is used. The 1 inch internals enhanced the gas holdup and specific interfacial area near to the wall regions. In the churn turbulent regime, Bubbles chord length and bubbles rise velocity were found to be larger with the presence of internals when compared to bubble column without internals.

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SECTION

1. INTRODUCTION

Bubble column reactors belong to a general class of multiphase reactors, which consists of three main categories: trickle bed reactor (fixed or packed bed), fluidized bed reactor and bubble column reactor. A bubble column reactor is basically a vertical cylinder with a gas distributor at the bottom. The gas is continuously sparged through the distributor and dispersed, in the form of bubbles, into either a liquid phase or a liquid–solid suspension. Bubble column reactors are referred to as slurry bubble column reactors when a solid phase exists. In these cases, the solids are typically fine catalyst particles. The liquid flow can be co-current, counter-current or in batch mode with respect to the gas flow. The type of the flow regimes in bubble columns depends on the applied superficial gas velocity. Three types of flow regimes are commonly observed in bubble columns. These are the homogenous flow regime (bubbly flow), the heterogeneous flow regime (churn turbulent flow) and the slug flow regime (Kantarci et al., 2005; Shaikh and Al-Dahhan, 2007). However, bubbly and churn-turbulent flow regimes are most frequently encountered.

The bubbly flow regime is characterized by bubbles of relatively uniform size and velocity. There is practically no coalescence and breakup, which results in a narrow bubble size distribution. Thus, bubble size in this regime is mainly governed by the distribution design and physical properties of the fluids. This type of flow regime can be obtained at superficial gas velocities that are less than 5 cm/s (Kantarci et al., 2005). The churn turbulent flow regime occurs at high superficial gas velocities, and it is characterized by an intense coalescence and breakage of bubbles. Therefore, both small and large bubbles appear in this regime leading to a broad bubble size distribution across the column (Wu and Al-Dahhan, 2008; Xue, 2004) . The average bubble size in this regime is controlled by the extent of the coalescence and breakup, which is decided by the local turbulence of the flow field (Kulkarni, 2007; Lehr et al., 2002). Depending on the operating conditions and the design parameters, the bubbly and churn turbulent flow regimes are separated by a transition regime (Shaikh and Al-Dahhan, 2007).

Bubble and slurry bubble column reactors have been employed in a wide range of applications in chemical, petrochemical and biochemical processes including hydrogenation, oxidation, chlorination, Fischer-Tropsch synthesis, liquid phase methanol synthesis, waste water treatment, algae culturing and the production of single cell protein (Deckwer and Field, 1992; Lehman. and Hammer, 1978; Youssef, 2010). Bubble column reactors are used in so many applications because of the advantages they have over other multiphase reactors. Some of these advantages are good heat and mass transfer rates due to excellent mixing of the phases, high thermal stability due to a relatively low axial and radial temperature gradient, the possibility of online catalyst addition and withdrawal and the absence of mechanically moving parts which lowers the maintenance and operation costs. In spite of their positive qualities, bubble column reactors do have some disadvantages. The complexity of the flow structure within the reactor makes scaling up and getting proper design more difficult. Also, there is a considerable amount of back-mixing within the phases. Proper design and scale-up of bubble/slurry bubble column reactors requires a thorough understanding of the prevailing hydrodynamic parameters such as gas holdup, liquid velocity, turbulent parameters, and bubble dynamics including bubble size and bubble velocity. These parameters impact the mixing intensity and the gas-liquid interfacial area. In turn; these affect the heat and mass transfer coefficients, which directly impacts the conversion and selectivity of the reactor.

Numerous design parameters (e.g., reactor geometry, sparger design, internals, etc.) and operating conditions (such as pressure and temperature, gas and liquid flow rates, catalyst particle size and loading, etc.), along with the fluids' properties and reaction kinetics influence the hydrodynamics of bubble/slurry bubble column reactors. In the last two decades, a considerable effort has been devoted to understanding the parameters' effect on the hydrodynamics of bubble columns reactors (Devanathan, 1991; Kumar et al., 1997; Degaleesan et al., 1997; Camarasa et al., 1999; Camarasa et al., 1999; Gandhi et al., 1999; Krishna et al., 2000; Wu et al., 2001; Xue, 2004; Wu et al., 2006; Han and Al-Dahhan, 2007; Kagumba and Al-Dahhan, 2015; Rados et al., 2005; Shaikh and Al-Dahhan, 2003; Youssef and Al-Dahhan, 2009; Youssef et al., 2012; Ahmed A. Youssef, 2013). However, due to the complex interaction among the phases, particularly in the churn turbulent flow regime which is of industrial interest, the flow field and hydrodynamics of bubble column reactors are not yet fully established.

2. MOTIVATION

The conversion of natural gas to liquid fuels (GTL) is currently a major interest of the energy industries. GTL involves the chemical conversion of natural gas into syngas and then into liquid fuels via Fisher-Tropsch (FT) synthesis. The main incentives for GTL technology are the growing availability of natural gas and the increasing demand for liquid fuels. The heart of a GTL plant is the FT synthesis where the reaction of syngas (H_2 and CO) into liquid hydrocarbons takes place. The primary chemical reaction of the FT synthesis can be expressed as follows:

$$CO + 2H_2 \longrightarrow -CH_2- + H_2O + heat \qquad (1)$$

The overall efficiency of FT synthesis mainly depends on the type of reactor technology. The challenge in FT synthesis is the rapid and efficient removal of the large amount of heat that accompanies the reaction.

The slurry bubble column reactor is considered the reactor of choice for handling FT synthesis reaction to produce middle distillate fuels from syngas (Espinoza et al., 1999; Krishna and Sie, 2000). Most significant characteristics of the slurry bubble column reactor are that they are well mixed, can provide isothermal condition, and the possibility of online catalyst renewal. The latter is of significant importance in FT synthesis where the catalyst needs to be replaced periodically. The aforementioned features are not achievable by the other reactor (Multi Tubular Fixed Bed Reactors) which has been used for the same process (Jager, 2003).

However, there are still considerable reactor design and scale-up issues associated with performing such energy conversion processes in bubble columns. The successful commercialization of bubble column reactors is crucially dependent on properly understanding their hydrodynamics. The knowledge of gas holdup and bubble properties including bubble velocity, bubble size and specific interfacial area, is of great importance for the proper design and operation of bubble columns. For instance, the overall volumetric mass transfer in a bubble column is governed by the liquid-side volumetric mass transfer coefficient ($k_l a$) **,** (Behkish, 2004; Han and Al-Dahhan, 2007), which varies mainly due to variations in the gas-liquid interfacial area (Han and Al-Dahhan, 2007). The specific gas-liquid interfacial area is related to the gas holdup and the bubble size distribution. The gas holdup, which is determined by the bubble size , bubble velocity, and bubble population, is an important factor in determining the reactor volume, system pressure drop, and gas-liquid mixing behavior (Xue, 2004). In the same way, these parameters play key roles in determining the heat transfer rate in bubble columns (Kagumba, 2013). Furthermore, bubble size distribution and bubble velocity distribution are key parameters in evaluating the drag forces on bubbles and in using the bubble population balance in Computational Fluid Dynamics (CFD).

The temperature profile within the bubble column significantly affects the selectivity of the reaction, so it is very important to keep the temperature under control. Additionally, it is essential to maintain a uniform temperature distribution so that the catalyst does not over-heat. Internal vertical heat exchanging tubes are used to remove the excess heat from the reaction.

Basically, the selection of the number of tubes or the cross-sectional area (CSA) occluded by the tubes, and the configuration of the tubes (including the diameter, arrangement, and inter-tube gap) are decided by the surface area necessary for the heat transfer. This mainly depends on the exothermic nature of the reaction and the overall heat transfer coefficient.

Although extensive research has been conducted in the last few decades to understand the hydrodynamics in bubble and slurry bubble column reactors, only a few of these studies have accounted for the presence of the heat exchanging tubes (Chen et al., 1999; Guan et al., 2015b; Hamed, 2012; Kagumba and Al-Dahhan, 2015; Larachi et al., 2006; Youssef and Al-Dahhan, 2009). These studies reported that the presence of the internals affect the hydrodynamics, mixing patterns, bubble dynamics as well as the heat and mass transfer inside the reactor. However, a fundamental description of this effect is currently not available.

The effects of the occluded CSA by the tube bundle on the bubble column's hydrodynamics have already been investigated in some studies. In 1991, Benemann investigated the effect of the occluded CSA by vertical tube bundle on gas velocity, liquid velocity, over all gas holdup and flow regime transition (Bernemann, 1989). Youssef and Al-Dahhan (2009) studied the effect of the occluded CSA on local gas holdup, specific gas-liquid interfacial area, bubble size (in terms of bubble chord length), and bubble velocity. In another study, Hamed (2012) examined the effect of the occluded CSA on the gas velocity, axial gas dispersion, and volumetric mass transfer coefficient. These studies all agreed that the effect of the internals is significant only when a large fraction of the column's CSA is equipped with internals.

Unfortunately, experimental data concerning the effect of different configurations of the tube bundle while covering the same CSA on the bubble column’s hydrodynamics has not been reported in the literature.

Larachi et al. (2006) carried out a 3D CFD simulation to study the effect of heat exchanging tube bundle configuration (uniformly and non-uniformly distributed tubes over column (CSA). Their result showed that the configuration of the tube bundle has significant effect on the flow pattern within the bubble columns. This effect was particularly noticeable when the tubes were non-uniformly distributed over the column’s CSA. However, their results were not validated against any benchmark experimental data because there are no such experimental studies that investigate the effect of the internal tube bundle configuration on the hydrodynamics of bubble columns. Thus, it is necessary to experimentally investigate the impact of the different configuration of the heat exchanging tube bundles while covering the same CSA of the column.

The diameter of the tubes is the other main parameter that is considered when designing the heat exchanging tubes. The effect of the tubes’ diameter on bubble dynamics has not yet been properly addressed. To the best of the author’s knowledge, there is only one study in the open literature that tackles the effect of tube diameter on the bubble dynamics in bubble column (Kagumba and Al-Dahhan, 2015). This study reported that the tube diameter had a significant effect on the properties of the bubble column. However, the tube bundles were configured differently in each case. For the tubes with smaller diameter, the tubes were distributed non-uniformly, in a hexagonal-like shape, over the column’s CSA, while the larger tubes were distributed evenly over the CSA. Therefore, it cannot be determined whether these changes were caused by the change in tube size or the configuration of the tube bundles. Moreover, this work only reports the results from one side of the column, but it has been proven that non-uniformly arranged internals yield an asymmetric profile (Guan et al., 2015a; Larachi et al., 2006). Hence, the effect of the internals cannot be confidently evaluated from this study. To fairly assess the effect of the tubes' diameter on the hydrodynamics of the bubble columns, the configuration of the tube bundles should be similar in both cases. Therefore, such investigation is necessary to properly understand the effect of the heat exchanging tubes' diameter on the hydrodynamics of bubble columns.

The effect of internals height above the gas Sparger (the gap between the internals and the gas distributor) on hydrodynamics in bubble or slurry bubble columns has not been reported in the literature. Therefore, it is necessary to investigate the effect of internals' height above the gas sparger on the hydrodynamics in bubble columns.

To summarize, in order to accomplish an improved understanding and quantification of the hydrodynamics of bubble columns equipped with heat exchanging internals, a close investigation of the effects that the configuration, size of the heat exchanging internals' have on gas holdup, gas-liquid interfacial area , bubble size and bubble rise velocity distributions which are considered among the most important hydrodynamic parameters that govern the performance of bubble column reactors, is required.

3. RESEARCH OBJECTIVES

The primary objective of this work is to advance the knowledge of *The Impact of Heat Exchanging Internals on Hydrodynamics of Bubble Column Reactor*. To achieve this goal, extensive experiments will be performed to examine the effect of heat exchanging tube bundle with different configurations on the diameter profiles of the key hydrodynamic parameters in bubble columns, such as gas holdup, gas-liquid interfacial area, bubble passage frequency, bubble chord length, and bubble rise velocity. The following objectives are set for this work as the main parameters to characterize the effect of internals:

1. For the first time, The impact of the heat exchanging tube bundle configurations on gas holdup and bubble dynamics. Uniformly and non-uniformly distributed heat exchanging tubes over the column's CSA is to be examined. The non-uniform distribution arrangement of the tube bundles will be designed in the same way as those used in earlier studies to properly compare it with the proposed uniform arrangement of the tube bundle.
2. The impact of tube size on gas holdup and bubble dynamics. Two different tube sizes will be studied for the uniform distribution of the heat exchanging tubes.
3. Evaluating the impact of heat exchainging internals' height above the gas distributor on the gas holdup and bubble dynamics.

Due to the high industrial significance of FT synthesis, the CSA that is occluded by the tube bundles in all configurations is proposed to meet the corresponding heat transfer requirements for this process, 25% of the column CSA (Al-Mesfer, 2013; Youssef, 2010). The above objectives will be pursued by conducting experiments over a wide range of superficial gas velocities including bubbly, transition and churn turbulent regimes. For the sake of comparison and simplicity, the experiments will be conducted using an air-water system in a bubble column with diameter of 6 in and height of 6ft. This is similar to those used in the studies with related parameters. The completion of this work will enhance the understanding of the hydrodynamics of bubble column reactors equipped with dense internals, and it will facilitate the proper design and scale-up of these kinds of reactors.

PAPER

I. IMPACT OF HEAT EXCHANGING INTERNALS CONFIGURATION ON GAS HOLDUP AND BUBBLE PROPERTIES IN A BUBBLE COLUMN FOR THE FISCHER-TROPSCH SYNTHESIS

ABSTRACT

A rapidly developing application of bubble column reactors utilizes the production of clean fuels such as sulfur-free diesel fuel *via* Fischer-Tropsch (FT), dimethyl ether (DME) and bioethanol processes. Many of these processes involve exothermic reactions for which heat exchanging internals are needed to achieve isothermal conditions resulting in the desired yield and product quality. The effect of vertical heat exchanging internals and their arrangements on local gas holdup and bubble dynamics including specific gas-liquid interfacial area, bubble chord length, and bubble rise velocity have been studied using the 4-point optical fiber probe technique. Two different internals arrangement were investigated which are uniformly distributed internals in a circular like shape and non-uniformly distributed internals in a hexagonal shape over the column cross-section area. 30 tubes, each with a diameter of 0.5 inch**,** were used in each arrangement occupying 25% of the column cross-section area. The experimental work was performed in a 0.14 m inner diameter Plexiglas bubble column using an air-water system. The applied superficial gas velocities were based on free cross-sectional area available for the flow and were in the range of 0.02 to 0.45 m/s covering bubbly, transition, and churn turbulent regimes. Although the cross-sectional area covered by both of the arrangements was similar, their effects on the hydrodynamics were found to be different. The circular arrangement at

higher superficial gas velocities, showed a significant increase in the local gas holdup in the core region and a decrease at the wall regions. Simultaneously, a substantial increase in the bubble chord length and bubble velocity was seen. Another important observation was the decrease in the interfacial area mainly influenced by the large bubble size along the diameter profile. A distinct asymmetrical effect on the radial profiles of gas holdup and specific interfacial area were observed when the hexagonal arrangement was used. The holdup and interfacial area significantly increased in one side of the column and decreased on the other side due to the non-uniform arrangement. The bubble chord length and bubble rise velocity decreased, exhibiting a narrower distribution with smaller values, in comparison to the bubble column without internals.

Keywords: Bubble column, internals, circular arrangement, hexagonal arrangement, gas holdup, gas-liquid interfacial area, bubble chord length, bubble rise velocity.

1. INTRODUCTION

Bubble and slurry bubble column reactors have been employed in a wide range of applications proving advantages mainly for their good heat and mass transfer characteristics, high thermal stability, absence of mechanically moving parts, low operating cost and inexpensive maintenance (Deckwer and Field, 1992). The application of bubble column reactors in the production of clean fuel such as sulfur-free diesel fuel via Fischer-Tropsch process, dimethyl ether (DME) and bioethanol processes is a significant development. These processes involve exothermic reaction for which heat exchanging internals are used to achieve isothermal conditions for desired product quality and yield (Al-Mesfer, 2013; Jhawar and Prakash, 2014; Kagumba and Al-Dahhan, 2015; Krishna and Sie, 2000; Youssef, 2010; Youssef and Al-Dahhan, 2009). However, the effect of these internals on hydrodynamics is not well known. Extensive research has been conducted in the last few decades to understand the hydrodynamics in bubble and slurry bubble column reactors, while only few of these studies have considered the presence of the heat exchanging internals.

Chen et al. (1999) studied the effect of internals on gas holdup, liquid velocity, and turbulent parameters in a bubble column with an 18 inch inner diameter (I.D.). The internals covered 5% of the column’s cross-sectional area (CSA) under superficial gas velocities in the range of 2–10 cm/s. The measured results indicated that the presence of internals covering such percentage of the column CSA decreased the turbulent stresses and eddy diffusivities, while had insignificant effect on liquid velocity and gas holdup.

Forret et al. (2003) used Pitot tube and standard tracer techniques to investigate the effect of adding vertical heat exchanging tubes on the liquid dispersion in a 1 m diameter bubble column for air water system. 56 tubes, each 63 mm in diameter were used in their work to cover 22.2% of the column's CSA. They observed that the presence of internals reduced liquid fluctuation velocity and significantly enhanced the axial liquid velocity in the core region creating large scale liquid circulation.

Larachi et al. (2006) carried out a 3D computational fluid dynamic simulation for five pilot scale bubble column geometries. This simulation included bubble columns without internals, with internals of uniform arrangement (dense and sparse), and with internals of non-uniform arrangement (core and wall clearance). The extent of occluded cross-sectional area (2-16 %) and the arrangement of the internals on flow behavior were studied. All of these simulations were performed for an air-water system under ambient temperature and pressure for an invariant superficial gas velocity of 12 cm/s. Their study revealed that the arrangement of the internal tubes and the inter-tube gaps had a significant effect on the liquid circulation and the flow pattern. Additionally, they reported that the liquid gross flow structure followed more or less core-annulus up flow when the internals were uniformly arranged. Contrarily, when the internals were not uniformly arranged, it resulted in a complex flow pattern with even liquid moving down flow in the core region when the core clearance arrangement was implemented. Moreover, a sharp decrease in the liquid kinetic energy was also observed upon adding the internals. However, their results were not validated against any benchmark experimental data due to lack of such experimental studies for bubble column with internals.

Youssef and Al-Dahhan (2009) experimentally investigated the effect of internals that mimic the heat exchanging tubes used in methanol synthesis (covering 5 % of CSA) and those that used in the Fischer-Tropsch process (covering 22% of the CSA) on the radial profile of gas holdup and bubble dynamics including the specific interfacial area, bubble chord length, and bubble velocity by using a 4-point fiber optical probe technique. Their experiments were performed in an 8 inch diameter bubble column for air-water system at superficial gas velocities ranging from 3 to 20 cm/s calculated based on total CSA. They reported that the dense internals (22% CSA) led to a significant increase in gas holdup and interfacial area but a decrease in bubble size and bubble velocity, while no significant effects for the less dense internals (5% CSA) were reported. This work provided a great insight of impact of vertical internals on local bubble dynamics. However, the occluded CSA by the internals was not accounted when the superficial gas velocities were calculated. This means that the same mass flow rate for the bubble column without internals passed into the column with internals. In order to fairly assess the impact of internals, the superficial gas velocity should be based on free cross-sectional area for the flow as highlighted by Al-Mesfer (2013) and Kagumba and Al-Dahhan (2015).

Zhang et al. (2011) experimentally measured gas holdup and liquid velocity in a 0.5 m I.D. bubble column with internals covering 0 – 11 % of column CSA. Their results indicated that the gas holdup profile became steeper and large scale liquid circulation was enhanced in the presence of internals.

Hamed (2012) studied the effect of dense internals (22% CSA) on the gas velocity profile and axial gas mixing over a wide range of superficial gas velocities ranging from 5 to 45 cm/s, based on the free CSA for flow in a lab-scale 8 inch bubble column and a pilot-scale 18 inch bubble column in the absence and presence of internals by using 4-point optical fiber probe and gas tracer techniques. The results showed that the center line gas velocity increased with the presence of internals, while the axial gas mixing and dispersion significantly decreased. The author reasoned the increase in center line gas velocity and the decrease in the axial gas dispersion was due to the decrease in turbulence intensity caused by the presence of internals.

Al-Mesfer (2013) applied Advanced Gamma Ray Computed Tomography (CT) and Radioactive Particle Tracking (RPT) techniques to a bubble column with and without internals. The effect of superficial gas velocity and vertical heat exchanging tube internals on the overall and time averaged cross-sectional gas holdup profile, axial liquid velocity, normal and shear stress profiles, turbulent kinetic energy, and eddy diffusivities were studied in a 0.14 m I.D. bubble column for air-water system. Thirty rods of 0.5 inch in diameter, covering 25% of the total CSA were implemented to mimic the heat exchanging tubes that used in the Fischer-Tropsch process. The experiments were conducted over a wide range of superficial gas velocities (5 cm/s - 45 cm/s) based on total and free CSA of the column in order to fairly compare the effect of internals. The author reported that in the bubble column without internals, the gas holdup, radial profiles of normal liquid stress, Reynolds shear stress, turbulent kinetic energy, and eddy diffusivity increased with the increasing superficial gas velocity. Moreover, at any of the studied superficial gas velocities, the presence of internals increased the magnitude of the axial liquid velocity (positive and negative). On the other hand, a sharp decrease in the normal and shear liquid stresses, eddy diffusivity and liquid turbulent kinetic energy profiles at any given gas velocity was found in the presence of internals.

Guan et al. (2015) experimentally investigated the hydrodynamics in a 0.8 m diameter and 5 m height Plexiglas bubble column with pin-fin tube internals covering 9.2% of column CSA for air-water system. The measurements were taken using an electrical resistance probe and a Pavlov tube. Their results indicated that the pin-fins on the tubes increased total gas holdup and altered radial gas holdup and liquid velocity profiles in the column. Moreover, the non-uniform arrangement of pin-fin tubes, through symmetrically removing two tubes in the annular region, caused sharp gas short-circuiting and even no downward liquid flow in the places where the tubes are removed.

Recently, Kagumba and Al-Dahhan (2015) examined the effect of internals and their size on gas holdup and bubble properties in a bubble column with 5.5 inch I.D. Two different sizes of vertical tube internals were used, 0.5 inch and 1 inch in diameter, were investigated. Both tubes covered the same cross-sectional area of the column (25%). Their experimental data showed that 0.5 inch internals consistently had higher overall and local gas holdup, specific interfacial area, and bubble passage frequency than the 1 inch internals and the column without internals. The 1 inch internals gave higher bubble velocities and larger bubble sizes than the other cases. However, the tube bundles were configured differently in each case. For the tubes with smaller diameter, the tubes were distributed non-uniformly, in a hexagonal-like shape, over the column's CSA**,** while the larger tubes were distributed evenly over the CSA. Therefore, it cannot be determined whether these changes were caused by the change in tube size or the configuration of the tube bundles.

The studies above indicate that internals alter the hydrodynamics of bubble column reactors. However, the quantitative description as to how this happens is not immediately available. It can be noticed that the impact of the internals diameter and the occluded CSA by the internals have been investigated but no experimental data is available on the effect of internals configuration on hydrodynamics of bubble column reactors**.** Hence it is beneficial to investigate the effect of different configurations of internals arrangements while covering the same CSA of the column. Accordingly, investigating the impact of two different arrangements of internals on some of the key hydrodynamic parameters such as local gas holdup, specific gas-liquid interfacial area, bubble size, and bubble velocity using 4-point optical fiber probe is the focus of this work.

2. EXPERIMENTAL SETUP

The experiments were carried out in a Plexiglas column of 0.14 m I.D. and height of 1.83 m. The column was aligned vertically and supported by a rigid metallic structure with rubber connection to eliminate mechanical vibrations as shown in the photo of the setup presented in Figure 2.1. The effect of different internal arrangements on overall and local gas holdup, specific gas-liquid interfacial area, bubble size, and bubble rise velocity were studied. In the current study, two different configurations of internals; a circular-like shape and a hexagonal-like shape as shown in Figure 2.2, were examined. The circular-like arrangement features uniformly distributed internals over the column CSA, whereas the hexagonal-like arrangement features non-uniformly distributed internals over the column CSA. The latter shape has been used by Al-Mesfer (2013) and Kagumba and Al-Dahhan (2015) . Hence, such arrangement can be used as base of comparison with these studies as well. Each configuration of the internals consisted of 30 Plexiglas rods/internals with 0.5 inch I.D. and 6.2 ft. height covering 25 % of the column CSA as used in Fischer-Tropsch process (Youssef and Al-Dahhan, 2009). Each arrangement was secured in the column by using three honeycombs which also minimized internals vibration during the experiments.

Compressed, filtered dry air was used continuously through the experiments as gas phase while purified water was used in batch mode as liquid phase. In the current study, air was introduced from the bottom through a 30 cm plenum and a perforated plate gas sparger containing 121 holes of 1.32 mm diameter oriented in a triangular pitch providing 1.09 % of open area. The gas flow rate was measured using a set of calibrated GT 1000 series of Brooks rotameters. The experiments were conducted over wide range of superficial gas velocities (2 cm/s to 45 cm/s) measured based on free CSA available for the flow, covering bubbly, transition, and churn turbulent regimes. The dynamic bed height was kept at a constant level of Z/D=11.25 (160 cm above the gas sparger) during all of the experiments. The dynamic level of the bed was preserved by varying the unaerated liquid height for each of the studied conditions. The liquid phase was fed from the bottom and replaced with a new batch after each experiment. 4-point optical fiber probe technique was manufactured and implemented. The probe was fixed at one axial height within the fully developed region, Z/D=5.1 (71 cm above the gas sparger) and moved radially in one line to investigate radial distributions of the studied parameters by taking measurements at seven dimensionless radial points along the diameter of the column (r/R=0, $\pm$0.3, $\pm$0.6, and $\pm$0.9).

The superficial gas velocity was calculated by dividing the volumetric gas flow rate into the column by the free CSA of the column available for the flow. The free CSA of the column was calculated from the following the relation;

$$\begin{Bmatrix} Free\ Cross-sectional \\ area\ of\ bubble\ column \\ with\ internals \end{Bmatrix} = \begin{Bmatrix} Cross-sectional\ area \\ of\ bubble\ column \\ without\ internals \end{Bmatrix} - \begin{Bmatrix} Cross-sectional\ area \\ occluded\ by \\ the\ internals \end{Bmatrix}$$

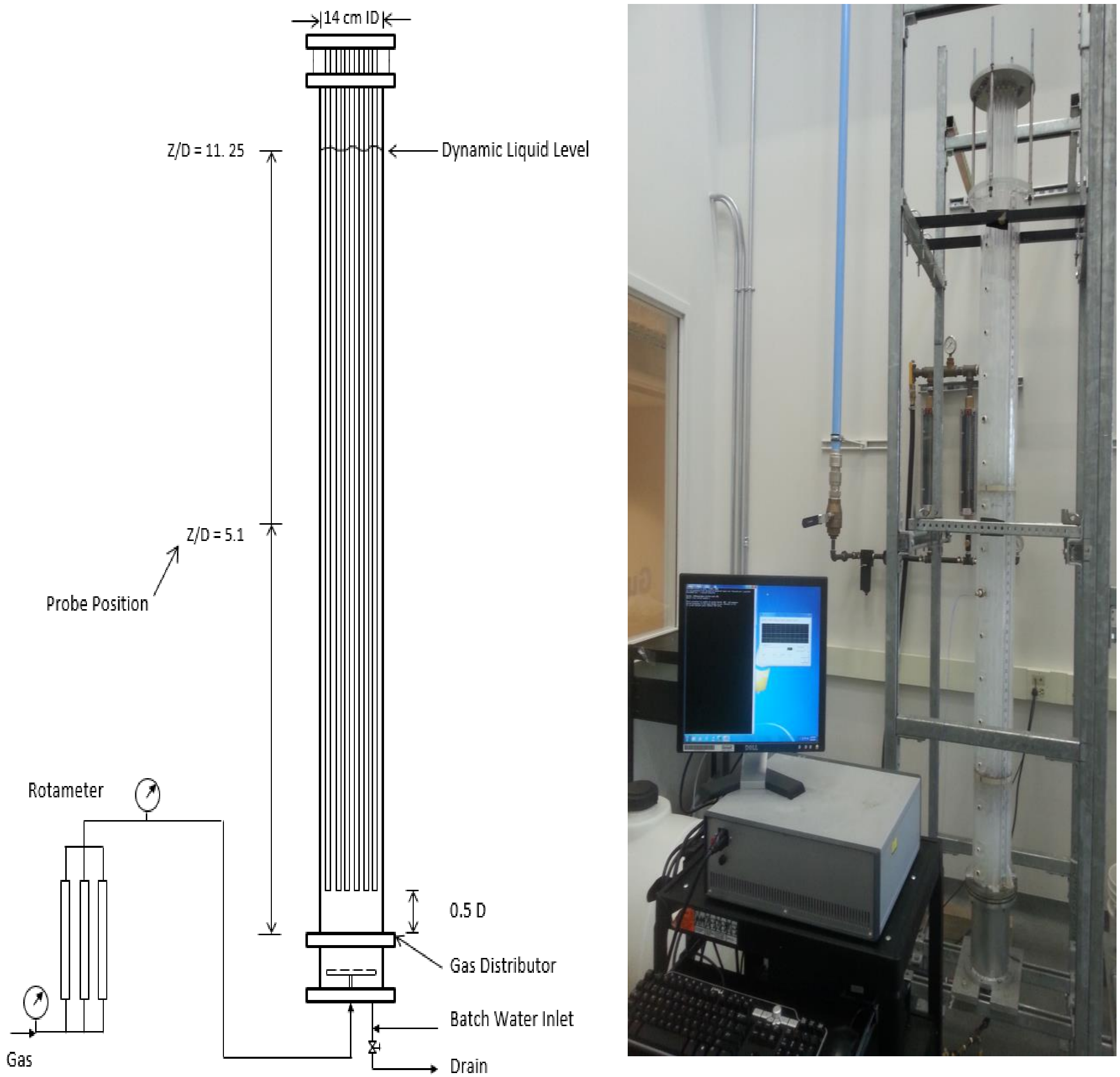
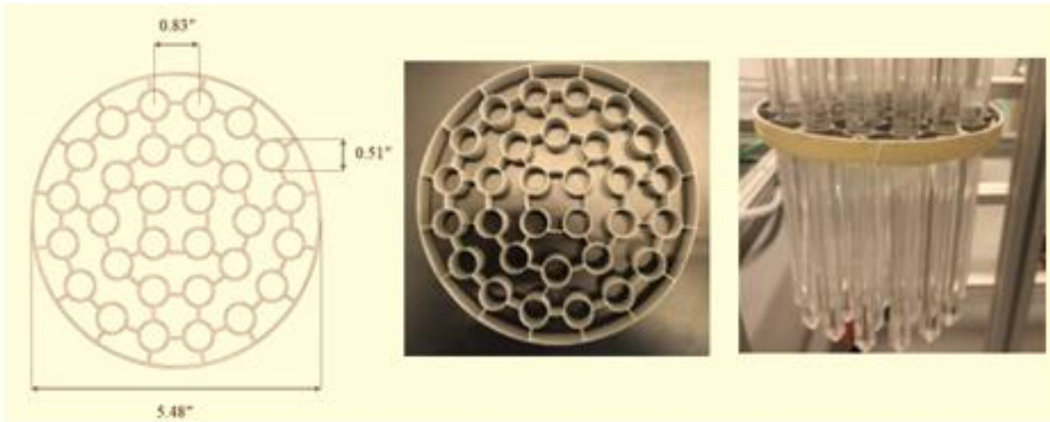
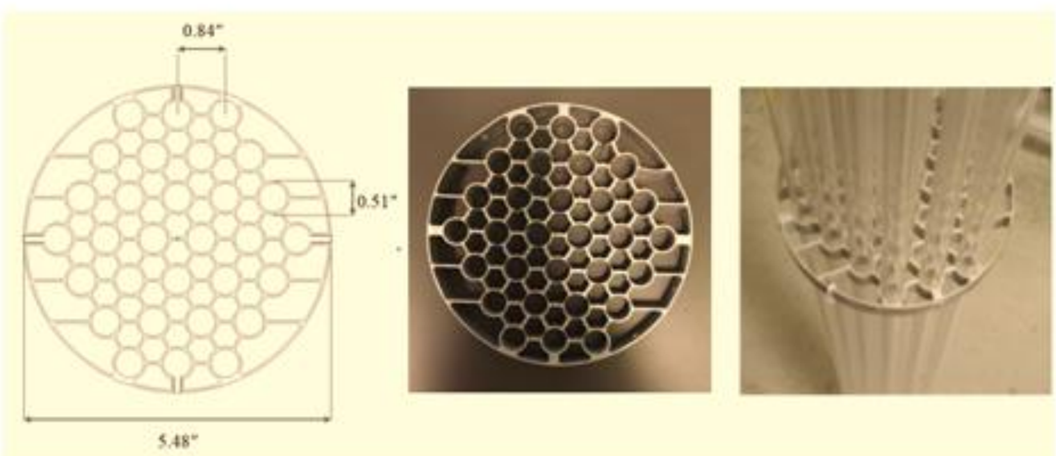


Figure 2.1 Schematic of the bubble column with internals and photo of the setup.



Schematic of internals support | Photo of internals support | Photo of internals on the support

(a) Circular arrangement



Schematic of internals support | Photo of internals support | Photo of internals on the support

(b) Hexagonal arrangement

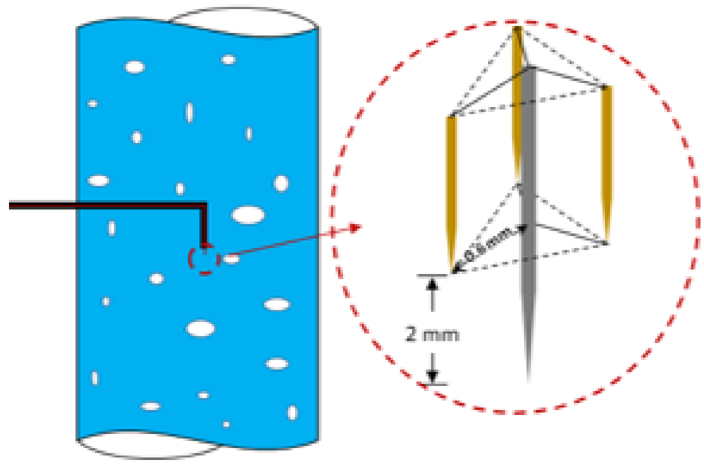
Figure 2.2 Schematic and photo of internals configuration and their support.
(a) Circular arrangement (b) Hexagonal arrangement

3. MEASUREMENT TECHNIQUE

4-Point optical fiber probe technique has been implemented in this work to measure local gas holdup, specific gas-liquid interfacial area, bubble rise velocity, bubble chord length, and bubble passage frequency. The 4-point optical probe was first developed by Frijlink (1987) at the Department of Multiscale Physics at the Technical University of Delft, and then was advanced by Xue (Xue et al., 2003) who developed new data processing algorithm and validated the 4-point optical fiber probe with CT and high speed camera. It has been extensively used since then in bubble and slurry bubble columns (Kagumba and Al-Dahhan, 2015; Manjrekar and Dudukovic, 2015; Wu and Al-Dahhan, 2008; Youssef and Al-Dahhan, 2009; Youssef et al., 2012).

The 4-point optical fiber probe used in this work was made up of 4 optical fibers each consisting of a quartz glass core (200 ± 20 micron in diameter), a cladding (380 ± 20 micron silicon) and a Teflon protective layer (600 ± 30 micron in diameter). Thus, the outside diameter of each fiber sums up to ~ 0.6 mm while the length was chosen as needed. At the extreme end of each fiber, several millimeters of the glass core were uncovered by removing the cladding and the protective layer. The glass tip was formed into a conical or round shape to account for the phenomena of the total internal reflection when bubbles pass through the tips (Frijlink, 1987; Vince et al., 1982; Xue et al., 2003). The tips were arranged as shown in Figure 3.1; a plastic jig was utilized to make the arrangement. The three peripheral tips were of the same length, and together they form an equilateral tringle. The fourth tip, 2 mm longer than the others, was placed at the center of the tringle with a radial distance of 0.6 mm from each of the other tips. Hence, the overall diameter of the probe is about 1.2 mm. After being arranged, the fiber tips were glued across several centimeters (behind the uncovered glass) and inserted into a piece of stainless steel with a 3/8 inch I.D. After solidification, the probe was taken out from the jig, and 3D coordination of the peripheral tips with respect to the central tip was measured by a high resolution camera to get the actual dimensions. The probe was then bent by 90 degrees to orient the tips toward the flow direction. The probe was positioned in the column at axial height of Z/D=5.1 and moved radially to take measurement at different dimensionless radial points.

The other ends of the fibers were connected using a standard optical connectors to an electronic unit (Developed by Kramer's Laboratory at the University of Delft) from which a laser beam was sent along the fibers to the tips. The optical probes operate on the principle of Total Internal Reflection Phenomenon, when the tip is in the liquid (glass-water interface) the light refracts in the liquid due to the relatively small difference in the refractive index between glass and water. However, when the tip is in a bubble (glass-air interface), due to the difference in the refractive index between air and glass, most of the light reflect at the tip back to the electronic unit where it get received and converted to voltage signals *via* a photodiode. The voltage signals are then saved in a data acquisition board (Power DAQ PD2-MFS-8-1M/12) at a sampling frequency of 40 kHz. A typical signal from the 4-point optical fiber probe is shown in Figure 3.1. The detailed information on the data process algorithm, signals analysis, and probe manufacturing can be found elsewhere (Xue, 2004). The advantage of 4-point optical fiber probe over other multipoint optical probes can be found elsewhere (Kagumba and Al-Dahhan, 2015; Xue et al., 2003). A comparison of the different techniques can be found in Boyer et al. (2002).



Schematic of the probe position and tips configuration

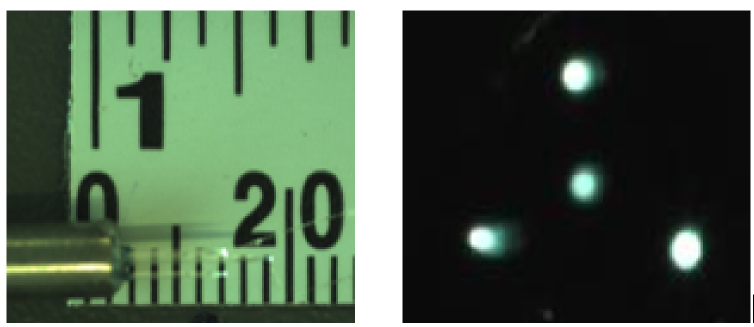
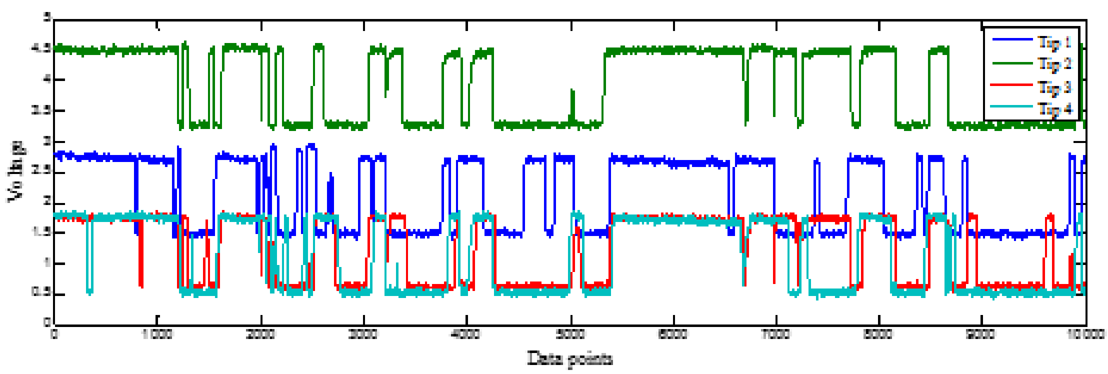


Photo of the probe tips configuration



Typical signal of the 4-point optical fiber probe

Figure 3.1 Tips configuration and typical signal of the 4-point optical fiber probe.

4. RESULTS AND DISCUSSION

4.1 GAS HOLDUP

Knowledge of gas holdup is very important for designing and scaling bubble column reactors. While the overall phase holdup is an important factor in determining reactor volume and system pressure drop, the local gas holdup provides insights about mixing behavior, extent of liquid circulation, heat and mass transfer and hence the reactor performance in terms of reaction rates and product selectivity (Anastasiou et al., 2013; Joshi, 1998; Krishna et al., 2001b; Shaikh and Al-Dahhan, 2013). Gas holdup is defined as the fraction of gas in a gas- liquid or gas-liquid-solid dispersion which refers either to the overall gas holdup or to the local gas holdup at a specific point or volume compartment in the reactor (Kantarci et al., 2005; Kumar et al., 1997). The effect of internals arrangement on the overall and local gas holdup is discussed in this section. The overall gas holdup is obtained from the change in the bed height using the following equation:

$$\text{Overall gas holdup } (\varepsilon_g) = \frac{H_d - H_S}{H_d} \tag{4.1}$$

Where H_d is the dynamic height of the bed and H_S is the static (unaerated) liquid height. The dynamic bed height was kept at constant level at Z/D=11.25, which is 160 cm above the gas sparger. The static liquid height varied according to each studied condition to preserve the constant dynamic bed height. The dynamic and the static bed heights are measured visually using a measuring tape attached on the bubble column. In order to reduce error associated with visual observations, both fluctuated maximum and minimum dynamic bed heights are measured and the average is used for the overall gas holdup estimation. Figure 4.1 shows the effect of internals and their arrangement on overall gas holdup at different gas velocities based on the free CSA for the flow. As shown, the effect of internals and their arrangement on the overall gas holdup is negligible but at high superficial velocity of 45 cm/s, the overall holdup value of bubble column without internals is slightly higher than that with the internals. This observation could be attributed to the impact of internals on bubble properties as will be discussed later. Similar findings have been reported in the the literature (Al-Mesfer, 2013; Kagumba and Al-Dahhan, 2015). Moreover, the difference in the overall gas holdup between the circular arrangement and the hexagonal arrangement internals is negligible.

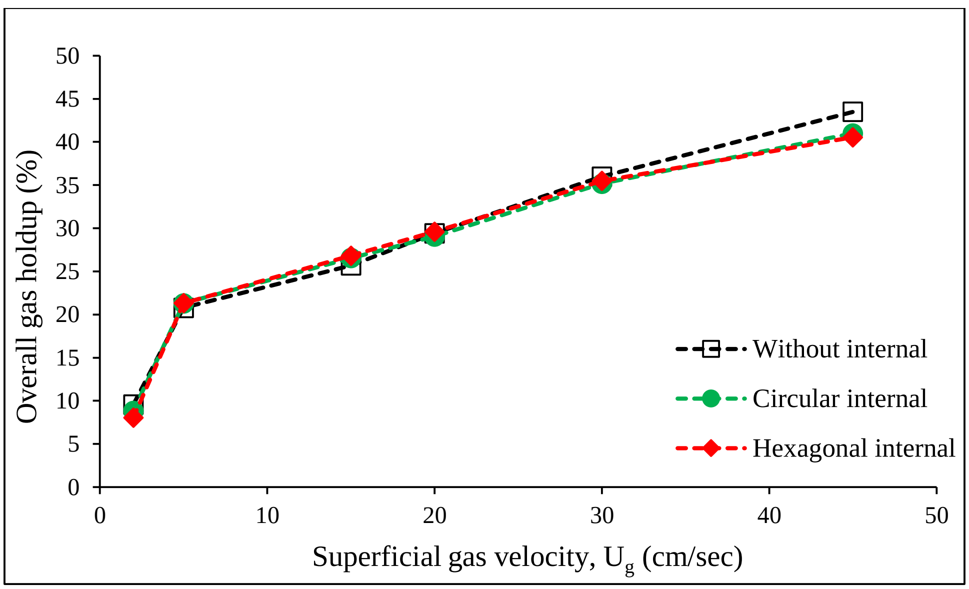


Figure 4.1 Effect of internals and their arrangement on the overall gas holdup at different superficial gas velocities.

The radial profiles of the local gas holdup for bubble column without internals, internals with hexagonal arrangement, and internals with circular arrangement at superficial gas velocities (2, 20, and 45 cm/s) measured based on free CSA for flow, are shown through Figures 4.2 to 4.4. In the bubbly flow regime (2 cm/s), the effect of the circular internals arrangement on gas holdup along the radial profile is nearly negligible (Figure 4.2) while a considerable increase is observed in the core region as the superficial gas velocity increased. For instance, at superficial gas velocity of 20 cm/s, an increase of ∼16% is obtained as can be noted in Figure 4.3. In the churn turbulent regime (45 cm/s), the circular arrangement internals causes significant increase in gas holdup in the core region and a reduction at wall regions as shown in Figure 4.4. The gas holdup increased by 25% at the center (r/R= 0) and decreased by 23% at the wall (r/R= ± 0.9). Therefore, it can be observed that with the circular arrangement internals, gas holdup radial profile is steeper than without internals. Similar observation has been reported in the literature (Zhang et al., 2011).

The enhancement in the gas holdup values in the core region could be attributed to the fact that internals decrease turbulent and turbulence related parameters such as turbulent kinetic energy (TKE), eddy diffusivities, normal and shear liquid stresses (Al-Mesfer, 2013; Larachi et al., 2006). On the other hand, the intensity of axial centerline liquid velocity and the negative axial liquid velocity have been found to increase with the presence of internals (Al-Mesfer, 2013; Forret et al., 2003; Larachi et al., 2006). The increase in negative axial liquid velocity (down flow liquid) results in an increase in the shear stress in the wall region (Al-Mesfer, 2013; Chen et al., 1999). This variation further impedes the gas bubbles to flow upwards in the wall and annular regions and induces gas bubbles to segregate in the core region where they are subjected to less shear stress. This behavior causes an increase in bubble population and bubble passage frequency in the core region and hence increases the gas holdup.

As the Figures show, the effect of the hexagonal arrangement internals on the radial profile of gas holdup is more complex. A distinct asymmetric gas holdup profiles were obtained when the hexagonal arrangement internals is used. This can be indicated from the high values of local gas holdup in one side of the column and low values on the other side of the column. For instance, at superficial gas velocity of 45 cm/s, the percentage difference of local gas holdups at radial position points, r/R= ± 0.6 and ± 0.9 are 100% and 180 % respectively, when the bubble column equipped with the hexagonal arrangement internals.

This observation can be explained by the fact that the hexagonal internals arrangement, by virtue of its geometric configuration, creates non-symmetric gaps between the internals bundle and the wall of the bubble column as can be observed in Figure 2.2**.** Visual observation also shows a similar pattern where the gas bubbles showed more tendencies to move towards the unobstructed areas where less resistance to the flow exists. This caused channeling in the majority of upward gas flow in one side and a reverse flow of liquid in the other side. The large bubbles population in one side of the column gives rise to higher bubble passage frequency resulting in higher gas holdup. In other words, increased gas holdup values obtained in one side were met with a decrease in the opposite side. This observation is in agreement with the result reported in the work of Al-Mesfer (2013) where advanced Computed Tomography (CT) was implemented using the hexagonal arrangement internals to assess the impact of dense internals on gas holdup.

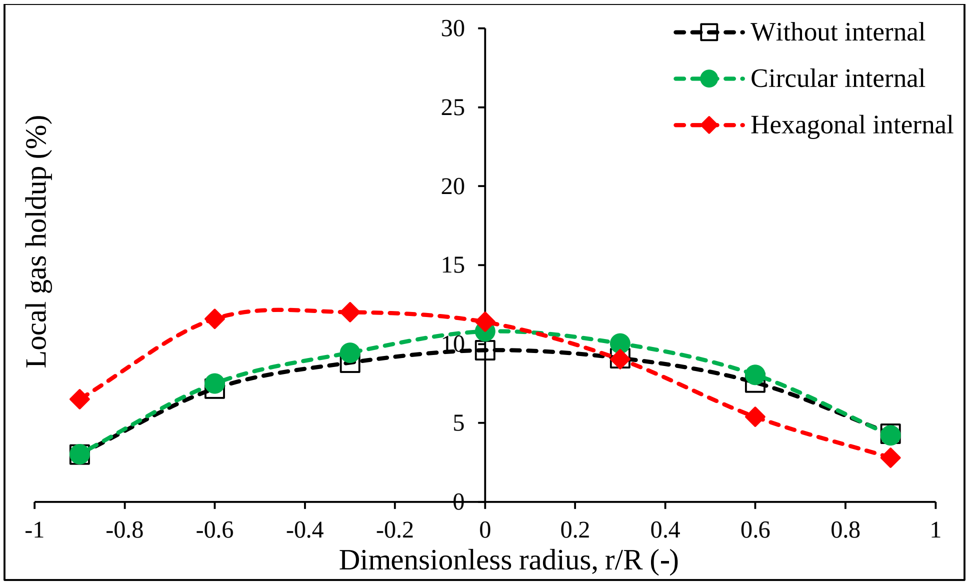


Figure 4.2 Effect of internals and their arrangement on the radial profile of local gas holdup at U_g = 2 cm/s.

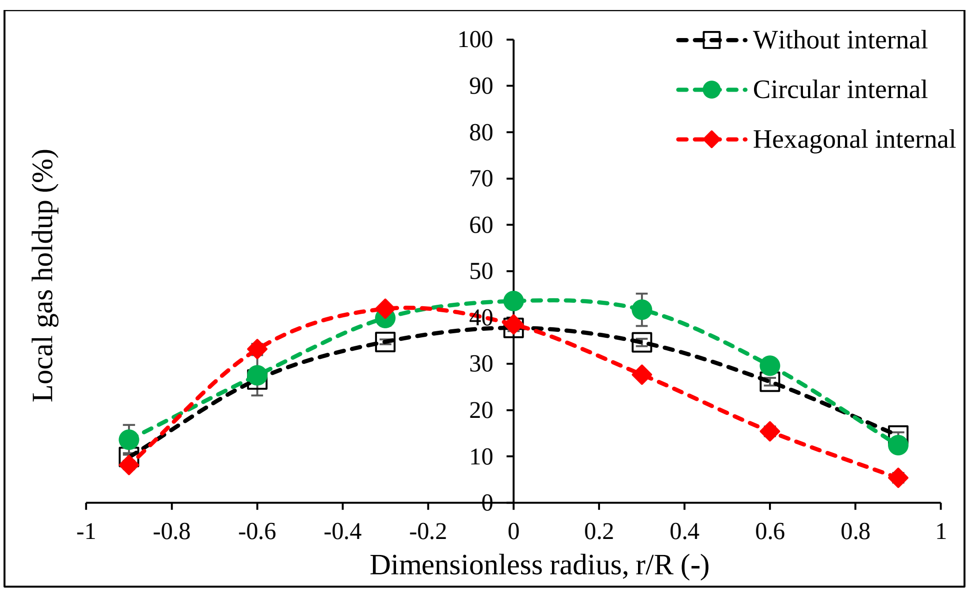


Figure 4.3 Effect of internals and their arrangement on the radial profile of local gas holdup at U_g = 20 cm/s.

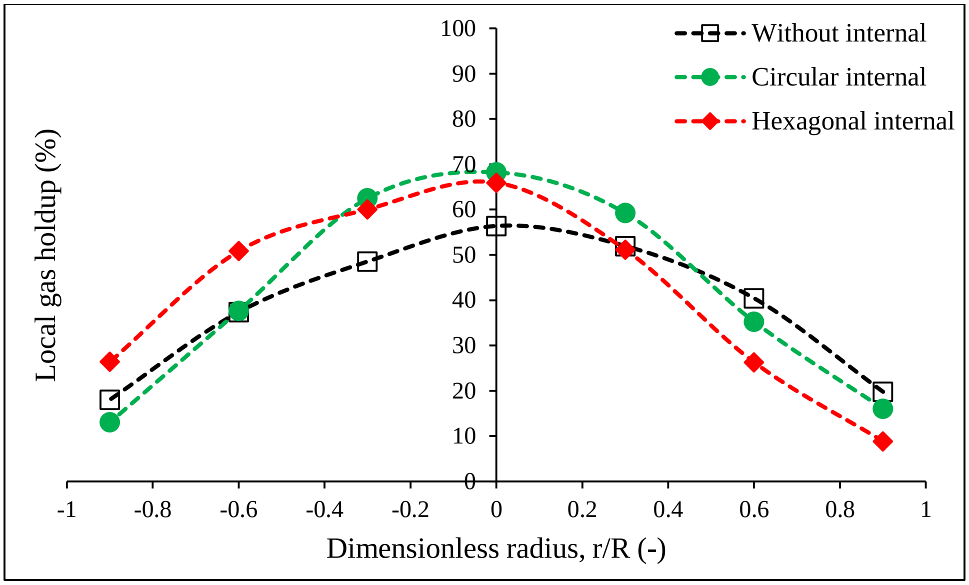
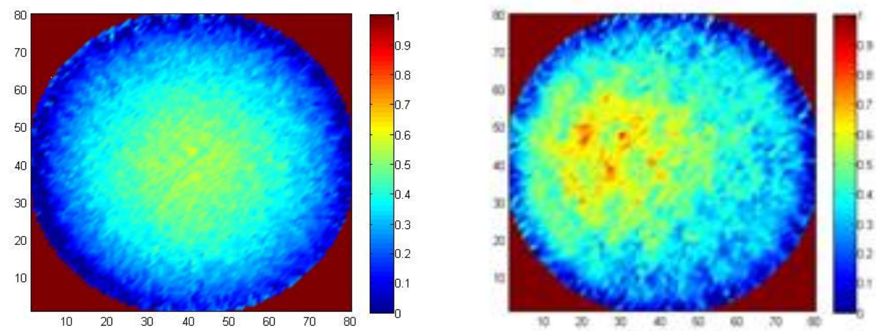


Figure 4.4 Effect of internals and their arrangement on the radial profile of local gas holdup at U_g = 45 cm/s.

The cross-sectional images of gas holdup profile in bubble column without internals and with internals of hexagonal arrangement obtained from CT scans is shown in Figure 4.5. The variation in color indicates the change in the gas holdup magnitude value. The red color indicates higher gas holdup values, while the blue color indicates lower values. It can be observed that the gas holdup profile for bubble column without internals is symmetric while it is asymmetric with the presence of the internals with higher gas holdup in one side of the column. Therefore, the symmetric assumptions used in the data reduction in both experimental and simulation studies in bubble column are not adequate when the column is equipped with unevenly distributed internals over the column CSA. Moreover, the existing predictive models of the radial profiles of gas holdup, based on column without internals, may not be suitable for a bubble column equipped with internals especially when the internals are not arranged uniformly.



(a) (b)

Figure 4.5 Time averaged cross-sectional gas holdup distribution at U_g = 45 cm/s. (a) without internals (b) with the hexagonal arrangement internals
Source: Al-Mesfer (2013)

4.2 BUBBLE PASSAGE FREQUENCY

In order to confirm the gas holdup findings, bubble passage frequency (the number of bubbles passing through a unit volume in the reactor per unit time, 1/s) is quantified. Bubble passage frequency is acquired by dividing the total number of bubbles hitting the central tip of the probe by the sampling time. Figures 4.6 and 4.7 show the effect of internals and their arrangements on the radial profile of bubble passage frequency obtained at different gas velocities. At gas velocity of 20 cm/s, the bubble passage frequency in the core region increases when circular arrangement is used over that of bubble column without internals. Also, the bubble passage frequency behavior exhibits an increase in the core and decrease at the wall when the superficial gas velocity is 45 cm/s. This trend is the same as the local gas holdup that was mentioned previously. The hexagonal internals arrangement shows similar asymmetric behavior for bubble passage frequency as local gas holdup. The current findings are consistent with previous studies that have been reported where the local bubble passage frequency in bubble column and local gas holdup have similar profile trend and strongly correlating to each other (Wu and Al-Dahhan, 2008; Xue et al., 2008).

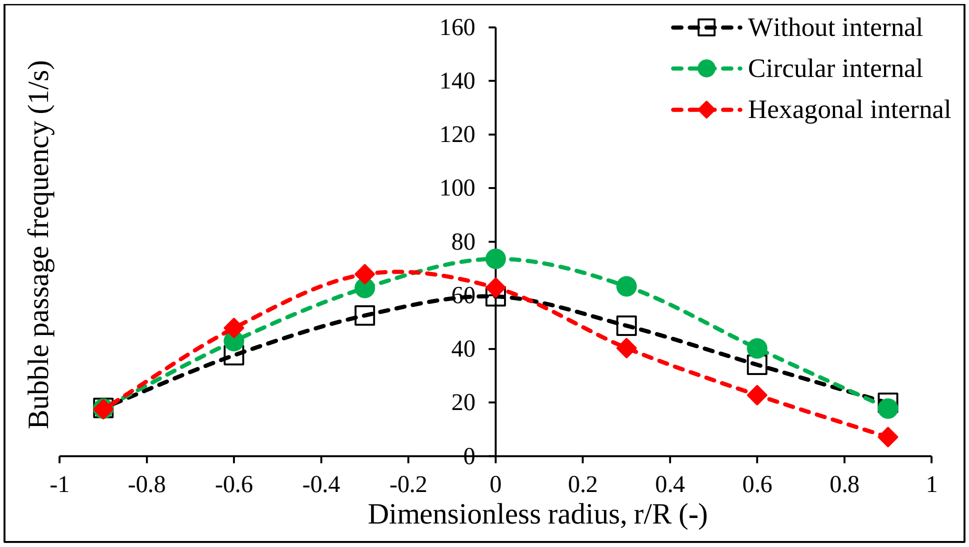


Figure 4.6 Effect of internals and their arrangement on the radial profile of bubble passage frequency at U_g = 20 cm/s.

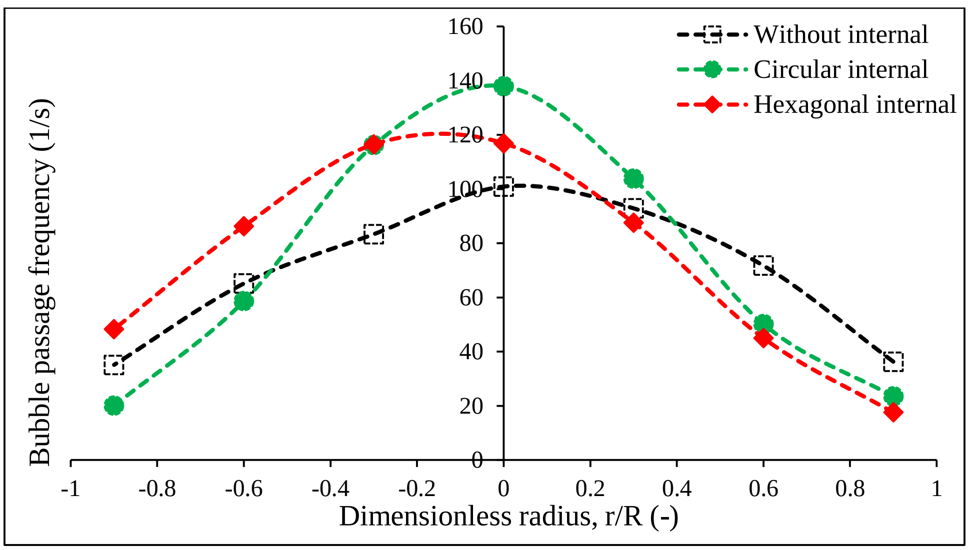


Figure 4.7 Effect of internals and their arrangement on the radial profile of bubble passage frequency at U_g = 45 cm/s.

4.3 BUBBLE CHORD LENGTH

Bubble size has been considered as a dominating factor for determination of the performance of bubble column reactors due to its significant effect on other hydrodynamic parameters such as gas-liquid interfacial area, bubble velocity, gas residence time (gas holdup) and hence on reactor performance. The average bubble size in a bubble column is mainly governed by the size at bubble formation (which depends mainly on the sparger design and phase properties) and the extent of coalescence and break-up which are governed by the local turbulence of the flow field (Kulkarni, 2007; Lehr et al., 2002) .

Despite the importance of bubble size in determining the overall performance of bubble column reactors, there is no reliable technique available at the present time that can directly capture true bubble size within a bubble column. This is especially true for the transition and churn turbulent flow regimes, which are of great industrial interest. Souter mean bubble diameter (SBD) (which is defined as the diameter of a sphere that has the same volume/surface area ratio as that of interest) has been widely characterized to express bubble size in bubble columns**.** However, it is well known that in bubble and slurry bubble columns, especially in transition and churn turbulent regimes most bubbles are not spherical. They are large and of irregular shape (Akita and Yoshida, 1974; Wu and Al-Dahhan, 2008; Xue, 2004) Therefore, Souter mean bubble diameter is not a proper way to express bubble size in transition and churn turbulent regimes**.** Thus, bubble chord length has been effectively employed as a characteristic of expressing the bubble size in bubble columns operating in bubbly, transition and churn turbulent regimes (Hoang et al., 2015; Kagumba and Al-Dahhan, 2015; Manjrekar and Dudukovic, 2015; Wu and Al-Dahhan, 2008; Xue et al., 2003; Yamada and Saito, 2012; Youssef et al., 2012)**.**

In this section, the effect of internals and their arrangement on the bubble chord length is discussed. At all studied superficial gas velocities, in the presence and absence of internals, the bubble chord length distributions were found to follow lognormal distribution as shown in Figure 4.8. Similar observation has been noticed in the literature (Kagumba and Al-Dahhan, 2015; Wu and Al-Dahhan, 2008; Youssef and Al-Dahhan, 2009).

To find the probability density function and to provide better comparison of the obtained bubble chord length distribution for the diffeent conditions, the lognormal distribution function is employed. The lognormal distribution function can be expressed as:

$$f(d_c) = pdf = \frac{1}{\sigma d_c\sqrt{2\pi}} exp\left[-\frac{(ln d_c-\mu)^2}{2\sigma^2}\right] \tag{4.2}$$

Where d_c is the chord length of individual bubbles obtained directly from the 4-point optical probe. μ and σ are related to the mean, m , and variance, v , of the chord length distribution.

$$\mu = \ln\frac{m}{\sqrt{1+\frac{v}{m^2}}} \quad , \quad \sigma = \sqrt{\ln\left(1+\frac{v}{m^2}\right)} \tag{4.3}$$

The bubble chord length distributions for columns with different internals arrangement and without internals are shown in Figures 4.9 and 4.10. These distributions have been analyzed statistically to provide the mean and the variance as listed in Tables 4.1, 4.2, and 4.3. At superficial gas velocities in the range of (2-20cm/s), the mean of bubble chord length distributions for bubble column without internals and bubble column with the circular arrangement internals are close to each other, implying that the effect of the circular arrangement internals at these velocities is negligible. This can be revealed by comparing the distributions shown in Figure 4.9 and also from the mean of the distributions in Tables 4.1 and 4.2.

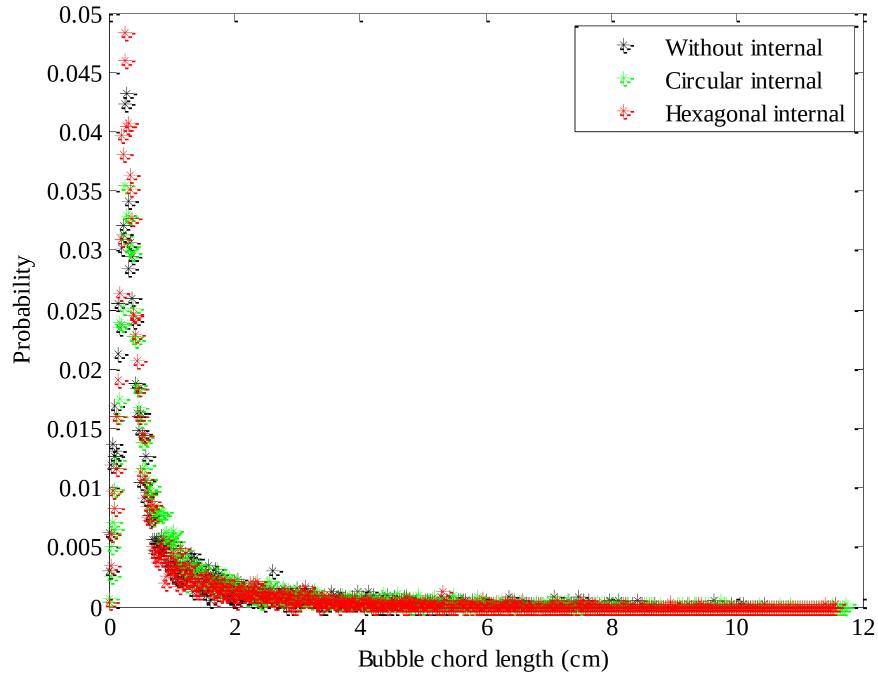


Figure 4.8 Histogram plot of the bubble chord length distribution in bubble column with and without internals at r/R=0 and U_g = 20 cm/s.

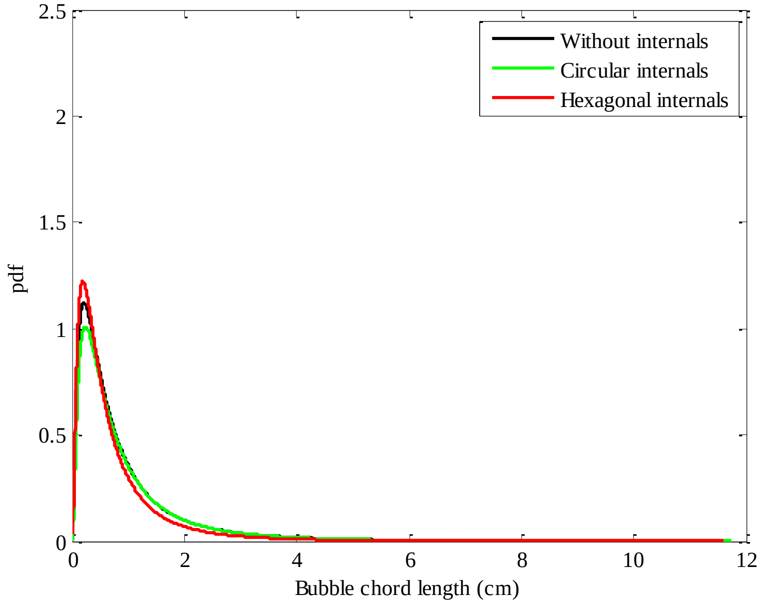
However, in the churn turbulent flow regime (45cm/s), bubble chord lengths increase across the column in the presence of the circular arrangement internals. This can be elucidated from the increase in the probability of large bubbles as shown in Figure 4.10 and confirmed from the mean and the variance of the distributions in Table 4.3. It can be noticed that at U_g = 45 cm/s, the mean of bubble chord length distribution increases by 33% in the core region and 32% at wall region upon the insertion of the circular internals. This observation implies that, in the churn turbulent flow regime, the presence of internals enhance bubble coalescence resulting in large bubbles in the system. Similar observation has been observed in the literature (Youssef et al., 2012).

On the other hand, at superficial gas velocities in the range (2-20 cm/s) the presence of hexagonal internal arrangement is found to decrease the bubble chord lengths in both the core and wall regions when compared to bubble chord lengths obtained in bubble column without internals. In Figure 4.9, it is seen that there is smaller probability for existence of large bubbles in the presence of hexagonal internals arrangement when compared to bubble column without internals. From the mean of the bubble chord length distributions, it is observed that the hexagonal arrangement internals reduce the mean bubble chord length in the core region by 17%, and 12% at gas velocities 2, and 20 cm/s, respectively.

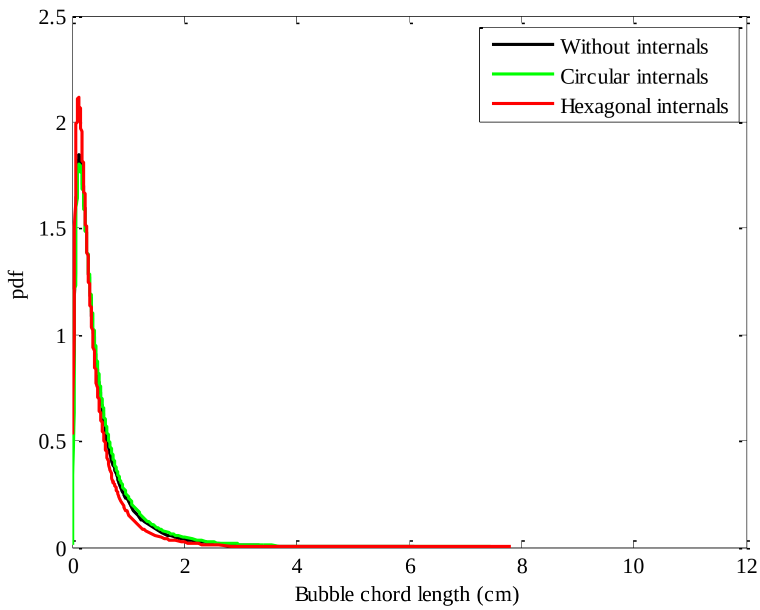
In churn turbulent flow regime (i.e., 45 cm/s), the effect of the hexagonal arrangement on the bubble chord length distribution is less significant. Qualitatively, an increase of ~6 % is observed in the mean of the bubbles chord length.

Table 4.1 Statistical parameters of bubble chord length distributions at U_g = 2 cm/s.

	r/R = 0		r/R = ± 0.9	
	Mean	Variance	Mean	Variance
Without internal	0.41	0.04	0.36	0.02
Hexagonal internal	0.34	0.02	0.30	0.01
Circular internal	0.40	0.03	0.34	0.02

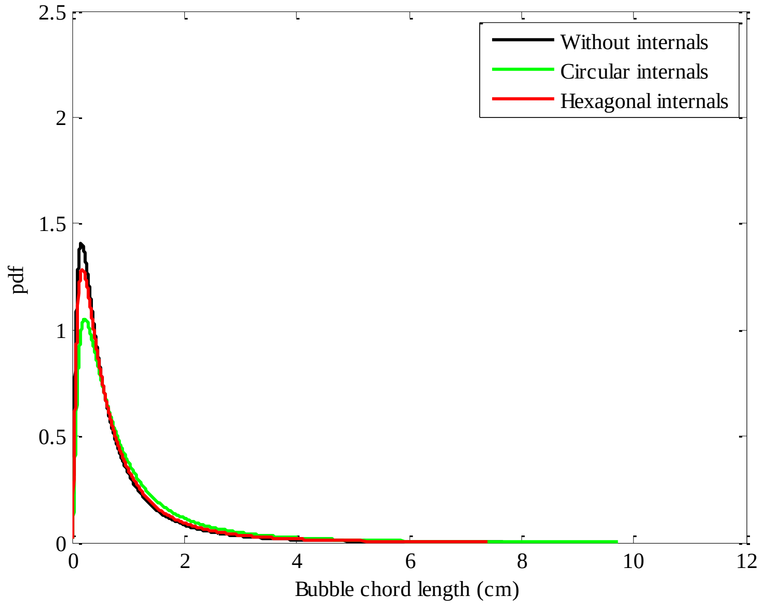


(a)

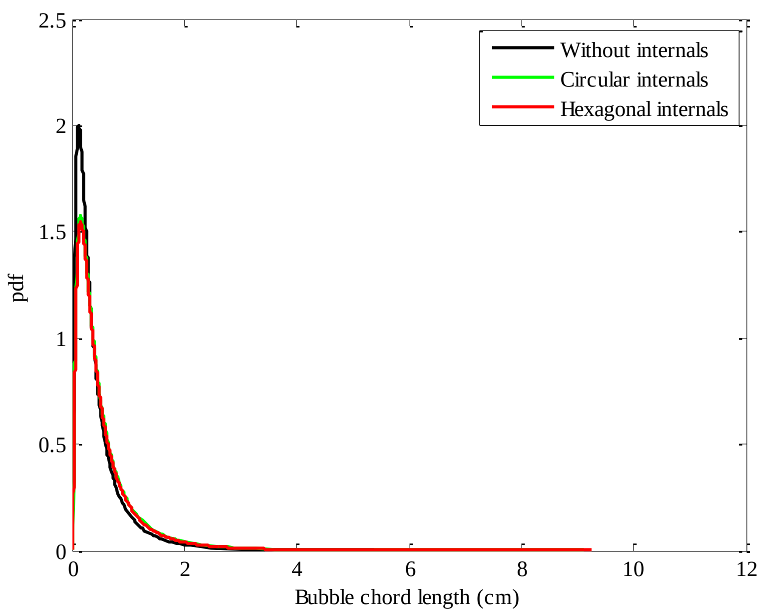


(b)

Figure 4.9 Effect of internals and their arrangements on bubble chord length distribution at U_g = 20 cm/s. (a) r/R = 0 , (b) r/R = $\pm$ 0.9



(a)



(b)

Figure 4.10 Effect of internals and their arrangements on bubble chord length distribution at U_g = 45 cm/s. (a) r/R = 0 , (b) r/R = $\pm$ 0.9

Table 4.2 Statistical parameters of bubble chord length distributions at U_g = 20 cm/s.

	r/R = 0		r/R = ± 0.9	
	Mean	Variance	Mean	Variance
Without internal	0.98	1.58	0.57	0.61
Hexagonal internal	0.86	1.42	0.52	0.50
Circular internal	1.06	2.02	0.61	1.24

Table 4.3 Statistical parameters of bubble chord length distributions at U_g = 45 cm/s.

	r/R = 0		r/R = 0.9	
	Mean	Variance	Mean	Variance
Without internal	0.80	0.99	0.52	0.53
Hexagonal internal	0.87	1.19	0.66	1.01
Circular internal	1.06	1.91	0.67	0.87

It should be noted that although the internals in both arrangements are of the same size and covering the same CSA, their influence on bubble size is totally different. This difference may be attributed to the internals arrangement and the space between the tubes. In the case of hexagonal arrangement, the inter-tube gaps are smaller and the internals tubes are denser restricting bubbles to pass through while larger gaps between the internals and the wall allow least resistance to the flow. Hence, higher break-up rate would be encountered in the hexagonal arrangement of internals leading to smaller bubbles. However, in the circular arrangement, the gaps between the tubes and the wall are uniform and wider through which relatively larger bubbles can escape.

It is also worth mentioning that when the superficial velocity increases from 20 cm/s to 45 cm/s in bubble column without internals, the mean of bubble chord lengths decreases by 19% and 15% in the core and wall regions, respectively. Similar observation was reported by Xue (2004). While an increase in the bubble size was observed in case of presence of internals at the same velocity range.

One possible reason for this could be due the fact that when the superficial gas velocity increases in bubble column without internals, the turbulence and turbulent related parameters such as TKE and eddy diffusivities increases (Al-Mesfer, 2013). This leads to vigorous gas liquid interactions causing frequent bubble breakage which results in smaller bubbles size in the system. This also leads to an increase in local and overall gas holdup as shown earlier. However, as mentioned earlier, the presence of internals decrease the TKE and eddy diffusivities and enhance large scale liquid circulation (Al-Mesfer, 2013; Guan et al., 2015a; Yu et al., 2009). The enhancement in liquid circulation hinders radial gas distribution and hence increases bubble population in the core region which enhances bubble coalescence and coherent gas flow yielding larger bubbles across the column as observed from the bubble size distribution for the circular internals arrangement. Such bubble and local gas holdup structure further improves the liquid circulation.

4.4 SPECIFIC INTERFACIAL AREA

In bubble and slurry bubble columns, the overall volumetric gas-liquid mass transfer coefficient (k_la) is governed by liquid side mass transfer coefficient (k_l) and gas-liquid interfacial area (a). Behkish (2004); Han and Al-Dahhan (2007); agreed that the variation in the observed volumetric mass transfer coefficient values was mainly due to changes in the interfacial area. Hence, knowledge of interfacial area is essential for proper design and operation of bubble and slurry bubble column reactors. In this work, the effect of internals and their arrangement on the gas-liquid interfacial area is examined The effect of internals and their arrangement on the radial profiles of specific interfacial area at superficial gas velocities 2, 20, and 45 cm/s are shown through Figures 4.11 to 4.13. In bubbly flow regime (2 cm/s), the presence of the circular arrangement internals does not have any significant effect on the radial profile of the interfacial area (Figure 4.11). This is expected since neither the gas holdup nor bubble size is influenced by the circular arrangement in this regime. At U_g = 20 cm/s, a slight increase (8%) in the interfacial can be observed in the core region while no significant change was observed elsewhere along the radial profile as can be seen in Figure 4.12.

The effect of the circular internals arrangement on the radial profile of the specific gas-liquid interfacial area in churn turbulent regime (45 cm/s) is more dramatic. Clearly, the presence of the circular internals arrangement substantially decreases the interfacial area in the column (except the center point, r/R=0) when compared to bubble column without internals as shown in Figure 4.13. A reduction of 37 % and 29 % is found in the annular and wall regions respectively. Such observation has not been reported in the literature. The observed decrease could be attributed to two factors. First, the reduction in bubble passage frequency observed in these regions at 45 cm/s as shown earlier and second, the increase in bubble size when compared to the bubble column without internals. Larger bubbles are known to have lower interfacial area per unit volume. A combination of these two factors results in a significant decrease in the interfacial area. At the center point, r/R= 0, at gas velocity of 45 cm/s, the significant increase in bubble passage frequency, while the bubble chord length is large, led to a slight increase in interfacial area at this point which is comparable with bubble column without internals.

The effect of the hexagonal internals arrangement on the radial profile of interfacial area is more intricate**.** The uneven distribution of the gas flow, caused by the non-uniform distribution of the internals, resulted in a non-uniform radial profile for the interfacial area across the column. The radial profile of interfacial area exhibits higher values with the presence of the hexagonal arrangement in the center and left side of the column (from r/R = 0 to r/R = - 0.9). On the other hand, it decreases on the other side of the column. For instance, at gas velocity of 20 cm/s, an increase of 32% is attained at r/R = - 0.6, while a decrease of 33% is observed at r/R = 0.6.

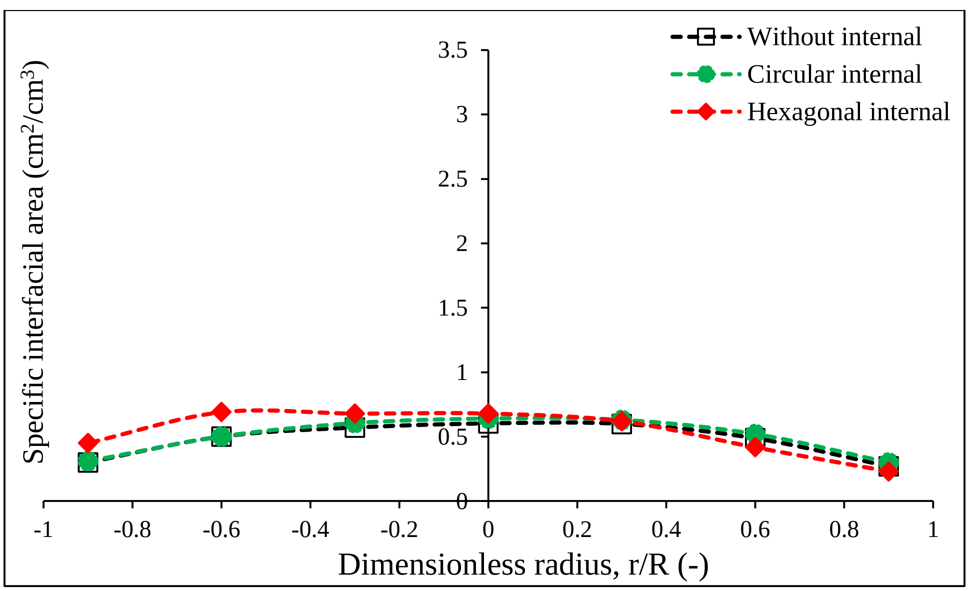


Figure 4.11 Effect of internals and their arrangements on radial profile of the specific gas-liquid interfacial area at $U_g = 2$ cm/s.

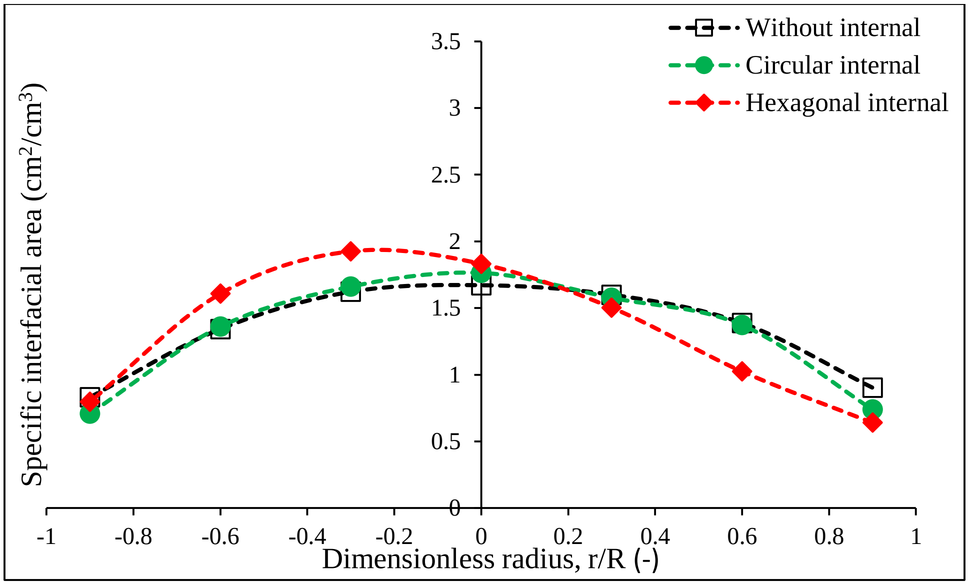


Figure 4.12 Effect of internals and their arrangements on radial profile of the specific gas-liquid interfacial area at $U_g = 20$ cm/s.

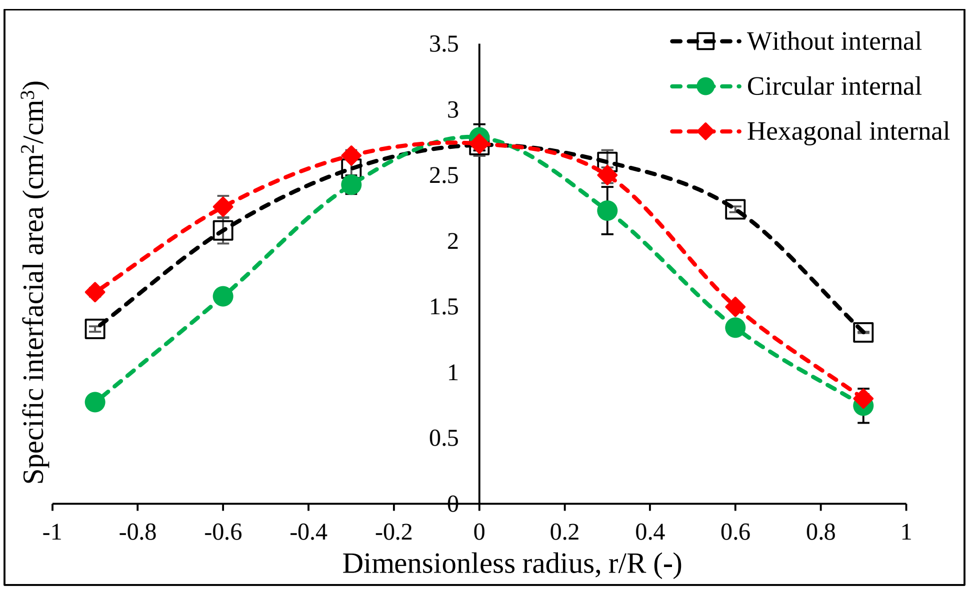


Figure 4.13 Effect of internals and their arrangements on radial profile of the specific gas-liquid interfacial area at $U_g = 45$ cm/s.

4.5 BUBBLE VELOCITY

Measurement of the bubble rise velocity is vital to characterize bubble and slurry bubble column reactors. It governs the gas phase residence time along with the contact time for the interfacial transport which subsequently contribute to the performance of the reactor. Moreover, the bubble velocity is needed for the development and validation of simulation models for efficient scale-up of bubble column reactors. Therefore, it has been a subject of many studies (Amaya-Bower and Lee, 2010; Amirnia et al., 2013; Hua et al., 2008; Krishna et al., 1999; Li and Prakash, 2000; Maceiras et al., 2007; Manjrekar and Dudukovic, 2015; Wu and Al-Dahhan, 2008; Xue, 2004; Youssef and Al-Dahhan, 2009; Youssef et al., 2012). However, most of the previous researches on the bubble rise velocity were conducted in bubble column without internals. Only a few studies have described bubble velocity in bubble column with internals (Hamed, 2012; Kagumba and Al-Dahhan, 2015; Youssef and Al-Dahhan, 2009; Youssef et al., 2012)**,** Howe ever, the reported results are inconsistent with each other. Some of these studies reported that bubble rise velocity decreases in the presence of vertical heat exchanging internals (Kagumba and Al-Dahhan, 2015; Youssef and Al-Dahhan, 2009) while others showed that bubble velocity increases with the presence of internals (Hamed, 2012; Youssef et al., 2012). It worth mentioning that the occluded CSA area in these studies was similar (~25 % of the column CSA). The difference could be due the difference in the configuration of the internals and the applied gas velocities. Therefore, it would be beneficial to investigate the effect of internals configuration on bubble rise velocity in bubble columns equipped with internals of different arrangements at different gas velocities based on free CSA for the flow. The circular internals arrangement does not have a significant effect on bubble rise velocity in the bubbly flow regime (2 cm/s) as shown in the bubble velocity distributions in Figure 4.15, and the average of the distributions as shown in Figure 4.14. However, as the gas velocity increases, the bubble rise velocity for the circular internals arrangement becomes higher than that of the bubble column without internals. This can be observed from the increase in the probability of large bubbles as shown in Figures 4.16 and 4.17 where the large bubbles tend to rise with higher bubble rise velocity. From the average bubble rise velocity shown in Figure 4.14, it is noticed that the bubble rise velocity increases in the core region by 7%, 12%, and 25 % at 15, 20, and 45 cm/s, respectively. This increase could be attributed to the increase in bubble size and the enhancement of the liquid circulation due to steep change in gas hold up radial profile caused by the structure of the circular internals arrangement. On the other hand, at superficial gas velocities in the range of (2-20 cm/s), the presence of hexagonal arrangement internals significantly reduce the bubble rise velocity in the column. This results in a narrower bubble velocity distribution when compared to the bubble column without internals, which can be noted form the reduction in the probability of high velocity bubbles as can be noticed in Figures 4.15 and 4.16. Qualitatively, the average bubble rise velocity in the core region decreases by 15%, 17%, and 15% at gas velocities 5, 15, and 20 cm/s, respectively. As it was previously explained, this could be attributed to the decrease in bubble size observed at these velocities with this arrangement. However, at higher gas velocities, the bubble rise velocity with the presence of the hexagonal internal arrangement is found to be slightly higher than bubble column without internals as reflected in the average of the bubble velocity distribution. Therefore, it can be concluded that the presence of internals enhance bubble rise velocity which could be the reason of liquid circulation enhancement that observed in the presence of internals reported in literature (Al-Mesfer, 2013; Forret et al., 2003; Yu et al., 2009).

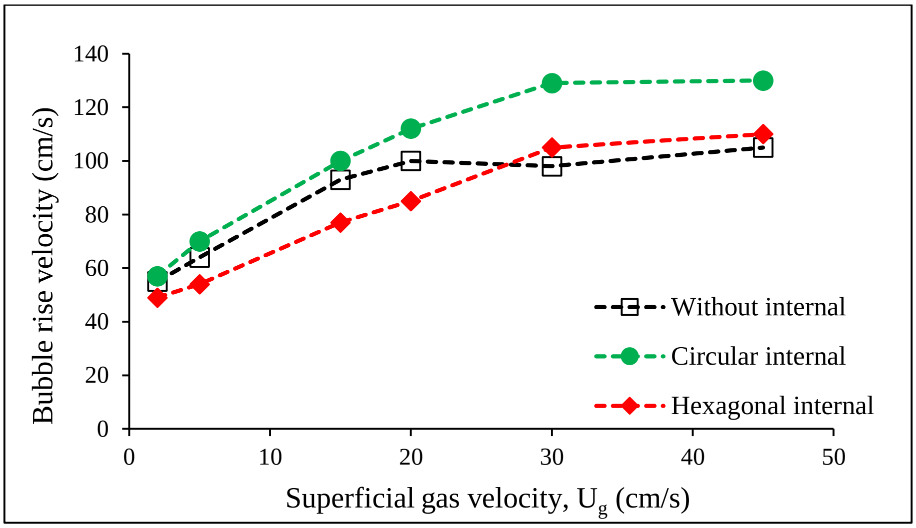


Figure 4.14 Effect of internals and their arrangement on average bubble rise velocity at different superficial gas velocities.

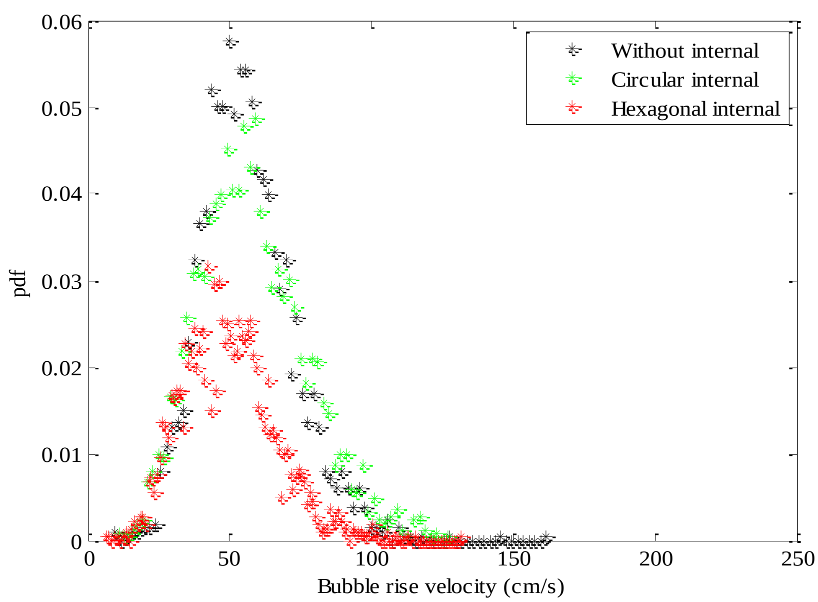


Figure 4.15 Effect of internals and their arrangement on bubble rise velocity distribution at U_g = 2 cm/s and r/R= 0.

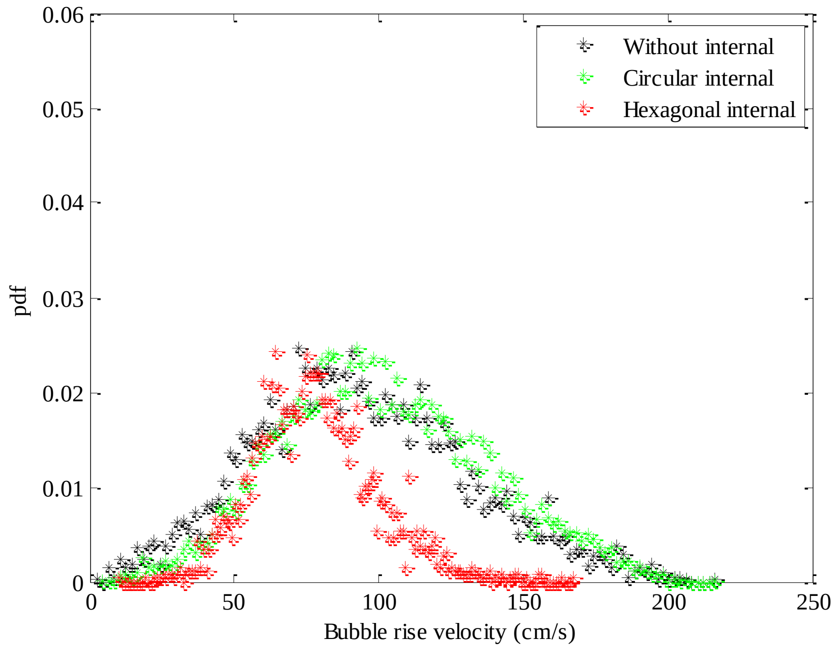


Figure 4.16 Effect of internals and their arrangement on bubble rise velocity distribution at U_g = 20 cm/s and r/R= 0.

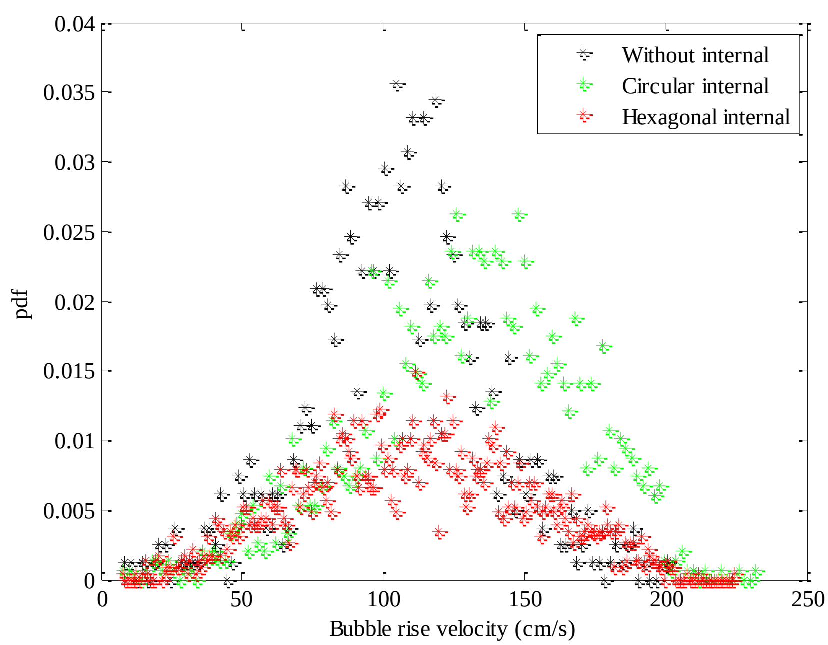


Figure 4.17 Effect of internals and their arrangement on bubble rise velocity distribution at U_g = 45 cm/s and r/R= 0.

5. REMARKS

The current study investigated the effect of internals and their arrangement on local hydrodynamic parameters including gas holdup, specific gas-liquid interfacial area, bubble chord length, and bubble velocity using 4-point optical fiber probe technique. Two configurations of dense heat exchanging internals, occupying 25 % of column CSA, were studied. Two different internals arrangement were investigated which are uniformly distributed internals over the column cross-section area in a circular shape and non-uniformly distributed internals in a hexagonal shape. The experiment performed in a 14 cm diameter bubble column using air-water system. The superficial gas velocities measured based on free cross-sectional area available for the flow. Steeper gas holdup and specific interfacial area profiles observed when the circular arrangement internals is used. A considerable increase in the bubble chord length and bubble velocity was noted. For the hexagonal internals arrangement, a clear asymmetrical effect on the radial profiles of gas holdup and specific interfacial area was observed. The holdup and interfacial area significantly increased in one side of the column while decreasing on the other side due to the non-uniform arrangement. There was a decrease in the bubble chord length and bubble rise velocity indicating a narrower distribution with smaller values in comparison with an empty bubble column.

II. IMPACT OF HEAT EXCHANGING INTERNALS DIAMETER ON GAS HOLDUP AND BUBBLE DYNAMICS IN A BUBBLE COLUMN

ABSTRACT

Bubble column reactors have many industrial applications including those with exothermic reactions such as Fischer-Tropsch synthesis, which is used to convert synthetic gas to liquid fuels. Heat removal internals have been used in these processes to achieve isothermal conditions and desired product quality. It has been reported that internals alter the mixing pattern, hydrodynamics, bubble dynamics, and heat and mass transfer, which in turn alters the performance of the bubble column reactors. Accordingly, this study aims to investigate the impact of the diameter of vertical heat exchanging tubes on gas holdup and bubble dynamics including the specific interfacial area, bubble chord length, and bubble velocity. Two different diameters, 0.5 inch and 1 inch, of vertical rods covering 25% of the column's cross-sectional area were used to represent the heat exchanging tubes utilized in the F-T process. In both cases the tubes were uniformly distributed over column cross-section area. The experiments were performed using air-water system, in a bubble column with a diameter of 6 inch, at superficial gas velocities of 20, 30, 45 cm/s measured based on free cross-section area for flow . These velocities were chosen to match the gas velocities applied in the industrial applications of the Fischer-Tropsch process. The experimental results indicated that the internals have a significant effect on the hydrodynamic properties of the bubble column reactor at high superficial gas velocities. The local gas holdup significantly increased in the core region and decreased at the wall regions when the 0.5 inch internals were used. Contrarily, the 1 inch internals enhanced the gas holdup near to the wall regions. The bubbles chord length was found to be larger

with the presence of internals, as was the bubble velocity. The specific interfacial area with the 0.5 inch internal was much lower than when the bubble column was tested without internals. The specific interfacial area was enhanced in the wall regions when the 1 inch internals were used.

Keywords: Bubble column, internals, gas holdup, gas-liquid interfacial area, bubble chord length, bubble rise velocity.

1. INTRODUCTION

The hydrodynamic properties of bubble column and slurry bubble column reactors are of great importance in the development of different industrial chemical processes such as Fischer-Tropsch and liquid phase methanol syntheses. These processes involve exothermic reactions for which the installation of dense internal heat exchanger tubes help control the process temperature. Although extensive research has been conducted to investigate the hydrodynamics in bubble columns (Devanathan, 1991; Kumar et al., 1997; Degaleesan et al., 1997; Camarasa et al., 1999; Camarasa et al., 1999; Gandhi et al., 1999; Krishna et al., 2000; Wu et al., 2001; Xue, 2004; Wu et al., 2006; Han and Al-Dahhan, 2007; Kagumba and Al-Dahhan, 2015; Rados et al., 2005; Shaikh and Al-Dahhan, 2003; Youssef and Al-Dahhan, 2009; Youssef et al., 2012), the influence of internal tubes on the hydrodynamic parameters of the bubble columns has hardly been investigated despite its potential applications in industry.

Chen et al. (1999) used Computed Tomography (CT) and Computer Automated Radioactive Particle Tracking (CARPT) techniques to study the time averaged with cross-sectional gas distribution, liquid recirculation, radial gas holdup profile and turbulent parameters in an 18 inch bubble column, with and without internals using air-water and air-Drakeoil systems. The internals were composed of 16 vertical rods of 1 inch in diameter, covering only 5% of the column’s cross-sectional area (CSA) mimicking those used in liquid phase methanol (LPMeOH) synthesis. The results showed that the internals have an insignificant effect on liquid velocity and gas holdup, while a considerable decrease was observed in the turbulent stresses and eddy diffusivities upon insertion of the internals. This study was carried out at low superficial gas velocities and only a small portion of the column CSA (5%) was equipped with internals. Thus, it's difficult to evaluate the effect of internals at high superficial gas velocities which would result in a high volumetric productivity as desired for the Fischer-Tropsch process. More ever, only 1 size of internals (1 inch rods) was investigated in this work. Thus the impact of the internals diameter cannot be evaluated from this work.

Larachi et al. (2006) performed a 3D computational fluid dynamic (CFD) simulation for five pilot scale bubble column geometries. The study consisted of bubble columns without internals and with internals of uniform arrangement (dense and sparse) as well as internals of non-uniform arrangement (core and wall clearance). The simulations were executed for an air-water system at a constant superficial gas velocity of 12 cm/s, under atmospheric conditions. The effects of the volume fraction (2-16 %) covered by the internals and the arrangement of the internals on flow behavior were stimulated. Only one size of internals was simulated in this work (1 inch in diameter). Their simulation showed that liquid circulation and flow pattern are significantly and complexly affected by the configuration of the internal tubes and the inter-tube gaps. In the uniform internal configuration the liquid gross flow structure was similar to that in bubble column without internals (core-annulus up flow structure). A complex flow pattern was noticed even with liquid flowing downward in the core region for the non-uniform internals arrangement when the number of tubes was greater near the wall. There was a steep decrease in the liquid's kinetic energy while the internals were used. The results from this study were not substantiated due to lack of existing benchmarking data in bubble columns equipped with internals.

Yu et al. (2009) utilized the Pavlov tube and the conductivity probe to study the influence of vertical pipe bundles on the axial liquid velocity and gas hold up distributions along the radial direction of a 500 mm × 500 mm slurry bubble column. The tubes used in this study were 1 inch in diameter and 4 m in height. It has been reported that the vertical pipes remarkably increased the axial liquid velocity and enhanced the large scale liquid circulation, but impeded the radial or lateral turbulent motion of the liquid and gas bubbles. This effect eventually led to steeper distributions of the axial liquid velocity and gas holdup profiles.

Youssef et al. (2012) experimentally investigated the extent of occluded CSA by the internals on gas holdups and bubble properties in an 18 inch diameter bubble column for an air-water system. Vertical rods with diameter of 1 inch and different configurations covering 5 to 25 % of the column's CSA have been used in this study. No significant change was observed in the gas holdup and bubble properties with internals covering 5% of the column's CSA, but an increase in the gas holdup and interfacial area, and a decrease in the bubble chord length and bubble velocity, was noticed when dense internals (25%) were used. However, the authors reported that at the highest superficial gas velocity (45cm/s), the bubble chord lengths obtained in the presence of internals were larger than those obtained in the bubble column without internals. This work provided a great insight of impact of vertical internals on local bubble dynamics. However, the occluded CSA by the internals was not accounted when the superficial gas velocities were calculated. This means that the same mass flow rate for the bubble column without internals passed into the column with internals. In order to fairly assess the impact of internals, the superficial gas velocity should be based on free cross-sectional area for the flow as highlighted by Al-

Mesfer (2013) and Kagumba and Al-Dahhan (2015). Moreover, only one size of internals was investigated. Thus, whether the internals diameter has effect or no can't be understood from this work.

Al-Mesfer (2013) examined the effect of using internals with a diameter of 0.5 inch (covering 25% of the column's CSA) on the time averaged cross-sectional gas holdup profile, axial liquid velocity, turbulent kinetic energy, eddy diffusivities and normal and shear stress. The experiments were performed using advanced gamma ray computed tomography and radioactive particle tracking techniques in a bubble column of 6 inch diameter. These studies used air-water system at superficial gas velocities ranging from 5 to 45 cm/s, based on the total and free CSA of the column. The results showed that at any applied superficial gas velocity, the presence of internals enhanced the axial liquid velocity, but significantly decreased the normal and shear stresses, eddy diffusivity, and liquid turbulent kinetic energy profiles. Gas holdup was found to significantly increase with the presence of the internals, when the measurement of the gas velocity was based on the total CSA. A diminishing effect was seen when the superficial gas velocity was based on the free CSA.

Kagumba and Al-Dahhan (2015) examined the effect of internals, and their size, on gas holdup and bubble properties in a bubble column with a diameter of 0.14 m using air-water system. Two sizes of vertical tube internals were investigated in their work, 0.5 and 1 inch diameter internals, covering 25% of the column's CSA. The authors reported that the 0.5 inch internals gave consistently higher local and overall gas holdup, specific interfacial area and bubble passage frequency than the 1 inch internals and the bubble column without internals. It is worth mentioning that in this work the internals were configured differently for each case. In the case of the 0.5 inch internals, the tubes were non-uniformly distributed over the column's CSA in a hexagonal-like shape, while the 1 inch internals were configured in a uniform circular-like shape. The gaps between each side of the tube bundles in the hexagonal like arrangement and the wall of the bubble column were not equally spaced. This resulted in large unobstructed areas between the internals bundle edges and column wall which may create severe gas short circuiting due to less resistance for the gas to flow. Hence, such arrangement eventually leads to asymmetric gas distribution across the column as has been reported in the literature (Guan et al., 2015a; Jasim, 2015). While the 1 inch internals tubes were equally spaced from the wall by virtue of the circular configuration. Thus, it's not clear whether these changes came from tube size or from the arrangement of the internals. Moreover, results from only one radial side at an angular location of the column were reported in this work, while it has been proven that non-uniformly arranged internals yield asymmetric profiles (Guan et al., 2015a; Larachi et al., 2006). Thus, it's difficult to confidently evaluate the effect of internals diameter on the hydrodynamics including gas holdup and bubble dynamic.

It is clear that the bubble column reactor's hydrodynamics can be affected by the presence of internals and their configurations through the change of its hydrodynamic and transport properties. Unfortunately, while all of the reported studies have indicated that internals can affect the reactor's performance, a lack of understanding of the impact of internals on hydrodynamic and transport characteristics remains.

In order to fairly assess the effect internals' diameters on the hydrodynamics of bubble column**,** different dimeter of internal heat exchanging tubes, uniformly arranged over the column's CSA, should be investigated at the same conditions.

Accordingly, the present study aims to properly study the effects of vertical heat exchanging tube diameter, uniformly distributed in a circular arrangement over the column CSA on the radial profiles of gas holdup, specific interfacial area, bubble chord length and bubble rise velocity, in a 14 cm diameter bubble column operated in churn-turbulent regimes at superficial gas velocities of 20, 30, and 45 cm/s measured based on the free CSA available for flow.

2. EXPERIMENTAL SETUP

The experiments were performed in a Plexiglas column of 14 cm I.D. and 183 cm in height. The schematic diagram of the experimental setup is shown in Figure 2.1. For the gas phase, compressed oil-free dry air was continuously introduced into the column through a 30 cm plenum and perforated plate gas sparger containing 121 holes of 1.32 mm diameter oriented in a triangular pitch providing 1.09 % of open area. For the liquid phase, water was used in batch mode. The dynamic bed height was kept at a constant level of Z/D=11.25 for all experiments. The unaerated liquid height varied accordingly for each studied condition to preserve the dynamic bed height. As previously stated, the configuration of the internals has a large impact on the hydrodynamic properties of the bubble column. In this work, the effect that the diameter of the uniformly distributed internals has on the local gas holdup, bubble passage frequency, specific interfacial area, and bubble chord length, and bubble velocity was investigated.

Two different diameters, 0.5 inch and 1 inch, of vertical heat exchanging internals, covering 25% of the column's CSA were examined to mimic the heat exchanging tubes utilized in Fisher-Tropsch process (Al-Mesfer, 2013; Hamed, 2012; Kagumba, 2013; Youssef, 2010; Youssef et al., 2012). In both cases, the internals were uniformly distributed over the column's CSA in a circular like arrangement. This circular like arrangement of the internals was implemented to maintain equal spacing between the internals and the wall of the bubble column reactor. The schematics and pictures of the internal configurations are shown in Figure 2.2. The experiments were performed in the churn-turbulent flow regime at different superficial gas velocities of 20, 30, and 45 cm/s to reflect the industrial applications of the Fisher-Tropsch process (Krishna et al., 2001a).

The superficial gas velocity was calculated by dividing the volumetric gas flow rate into the column by the free cross-sectional area (CSA) of the column available for the flow. The free CSA of the column was calculated from the following the relation;

$$\begin{Bmatrix} Free\ Cross-sectional \\ area\ of\ bubble\ column \\ with\ internals \end{Bmatrix} = \begin{Bmatrix} Cross-sectional\ area \\ of\ bubble\ column \\ without\ internals \end{Bmatrix} - \begin{Bmatrix} Cross-sectional\ area \\ occluded\ by \\ the\ internals \end{Bmatrix}$$

4-point optical fiber probe technique was used to collect hydrodynamic property values, specifically the gas holdup, specific interfacial area, bubble passage frequency, bubble rise velocity, and bubble chord length. The probe was fixed at one axial height within the fully developed region, Z/D=5.1, where the gas holdup and the bubble properties are not dependent on the axial height (Xue, 2004). The radial distribution of the mentioned hydrodynamic parameters was investigated by moving the probe radially in line along the diameter of the column (r/R= 0, $\pm$0.3, $\pm$0.6, and $\pm$0.9). Detailed information about the manufacturing process and signal analysis of the 4-point optical fiber probe technique can be found elsewhere (Kagumba and Al-Dahhan, 2015; Xue, 2004; Xue et al., 2003).

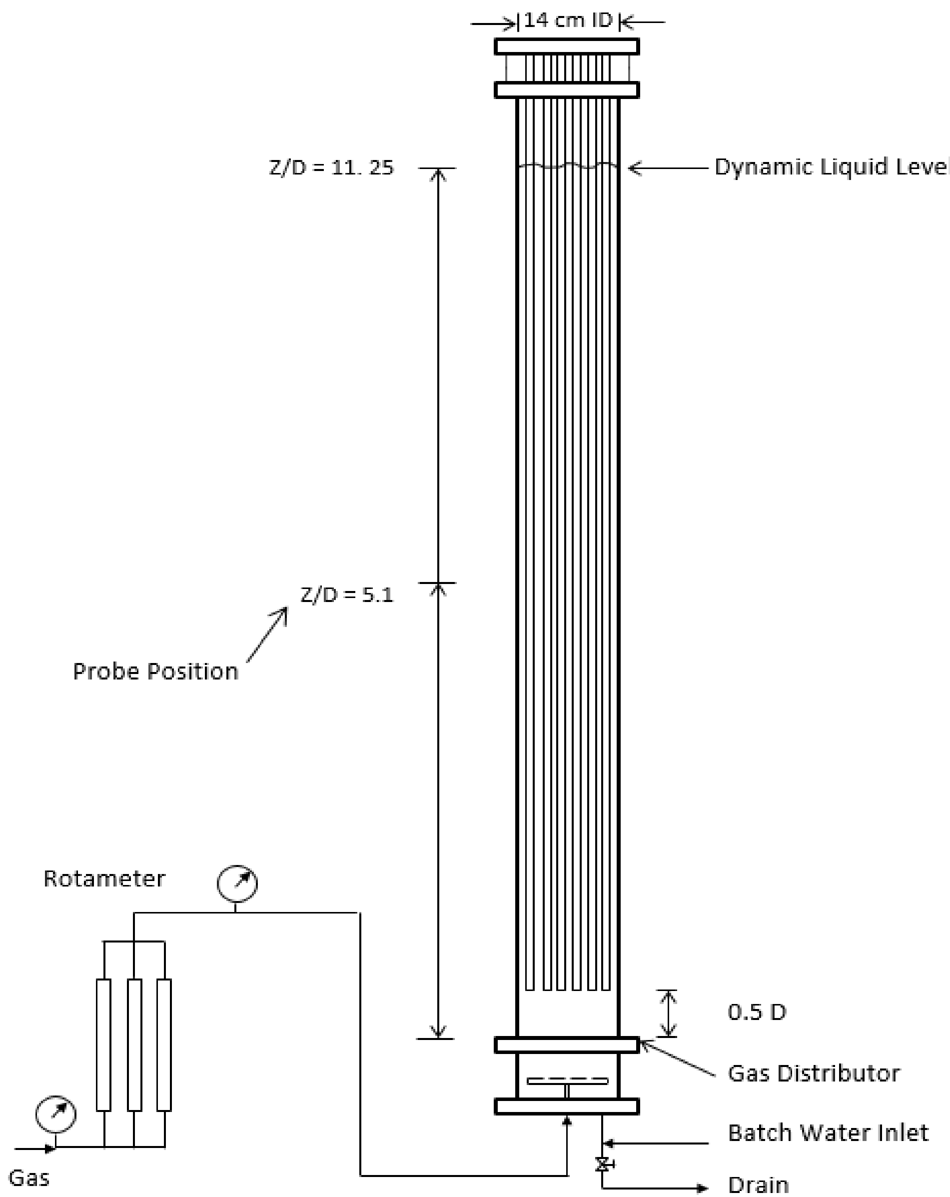
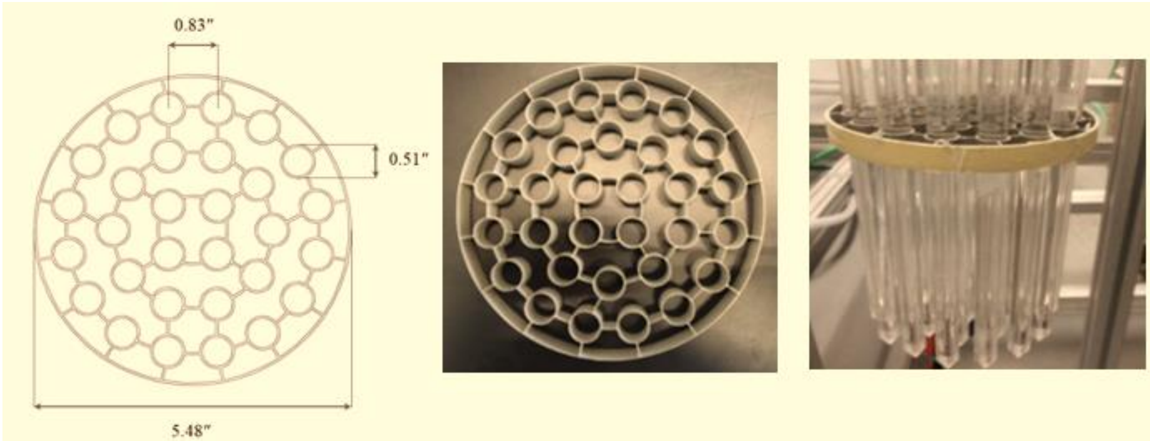
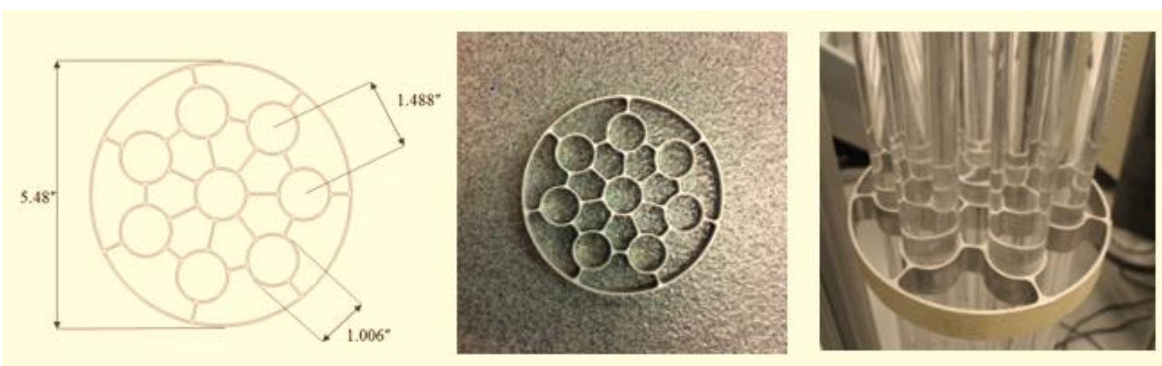


Figure 2.1 Schematic of the bubble column with internals.



(a) Schematic and photo of the 0.5 inch internals configuration



(b) Schematic and photo of the 1 inch internals configuration

Figure 2.2 Schematic and photo of internals arrangement.
(a) 0.5 inch internals (b) 1 inch internals

3. RESULT AND DISCUSSION

3.1 GAS HOLDUP

Figure 3.1 shows the effect of internals and their diameter on the radial profiles of local gas holdup at a superficial gas velocity of 20 cm/s based on free CSA available for flow. It was noticed that the gas holdup in the core region was enhanced when the internals were used. An increase of 16% was achieved when 0.5 inch internals were used, while the 1 inch internals yielded an enhancement of 10 %. Regardless of the size, the internals show a negligible effect on the gas holdup near the wall regions at this superficial gas velocity.

It was observed that the enhancement of the gas holdup in the core region, in the presence of 0.5 inch internals, increased proportionally with the superficial gas velocity. For instance, at the superficial gas velocity of 45 cm/s, the gas holdup is found to be 33% higher in the bubble column with 0.5 inch internals than in the bubble column without internals. Moreover, a reduction in the gas holdup is observed in the regions that are close to wall, as shown in Figure 3.3. Thus, the gas holdup exhibits a steeper radial profile with the presence of 0.5 inch internals. This finding is in agreement with the literature (Yu et al., 2009).

Contrary to the 0.5 inch internals, the presence of 1 inch internals tends to enhance the gas holdup when the superficial gas velocity is increased. This is significant in the annular ($r/R = \pm 0.6$) and wall regions, but not in the core regions. The gas holdup increased by 17% and 22% in regions near the wall at superficial gas velocities of 30 cm/s and 45 cm/s, respectively (Figure 3.2 and Figure 3.3).

One explanation for the significant increase in the gas holdup values of the core region when the 0.5 inch internals were used could be that the internals dampen the turbulence in the system and enhance large scale liquid circulation (Al-Mesfer, 2013; Chen et al., 1999). This in return leads to increased shear stress at the wall regions (Al-Mesfer, 2013; Chen et al., 1999), and it induces gas bubbles to move toward the column center where less shear stress exists. This leads to an increase in that area's bubble population, which increases the gas holdup.

The same CSA is maintained in the arrangement of the 1 in internals as it was in the 0.5 inch internal arrangement with a symmetric distribution. To configure the symmetry, one rod of the 1 inch internals is placed in the center of the column (r/R=0). This arrangement hinders the vigorous gas up flow in the center region and enhances the radial gas dispersion. This was indicated from the increased number of bubbles near the wall regions observed upon the insertion of the 1 inch internals, as will be shown later. This finding suggests that the position of the internals governs the flow pattern in the bubble column.

From the increase in the gas holdup values near to the wall regions, it can be understood that the configuration of the 1 inch internals enhances gas-liquid mixing and reduces large scale liquid circulation. Similar findings have not been reported in the literature. Thus, it may be necessary to further investigate the effect of such configuration on other related parameters such as axial liquid velocities and eddy diffusivities.

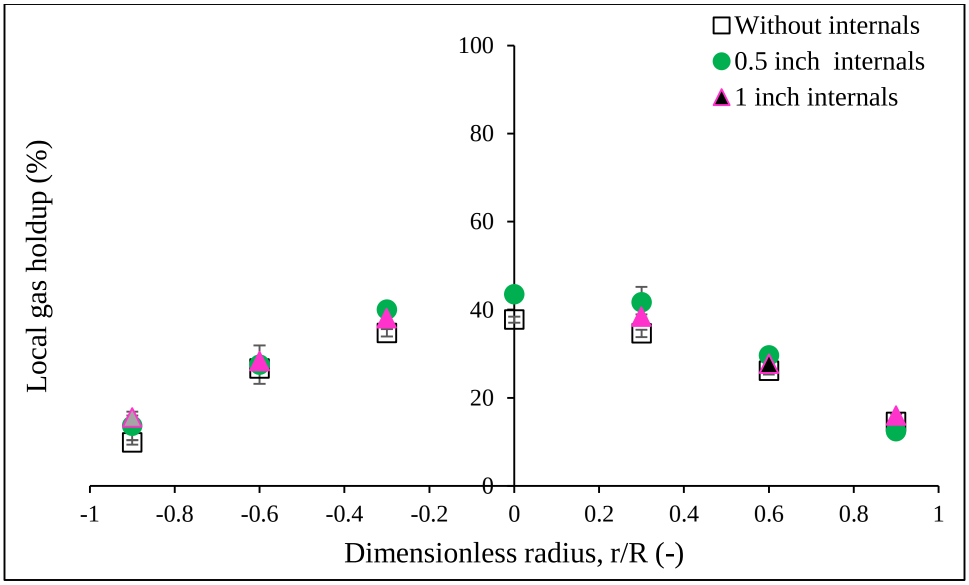


Figure 3.1 Effect of internals and their diameter on the radial profile of local gas holdup at U_g = 20 cm/s.

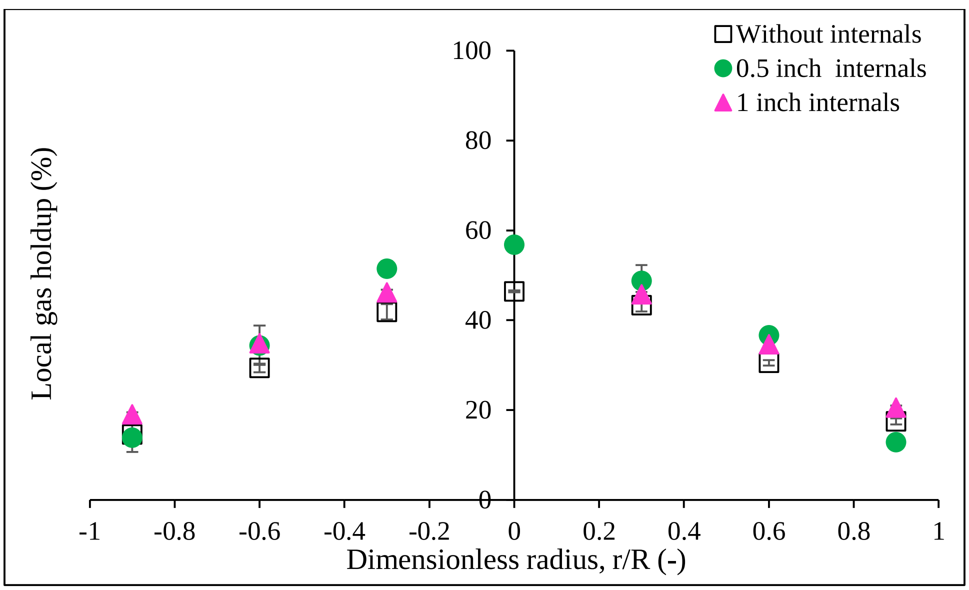


Figure 3.2 Effect of internals and their diameter on the radial profile of local gas holdup at U_g = 30 cm/s.

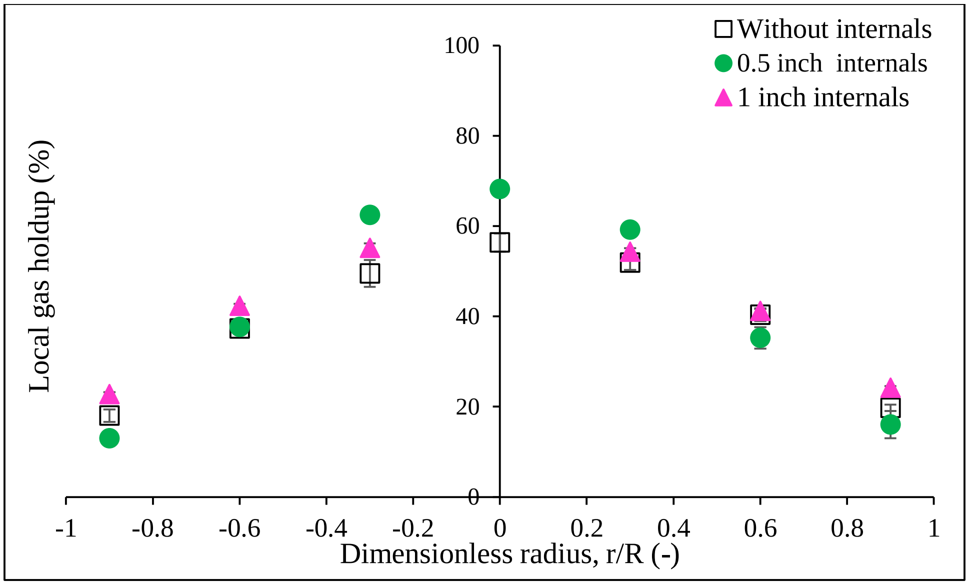


Figure 3.3 Effect of internals and their diameter on the radial profile of local gas holdup at U_g = 45 cm/s.

3.2 BUBBLE CHORD LENGTH

The effect of the diameter of the internals on the bubble chord length distribution is investigated at different gas velocities of 20, 30, and 45 cm/s based on free cross-sectional area (CSA) of the column available for the flow. The bubble chord length distribution for bubble columns with and without internals was found to follow lognormal distribution. This observation is in agreement with the literature (Kagumba and Al-Dahhan, 2015; Wu and Al-Dahhan, 2008; Xue et al., 2008; Xue et al., 2003; Youssef and Al-Dahhan, 2009).

To find the probability density function of the obtained bubble chord length distribution for the diffeent conditions, the lognormal distribution function is employed. The lognormal distribution function can be expressed as:

$$f(d_c) = pdf = \frac{1}{\sigma d_c \sqrt{2\pi}} exp\left[-\frac{(ln d_c - \mu)^2}{2\sigma^2}\right] \tag{3.1}$$

Where d_c is the chord length of individual bubbles obtained directly from the 4-point optical probe. μ and σ are related to the mean, m , and variance, υ , of the chord length distribution.

$$\mu = \ln \frac{m}{\sqrt{1+\frac{\upsilon}{m^2}}} \quad , \quad \sigma = \sqrt{\ln\left(1+\frac{\upsilon}{m^2}\right)} \tag{3.2}$$

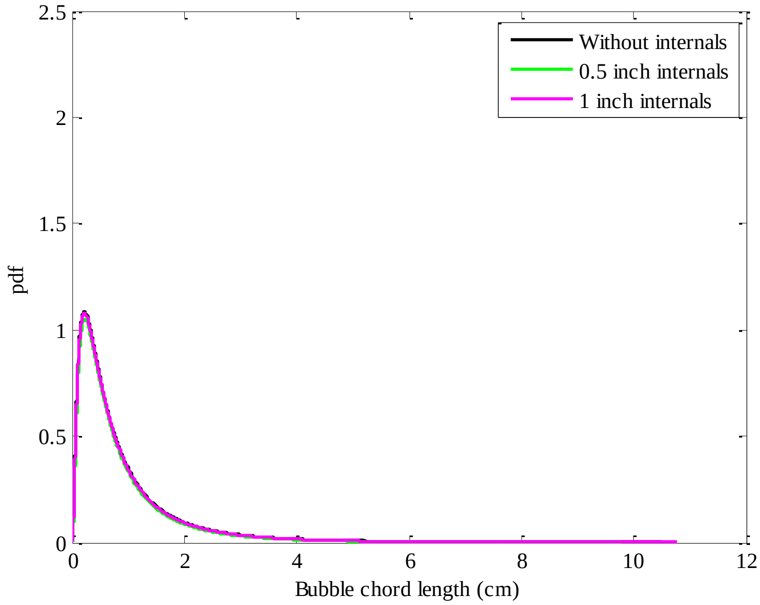
Figure 3.4 shows the effect of internals diameter on the probability distribution of bubble chord length at a superficial gas velocity of 20 cm/s. It can be observed that the internals have an insignificant impact on the bubble chord length distributions in the core region when compared to bubble columns without internals. This can also be proved by the mean and the variance of the distributions, as shown in Table 3.1. However, a considerable increase in the bubble chord lengths was observed at the wall regions when the 1 inch internals were used.

From the mean of the distributions presented, it is clear that bubble chord lengths in bubble columns without internals decreased when the superficial velocity increased from 20 to 45 cm/s. However, the difference is negligible in case of the internals. Therefore, at superficial gas velocities of 30 and 45 cm/s, the observed bubble chord length in bubble columns with internals is larger than that in bubble columns without internals in both core and wall regions (see Table 3.1). It can be noted from Figures 3.5 and 3.6 that there is a much higher probability for larger bubbles in the presence of internals than there is in bubble columns without internals. This observation is in line with literature (Youssef et al., 2012).

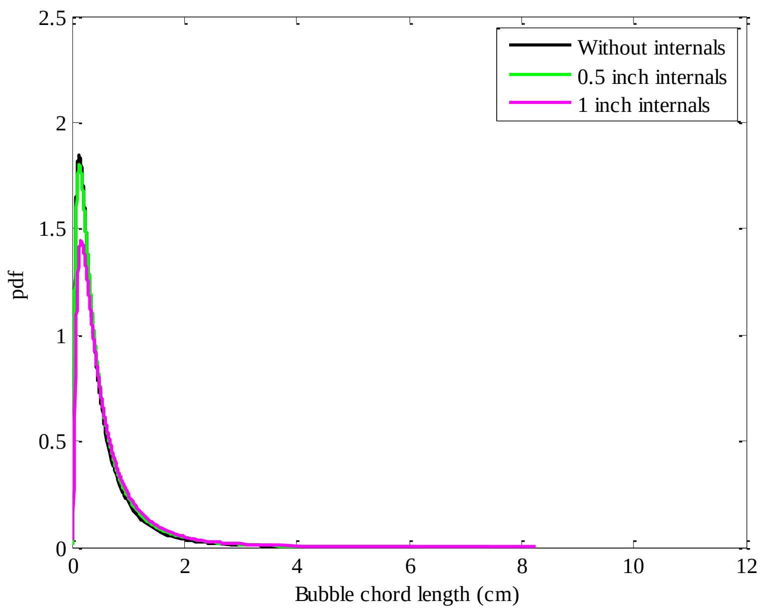
A possible reason for this could be that increasing the superficial gas velocity in bubble columns without internals leads to increase in turbulence and turbulent related parameters such as turbulent kinetic energy (TKE) and eddy diversities (Al-Mesfer, 2013). This leads to vigorous gas liquid interactions and enhanced bubble breakage, which creates smaller bubbles in the system and increases the local and overall gas holdup and interfacial area. However, the presence of internals decreases the turbulent intensity by preventing the development of large eddies (Al-Mesfer, 2013; Chen et al., 1999; Hamed, 2012; Larachi et al., 2006), leading to vigorous and coherent gas flow whose size and location are governed by the structure of the internals.

The bubble chord lengths for the 0.5 inch internals and 1 inch internals in the core region are comparable; while in the wall region 1 inch internals give higher chord lengths than the 0.5 inch internals, which is in agreement with results of (Kagumba and Al-Dahhan, 2015).

It is also worth mentioning that the variance of the distribution for 1 inch internals in the wall regions is considerably higher than in other cases. This observation indicates that a wide range of bubble chord lengths exist near the wall regions revealing a higher bubble population. This tends to support the results mentioned earlier regarding the increased gas holdup near the column’s wall with the presence of 1 inch internals. From the above observations, it can be concluded that in the churn-turbulent regime the presence of vertical heat exchanging internals enhances the bubble coalescence and results in larger bubbles in the system.

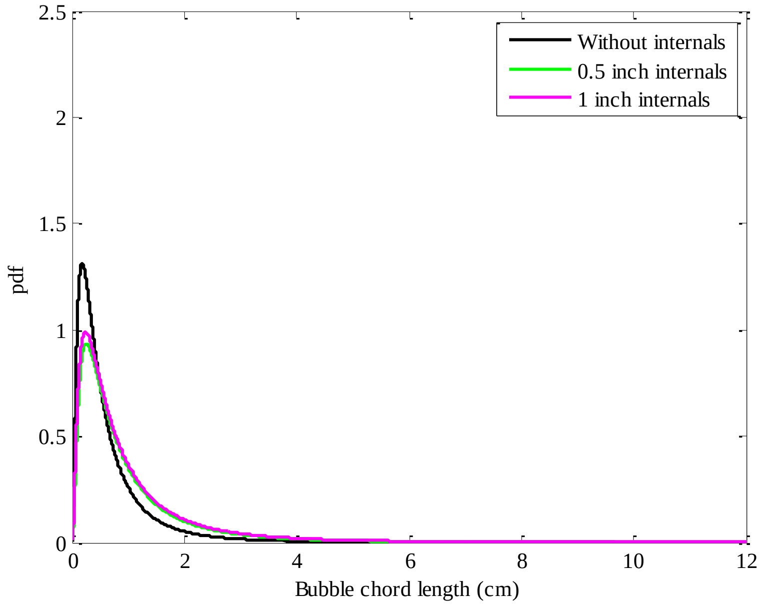


(a)

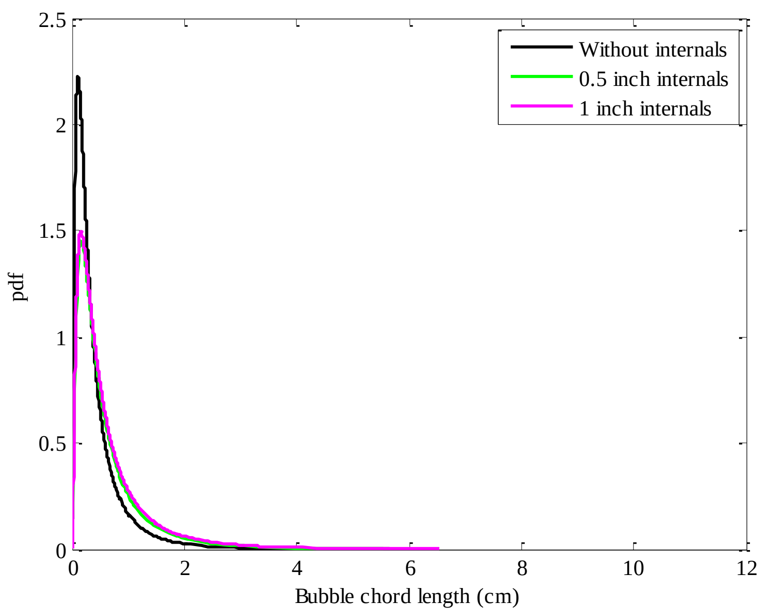


(b)

Figure 3.4 Effect of internals and their diameter on the bubble chord length distribution at U_g = 20 cm/s. (a) $-0.3 \leq r/R \leq +0.3$, (b) $r/R = \pm 0.9$

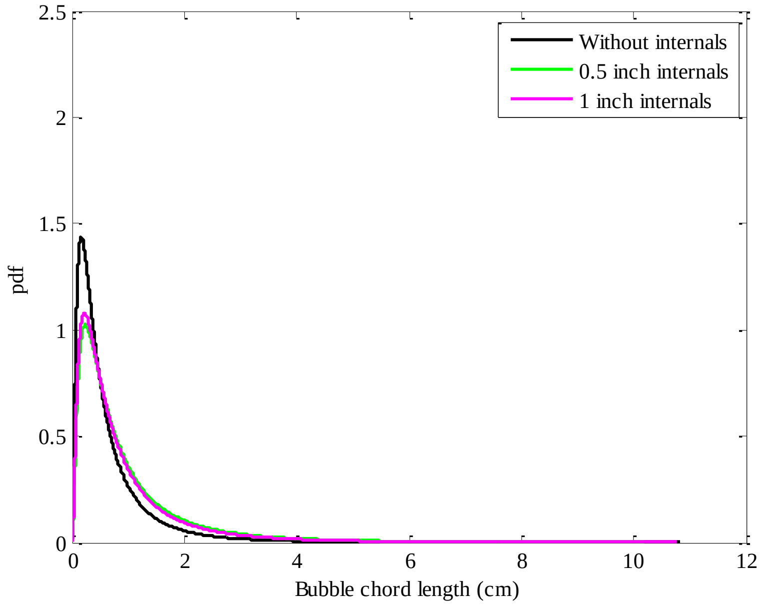


(a)

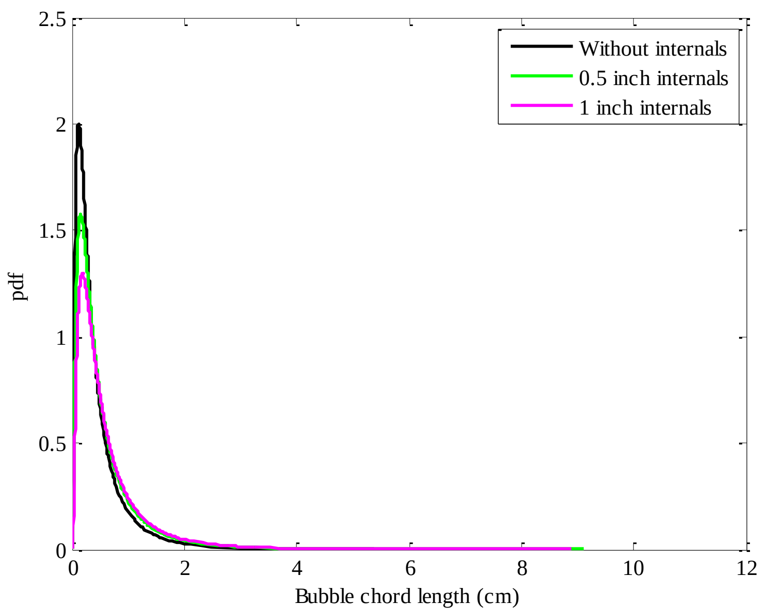


(b)

Figure 3.5 Effect of internals and their diameter on the bubble chord length distribution at U_g = 30 cm/s. (a) $-0.3 \leq R/r \leq +0.3$, (b) $r/R = \pm 0.9$



(a)



(b)

Figure 3.6 Effect of internals and their diameter on the bubble chord length distribution at U_g = 45 cm/s. (a) $-0.3 \leq r/R \leq +0.3$, (b) $r/R = \pm 0.9$

Table 3.1 Mean and variance of bubble chord length distributions at superficial gas velocities, U_g, 20, 30, and 45 cm/s.

20 cm/s				
	$-0.3 \leq r/R \leq +0.3$		$r/R = \pm 0.9$	
	Mean	Variance	Mean	Variance
without internals	0.97	1.73	0.57	0.61
0.5 inch internals	1.00	1.90	0.6	0.62
1 inch internals	0.99	1.76	0.72	1.03
30 cm/s				
	$-0.3 \leq r/R \leq +0.3$		$r/R = \pm 0.9$	
without internals	0.78	1.33	0.45	0.36
0.5 inch internals	1.12	2.4	0.81	1.65
1 inch internals	1.1	2.07	0.84	1.94
45 cm/s				
	$-0.3 \leq r/R \leq +0.3$		$r/R = \pm 0.9$	
	Mean	Variance	Mean	Variance
without internals	0.79	0.9	0.52	0.53
0.5 inch internals	1.08	1.57	0.672	0.87
1 inch internals	1.01	1.92	0.78	1.37

3.3 SPECIFIC INTERFACIAL AREA

Figure 3.7 shows the effect internals and their diameter on the specific gas-liquid interfacial area at a superficial gas velocity of 20 cm/s. A slight increase in the specific interfacial area was obtained along the radial profile when the 1 inch internals were used. The increase was greater near the wall regions in the bubble column with the 1 inch internals, but the presence of the 0.5 inch internals shows a negligible effect. However, at higher superficial gas velocities, the presence of the 0.5 inch internals significantly decreased the specific interfacial area when compared to bubble column without internals. The reduction was higher in the annular and wall regions. For example, at r/R= ± 0.9, the specific interfacial area was decreased by 55% and 42% when the 0.5 in internals were used at Ug = 30 cm/s and Ug = 45 cm/s, respectively. Therefore, the radial profile of the interfacial area is steeper in comparison to bubble column without internals, as shown in Figure 3.8 and Figure 3.9. On the contrary, the interfacial area increased in the wall regions and decreased in the core region when the 1 inch internals were used. Qualitatively, at gas velocity of 45 cm/s, an average increase of 30% is obtained at r/R=0.9 while a decrease of 19% is noticed at r/R=± 0.3, when compared to bubble columns without internals. Therefore, it can be observed that the radial profile of the interfacial area is less parabolic than it is in bubble column without internals.

A possible explanation of the increase in the interfacial area of the wall regions when 1 inch internals were used is that the increase in the bubble population near to the wall regions which is caused by the configuration of the 1 in internals.

To confirm this, bubble passage frequency which is defined as “the number of bubbles passing through a unit volume of the reactor per unit time” was measured. The bubble passage frequency was obtained by dividing the number of bubbles hitting the central tip of the 4-point optical fiber probe by sampling time (Wu and Al-Dahhan, 2008; Xue et al., 2003). The effect of the internals on the bubble passage frequency at Ug = 45 cm/s shown in Figure 3.10.

As expected, the results show the bubble passage frequency increases at the wall region and decreases in the core region when the 1 in internals were used. The significant increase in the bubble passage frequency outweighs the increased bubble size, yielding a higher interfacial area. On the other hand, it can be noticed that the bubble passage frequency increased in the core region and decreased in the annular and wall regions when the 0.5 inch internals were used.

Previous studies on bubble passage frequency have reported that an increase in bubble frequency leads to an increase in gas holdup and specific interfacial area (Kagumba and Al-Dahhan, 2015; Wu et al., 2008; Xue, 2004; Xue et al., 2003; Youssef and Al-Dahhan, 2009; Youssef et al., 2012). Alternately, a decrease in the bubble passage frequency negatively affects gas holdup and interfacial area. Moreover, large bubbles that were observed in the presence of internals are well known to have a lower surface area per unit volume when compared to small bubbles. Thus, by combining these two factors, one can explain the substantial decrease in the total interfacial area observed in the annular and wall regions when the 0.5 in internals were used.

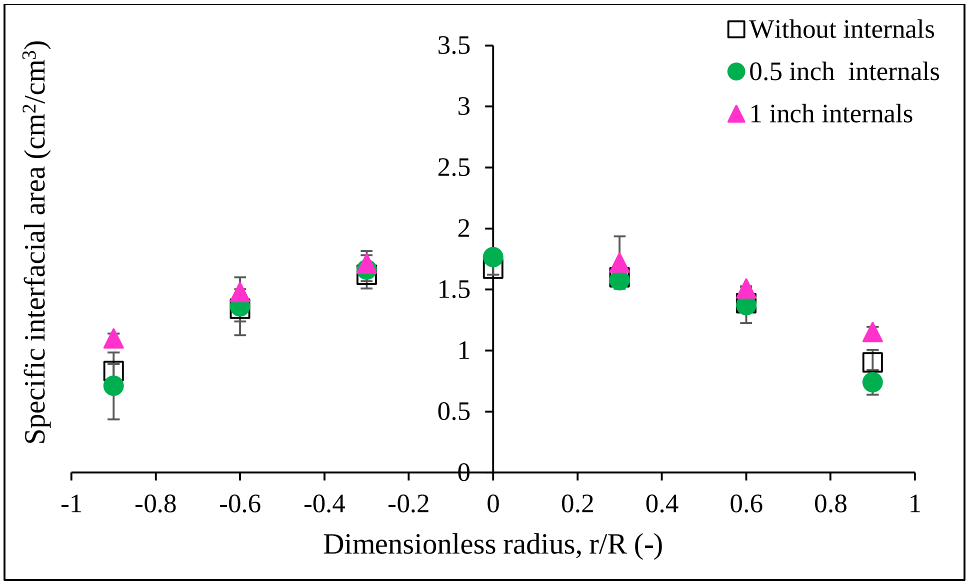


Figure 3.7 Effect of internals and their diameter on the radial profile of specific interfacial area at $U_g = 20$ cm/s.

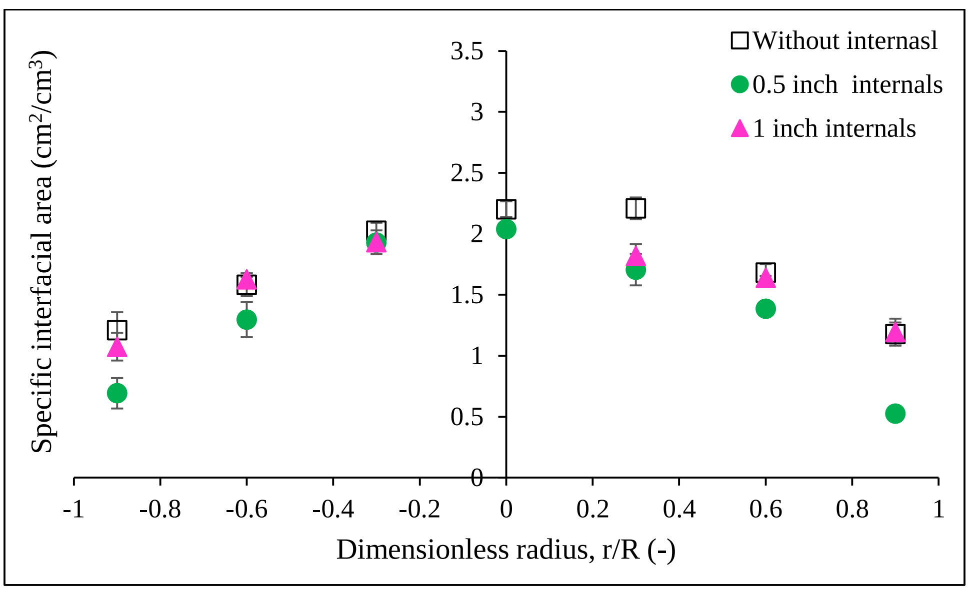


Figure 3.8 Effect of internals and their diameter on the radial profile of specific interfacial area at $U_g = 30$ cm/s.

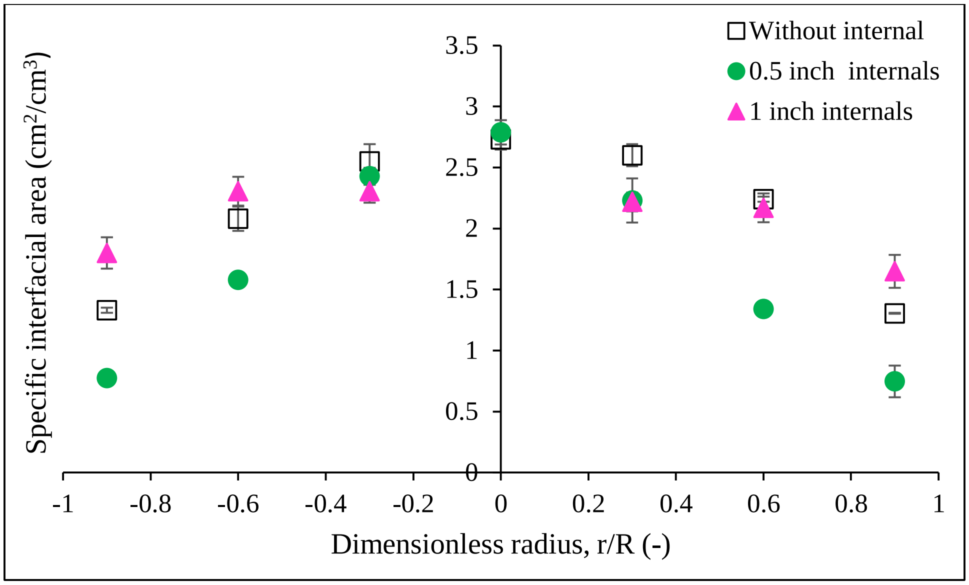


Figure 3.9 Effect of internals and their diameter on the radial profile of specific interfacial area at U_g = 45 cm/s.

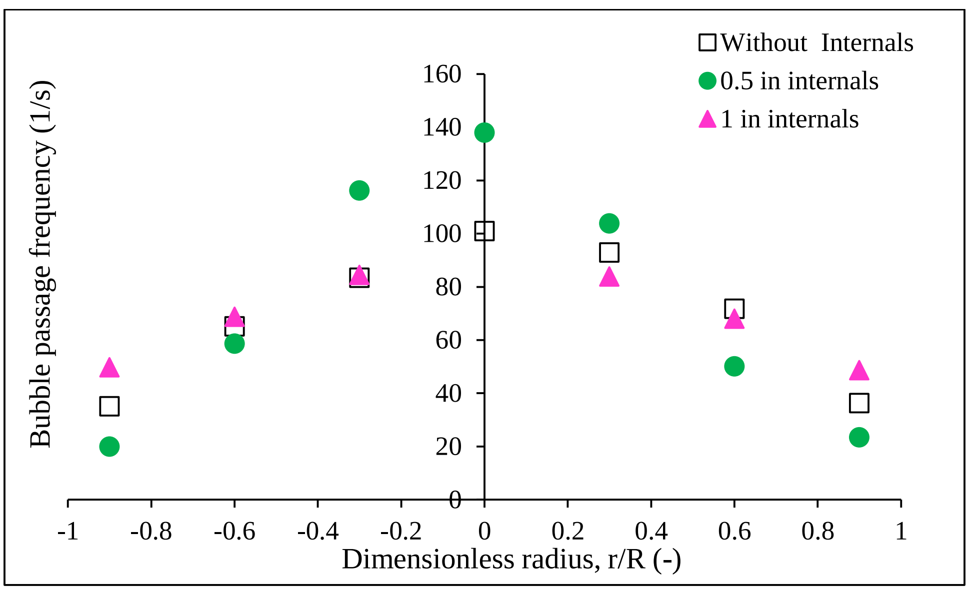


Figure 3.10 Effect of internals diameter on the radial profile of bubble passage frequency at U_g = 45 cm/s.

3.4 BUBBLE RISE VELOCITY

The impact of the internals diameter on the bubble rise velocity was investigated in the churn-turbulent regime at superficial gas velocities of 20, 30, and 45 cm/s. Figure 3.11 shows the effect of the diameter of the internals on the probability distribution of the bubble rise velocity at a superficial gas velocity of 20 cm/s. A comparison of the distributions reveals that, regardless the diameter, the internals had no significant effect on the bubble rise velocity at 20 cm/s. Qualitatively, the distribution was slightly shafted toward higher velocities, and the probability of high velocity bubbles was slightly increased when the 0.5 inch internals were used. To quantify this, the mean value (average) of each distribution was measured and presented. It was found that the presence of the 0.5 inch internals slightly increased (9%) the average bubble rise velocity in the core region when compared to bubble columns without internals. Moreover, the average bubble rise velocity for 1 inch internals and that of bubble columns without internals are alike. The effect of the internals was found to be more significant at higher superficial gas velocities, as shown in Figures 3.12 and 3.13. For example, at 45 cm/s, it was observed that the average bubble rise velocity in the core region for the 0.5 in internals was 25% higher than that of bubble columns without internals. A similar finding was reported by Hamed (2012). This increase could be attributed to the increase in bubble size and the enhancement in the liquid circulation due to the change in the gas hold up profile caused by the circular arrangement of the internals. On the other hand, the effect of the 1 inch internals was found to be higher at the wall regions rather than the core region. An increase of ∼18% in the average bubble rise velocity was obtained at $r/R = \pm 0.9$. Therefore, that the difference in the average bubble rise velocity between the core and wall regions for the 1 inch internals is less than other cases.

Table 3.2 Mean and variance of bubble rise velocity distributions at superficial gas velocities, U_g, 20, 30, and 45 cm/s.

20 cm/s				
	$-0.3 \leq r/R \leq +0.3$		$r/R = \pm 0.9$	
	Mean	Variance	Mean	Variance
Without internals	98.8	1.6401e+03	79.3	1.2048e+03
0.5inch internals	107.9	1.5336e+03	72.2	1.1939e+03
1 inch internals	99.0	1.4219e+03	81.3	1.3446e+03
30 cm/s				
	$-0.3 \leq r/R \leq +0.3$		$r/R = \pm 0.9$	
	Mean	Variance	Mean	Variance
Without internals	95.5	1630	74.8	1.250+03
0.5inch internals	125.7	1687	92.7	1.434+03
1 inch internals	103.2	1587	88.6	1.460+03
45 cm/s				
	$-0.3 \leq r/R \leq +0.3$		$r/R = \pm 0.9$	
	Mean	Variance	Mean	Variance
Without internals	101.5	1.5864e+03	76.8	1.3383e+03
0.5inch internals	126.4	1.6526e+03	97.1	1.7466e+03
1 inch internals	109.2	1.6988e+03	90.1	1.6752e+03

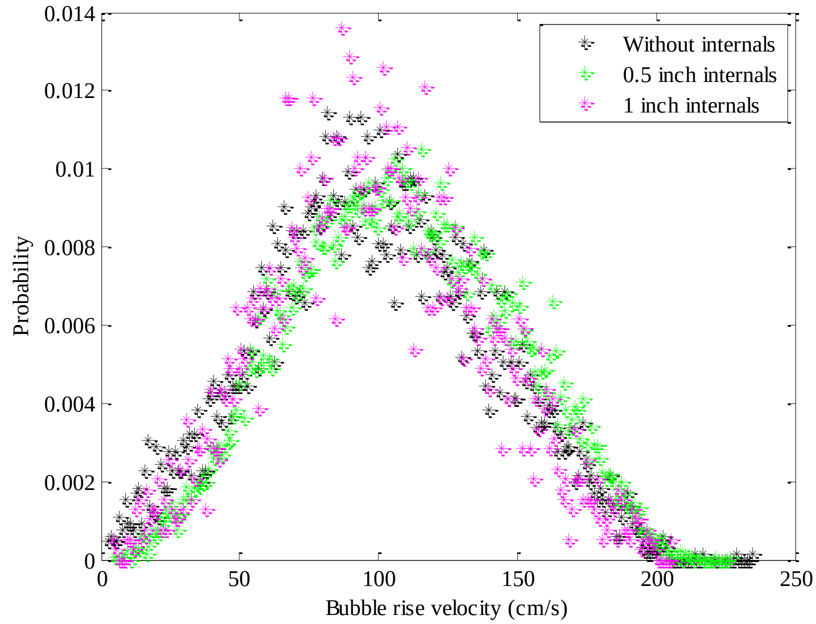


Figure 3.11 Effect of internals diameter on the bubble rise velocity distribution at $U_g = 20$ cm/s and $-0.3 \leq r/R \geq +0.3$

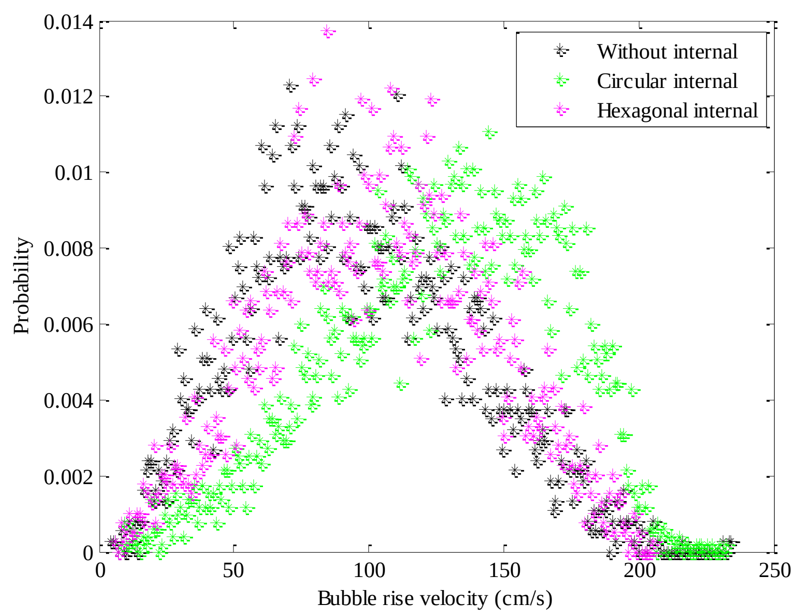


Figure 3.12 Effect of internals diameter on the bubble rise velocity distribution at $U_g = 30$ cm/s and $-0.3 \leq r/R \geq +0.3$

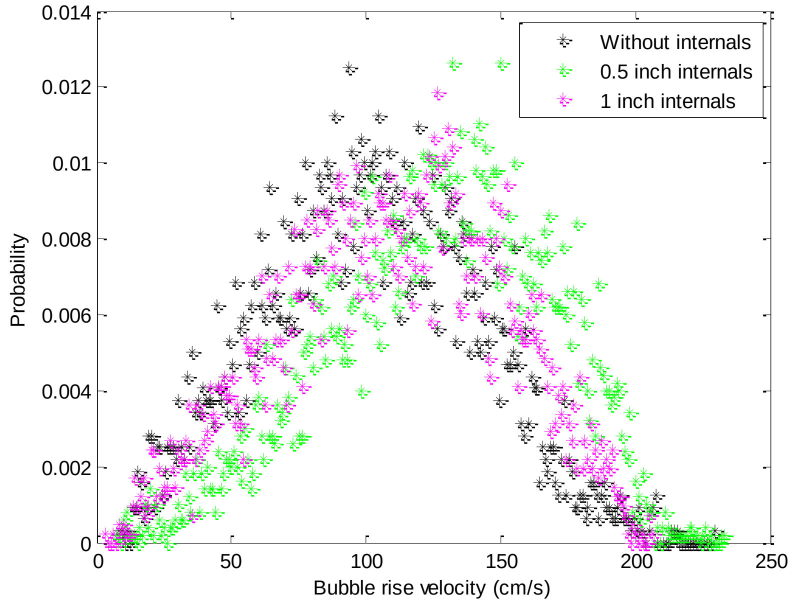


Figure 3.13 Effect of internals diameter on the bubble rise velocity distribution at $U_g = 45$ cm/s and $-0.3 \le r/R \ge +0.3$

4. REMARKS

The impact of uniformly distributed vertical heat exchanging internals and their diameter on gas holdup and bubble dynamics including the specific interfacial area, bubble chord length, and bubble velocity were investigated. Two different diameters, 0.5 inch and 1 inch, of vertical rods covering 25% of the column's cross-sectional area were used to represent the heat exchanging tubes utilized in the F-T process. The experiments were conducted in a 6 in diameter bubble column using air-water system, at superficial gas velocities of 20, 30, 45 cm/s, measured based on free cross-section area for flow.

The experimental results indicated that the heat exchanging internals diameter and the location of the tubes have significant effect on the hydrodynamics and flow resistance of bubble columns. The local gas holdup significantly increased in the core region and decreased at the wall regions when the 0.5 inch internals were used. Contrarily, the 1 inch internals enhanced the gas holdup near to the wall regions. The bubbles chord length was found to be larger with the presence of internals, as was the bubble velocity. The specific interfacial area with the 0.5 inch internal was much lower than when the bubble column was tested without internals. The specific interfacial area was enhanced in the wall regions when the 1 inch internals were used. This is new finding. Thus, it would be necessary to further investigate the effect of such configuration on other related parameters such as axial liquid velocities and eddy diffusivities. This study was limited to air-water system while the FT synthesis involves a 3-phase system running at high temperature and pressure. Therefore, it is important to investigate the impact of internals and their configuration in slurry bubble column operating at FT conditions.

SECTION

4. RECOMMENDATIONS

Although the current study provides useful information about bubble columns with internals, many questions remain unanswered in topics of relevance to this work. Below are few recommendations for potential future research opportunities to yield a better understanding of the subject.

1. This work presents a deep insight on the influence of dense internals configuration and size on bubble dynamics. However, it is limited to air water system under ambient temperature and pressure while the FT synthesis involves a 3-phase system (gas-liquid-solid) running at high pressure and temperature. Therefore, it is important to adopt a study investigating the impact of dense internals' configuration and size in 3-phase system at high temperature and pressure to mimic FT conditions and to assure the validity of the findings and results of the current work.
2. In future studies, it is necessary to investigate the effect of different internals' configuration, size and the height from the gas distributor on other related hydrodynamic parameters such as turbulent parameters, liquid velocity, phase residence time and eddy diffusivity using Radioactive Particle Tracking.
3. In future work, Flow regime identification in bubble column with dense heat exchanging internals should be investigated since it is lack in the literature.

APPENDIX

IMPACT OF INTERNALS HEIGHT ABOVE THE GAS DISTRIBUTOR ON GAS HOLDUP AND BUBBLE DYNAMICS

The effect of internals height from the gas distributer (the gap between the internals and the gas distributor) on Hydrodynamics in bubble or slurry bubble columns has not been reported in the literature. In this work, the impact of dense heat exchanging internals and their height from the gas distributor on the radial profiles of key hydrodynamic parameters such as local gas holdup, specific interfacial area, and local bubble dynamics including bubble velocity, bubble passage frequency, and bubble chord length were experimentally investigated using 4-point optical fiber probe technique. 30 vertical rods each of 0.5 inch in diameter, covering 25% of the column's cross-sectional area were used to represent the heat exchanging tubes utilized in the F-T process. The effect internals height above the gas distributor was investigated by placing these internals at different height above the gas distributor each time. Four different height, 0.07D (Just above the distributor), 0.5D, 1D, and 1.5D were investigated. The experiments were performed in a 0.14 m inner diameter Plexiglas bubble column using an air-water system. The applied superficial gas velocities were based on free cross-sectional area of the column available for fluid flow and were in the range 5 to 45 cm/s.

A.1 Impact of internals height above the gas distributor on the radial profile of gas holdup

At low superficial gas velocity (5 cm/s), higher gas holdup values along the column diameter were observed when the internals placed at height of Z/D=1.5D as shown in figure A.1.1. In the churn turbulent flow regime (45 cm/s), steeper gas holdup profiles obtained as the gap between the internals and the gas distributor decreased as shown in Figure A.1.3, where it can be seen that the internals cause significant increase in gas holdup in the core region and a reduction at wall regions when they placed at heights of Z/D=0.07D and Z/D=0.5D. While less steep profile is observed for when the internals placed at Z/D=1.5D.

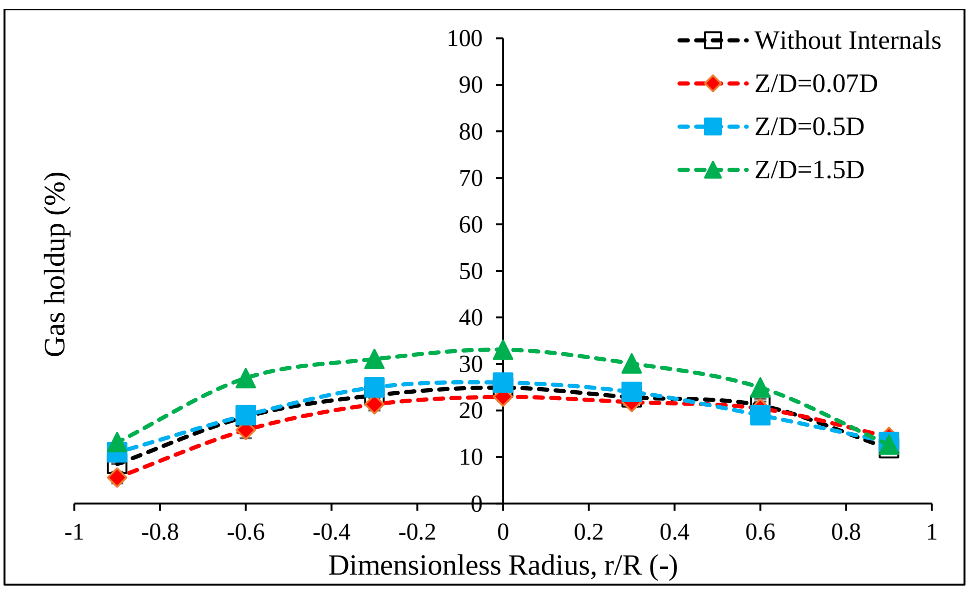


Figure A.1.1 Impact of internals height above the gas distributor on the radial profile of gas holdup at U_g = 5 cm/s.

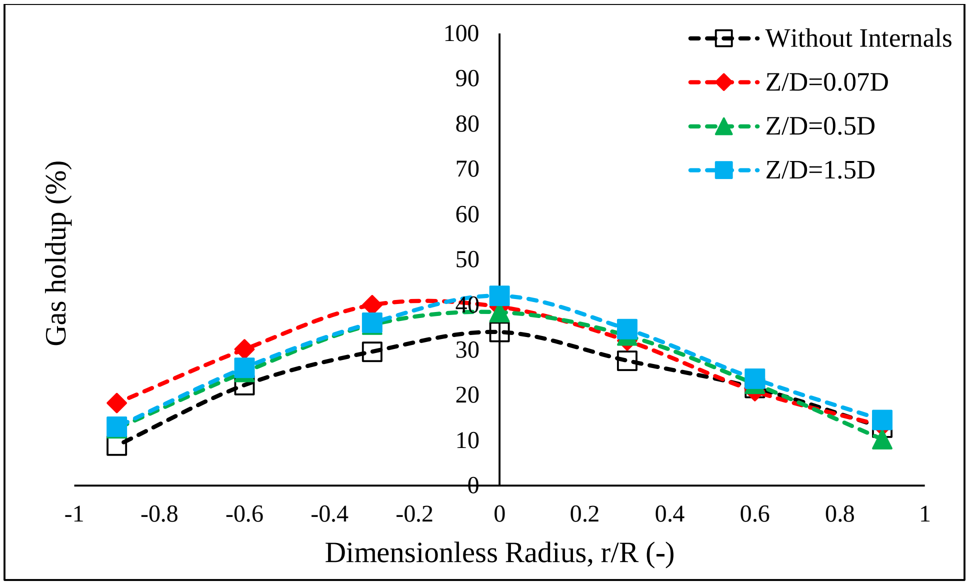


Figure A.1.2 Impact of internals height above the gas distributor on the radial profile of gas holdup at U_g = 15 cm/s.

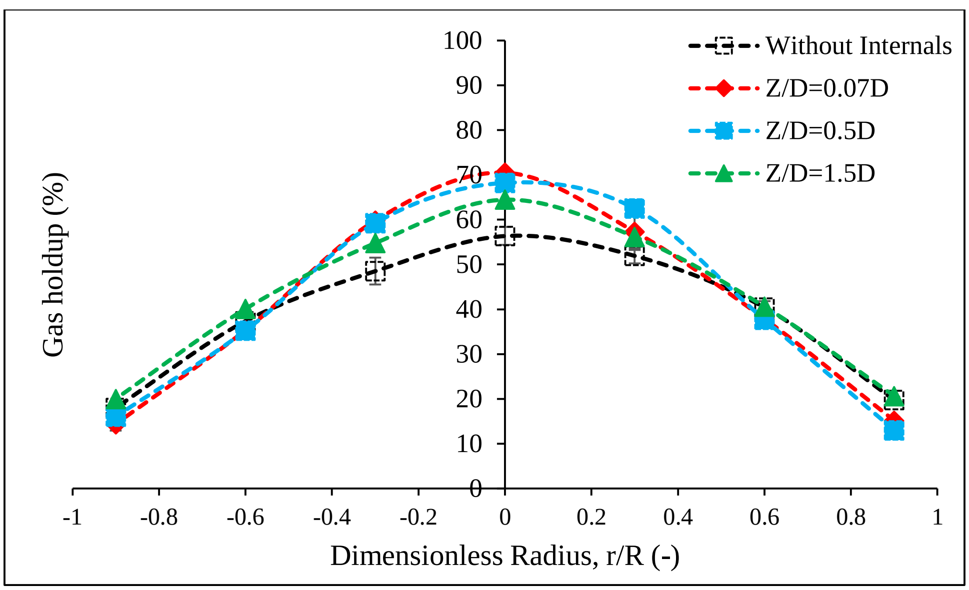


Figure A.1.3 Impact of internals height above the gas distributor on the radial profile of gas holdup at U_g = 45 cm/s.

A.2 Impact of internals height above the gas distributor on the radial profile of the specific interfacial area

Figures A.2.1 to A.2.3 show the effect internals height above the gas distributor on the radial profile of the specific gas-liquid interfacial area at superficial gas velocities 5, 15, and 45 cm/s. Higher specific interfacial area obtained when the internals positioned at height of Z/D=1.5D when compared to the case of Z/D=0.07D. At low superficial gas velocity (5 cm/sec), the specific interfacial area obtained in bubble column with internals placed at Z/D=1.5D was higher than bubble column without internals. On the other hand, the interfacial area obtained at Z/D=0.07D was lower than that obtained in bubble column without internals. At High superficial gas velocities (e.g., 30 and 45 cm/s), regardless the gap between the internals and the gas distributor, the interfacial area obtained in bubble column with internals was lower than that obtained in bubble column without internals.

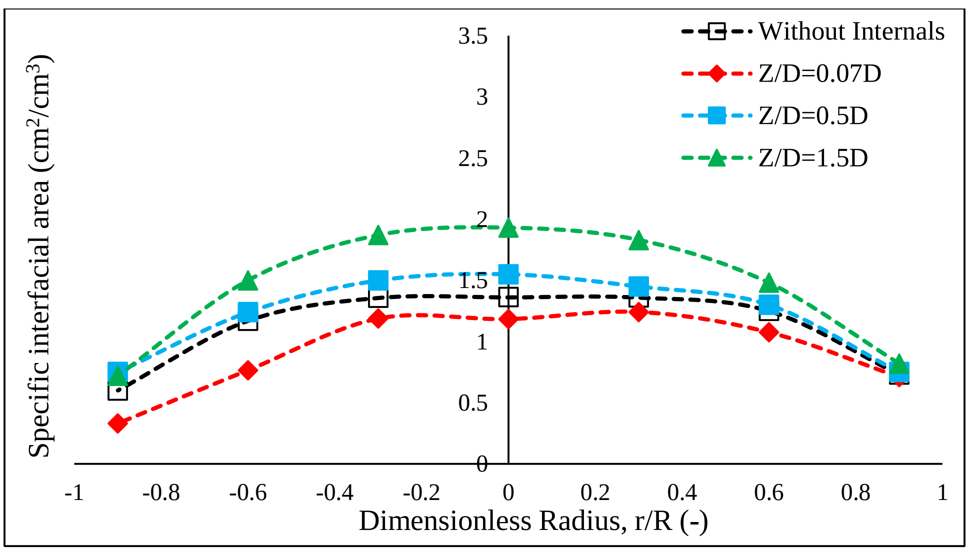


Figure A.2.1 Impact of internals height above the gas distributor on the radial profile of the specific interfacial area at U_g = 5 cm/s.

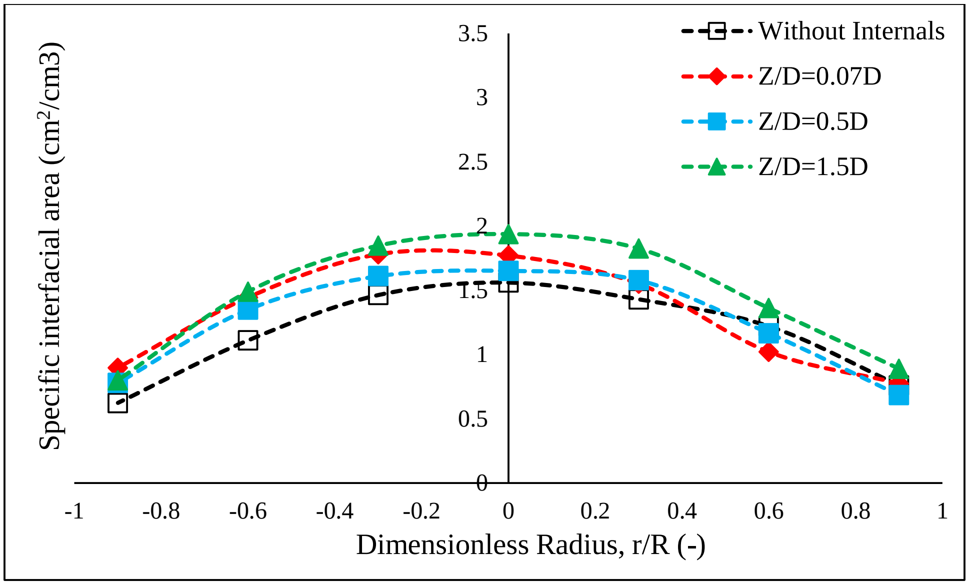


Figure A.2.2 Impact of internals height above the gas distributor on the radial profile of the specific interfacial area at U_g = 15 cm/s.

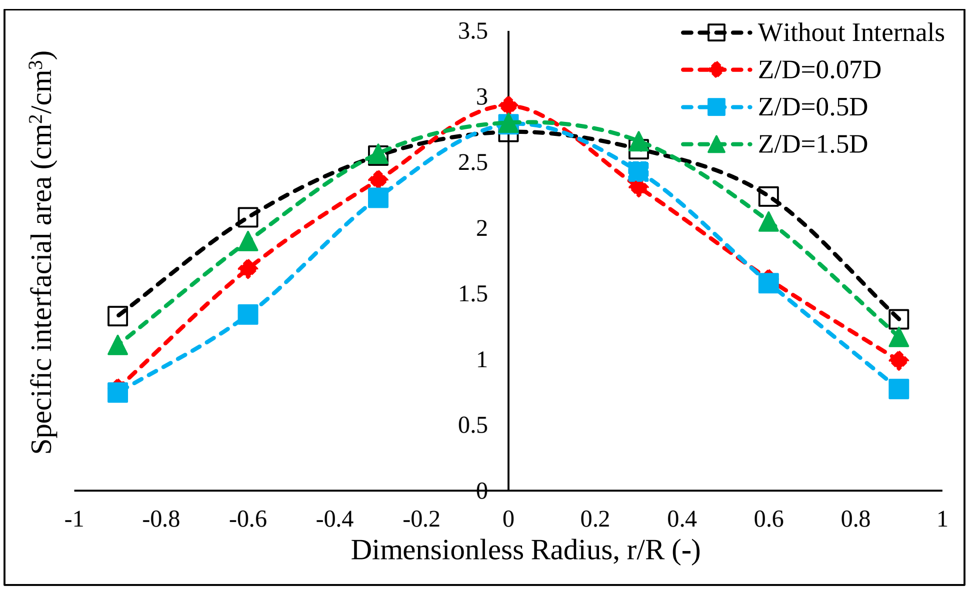
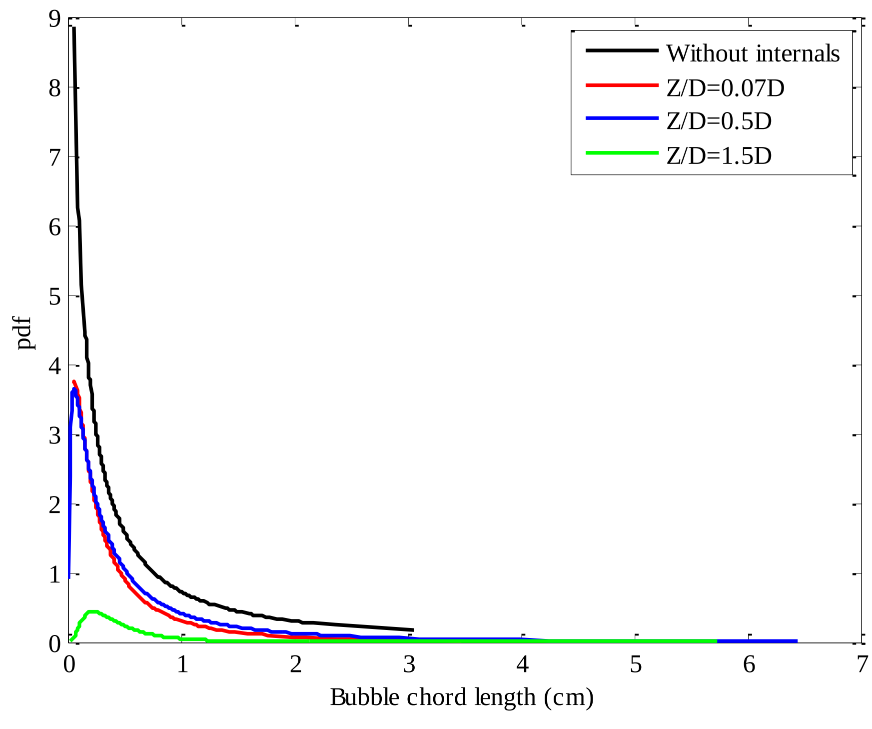


Figure A.2.3 Impact of internals height above the gas distributor on the radial profile of the specific interfacial area at U_g = 45 cm/s.

A.3 Impact of internals height above the gas distributor on bubble chord length distribution

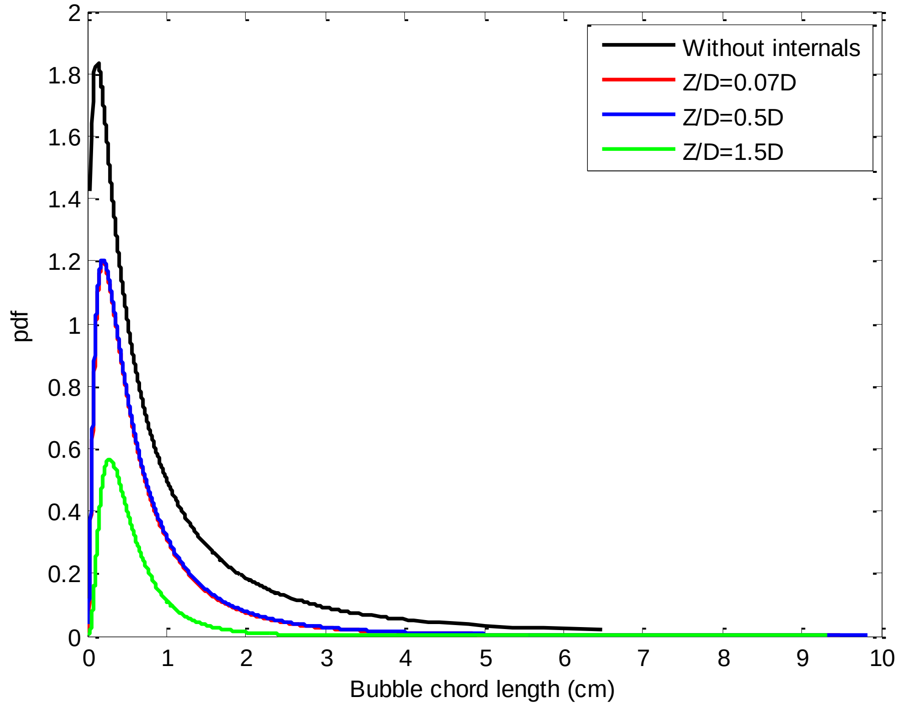
Figures A.3.1 to A.3.3 show the probability density function of the bubble chord length distribution at different superficial gas velocities. These distributions are further analyzed to provide the mean and the variance of the distribution as presented through tables A.3.1 to A.3.3. Smaller bubbles are observed when the internals placed at height of Z/D=1.5D compared to bubble chord lengths obtained when the internals placed at heights Z/D=0.5D and Z/D=0.07D.



A.3.1 Impact of internals height above the gas distributor on bubble chord length distribution at U_g = 5 cm/s.

Table A.3.1 Statistical parameters of bubble chord length distributions at U_g = 5 cm/s.

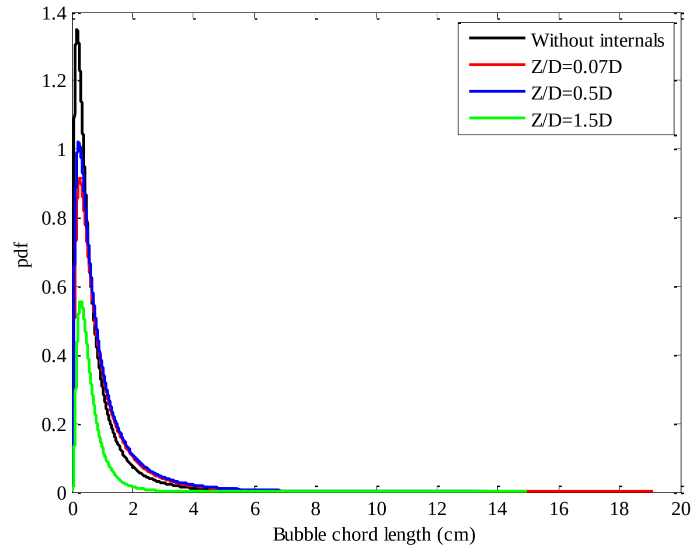
	Mean	Variance
Without internal	0.49	0.07
Z/D = 0.07D	0.48	0.14
Z/D = 0.5D	0.49	0.17
Z/D = 1.5D	0.46	0.11



A.3.2 Impact of internals height above the gas distributor on bubble chord length distribution at U_g = 15 cm/s.

Table A.3.1 Statistical parameters of bubble chord length distributions at U_g = 15 cm/s.

	Mean	Variance
Without internal	0.89	0.62
Z/D = 0.07D	0.88	1.47
Z/D = 0.5D	0.88	1.42
Z/D = 1.5D	0.79	1.18



A.3.3 Impact of internals height above the gas distributor on bubble chord length distribution at U_g = 45 cm/s.

Table A.3.1 Statistical parameters of bubble chord length distributions at U_g = 45 cm/s.

	Mean	Variance
Without internal	0.81	1.10
Z/D = 0.07D	1.15	2.51
Z/D = 0.5D	1.07	1.91
Z/D = 1.5D	0.90	1.82

A.4 Impact of internals height above the gas distributor on the bubble rise velocity

It can be seen that in Figure A.4.1, regardless the internals' height above the gas distributor, the internals have insignificant effect on the bubble rise velocity at low superficial gas velocity. However, Up to 25 % increase in average axial bubble velocity is obtained when the internals are placed at Z/D=0.07D when compared to bubble velocity in case of no internals and up to 12 % increase when compared with case when internals are placed Z/D=1.5D. This observation indicates bubble rise velocity increase as the gap between the internals and the gas distributor and the internals decreased.

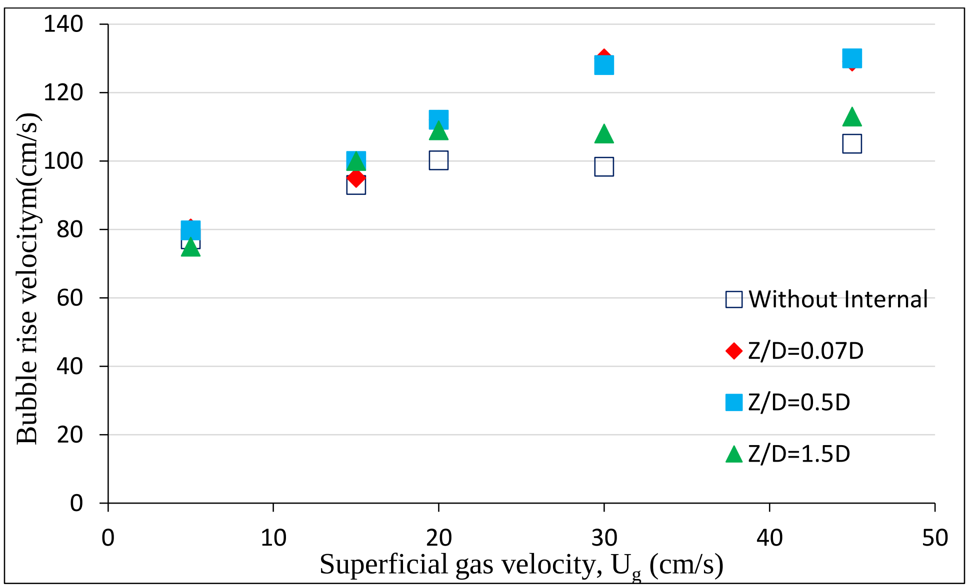


Figure A.4.1 Impact of internals height above the gas distributor on average bubble rise velocity at U_g = 15 cm/s.

BIBLIOGRAPHY

Akita, K., and Yoshida, F., 1974, Bubble size, interfacial area, and liquid-phase mass transfer coefficient in bubble columns: Industrial & Engineering Chemistry Process Design and Development, v. 13, no. 1, p. 84-91.

Al-Mesfer, M. K. A., 2013, Effect of Dense Heat Exchanging Internals on the Hydrodynamics of Bubble Column Reactors Using Non-invasive Measurement Techniques [PhD Thesis]: Missouri University of Science and Technology.

Amaya-Bower, L., and Lee, T., 2010, Single bubble rising dynamics for moderate Reynolds number using Lattice Boltzmann Method: Computers & Fluids, v. 39, no. 7, p. 1191-1207.

Amirnia, S., de Bruyn, J. R., Bergougnou, M. A., and Margaritis, A., 2013, Continuous rise velocity of air bubbles in non-Newtonian biopolymer solutions: Chemical Engineering Science, v. 94, p. 60-68.

Anastasiou, A. D., Passos, A. D., and Mouza, A. A., 2013, Bubble columns with fine pore sparger and non-Newtonian liquid phase: Prediction of gas holdup: Chemical Engineering Science, v. 98, p. 331-338.

Behkish, A., 2004, Hydrodynamic and Mass Transfer Parameters in large-scale Slurry Bubble Column Reactors [Ph.D Thesis]: University of Pittsburgh, Pittsburgh, PA.

Bernemann, 1989, On the hydrodynamics and mixing of the liquid phase in bubble columns with longitudinal tube bundles [Ph.D Thesis]: University of Dortmund.

Boyer, C., Duquenne, A.-M., and Wild, G., 2002, Measuring techniques in gas–liquid and gas–liquid–solid reactors: Chemical Engineering Science, v. 57, no. 16, p. 3185-3215.

Chen, J., Li, F., Degaleesan, S., Gupta, P., Al-Dahhan, M. H., Dudukovic, M. P., and Toseland, B. A., 1999, Fluid dynamic parameters in bubble columns with internals: Chemical Engineering Science, v. 54, no. 13–14, p. 2187-2197.

Deckwer, W.-D., and Field, R. W., 1992, Bubble column reactors, Wiley New York.

Espinoza, R. L., Steynberg, A. P., Jager, B., and Vosloo, A. C., 1999, Low temperature Fischer–Tropsch synthesis from a Sasol perspective: Applied Catalysis A: General, v. 186, no. 1–2, p. 13-26.

Forret, A., Schweitzer, J.-M., Gauthier, T., Krishna, R., and Schweich, D., 2003, Liquid Dispersion in Large Diameter Bubble Columns, with and without Internals: The Canadian Journal of Chemical Engineering, v. 81, no. 3-4, p. 360-366.

Frijlink, J. J., 1987, Physical aspects of gassed suspension reactors [Ph.D Thesis]: Delft University of Technology.

Guan, Gao, Tian, Wang, Cheng, and Li, 2015a, Hydrodynamics in bubble columns with pin-fin tube internals: Chemical Engineering Research and Design, v. 102, p. 196-206.

Guan, X., Gao, Y., Tian, Z., Wang, L., Cheng, Y., and Li, X., 2015b, Hydrodynamics in bubble columns with pin-fin tube internals: Chemical Engineering Research and Design, v. 102, p. 196-206.

Hamed, M., 2012, Hydrodynmaics, Mixing, And Mass Transfer In Bubble Columns With Internals [Ph.D Thesis]: Washington University In St. Louis.

Han, L., and Al-Dahhan, M. H., 2007, Gas–liquid mass transfer in a high pressure bubble column reactor with different sparger designs: Chemical Engineering Science, v. 62, no. 1–2, p. 131-139.

Hoang, N. H., Euh, D. J., Yun, B. J., and Song, C. H., 2015, A new method of relating a chord length distribution to a bubble size distribution for vertical bubbly flows: International Journal of Multiphase Flow, v. 71, p. 23-31.

Hua, J., Stene, J. F., and Lin, P., 2008, Numerical simulation of 3D bubbles rising in viscous liquids using a front tracking method: Journal of Computational Physics, v. 227, no. 6, p. 3358-3382.

Jager, 2003, Development of Fischer-Tropsch Reactors, AICHE Spring meeting: New Orleince.

Jhawar, A. K., and Prakash, A., 2014, Bubble column with internals: Effects on hydrodynamics and local heat transfer: Chemical Engineering Research and Design, v. 92, no. 1, p. 25-33.

Joshi, J. B. V. U. P. P., V. C, 1998, Gas Hold-up structure in bubble column reactors: PINSA, v. 64, no. A, p. 441-567.

Kagumba, 2013, Heat transfer and bubble dynamics in bubble and slurry bubble columns with internals for fischer-tropsch synthesis of clean alternative fuels and chemicals [Phd Thesis]: Missouri University Of Science And Technology.

Kagumba, M., and Al-Dahhan, M. H., 2015, Impact of Internals Size and Configuration on Bubble Dynamics in Bubble Columns for Alternative Clean Fuels Production: Industrial & Engineering Chemistry Research, v. 54, no. 4, p. 1359-1372.

Kantarci, N., Borak, F., and Ulgen, K. O., 2005, Bubble column reactors: Process Biochemistry, v. 40, no. 7, p. 2263-2283.

Krishna, R., and Sie, S. T., 2000, Design and scale-up of the Fischer–Tropsch bubble column slurry reactor: Fuel Processing Technology, v. 64, no. 1–3, p. 73-105.

Krishna, R., Urseanu, M. I., van Baten, J. M., and Ellenberger, J., 1999, Rise velocity of a swarm of large gas bubbles in liquids: Chemical Engineering Science, v. 54, no. 2, p. 171-183.

Krishna, R., van Baten, J. M., Urseanu, M. I., and Ellenberger, J., 2001a, Design and scale up of a bubble column slurry reactor for Fischer–Tropsch synthesis: Chemical Engineering Science, v. 56, no. 2, p. 537-545.

-, 2001b, A scale up strategy for bubble column slurry reactors: Catalysis Today, v. 66, no. 2–4, p. 199-207.

Kulkarni, A. A., 2007, Mass transfer in bubble column reactors: effect of bubble size distribution: Industrial & Engineering Chemistry Research, v. 46, no. 7, p. 2205-2211.

Kumar, S. B., Moslemian, D., and Dudukovic, M. P., 1997, Gas-holdup measurements in bubble columns using computed tomography: American Institute of Chemical Engineers. AIChE Journal, v. 43, no. 6, p. 1414.

Larachi, F. ç., Desvigne, D., Donnat, L., and Schweich, D., 2006, Simulating the effects of liquid circulation in bubble columns with internals: Chemical Engineering Science, v. 61, no. 13, p. 4195-4206.

Lehman., and Hammer, 1978, Continuous fermentation in tower fermentor, Interlaken, Volume Part 1, 1, European congress on biotechnology.

Lehr, Millies, and Mewes, 2002, Bubble-Size distributions and flow fields in bubble columns: AIChE Journal, v. 48, no. 11, p. 2426-2443.

Li, H., and Prakash, A., 2000, Influence of slurry concentrations on bubble population and their rise velocities in a three-phase slurry bubble column: Powder Technology, v. 113, no. 1–2, p. 158-167.

Maceiras, R., Santana, R., and Alves, S. S., 2007, Rise velocities and gas–liquid mass transfer of bubbles in organic solutions: Chemical Engineering Science, v. 62, no. 23, p. 6747-6753.

Manjrekar, O. N., and Dudukovic, M. P., 2015, Application of a 4-point optical probe to a Slurry Bubble Column Reactor: Chemical Engineering Science, v. 131, p. 313-322.

Shaikh, A., and Al-Dahhan, H., 2007, A Review on Flow Regime Transition in Bubble Columns, International Journal of Chemical Reactor Engineering, Volume 5.

Shaikh, A., and Al-Dahhan, M., 2013, Scale-up of bubble column reactors: a review of current state-of-the-art: Industrial & Engineering Chemistry Research, v. 52, no. 24, p. 8091-8108.

Vince, M., Breed, H., Krycuk, G., and Lahey, R., 1982, Optical probe for high-temperature local void fraction determination: Applied optics, v. 21, no. 5, p. 886-892.

Wu, C., and Al-Dahhan, M., 2008, Bubble dynamics investigation in a slurry bubble column: AIChE Journal, v. 54, no. 5, p. 1203-1212.

Wu, C., Suddard, K., and Al-dahhan, M. H., 2008, Bubble dynamics investigation in a slurry bubble column: AIChE Journal, v. 54, no. 5, p. 1203-1212.

Xue, J., 2004, Bubble velocity, size and interfacial area measurements in bubble columns [Ph.D Thesis]: Washington University, Saint Louis, MO, 2004.

Xue, J., Al-Dahhan, M., Dudukovic, M. P., and Mudde, R. F., 2008, Four-point optical probe for measurement of bubble dynamics: Validation of the technique: Flow Measurement and Instrumentation, v. 19, no. 5, p. 293-300.

Xue, J., Al-Dahhan, M., Dudukovic, M. P., and Mudde, R. F., 2003, Bubble Dynamics Measurements Using Four-Point Optical Probe: The Canadian Journal of Chemical Engineering, v. 81, no. 3-4, p. 375-381.

Yamada, M., and Saito, T., 2012, A newly developed photoelectric optical fiber probe for simultaneous measurements of a CO2 bubble chord length, velocity, and void fraction and the local CO2 concentration in the surrounding liquid: Flow Measurement and Instrumentation, v. 27, p. 8-19.

Youssef, A., 2010, Fluid Dynamics and Scaule-up of Bubble Columns with Internals [Ph.D Thesis]: Washington University In St. Louis.

Youssef, A. A., and Al-Dahhan, M. H., 2009, Impact of Internals on the Gas Holdup and Bubble Properties of a Bubble Column: Industrial & Engineering Chemistry Research, v. 48, no. 17, p. 8007-8013.

Youssef, A. A., Hamed, M. E., Grimes, J. T., Al-Dahhan, M. H., and Duduković, M. P., 2012, Hydrodynamics of Pilot-Scale Bubble Columns: Effect of Internals: Industrial & Engineering Chemistry Research, v. 52, no. 1, p. 43-55.

Yu, Z., Jia, L., Lijun, W., and Xi, L., 2009, Studies on hydrodynamics of turbulent slurry bubble column (III)Effect of vertical pipe bundles.

Zhang, Y. E., Vibranovski, M. D., Krinsky, B. H., and Long, M., 2011, Supplementary Data, Volume 27.

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Publications

Ahmed Jasim and Muthanna Al-Dahhan, Impact of Heat Exchanging Internals Configuration on Gas Holdup and Bubble Properties in a Bubble Column for the Fischer-Tropsch Synthesis, *submitted*.

Ahmed Jasim and Muthanna Al-Dahhan, Impact of Heat Exchanging Internals Diameter on Gas Holdup and Bubble Dynamics in a Bubble Column, *to be submitted*

Presentations

Impact of Configuration of Heat Exchanging Internals on Symmetric Behavior of Bubble Dynamics of a Bubble Column, AIChE conference, Salt Lake city, Utah 2015.

Impact of Internals and Their Height from The Gas Distributor on Hydrodynamics in a Bubble Column, 12th International conference on gas-liquid and gas-liquid solid reactor (GLS12), New York 2015.