HEAT TRANSFER BEHAVIOUR IN A TWO-PHASE BUBBLE COLUMN

Dr.Balasim A. Abid
University of Technology
Chemical Department

Dr. Rahman Sh. Abdulmohsin
Thi-Qar University
Mechanical Department

Mr. Hisham M. Al.Tamimi
Al-Qadisiya University
Chemical Department

Abstract

Time-averaged local heat transfer coefficient profiles were studied in a 0.2 m bubble column diameter using air-water system. The effects of the superficial gas velocity and axial locations (Z/D) on the heat transfer coefficient and its radial (r/R) profiles were investigated in bubble column. Significant differences were observed between heat transfer coefficients in the axial directions viz. in the bulk flow region (Z/D=4.8) higher than in the distributor region (Z/D=0.28) by 15% -23% for increasing the superficial gas velocity from 0.03-0.35 m/s. The heat transfer coefficient increase with superficial gas velocities and the values in the center of the column were 8–12% greater than those near the wall region .The characteristics of bulk flow region have large variation in radial direction and little in axial direction for the values of heat transfer coefficients.

Keywords: bubble columns; large-scale; heat transfer coefficient; axial location; radial profile**.**

سلوك انتقال الحرارة في العمود الفقاعي ذات الطورين

د.بلاسم احمد عبـــــد
الجامعة التكنولوجية
الهندسة الكيمياوية

د.رحمن شنين عبد المحسن
جامعة ذي قار
الهندسة الميكانيكية

هشام محمد التميمـــــي
جامعة القادسية
الهندسة الكيمياوية

الخلاصة

تم دراسة توزيع معاملات انتقال الحرارة في عمود فقاعي قطره ٠.٢م وباستخدام نظام الهواء-الماء. تم فحص سرعة الغاز والارتفاع المحوري والتوزيع القطري على معامل انتقال الحرارة في العمود الفقاعي .تم ملاحظة فروقات مهمة بين معاملات انتقال الحرارة بالاتجاه المحوري، اي معامل انتقال الحرارة في منطقة التشكيل التام*(Z/D=4.8)* اعلى من معامل انتقال الحرارة في منطقة الموزع*(Z/D=0.28)* بنسبة ١٥% إلى ٢٣% للزيادة في سرعة الغاز من ٠.٠٣ م/ثا الى ٠.٣٥ م/ثا. معاملات انتقال الحرارة تزداد بزيادة سرعة الغاز ،والقيم عند مركز العمود اعلى بنسبة ٨% الى ١٢% من القيم قرب الجدار. الخصائص في منطقة التشكيل التام كانت أكثر تغيرا بالاتجاه القطري واقل بالاتجاه المحوري بالنسبة لقيم معاملات انتقال الحرارة.

Nomenclature

D	diameter of the column	m
h	heat transfer coefficient	kW/m^2.
A	probe heat transfer area	m^2
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 bottom	m

Subscripts

avg	average
b	bed
G	gas
i	instantaneous
s	surface

Introduction:

Bubble column is regarded as one of the most important multiphase flow systems, which is widely used in many industrial applications including chemical, biochemical, petrochemical, environmental and metallurgical processes(Abdulmohsin,2008). The industrial importance of bubble column remains undisputed mainly due to the advantages that it offers from absence of moving parts, leading to 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 in either a bubbly flow (homogeneous) regime or churn-turbulent flow (heterogeneous) regime depending on the chemical reaction and the system characteristics introduced (Shaikh, 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, 2005). Design and scale-up of bubble columns are critical due to the complexity of non-linear hydrodynamics. Since the use of large-scale bubble column is desirable because large gas throughout can be achieved which causes increasing liquid circulation intensity that affect the acceleration of the bubbles and as a result decreasing the gas holdup. Additionally, larger heights are needed to obtain the desired residence time distribution (RTD) to achieve the larger conversion level. In many industrial processes where bubble column found applications, thermal control is of importance because the reaction is usually accompanied by heat supply or removal for the endothermic or exothermic operations, respectively. Therefore, maintaining desirable bulk media temperature is necessary because it plays an important role in the performance of the reactor. Hence, the knowledge and understanding of heat transfer phenomena and quantity of the heat transfer coefficients are essential and required for proper safe, efficient design and operation of these reactors. Thus, significant studies on heat transfer in bubble column has been conducted and reported in literatures (Abdulmohsin, 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. However, most of these studies are concerned with the steady state time-averaged heat transfer coefficients (Wu, 2007). It is noteworthy that the local time-averaged heat transfer coefficients and their radial profiles or cross-sectional profiles that closer, provide valuable insight into mechanisms of heat transfer and qualitatively the bubble dynamic and liquid circulation intensity in bubble column. (Saxena and Chen,1994) reviewed the pervious investigations that have measured the heat transfer coefficients in bubble columns based on the measurements of energy input method using slow response assembly probe (for more details see (Abdulmohsin,2008). Recently, heat transfer coefficients have been measured based on the measurement of the directed heat flux with aid of fast response advanced probe. However, most of these studies were performed using up to with 0.16 m column diameter. Therefore heat transfer coefficient is still poorly in large-scale diameter bubble columns to avoid wall effects. In additions, the measurements of heat transfer have been restricted to few locations inside the column and there is a strong need for detailed experimental measurements for local time-averaged heat transfer coefficient. This investigation focuses for the first time on the study of local heat transfer coefficients and its behavior in a larger diameter (0.٢٠ m) bubble column using high response heat transfer probe. The experimental measurements have included many locations inside the column starting from the distributor region up to within the fully developed bulk flow region. The use of fast response and movable heat transfer probe has provided the instantaneous heat transfer measurements at different axial and radial positions, over a wide range of superficial gas velocity of practical importance. Hence, the effects of the superficial gas velocity on the heat transfer characteristics are analyzed.

Experimental Work:

Experiments were conducted in a large-scale grid of Plexi glass column of 0.2m internal diameter and height ٢.65 m (**Figure 1**). The column was supported by rigid metallic structure to keep it vertical and to minimize the mechanical vibrations which might affect the measured heat transfer signals. Oil-free compressed air constituted the gas phase, while tap water was used as the liquid phase. The effects of liquid velocity are small or negligible in bubble columns, therefore the experiments conducted in a semi-batch mode; continuous in relation to the gas flow and batch with reference to the liquid flow. Gas flow was supplied by two compressors connected in parallel, after it passed through a dryer and several air filter units. The flow rate of the filtered dry air was adjusted by a pressure regulator and rotameters system, consisting of two rotameters from Engineering, Inc. (Omega HFL6715A-0045-14) connected in parallel to increase gas velocity range. The superficial gas velocity was varied in the range of 0.0٣ -0.٣5 m/s which cover both bubbly and churn-turbulent flow regimes. Air was introduced into the column through a perforated plate gas distributor with 241 holes of 3 mm diameters and the open area is 5.42%. During the experiments the dynamic liquid height was maintained at around ٢.2 m (equal to 11D times) by varying the static height at each studied condition. It was found that the range of static height variation does not affect the column hydrodynamics at the conditions studied (Wu, 2007)· The temperature was maintained at about 21^{o}C in the column and during the experiments, the liquid phase was regularly replenished due to the loss of small liquid quantity because of evaporation. Copper-constant thermocouples (Omega TMTSS-125U-12) were arranged at various axial positions and located at different radial locations to monitor bed temperatures of the media in the column adjacent to the heat transfer probe. A fast response heat transfer rode type probe with 11.4 mm diameter and 38 mm length of the brass shell were used for the measurements. The heat flux sensor (overall dimensions 11mm×14mm×0.08 mm) used on the probe is from RDF Corporation (micro-foil heat flow sensor No. 20453-1), which measures simultaneously both the local heat flux and the surface temperature of the probe. The response time of the sensor is about 0.02 s (more details of the probe design are given by Abdulmohsin, 2008). During experiments, the heat transfer probe was horizontally introduced into the bubble column and moved radially from center to wall region, at r/R =0, 0.3, 0.65 and 0.9, respectively. Four different axial heights to column diameter ratios (Z/D) were used of 0.28, 1.6, 3.2 and 4.8, respectively, that cover sparger to bulk regions. The measurements were performed two-three times at each condition and the average values are reported. 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. After being amplified, the heat flux signals, together with the signals from the thermocouples, were sampled at 50 Hz for more than 40 s. The, instantaneous heat transfer coefficient can be determined by direct measurement of heat flux and the difference between surface and bulk temperatures at a given time:

$$h_i = \frac{q_i / A}{T_{si} - T_{bi}} \qquad (1)$$

Where (kW/(m^2.K)), q_i the instantaneous heat flux across the sensor (kW/m^2), T_{si} the instantaneous surface temperature of the probe (K) and T_{bi} the instantaneous bulk temperature of the media (K).The local time-averaged heat transfer coefficient at a given location was obtained by averaging the instantaneous heat transfer data over a large number of sampling points as follows:

$$h_{ava} = \frac{1}{n} \sum_{i=1}^{n} \frac{q_i / A}{T_{si} - T_{bi}} \qquad (2)$$

Where n is the total number of data points, In this work $n = 2050$ samples to establish a high stable value of heat transfer coefficients for all operating conditions.

Results and Discussion:

1 Effect of Superficial Gas Velocity

The effects of superficial gas velocity were investigated for different axial locations at four radial positions from the center of the column towards the wall viz. r/R=0.0, 0.3, 0.65 and 0.9. **Figures 2 a** and **b** show the heat transfer in the center (r/R=0.0) of the column and near the column wall (r/R=0.9). It can be seen that the strong influence of the superficial gas velocity on the heat transfer coefficients between the bubbly and churn-turbulent flow regimes is evident. In the center region of the column for bulk flow region (Z/D=4.8) increasing in the superficial gas velocity from 0.0٣-0.٣5 m/s causes increase in the average heat transfer coefficients by about 1.3 times . For all axial levels, both the heat transfer coefficients in the center region and those in the wall region initially increased rapidly with the superficial gas velocity in the bubbly flow regime towards the transition regime, and the increase became smaller at higher superficial gas velocities (within the churn-turbulent flow regime), This must be related to the fact that at low superficial gas velocity the small bubble sizes are formed in bubbly flow regime. When the superficial gas velocity increase some definite value, the transport mechanism for large bubbles with their individual rates of rise increase gradually to apply for the transport of the gas through the dispersion two-phase and large coalescence bubbles then arises, so that a significant gas transport occurs through the large bubbles which occurred in churn-turbulent flow regimes which caused slowly down in heat transfer coefficients. In addition, when the superficial gas velocity continuing increased, the magnitude of the increase in heat transfer coefficients began approaches asymptotically to constant values in the churn turbulent flow regime, since faster bubbles coalescence and breakup come to balance at a certain velocity. On the other hand, it can be seen that the heat transfer coefficients in the center are larger than those in the wall region, and the amount varies from 9% to 13% with the increase in the superficial gas velocity from 0.0٣ to 0.٣5 m/s for bulk flow region (Z/D=4.8). These differences at low superficial gas velocities are relatively small, but at higher superficial gas velocities the differences became larger. This reflects that bubbles with relatively small diameters are uniformly distributed across the column radius at low superficial gas velocities. With a further increase in superficial gas velocity, large bubble are formed , and most of them rise through the core region of the column at high bubble frequency, caused high gas holdup in the center region. However, most small bubble moves in the wall region of the column, where the liquid flow downward at low bubble frequency causing low gas holdup (Wu,2007). In the four axial locations, the heat transfer coefficients in the center of the column are greater than that in the near wall due to the fact that large bubbles exist at center and they are more effective in enhancing heat transfer in the system.

2 Effect of Probe Axial Location

For the first time, the profiles of the heat transfer coefficients along different axial locations in bubble column were provided at several superficial gas velocities for different radial locations from the center to the wall regions, as shown in **Figure 3 a** and **b** .The results show that, the local heat transfer coefficient increases gradually as the distance from gas distributor increased along the column height and that indicated the liquid column above the gas distributor can be divided into three different sections. Section one in the bottom of column, referred to distributor region (Z/D=0.28) where the bubble properties are determined by the bubble formation process at the gas distributor and this region characterized by small bubbles. Section two in the height of the column located less than twice diameter of the column where the bubbles began growth and their properties depend on what happens in region one of the column and on the bulk liquid phase motion, this referred to the developing region (Z/D=1.6). Section three is the intermediate and top parts of the liquid column where gross recirculation established, gas liquid phase separation began take place and large bubbles completely formed with fast flow; this refers to the bulk flow regions (Z/D=3.2 and Z/D=4.8). From **Figure (3)**,It can be seen that the heat transfer coefficients increase dramatically to the maximum at around ١10 cm (Z/D=4.8) away from distributor, the same location of fast bubble flow region. In additions, heat transfer coefficients in the bulk region (Z/D=4.8) are significantly higher than the distributor region (Z/D=0.28) and the differences increase from 14% - 22% with increase of superficial gas velocity from 0.05-0.45 m/s in the center of the column, these differences indicate that different heat transfer processes dominate those two flow regions. On the other hand, there are small differences and similarity in axial heat transfer coefficients profiles in the intermediate and top sections, indicating the overall mixing behavior in these regions could be similar at fully developed flow regions and no significant axial variation are observed. While at developing region (Z/D=1.6) the heat transfer coefficients still lower than both two bulk regions, but do not seem to reach below the distributor region, this attributed to growth of bubbles in this region towards the gas flow direction. If the data are normalized with respect to the maximum heat transfer coefficients at fully developed bulk flow region (Z/D=4.8), as shown in **Figure 4** a and b. It can be seen that the axial profiles are similar for higher superficial gas velocities, but are different for low superficial gas velocities. This indicates similarity of hydrodynamics in fully developed churn-turbulent flow regime that developing for higher superficial gas velocities. The slopes at high superficial gas velocities are more than for the high superficial gas velocities.

3. Profile of Heat Transfer Coefficients

The radial heat transfer coefficients were measured by moving the probe along the column radius at four different positions from center to the wall of the column. **Figure 5** a and b show the local radial profiles of heat transfer coefficients obtained at different axial locations with high and low superficial gas velocities. It can be seen that at the same superficial gas velocity for the fully developed bulk flow region (Z/D= 4.8), the local average heat transfer coefficient reduced by 9% for low superficial gas velocity (V_G = 0.0٣m/sec) while it reduced by 13% for high superficial gas velocity (V_G= 0.35m/sec). In addition, these comparisons for variations of the local heat transfer coefficients at center and wall at low and higher superficial gas velocities showed that the heat transfer coefficients at wall significantly smaller than that of the center, this indicates that wall region is relatively free from large bubbles or faster moving bubble chain. From **Figure 5 a** ,It was shown that the Radial differences are observed to be small in the distributor region (Z/D=0.28) indicating more radial uniformity in this region at high superficial gas velocity (V_G > 0.1m/s) and the less uniform at low superficial gas velocity due to more differences in heat transfer coefficients. From **Figure 5 b**, the radial profiles for the developing region (Z/D=1.6) shows some differences between central and wall regions, these differences indicate that the flow structure at the center evolve differently than at wall of the column, this attributed to bubble-bubble interactions and evolving bubble wake region at wall. While in two bulk regions (Z/D=3.2 and Z/D=4.8), significant radial differences can be observed in these regions and these differences decreases with increasing gas velocity. If the data are normalized with respect to the center heat transfer coefficients for each axial location as shown in **Figure 6 a** and **b**, it can be observed that the radial profiles of local average heat transfer coefficients at low superficial gas velocities had lower gradient than those at high superficial gas velocities for all axial locations, this mean the profiles nearly flat in the bubbly flow regime and becomes steeper with churn-turbulent flow regime. This is attributed to different mixing characteristics and resulting different mechanisms in two regimes that it is regarded as one of the most important characteristics of bubble columns (Abdulmohsin, 2008).

3.4 Comparison with Literatures

The radial average heat transfer coefficient over cross-section area of the column can be obtained from the radial heat transfer coefficient at different locations as follows:

$$h = \frac{1}{R^2}\int_0^R h(r)rdr \qquad (3)$$

Fig. 7 show a comparison between the heat transfer coefficients measured in this work of a bubble column for fully developed flow regime (Z/D=4.8) and reported values under similar operating conditions.(Fair,1962) used low velocity range under the same diameter. However, at a superficial gas velocity 0.1m/sec, the agreements were not good. The differences were attributed to the possible differences in the operating regimes, where this study was mainly for the heterogeneous regime, whereas, it was conjectured that, the flow under experimental conditions (of V_G) was not fully heterogeneous but prevailing in the transition regime. (Hikita., 1981) measured the heat transfer coefficient between the wall of the column and the gas-liquid dispersion in the bubble column, and they directly used the energy input to calculate the heat transfer coefficients. Hence, their results are not considered in following comparison and it was concluded that, the bubble column of immersed heater give heat transfer coefficient values different from that of the wall heating mode. The results in this work and those reported by (Verm,1989) and (Saxena and co-workers,1994,1989,1990 and 1992) were obtained by assembly immersed cylindrical heaters within column of small diameter (0.108 m), while the column diameter used in this work was 0.45m.Therfore, they get results lower than in this work , as reported by (Saxena,1992), column diameter can affect the heat transfer coefficients, and the heat transfer coefficients increase with increase in the column diameter in a bubble column without internals. (Chen ,2003) used different diameter columns for measurements of heat transfer coefficients with the aid of hot-wire probe and this different technique led to high differences in the results from this work, in addition, they used low range of superficial gas velocity (0.02-0.09 m/s). The results shown in **Figure 7** are consistent with this finding particularly at high superficial gas velocities, where the column diameter used by (Prakash and co-workers' 1997, 1999, 2002) and (Wu, 2007) were 0.28 and 0.16 m, respectively. In addition, since Prakash and co-workers did not explain the experimental heat flux values used that maybe led to lower heat transfer coefficient relatively specially al low superficial gas velocity.

Conclusion:

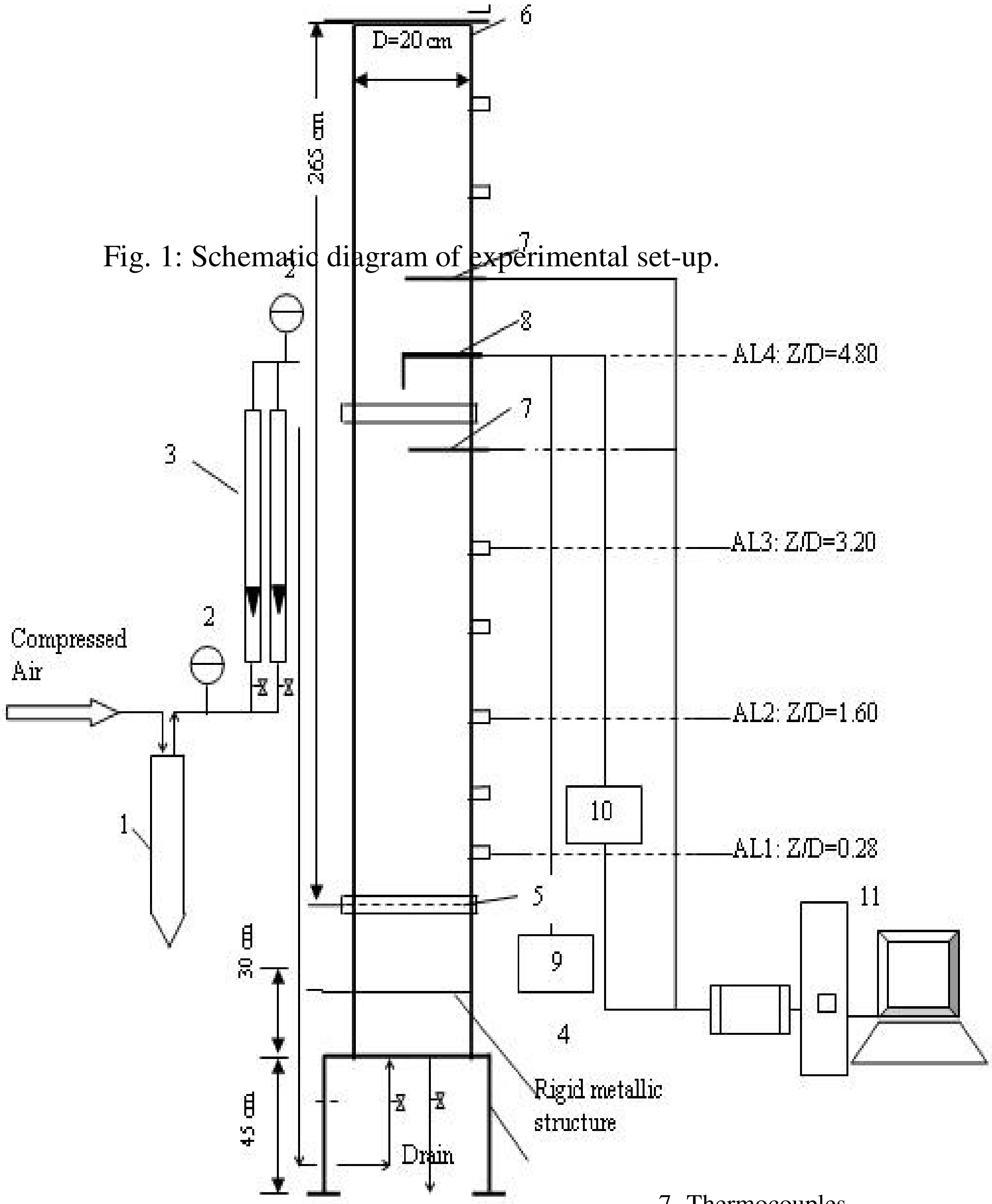
Local averaged heat transfer measurements are obtained in different regions of two-phase bubble column based on constant heat flux fast response probe, over a wide range of superficial gas velocities and large-scale diameter trend to industrial applications. The heat transfer coefficients increasing with increase in the superficial gas velocity, the increase is rapid in the beginning (bubbly flow regime), but slows down as the superficial gas velocity is increased (vertical-spiral regime) and approaches asymptotically to constant values at higher superficial gas velocities (churn-turbulent flow regime), that could be used to identify transition from one flow regime to another. The mechanism of heat transfer processes of a large-scale column elucidate that significant differences were observed between local heat transfer processes in the distributor and bulk regions. Axial profiles of heat transfer measurements in the radial direction indicate that the same profiles are reported for bulk and distributor regions, basically the bulk has the highest heat transfer rate in the distributor region, this is attributed to different mixing characteristics and resulting mechanisms in those two regions. The heat transfer coefficients in the center of the column is greater than near the wall due to the fact that large bubbles collect at center and they are more effective in enhancing heat transfer in the system. This information captures more insight mechanism of heat transfer in the industrial column and could be useful for the optimum design and proper placement of internals for heat transfer in a bubble column reactor.

References:

1. Abdulmohsin, R., “Heat transfer in bubble column operating in churn-turbulent flow regime”, Ph.D. Thesis, University of Technology,Baghdad,Iraq (2008).
2. Chen,W.,Hasegawa,T.,Tsutsumi,A.,Otawara,K., and Shigaki,Y., “ Generalized dynamic modeling of local heat transfer in bubble columns”, Chem. Eng. Journal, 96,37-44 (2003).
3. Dhotre, M.T, Vitankar, V.S., and Joshi, Y.B ,“CFD simulations of steady state heat transfer in bubble columns”, Chem. Eng. Journal, 108, 117-125 (2005).
4. Fair, J. R., Lambright, A. J., and Andersen, J. W., “Heat transfer and gas holdup in a sparged contactor”, Ind. & Eng. Chem. Proc. Des. and Develop.,1 ,33-36 (1962).
5. Hikita, H., Asai, S., Kikukawa, H., Zaike, T., and Ohue, M., “Heat transfer coefficient in bubble columns”, Ind. & Eng. Chem. Proc. Des. and Develop., 20, 540-545 (1981).
6. Li, H., and Prakash, A., “Heat transfer and hydrodynamics in a three-phase slurry bubble column “Ind. Eng. Chem. Res, 36, 4688-4694 (1997).
7. Li, H., and Prakash, A., “Analysis of bubble dynamics and local hydrodynamics based on instantaneous heat transfer measurements in a slurry bubble column” Chem. Eng. Sci., 54,5265-5271(1999).
8. Li, H., and Prakash, A. "Analysis of flow pattern in bubble and slurry bubble columns based on local heat transfer measurements” Chem. Eng. Journal, 86, 269-276 (2002).
9. Shaikh, A., and Al-Dahhan, M. H., “A review on flow regime transition in bubble columns”, Intern. Jour. of Chem. Reac. Eng., Vol. 5, R1 (2007).
10. Saxena, S.C, and Chen, Z. D., “Hydrodynamics and heat transfer of baffled and un-baffled slurry bubble columns”, Review Chemical Engineering, 10, 193-400 (1994).
11. Saxena, S.C, Vadivel, R., and Saxena, A. C., “Gas holdup and heat transfer from immersed surfaces in two and three phase in bubble columns”, Chem. Eng. Commun., 85, 63-83 (1989).
12. Saxena, S.C, Rao, N.S, and Saxena, A. C., “Estimation of heat transfer coefficient for immersed surface in bubble columns involving fine powders”, Chem. Eng. Commun., 63,197-202 (1990).
13. Saxena, S.C, Rao, N.S, and Saxena, A. C., “Heat transfer and gas holdup studies in a bubble column: air-water-sand system”, The Cana. Jour.of Chem. Eng., 70, 33-41(1992).
14. Verma, A. K., (1989) “Heat transfer mechanism in bubble columns” The Chem. Eng. Journal, 42, 205-208.

15. Wu, C., Al-Dahhan, M., and Prakash, A., “Heat transfer coefficients in a high pressure bubble columns”, Chem. Eng. Sci., 62,140-147(2007).

Fig. 1: Schematic diagram of experimental set-up.



1-Air filter units
2- Pressure indicator
3-Rotameter system (up to 3.4 m^3/s)
4- Plenum
5- Perforated Distributor
6- Plexiglas bubble column

7- Thermocouples
8- Vertical rod type heat transfer probe
9- DC power
10- Amplifier
11- DAQ system
12- AL: Axial Location

Figure 1: Schematic diagram of experimental set-up.

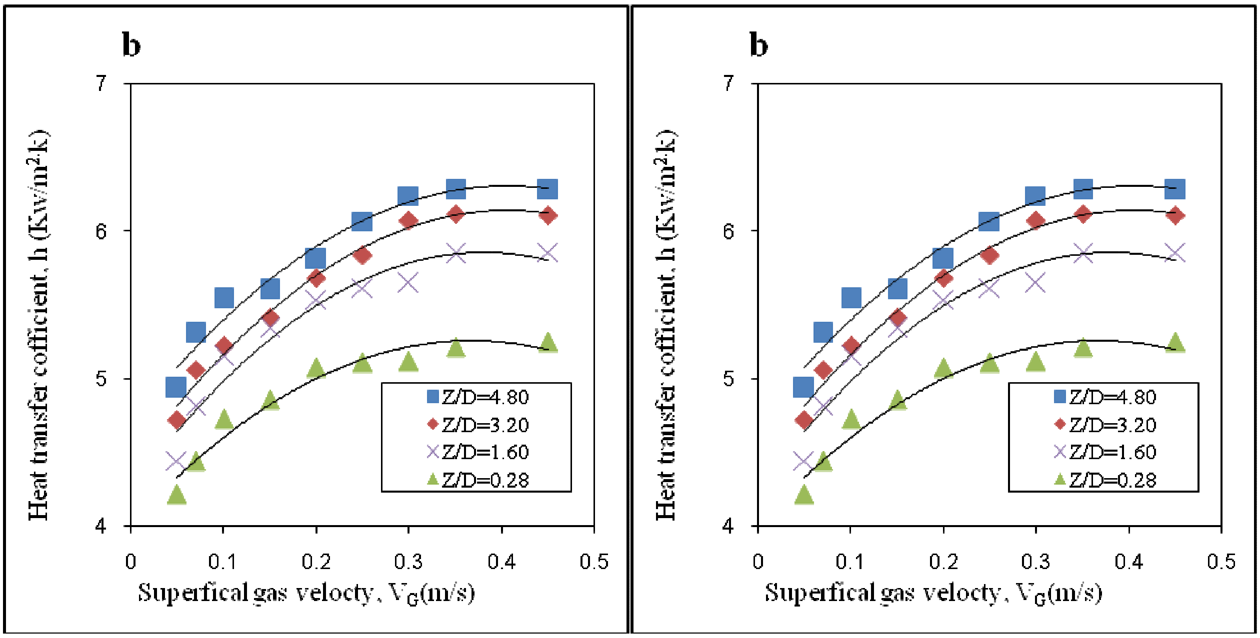


Figure 2: Effect of superficial gas velocity on heat transfer coefficients at different axial locations: (a) in the center of the column (r/R=0), (b) near the wall of the column (r/R=0.9).

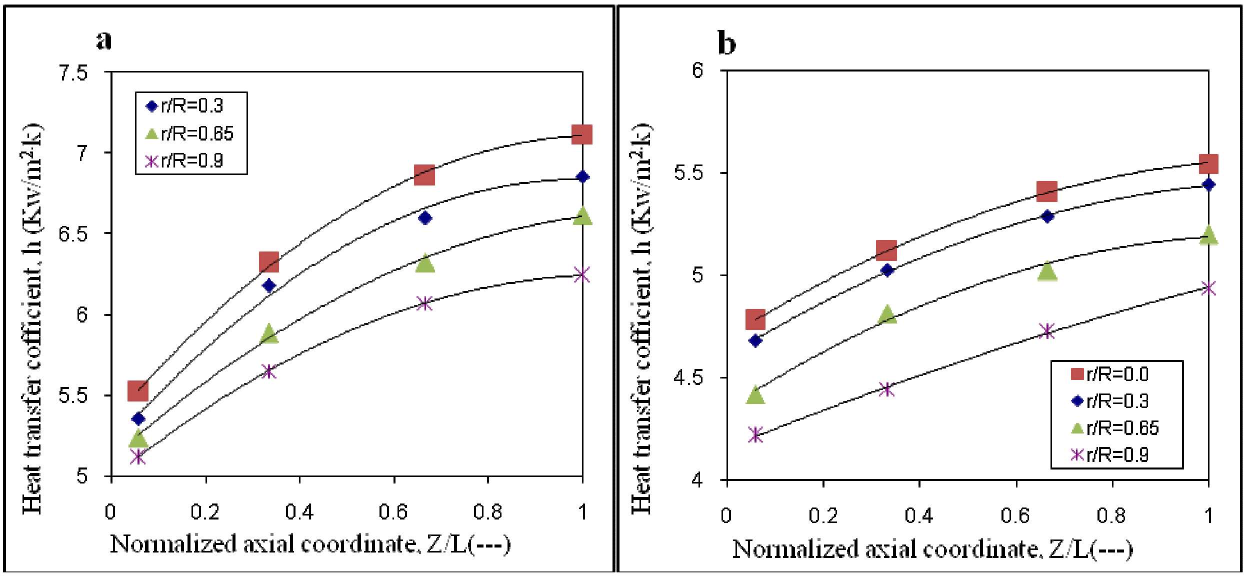


Figure 3: Effect of probe locations on local heat transfer coefficients for different radial positions: (a) at high superficial gas velocity (V_G =0.35m/s), and (b) at low superficial gas velocity (V_G =0.0٣m/s).

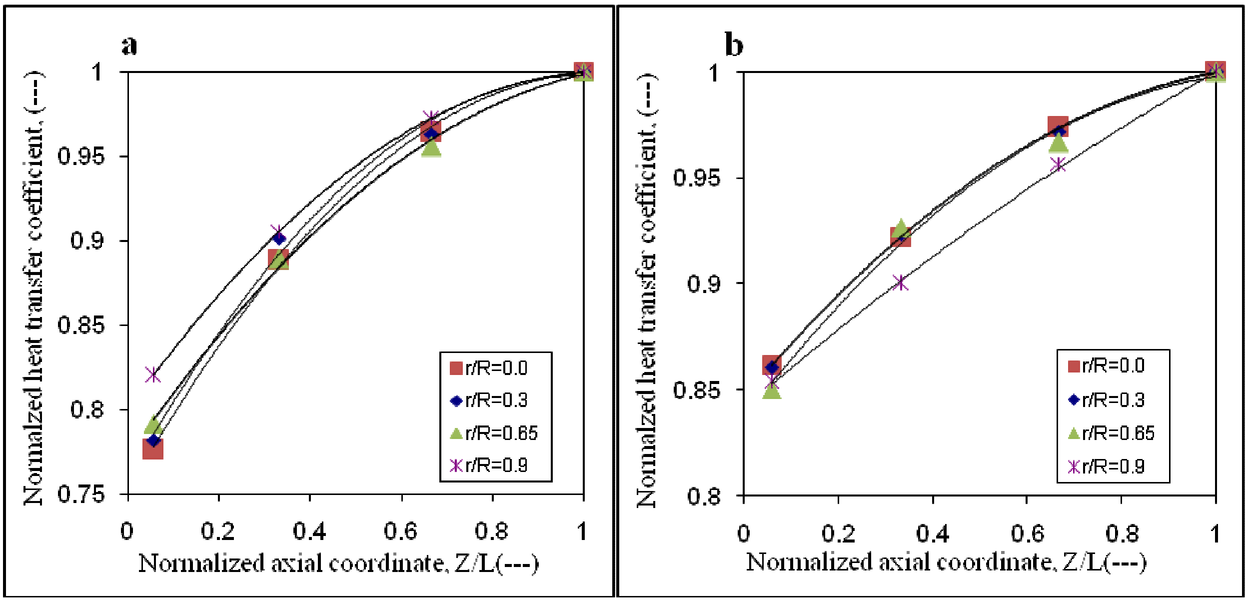


Figure 4: Effect of probe location on normalized heat transfer coefficients for different radial positions: (a) at high superficial gas velocity (V_G =0.35m/s), and (b) at low superficial gas velocity (V_G =0.0٣m/s).

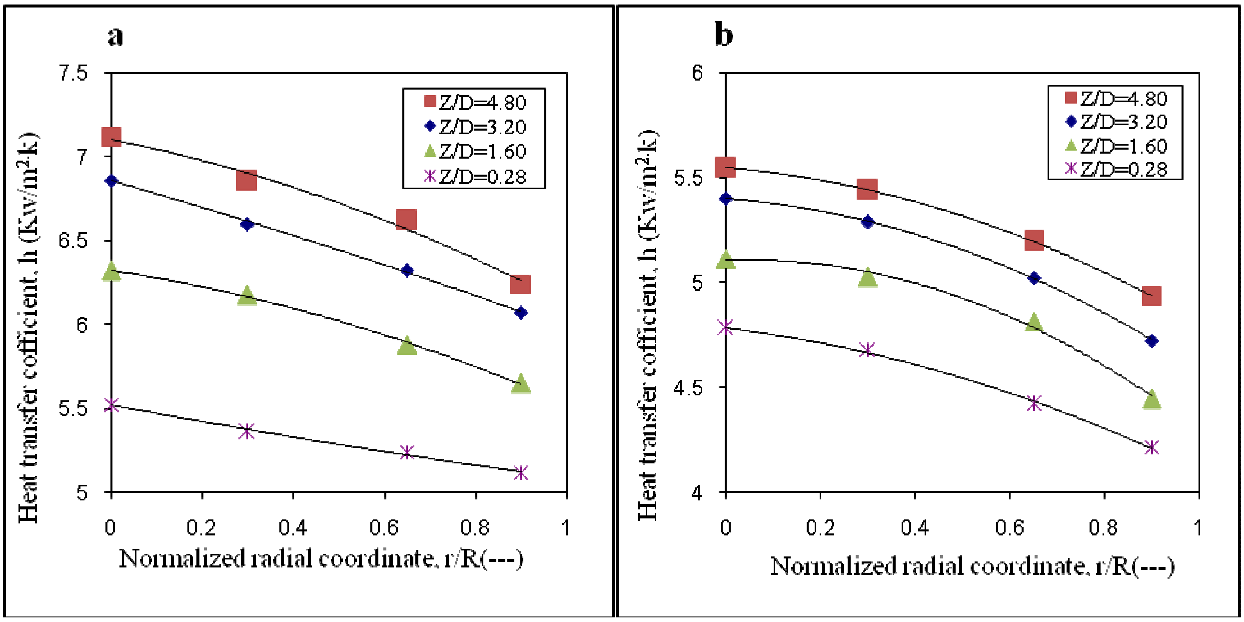


Figure 5: Radial profiles of local heat transfer coefficients for different axial locations: (a) at high superficial gas velocity (V_G =0.35m/s), and (b) at low superficial gas velocity (V_G =0.0٣m/s).

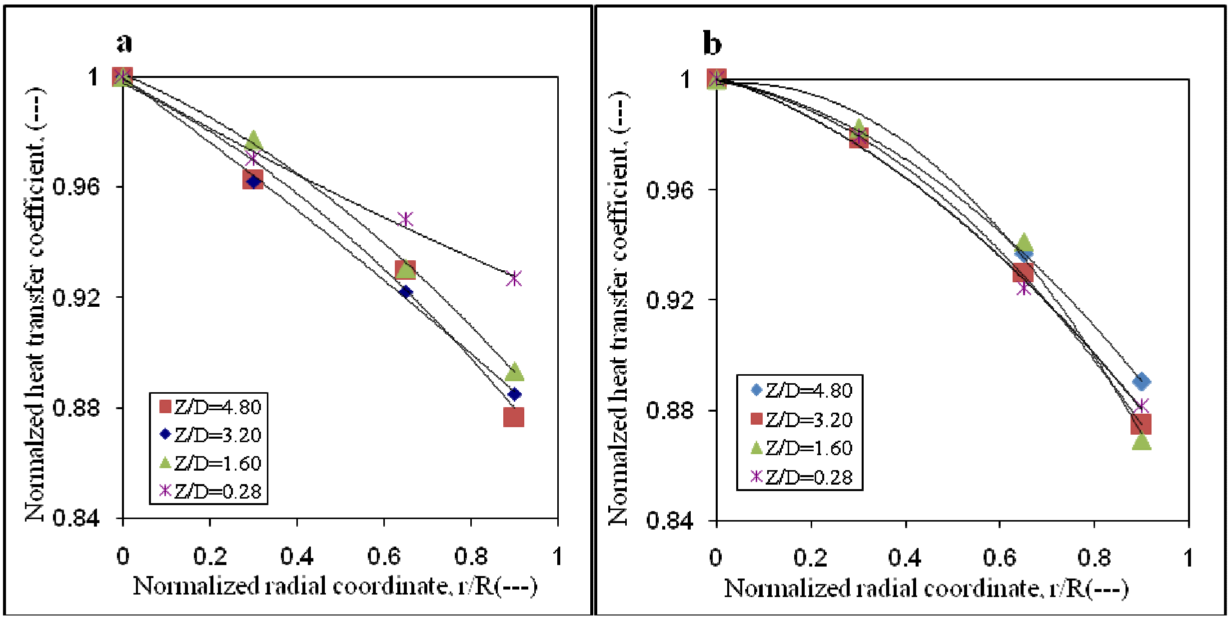


Figure 6: Radial profiles of normalized heat transfer coefficients for different axial locations: (a) at high superficial gas velocity (V_G =0.35m/s), and (b) at low superficial gas velocity (V_G =0.0٣m/s).

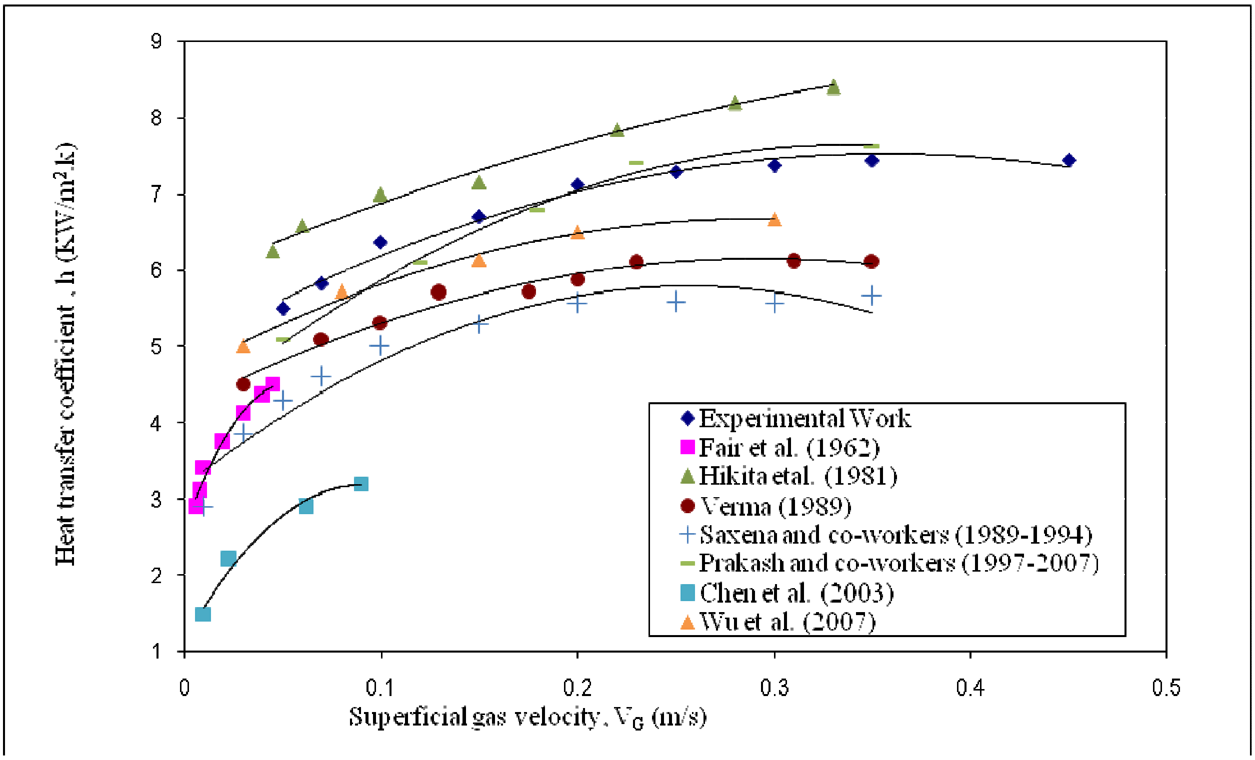


Figure 7: Comparison of heat transfer coefficient with the reported experimental data.