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# Heat Transfer Characteristics in a Large-Scale Bubble Column Operating in a Semi – Batch Mode

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## Abstract

Time-averaged local heat transfer coefficient profiles were studied in a 0.45 m bubble column using air-water system. The effect 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 14% -22% for increasing the superficial gas velocity from 0.05-0.45 m/s. The heat transfer coefficients increase with superficial gas velocities and the values in the center of the column were 9–13% greater than those near the wall region .The characteristics of bulk flow region are 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.

## خصائص انتقال الحرارة في العمود الفقاعي الكبير الحجم

## الخلاصة

تم دراسة توزيع معاملات انتقال الحرارة في عمود فقاعي بقطر 0.45 م وباستخدام نظام الهواء-الماء. تم فحص سرعة الغاز ,الارتفاع 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 اعلي*(Z/D=4.8)* من معامل انتقال الحرارة في منطقة الموزع*(Z/D=0.28)* بنسبة 14% إلى 22% للزيادة في سرعة الغاز من 0.05 م/ثا الى 0.45 م/ثا. معاملات انتقال الحرارة تزداد بزيادة سرعة الغاز ,والقيم عند مركز العمود اعلي بنسبة 9% الى 13% من القيم قرب الجدار. الخصائص في منطقة التشكيل التام كانت أكثر تغيرا بالاتجاه القطري واقل بالاتجاه المحوري بالنسبة لقيم معاملات انتقال الحرارة.

**Nomenclature**

| | | |
|---|---|---|
| A | probe heat transfer area | $m^2$ |
| D | diameter of the column | m |
| H | heat transfer coefficient | $kW/m^2.K$ |
| L | test section of column | m |
| n | number of data points | --- |

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| | | |
|---|---|---|
| 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 |
| $\Delta x$ | thickness of thermal barrier | m |
| Z | axial location from bottom | m |

*Subscripts*

| | |
|---|---|
| avg | average |
| b | bed |
| G | gas |
| i | instantaneous |
| s | surface |

## 1. 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(1). 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 either in a bubbly flow (homogeneous) regime or churn-turbulent flow (heterogeneous) regime depending on the reaction chemically and the system characteristics introduced (2). 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 (3). 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 reactions is usually accompanied by heat supply or removal for the endothermic or exothermic operations, respectively. Therefore, maintaining desirable bulk media temperature is necessary which plays an important role in the performance of the reactor. Hence, the knowledge and understanding of heat transfer phenomena and quantity 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 (1). 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 (4). It is noteworthy that the local time-averaged heat transfer coefficients and their radial profiles or cross-sectional which closer provide valuable insight into mechanisms of heat transfer and qualitatively the bubble dynamic and liquid circulation intensity in bubble column. Saxena and Chen(5) 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(1)). 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. Therefore, this investigation focuses for the first time on the study of local heat transfer coefficients and its behavior in a larger diameter (0.45) 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.

## 2. Experimental Work

Experiments were conducted in a large-scale grid of Plexiglas column of (0.45) m internal diameter and height (3.65) m (Fig. 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 unit. 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 increasing gas velocity range. The superficial gas velocity was varied in the range of 0.05 -0.45 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 (1.09%). During the experiments, the dynamic liquid height was maintained at around 3.2 m (equal to 7D times) by varying the static height at each studied condition. The temperature was maintained at about (21)°C in the column and during experiments, the liquid phase was regularly replenished due to the loss of small liquid quantity as a result of evaporation. Copper-constant thermocouples (Omega TMTSS-125U-12) were arranged at various axial positions and located at different radial locations to monitor bed temperature 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 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(1) ). 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 & 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:

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

Where $h_i$ is the instantaneous local heat transfer coefficient (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:

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

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.

## 3. Results and Discussion

### 3.1 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), respectively. Figures 2 a and b shows the heat transfer in the center (r/R=0.0) of the column and near the column wall (r/R=0.9), respectively, 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 (0.05-0.45) 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 increased continued 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 is seen that the heat transfer coefficients in the center are larger than those in the wall region, and amount varies from (9% to 13%) with the increase in the superficial gas velocity from (0.05 to 0.45) 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. It 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 (4). In the four axial locations, the heat transfer coefficients in the center of the column are greater that 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.

### 3.2 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 Fig. 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). Fig. 3 a and b shows the local heat transfer coefficients for different axial locations in the center of the column and near the wall. It can be seen that the heat transfer coefficients increase dramatically to the maximum at around 210 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 Fig. 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.

### 3.3 Profile of Heat Transfer Coefficients

The radial heat transfer coefficients were measured by moving the probe along the column radius for four different positions from center to the wall of the column. Fig. 5 a and b shows 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 ($V_G$ = 0.05m/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 the heat transfer coefficients at wall significantly small than of the center, this indicates that wall region is relatively free from large bubbles or faster moving bubble chain. From Fig. 5 a, 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 Fig. 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 Fig. 6 a and b, it can 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, that 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(1).

### 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:

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

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 et al.(6) used low velocity range under the same diameter. However, at a superficial gas velocity (0.1) m/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 et al.(7) 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 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(8) and Saxena and co-workers(5,9,10,11) 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 et al.(11), 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 et al.(12) 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 Fig. 7 are consistent with this finding particularly at high superficial gas velocities, where the column diameter used by Prakash and co-workers (13, 14, 15) and Wu et al.(4) 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.

## 4. Conclusions

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 increase 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. It was found that the range of static height variation (about 5 cm) does not affect the column hydrodynamics at the conditions studied. 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.

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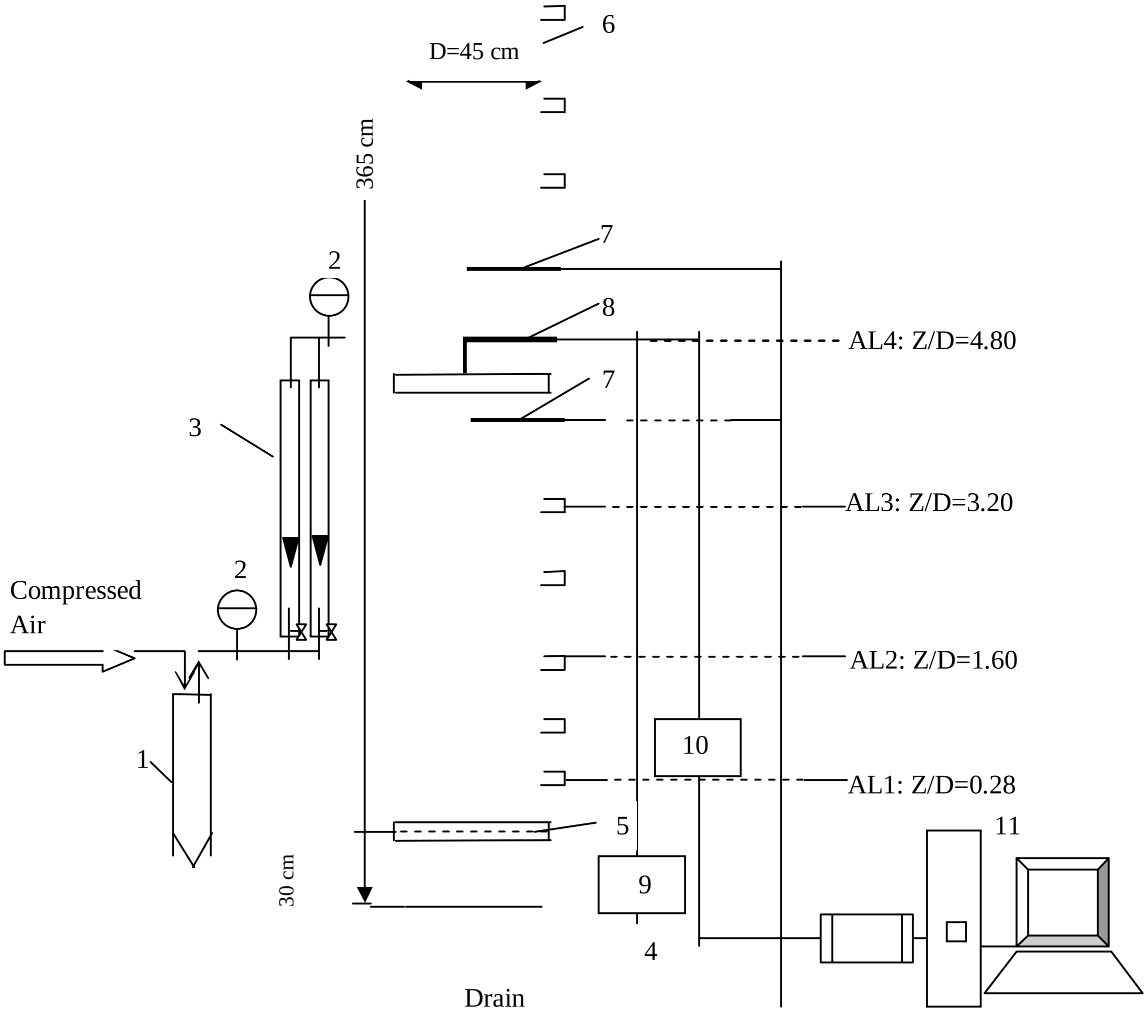

1-Air filter units
2- Pressure indicator
3-Rotameter system (up to 3.4 $m^3/s$)
4- Plenum
5- Perforated Distributor
6- Plexiglas bubble column
7- Thermocouples
8- Vertical rod type heat transfer probe
9- DC power
10- Amplifier
11- DAQ system
12- AL: Axial Location

**Figure (1) Schematic diagram of experimental set-up.**

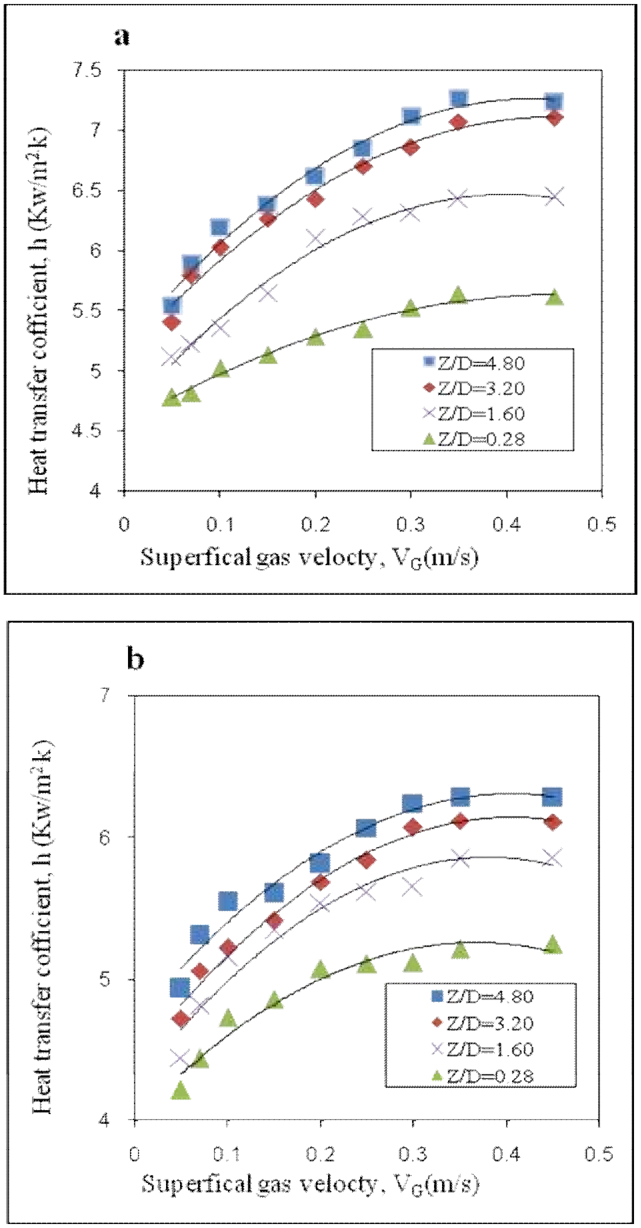

**Figure (2) Effect of superficial gas velocity on heat transfer coefficients at different axial locations: (a) in the center of the column (r/R=0), (b) near the wall of the column (r/R=0.9).**

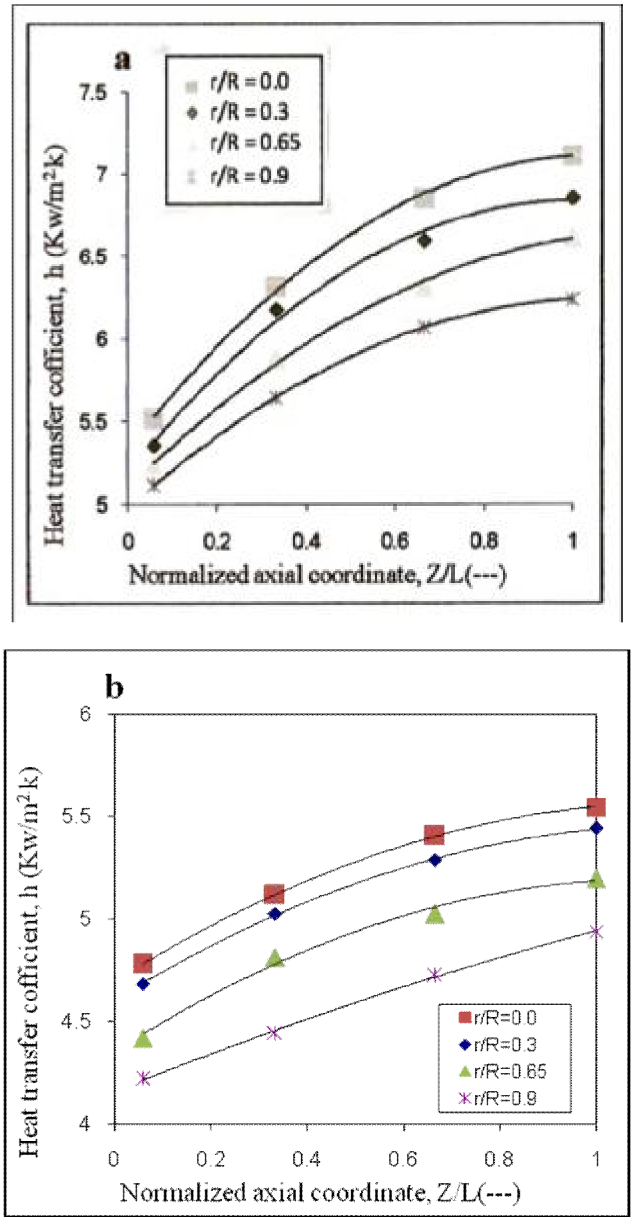

**Figure (3) Effect of probe locations on local heat transfer coefficients for different radial positions: (a) at high superficial gas velocity ($V_G$ =0.35m/s), and (b) at low superficial gas velocity ($V_G$ = 0.05m/s).**

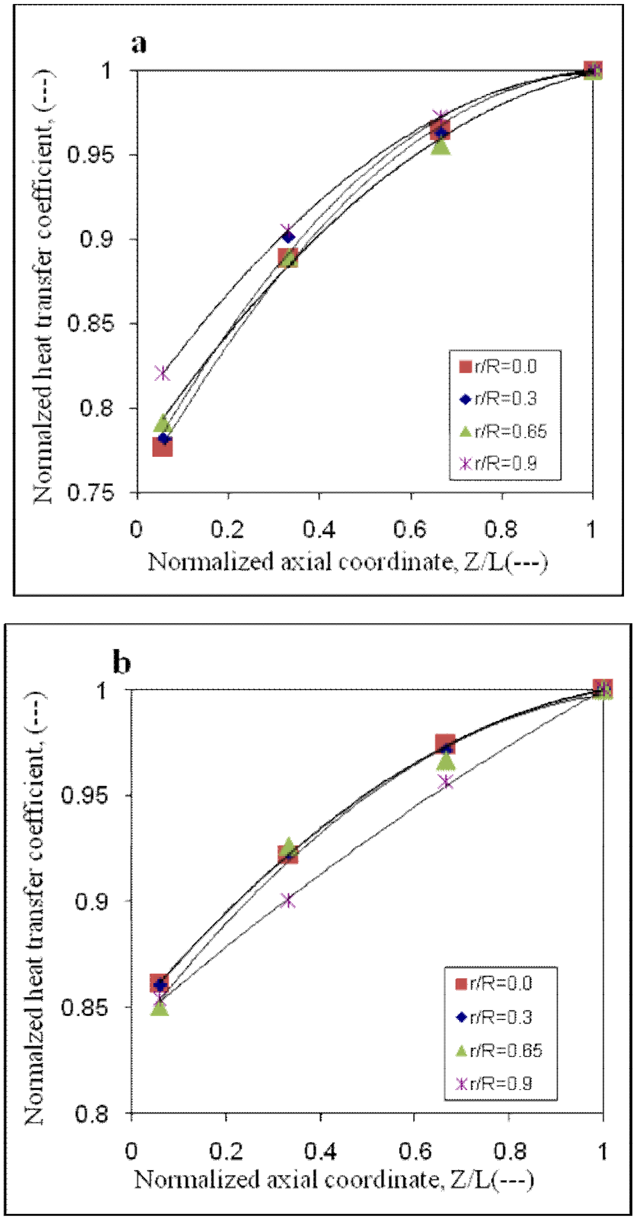

**Figure (4) Effect of probe location on normalized heat transfer coefficients for different radial positions: (a) at high superficial gas velocity ($V_G$ =0.35m/s), and (b) at low superficial gas velocity ($V_G$ =0.05m/s).**

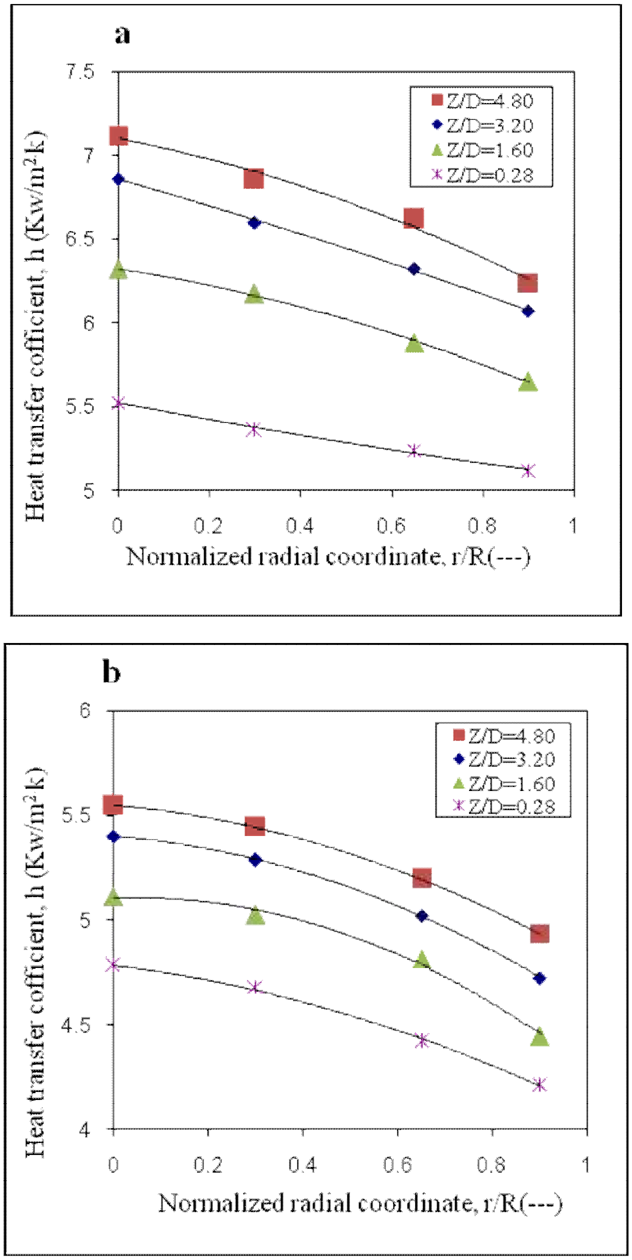

**Figure (5) Radial profiles of local heat transfer coefficients for different axial locations: (a) at high superficial gas velocity ($V_G$ =0.35m/s), and (b) at low superficial gas velocity ($V_G$ =0.05m/s).**

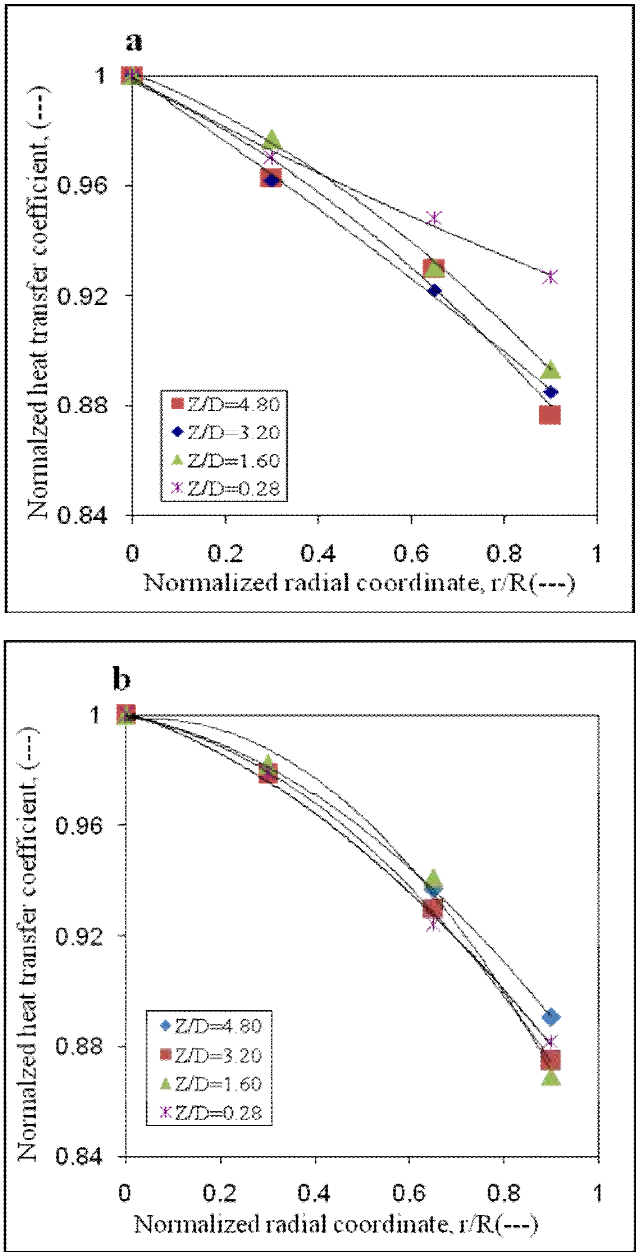

**Figure (6) Radial profiles of normalized heat transfer coefficients for different axial locations: (a) at high superficial gas velocity ($V_G$ =0.35m/s), and (b) at low superficial gas velocity ($V_G$ =0.05m/s).**

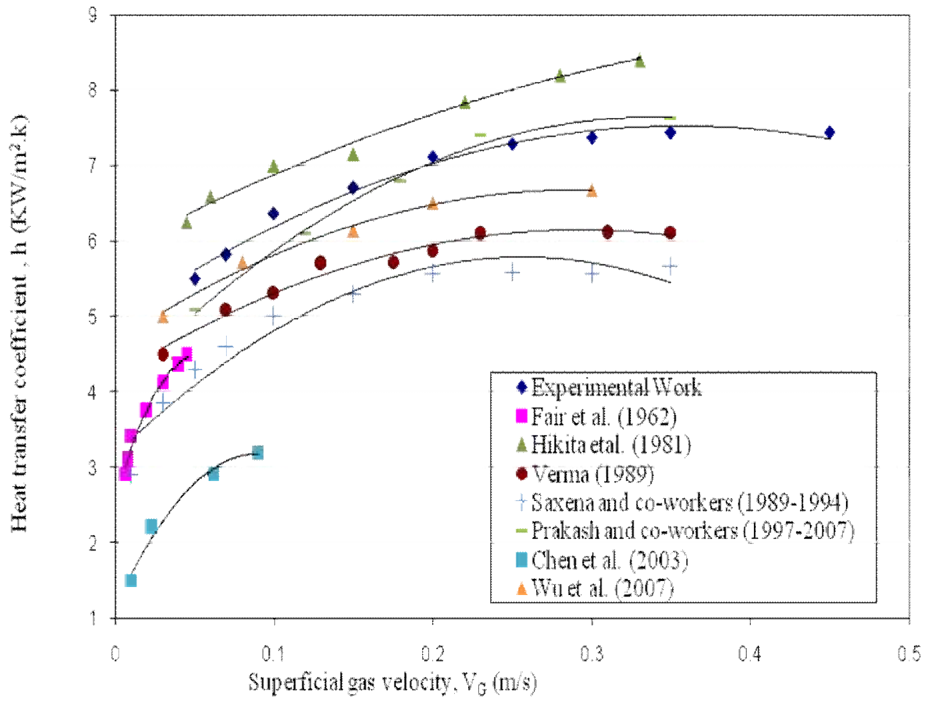

**Figure (7)Comparison of heat transfer coefficient with the reported experimental data.**