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Heat transfer study in a pilot-plant scale bubble column

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ABSTRACT

The effects of superficial gas velocity on heat transfer coefficient and its time-averaged radial profiles along the bed height have been investigated in a pilot-plant scale bubble column of 0.44 m diameter using air–water system. Notable differences were observed in heat transfer coefficients along the bed axial locations particularly between the sparger ($Z/D = 0.28$) and the fully developed flow ($Z/D = 4.8$) regions. In the fully developed flow region larger heat transfer coefficient values were obtained compared to those in the sparger region. About 14–22% increase in heat transfer coefficients measured in the fully developed flow region has been observed compared to those measured in the distributor region when the superficial gas velocity increases from 0.05 to 0.45 m/s. The heat transfer coefficients in the column center for all the conditions studied are about 9–13% larger than those near the wall region. It has been noted that in the fully developed flow region, the axial variation of the heat transfer coefficients was not significant.

Keywords: Bubble columns; Pilot-plant scale; Heat transfer coefficient; Axial location; Radial profile; Flow regime

1. Introduction

Bubble column reactors are widely used in many industrial applications including chemical, biochemical, petrochemical, environmental and metallurgical processes. The industrial importance of bubble columns is due to the advantages that they offer which include absence of moving parts, easier maintenance, simple construction, high effective interfacial area, excellent temperature control and high heat and mass transfer rates caused by strong gas–liquid interactions. Usually bubble columns operate either in a bubbly flow (homogeneous) regime or churn-turbulent flow (heterogeneous) regime depending on the phases physical properties, operating conditions and the system flow characteristics (Shaikh and Al-Dahhan, 2007). Recently, in many of the commercial installation and industrial applications of bubble columns the churn-turbulent flow regime has been found of considerable and practical interest (Dhotre et al., 2005). In churn-turbulent flow regime high gas throughout is used which yields higher volumetric productivity. This causes increased liquid circulation intensity that affects the dynamics of the bubbles and transport (heat and mass) characteristics. Hence, design and scale-up of bubble columns remain challenging tasks due to the complexity of their non-linear hydrodynamics and phases interactions. In many industrial processes where bubble column found applications, thermal control is of importance because the reactions are usually accompanied by heat supply or removal for endothermic or exothermic operations, respectively. Therefore, maintaining desirable bulk media temperature is necessary which plays an important role in the performance of the reactor. The knowledge and understanding of heat transfer phenomena in bubble columns and quantifying the heat transfer rates and coefficients are important since they are required for proper, safe and efficient design and operation of these reactors.

Significant studies on heat transfer in bubble columns have been conducted and reported in the literatures (Wu et al., 2007; Wu, 2008). In general, these studies can be divided into: (i) estimation of wall-to-bed heat transfer and (ii) estimation of inserted objects-to-bed heat transfer. Most of these studies measured the time-averaged local heat transfer coefficients (i.e. a certain point location inside the column) (Li and Prakash, 2001, 2002; Kantarci et al., 2005; Wu et al., 2007). It is noteworthy that the local time-averaged heat transfer coefficients and their radial profiles or cross-sectional distribution provide valuable insight into the mechanisms of heat transfer

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Nomenclature

A	probe heat transfer area (m^2)
D	diameter of the column (m)
h	heat transfer coefficient (kW/(m^2 K))
k	thermal conductivity of the liquid (kW/(m K))
L	test section of column (m)
n	number of data points
q	heat flow rate (kW)
r	radial location (m)
R	radius of the column (m)
T	temperature (K)
V_G	superficial gas velocity (m/s)
Δx	thickness of thermal barrier (m)
Z	axial location from the bottom of the column (m)

Subscripts

avg	average
b	bed
G	gas
i	instantaneous
s	surface

in bubble columns. In addition, the bubble dynamics and liquid circulation intensity in bubble column can be qualitatively assessed using such measurements. Heat transfer coefficients in bubble columns have been measured based on the measurement of energy input using slow response assembly probe (Saxena and Chen, 1994) and based on the measurement of the direct heat flux using fast response sensor (Wu et al., 2007). In general, most of these studies were performed using up to 0.16 m column diameter and hence, heat transfer rate and coefficient are still not well characterized in larger scale bubble columns where wall effects are further diminished. In addition, except the study of Wu et al. (2007) and Wu (2008), the measurements of heat transfer coefficients have been restricted to few locations inside the column.

Therefore, this study focuses on the investigation of heat transfer coefficients and their radial profiles in a pilot-plant scale bubble column of 0.44 m in diameter using the high response heat transfer probe developed by Wu et al. (2007). The experimental investigations of this work include various radial locations along the height of the column starting from the distributor region ($Z/D = 0.28$) up to within the fully developed flow region ($Z/D = 4.8$). The probe provides the instantaneous and time-averaged heat transfer coefficient measurements, over a wide range of superficial gas velocities (0.05–0.45 m/s). Based on the change in the slope of overall gas holdup with superficial gas velocity and based on the radial profiles of the gas holdup measured using four-point optical probe in the same column with the same distributor design (Youssef, 2010), such range of superficial gas velocities cover both bubbly and churn-turbulent flow regimes. Hence, the effects of the superficial gas velocity and the nature of the flow regime on the heat transfer characteristics are analyzed.

2. Experimental work

Experiments were conducted using a pilot-plant scale grid of 0.44 m in diameter Plexiglas column with 3.65 m height (Fig. 1). Oil-free compressed air was used as the gas phase, while tap water was used as the liquid phase. It should be noted that air–water system is used in this study since such system has been used widely in literature and represents the base for the development of the reported heat transfer coefficient correlations to compare their predictions with the obtained results. The experiments were conducted in a semi-batch mode where it is continuous with respect to the gas phase and batch with respect to the liquid phase. The flow rate of the filtered dry air was adjusted by a pressure regulator and rotameters system, which consists of two rotameters (Omega HFL6715A-0045-14) connected in parallel. The superficial gas velocity was varied within the range of 0.05–0.45 m/s which covers both bubbly and churn-turbulent flow regimes. Air was introduced into the column through a 0.3 m height plenum and perforated plate gas distributor with 241 holes of 3 mm diameters and an open area of 1.09%. During the experiments the dynamic liquid height was maintained at about 3.2 m (equal to 7D) by varying the initial static height for each condition. It was found that the range of initial static height variation does not affect the column hydrodynamics at the studied conditions (Wu et al., 2007). During the experiments and due to the loss of small liquid quantity as a result of evaporation, the liquid phase was regularly replenished to maintain the dynamic liquid level. Copper-constant thermocouples (Omega TMTSS-125U-12) were arranged at various axial positions and were located at different radial locations to monitor the bed temperature adjacent to the heat transfer probe. As mentioned earlier, a fast response heat transfer rod type probe developed by Wu et al. (2007) (11.4 mm diameter and 38 mm length of its brass shell) was used for the measurements. The heat flux sensor (11 mm × 14 mm × 0.08 mm) mounted on the probe rod was obtained from RDF Corporation (micro-foil heat flow sensor No. 20453-1). The sensor can measure simultaneously the local heat flux (q_i) and the sensor surface temperature (T_{si}). The response time of the sensor is about 0.02 s (more details of the probe design are given by Wu et al. (2007) and Wu (2008)). During the experiments, the heat transfer probe was horizontally introduced into the bubble column and the sensor local location was moved radially from the center to the wall region, at $r/R = 0$, 0.3, 0.65 and 0.9, as illustrated in Fig. 1. Four different axial heights to column diameter ratios (Z/D) of 0.28, 1.6, 3.2 and 4.8 were used. These axial levels cover sparger to fully developed flow regions. Each measurement was repeated 2–3 times and the average value is reported. The reproducibility of the measurements was within 3%. Since the measured signals of the heat flux are in the range of micro-volts, they were amplified before received by the data acquisition system. The heat flux signals and the signals from the thermocouples were sampled at 50 Hz for about 40 s. The following equation has been used to estimate the heat transfer coefficient (Jhawar and Prakash, 2007):

$$\frac{1}{h_i} = \frac{T_{si} - T_{bi}}{q_i/A} - \frac{\Delta x}{k} \quad (1)$$

where h_i is the instantaneous local heat transfer coefficient (kW/(m^2 K)), q_i is the instantaneous heat flux across the sensor (kW/m^2), T_{si} is the instantaneous surface temperature of the probe (K), T_{bi} is the instantaneous bulk temperature of the media (K), Δx is the thermal thickness and k is the thermal conductivity of the liquid (kW/(m K)). The second term on the right hand side of Eq. (1) is negligible compared to the first term (<1%) due to high conductivity (k) and small thickness (Δx) of the thermal barrier film. Therefore, the instantaneous