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Effect of a Triangular Configuration of Heat Exchanging Tubes on Local Heat Transfer Coefficient in Bubble Column Reactor

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Abstract

The effect of a triangular configuration of heat exchanging tubes (HETs) on the instantaneous and local heat transfer coefficient (LHTC) has been investigated and quantified in an air-water bubble column (BC) utilising an advanced heat transfer technique. The bundle of heat exchange tubes was designed to cover 25% of the column's cross-sectional area (CSA) to simulate the heat exchanger tubes used in the industrial Fischer Tropsch (FT) process. The local heat flux, surface temperature, bulk temperature, and heat transfer coefficient (HTC) were investigated instantaneously in a Plexiglass BC under a wide range of superficial gas velocity (5-45 cm/s). The obtained results reveal that the presence of a bundle of (HETs) and their arrangement effect the (HTC) in the bubble column, where unsymmetrical profiles for (HTC) were obtained with triangular tube pitch arrangement. Additionally, steeper (HTC) profiles notice were when the triangular tube pitch arrangement was utilized. High (HTC) values were obtained at the core region of the column relative to the wall region under all the studied operating conditions. It was discovered that the local and (HTC) increase as superficial gas velocity increases despite the fact that the bubble column is heavily packed with a bundle of (HETs). The rise in HTCs was higher at the core than at the wall region of the column. For example, at a superficial gas velocity of 45 cm/s and at an axial height of 65 cm (Z/D=5), compared to the wall, the HTC in the core of the column increased by 131 %.

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1. Introduction

Nowadays, energy has become a primary global concern, with a steadily rising; oil demand resulting in a reduction in oil reserves. Moreover, the petroleum demand will grow with stagnant or declining oil production[1]. Therefore, there is a need to seek clean and renewable energy sources to fill the energy consumption shortage and preserve the climate and the environment. One of these alternative energy sources is converting natural gas or biomass to clean and high-quality liquid fuel and chemical products through the (FT) process[2], [3]. Various reactors were used in the FT process, such as fixed bed reactor, fluidized bed reactor, circulated fluidized bed reactor, and bubble/slurry bubble column reactor[4]. However, the BC is preferred among the rest of the reactors for its advantages compared to other reactors, and this is evident through its wide industrial applications such as oxidation[5], fermentation[6], wastewater treatment[7], methanol synthesis (MEOH)[8], and Fischer−Tropsch (FT) synthesis[9].

The majority of industrial applications of bubble/slurry bubble columns involve high exothermic reaction, which requires different means of heat elimination in these reactors to control the operating temperature of the reaction for achieving the desired product quality and productivity of liquid fuels[10]–[12]. This can be achieved by equipping the reactor with a bundle of HETs. However, the presence of this bundle of HETs will make the process of designing this reactor more complicated than designing a reactor without this bundle, which is also an engineering challenge because of the interaction between phases. This engineering challenge for design and scale-up comes from the lack of experimental and numerical works on these reactors when equipped densely with a bundle of cooling tubes which contributes to a poor knowledge of the impact of the bundle on fluid dynamics, heat, and mass transfer.

Even though this reactor is used in alotof industrial applications, few studies have focused on the effect of a bundle of HETs on hydrodynamic, heat, and mass transfer rates[13]–[19]. In addition, very little researchers have investigated the influence of a bundle of HETs on heat transfer in the BC reactor[20]–[22]. Therefore, there is a requirement to investigate further the influence of the presence of bundle of the cooling tube on heat transfer to predict better the thermal performance of such kind reactor toward designing an efficient reactor for conducting high exothermic reactions.

Among these few studies, Wu and Al-Dahhan[23] evaluated the LHTC in a BC reactor with an air-water system. Their work involved investigating the impact of the operating conditions such as pressure (up to 10 bar), superficial gas velocity (up to 0.30 m/s), probe location, and orientation. They found that the HTC increased under atmospheric pressure as the superficial gas velocity increased, and the HTC values were higher at the column's core than at the wall region. Additionally, they found that as pressure increased, HTC values reduced. Abdulmohsin and Al-Dahhan [20] quantified the effect of a bundle of a bundle of heat exchanging tubes on LHTCin a 19 cm diameter BC for the air-water system. They used a fast response heat transfer technique to evaluated the HTC in a BC with and without vertical with HETs under a range of superficial gas velocity of 3-20 cm/s. They measured the HTC in the BC without HETs; the bubble columns equipped with HETs covered 5% of the column's CSA, and the BC equipped with HETs covered 22% of the column's CSA. Their results revealed that higher values of HTC were obtained in the BC equipped with internals occupied 22% of the cross-sectional area of column (mimicking FT process) compared to bubble without and BC with with HETs covering 5% of the CSA of the column (representing methanol process). Additionally, they found that the heat-transfer coefficient values at the core region of the column were higher than values at the wall regions for bubble columns with and without HETs for such studied operating superficial gas velocities. Another technique to measure the HTC was made by Jhawar and Prakash[24], who evaluated the HTC in a 15 cm ID bubble and slurry bubble columns with and without HETs. They measured the HTC under a wide range of operating superficial gas velocities covering bubbly, transition, and churn turbulent flow regimes. Their investigation includes the use of a different of a bundle of HETs arrangement that accounts for 6% of the cross-sectional area (CSA) of the column. Their experimental HTC data indicated that the arrangement of the internals had a considerable effect on the steepness of the HTC's radial profiles. Kagumba[25] investigated the influence of the bundle of HETs and their size on HTC in two different sizes of BCs with a diameter of 14 cm and 44 cm, respectively. In his study, the bundle of HETs was designed to cover 22% of the CSA of the bubble columns to mimic the industrial FT reactor. The HETs were arranged inside the BC using a triangular configuration. The effect of using two different sizes of the HETs of 0.5 and 1-inch on HTC under wide a range of superficial gas velocity of 0.05-0.45 m/s was examined in his study. Kagumba reported that the higher HTCs were achieved in BC equipped with half inches internals compared to BC equipped with one-inches internals for all studied superficial gas velocities. Also, he found that higher HTCs were obtained in the large BC (44 cm) compared to the small column (14 cm). According to the heat transfer studies in a BC with HETs mentioned above, these studies were limited to measuring HTCs in one axial height, three radial positions, and a narrow range of operating superficial gas velocity. Moreover, all measurements of the above investigations were performed utilizing an inserting heat transfer probe in the space between the internals, which could distort the flow through this compartment and influence the flow behavior and thus HTC. Therefore, the primary aim of this study is to investigate the impact of the presence of a bundle of HETs, tubes arrangement, superficial gas velocity, and axial height on the instantaneous and LHTC and its radial profile. Such findings and experimental data of this study and the previous investigations in literature are valuable as benchmark data to develop and verify mathematical models and simulations for better thermal performance prediction to achieve the efficient design and scaleup and hence the desired product quality and yield.

1. Experimental work

1.1. Experimental setup

The tests were conducted in a Plexiglas BC with a 13 cm internal diameter and a height of 183 cm. **Figure 1** displays a diagram representation of the experimental setup for the BC with the heat-exchanging tubes. A bundle of thirty stainless tubes was designed and manufactured to occupy 25% of (cross saction area CSA) of the BC to simulate the industrial heat-exchanging tubes used in the manufacturing Fisher Tropsch reactor[26], [27]. The dimension of each tube is 12 mm in diameter and 190 cm in height. The thirty tubes were arranged and supported using a triangular tube pitch arrangement, designed and printed by a 3D printer, as shown in **Figure 3**. The bundle of HETs was installed vertically inside the reactor at a distance of 13 cm from the gas distributor. It is important to mention that the bundle was lifted and lowered inside the column using an automated motor to quantify the

HTC at various axial levels along the bubble column. In this study, the air-water system was employed as the working fluid, with air serving as the continuous gas phase and purified water serving as the liquid phase in batch mode. The air was provided by an industrial compressor, where the compressed air was filtered and dried before entering a set of calibrated flowmeters. The calibrated flowmeters were connected parallel to control and measured a range of superficial gas velocity utilized in this work. A perforated plate distributor made of stainless steel is constructed of 121-holes with a diameter of (1mm) arranged in a triangular form with a free overall area of 1.09% was used as a gas distributor in this work. Experiments for measuring HTC were conducted at constant atmospheric pressure, dynamic level (1.45 m), and a wide range of superficial gas velocity (0.05-0.45m/s) to cover the bubbly,transition,and churn turbulentflowregimes.

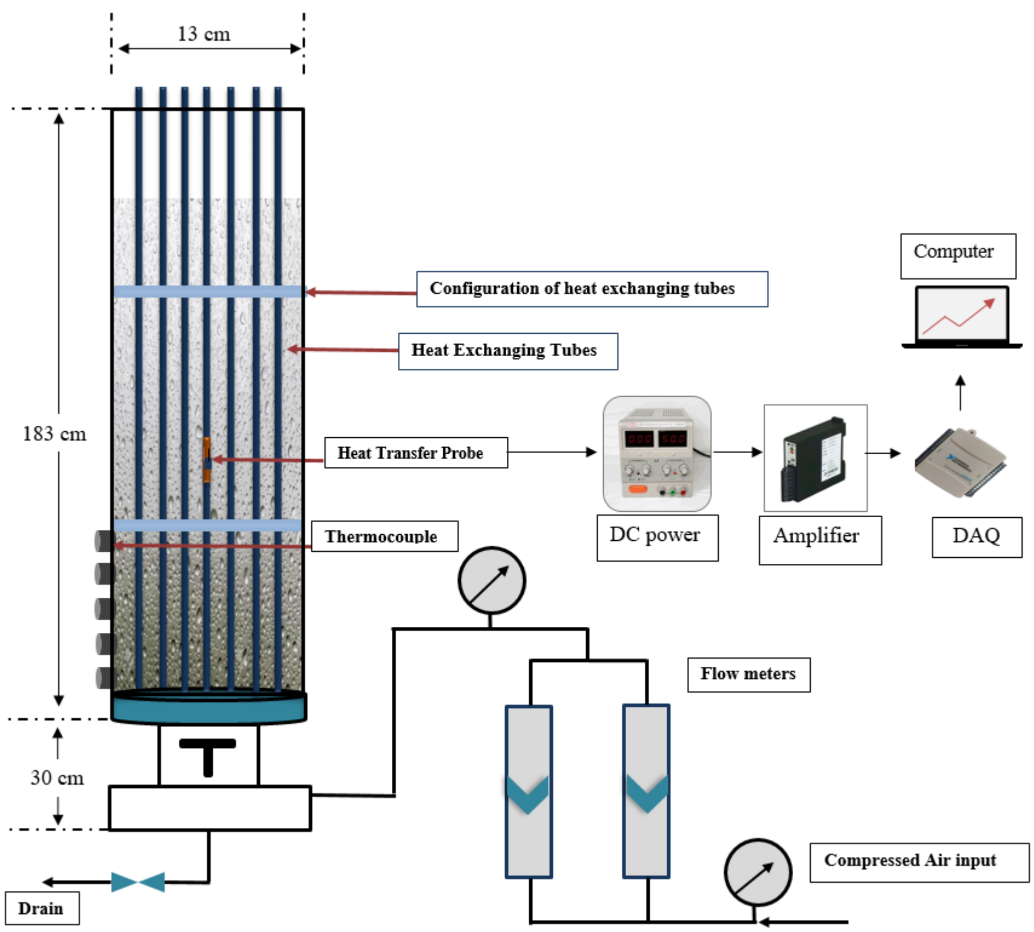

Figure 2: Schematically diagram of bubble column equipped with a bundle of vertical tubes

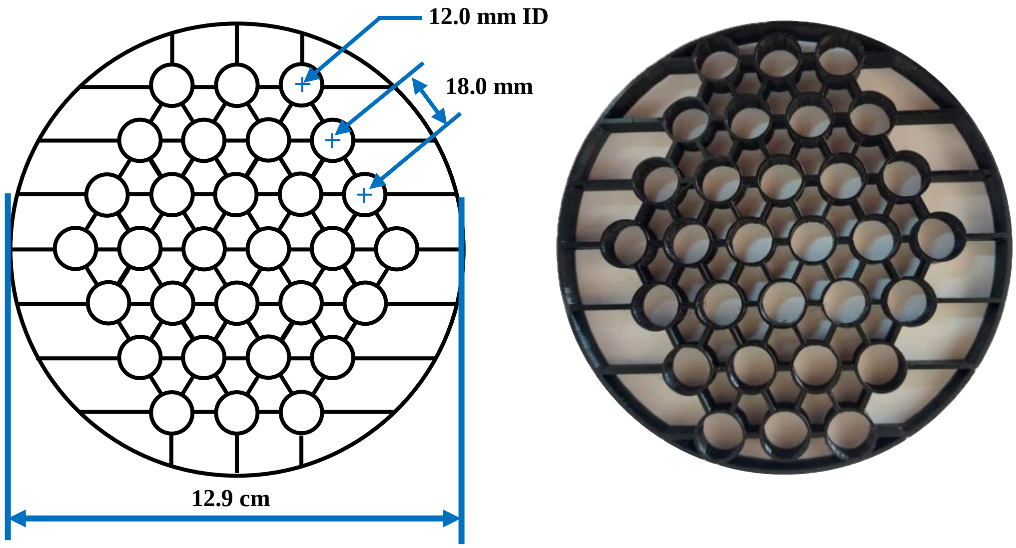

Figure 3: Schematic and image of triangular tube pitch arrangement

1.2. The advanced heat transfer technique

At the University of Technology, a new version of heat transfer technique developed by Li and Prakash[28] is designed and manufactured.. The main part of the heat transfer technique is the heat transfer probe. The heat transfer probe consists of a brass piece, cartridge heater, heat flux sensor, two pieces of Teflon as presented in **Figure 4**. The probe was made first by machining the inside of the brass piece to fit the heater cartridge (Heatron, Inc. Leavenworth, Kans., US005136143, USA). Then, two pieces of Teflon connected at the top and bottom of brass to prevent any heat loss. Finally, a new high sensitivity and response heat flux senor (PHFS, USA) of dimension 10mm by 10 mm was attached on the outside of the brass piece by using conducted glue. Once the heat transfer probe is manufactured and tested, this probe can be connected to any tube of a bundle of HETs and become part of the tube to overcome the problem of distributing the flow that faced the researchers when they measured the heat transfer when they employed an L-shape heat transfer probe. Therefore, designing the heat transfer technique in this way allows researchers to measure the heat transfer at any position inside the column in a non-invasive way. An amplifier (JH-Technology, Inc., model JH5200, USA) is used to amplify the output signal of the PHFS sensor because it is in the micro voltage range. This provides an isolated DC output proportional to the sensor input to get a linear output with a low drift input and in the terminal cold junction compensation that maintains accuracy under varying ambient conditions.

In addition, another amplifier (Ordel, Inc., model UST100) was utilized to measure the surface temperature of the sensor and convert an analog signal generated from the sensor to an isolated standard analog signal before being obtained by the data acquisition instrument (DAQ, model NI USB – 6008, USA). Six thermocouples types K were used to measure bulk temperatures of BC at different heights with a range of 10-60 cm from the gas distributor. These thermocouples were connected to another data acquisition instrument (Pico Log recorder). Furthermore, the PicoLog recorder contained cold junction compensation sensing and correction, a digital controller, associated control logic, and displays the measuring signals of the thermocouple, which was connected to the computer. From measuring the heat flux signal, surface temperature, and temperature of the bulk, the instantaneous heat transfer coefficient between the heat transfer probe and the bulk can be calculated according to the Newton law of cooling:

$$h_i = \frac{q_i''}{(T_{si} - T_{bavg.})} \quad (1)$$

Where h_i is the instantaneous local heat transfer coefficient (KW/m^2.°C), q_i'' is the instantaneous heat flux (KW/m^2), T_{si} is the surface temperature measured instantaneously, and $T_{bavg.}$ is the average bulk temperature obtained from six thermocouples signals.

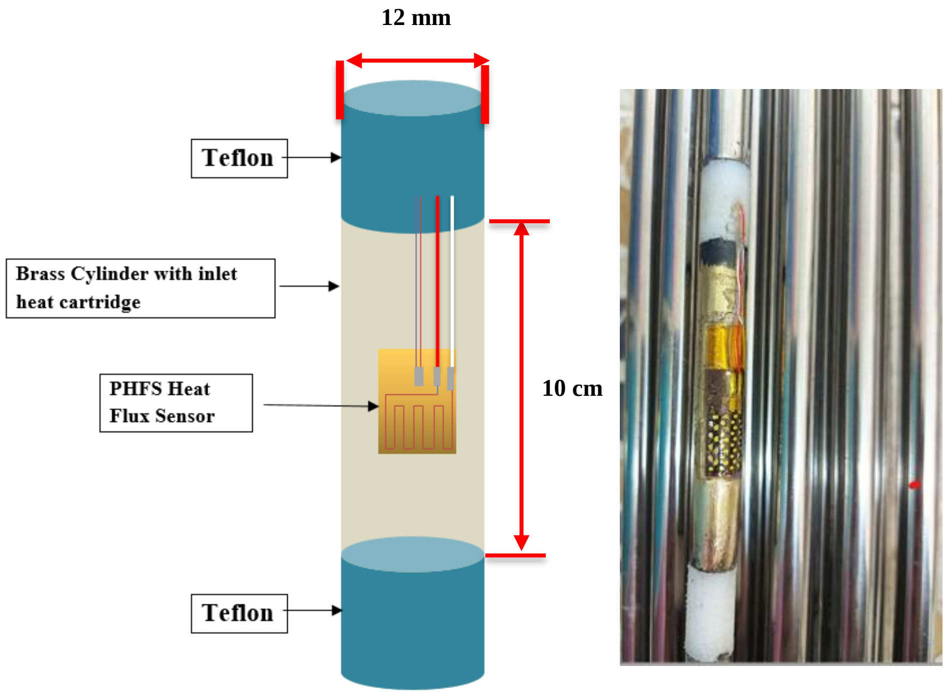

Figure 4: Schematic and photo of heat transfer technique

1.3. The accuracy and reproducibility of the measurements

Before conducting the experiments, the uncertainty and reproducibility of measurements for the heat transfer technique were checked to make sure the reliability of acquired data. This was performed by repeating the HTC measurement in the 13 cm diameter column with the air-water system on two successive days at specified conditions. The replications for experiments for reproducibility analysis were conducted in the BC endowed with a bundle of HETs configured by using a triangular tube pitch arrangement throughout a wide range of superficial gas velocities (0.05-0.45 m/s). The HTC measurements were evaluated at an axial level of 35 cm and a dimensionless radius (r/R) of +0.58. **Figure 5** shows the results of replications for two runs conducted in two successive days for the time average HTC versus superficial gas velocity. Excellent reproducibility for experimental data was obtained for all studied operating superficial gas velocities, as exhibited in **Figure 5**. For example, the absolute relative variance between the two profiles is 1.8%. These results confirm the reliability of this technique for measuring the HTC under various conditions with high accuracy. Moreover, the HTC measurement was replicated three times during each experiment to check the certainty of acquired data.

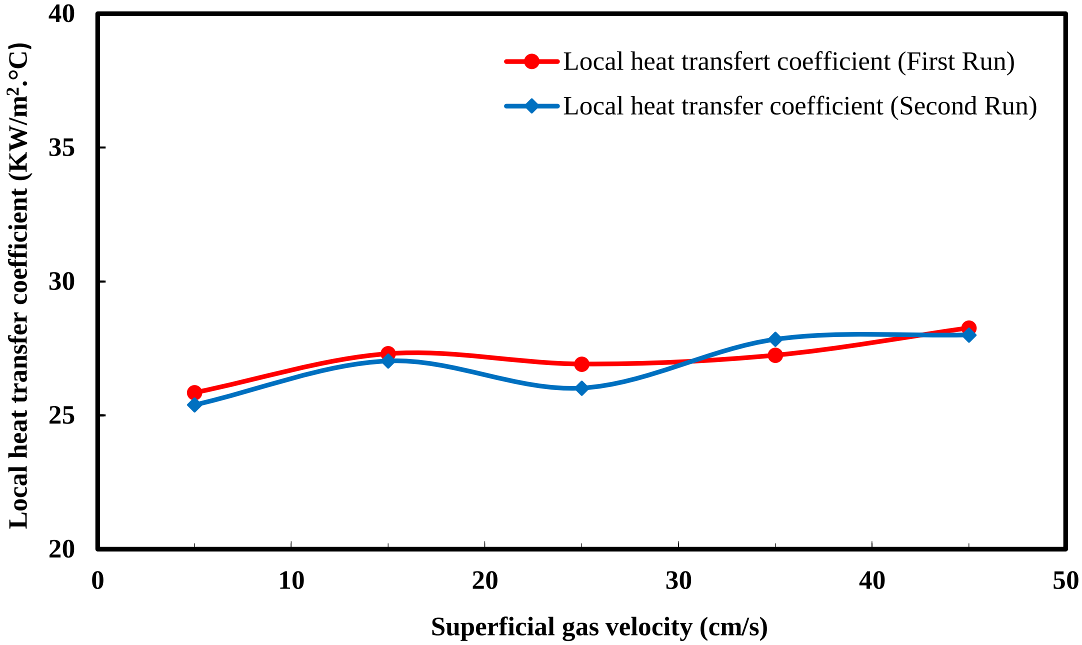

Figure 5: Reproducibility of the advanced heat transfer technique measurements

2. Results and Discussion

2.1. Radial profiles of the heat transfer coefficients

Heat transfer coefficients were determined at six different radial locations and two axial heights (35 and 65 cm) of a BCdensely packed with vertical tubes under a wide range of superficial gas velocity (5-45 cm/s). The diametrical profiles of the HTC were achieved by moving the heat transfer probe along the column diameter under the studied superficial gas velocities. **Figure 6** and **Figure 7** demonstrate the diametrical heat transfer profiles obtained at two different axial heights (35 cm, (Z/D=2.7) and 65 cm (Z/D=5)) and with a superficial gas velocity between (5-45 cm/s). It can be noticed from these figures that the HTC values rise as superficial gas velocity increases irrespective of the presence of a bundle of HETs and axial height. However, the rise in HTCs was higher at the core than at the wall region of the column. For example, at a superficial gas velocity of 45 cm/s and at an axial height of 65 cm (Z/D=5), compared to the wall, the HTC in the core of the column increased by 131 %.This rise in HTC with increasing the superficial gas velocity is because increased liquid circulation velocity, driven by the gas phase (i.e., air bubbles) inside the column. As a result, many large bubbles will be created, which increases liquid velocity and the HTC between the heat transfer probe and the bulk of the liquid. Such results were also reported by Wu and Al-Dahhan[23], who works on heat transfer in bubble columns. The reason behind the high values of HTC obtained at the center column compared to the wall region is the increase in chord length of bubbles and local gas holdup in the center with a rises in superficial gas velocity while the bubble chord length and local gas holdup do not change much at the wall region[29]. The obtained HTC profiles in this investigation are different from those obtained in the BC without HETs. For example, it is well known in the literature that the heat transfer profiles in bubble columns without HETs are parabolic[20], [28], [30], [31]. However, this is not the case in the

BC connected with a bundle of HETs as evaluated in this study and demonstrated in **Figure 6** and **Figure 7**. It is clear from these figures that the profiles are steeper and differ from what was reported for bubble columns without HETs Not only this, but also the obtained HTC profiles are unsymmetrical where the HTC values on the right side of the column are higher than those on the left side. This difference in the shape of the heat transfer profiles is due to the HETs and their configuration. According to current literature, the presence of the HETs and their arrangement inside a BC has a significant impact on the local hydrodynamic, bubble characteristics and thus the LHTC. Recently, Jasim et al.[16] used a four-point optical probe to study the effects of the bundle of HETs and their configurations on the local gas holdup and bubble parameters, such as bubble rise velocity, chord length and frequency and interfacial area of bubbles in an air-water BC. They used two different arrangements, namely circular and hexagonal arrangements, to examine the effect of configuration on local gas holdup and bubble characteristics. Their results reveal that symmetrical gas holdup and bubble properties were obtained when the circular tube configuration was used. Conversely, they found a distinguished unsymmetrical behavior on the radial profiles of gas holdup and bubble properties was obtained when hexagonal configuration was used.

Furthermore, HTC values on the left side of the column are larger than those on the right side of the column, as seen by the triangular tube arrangement, which indicates asymmetric distribution. When the triangular pitch tube configuration was used with the investigated bubble column, these unique asymmetric local heat transfer coefficient profiles were found. This asymmetric profile can be demonstrated by the high values of LHTC on one side of the column and low values on the other. For example, at a superficial gas velocity of 45 cm/s, the percentage difference of local gas holdups at dimensionless radius points, r/R = ± 0.33 and ± 0.58, are 100% and 180%, respectively. The design of the triangular tube arrangement, which generates additional clearance and nonsymmetrical gaps between the bundle of tubes and the wall of the bubble column, can be linked to the observed different asymmetric HTC profiles in BC, as illustrated in **Figure 2**. This clearance and nonsymmetrical gaps cause a channelling gas flow on one side and a liquid reverse flow on the other. As a result, the liquid circulation inside the column is altered by this triangle tube arrangement, which causes more gas bubbles to travel toward the clearance between the bundle and the wall, where there is less resistance to the flow, as seen visually.

Moreover, a significant effect of axial height on heat transfer values was observed and quantified, as exhibited in **Figure 6** and **Figure 7**. Higher HTC values are obtained at an axial level of ((Z/D=5) 65 cm)compared to those achieved at the axial level of 35 cm (Z/D=2.7). This difference in HTC values between axial locations can be attributed to the different fluid behavior at these regions. For example, the region at an axial height of 35 cm represents the gas distributor region (i.e., developing flow region), wherein most of the air distributor and tubes effect appears on the bubbles in this region and thus affects the rate of collision and coalescence for these bubbles, thus changing bubble properties. On the other hand, the rate of coalescences and breakup for bubbles reach an equilibrium state at an axial height of 65 cm (Z/D=5), which indicates the fully developed flow region.

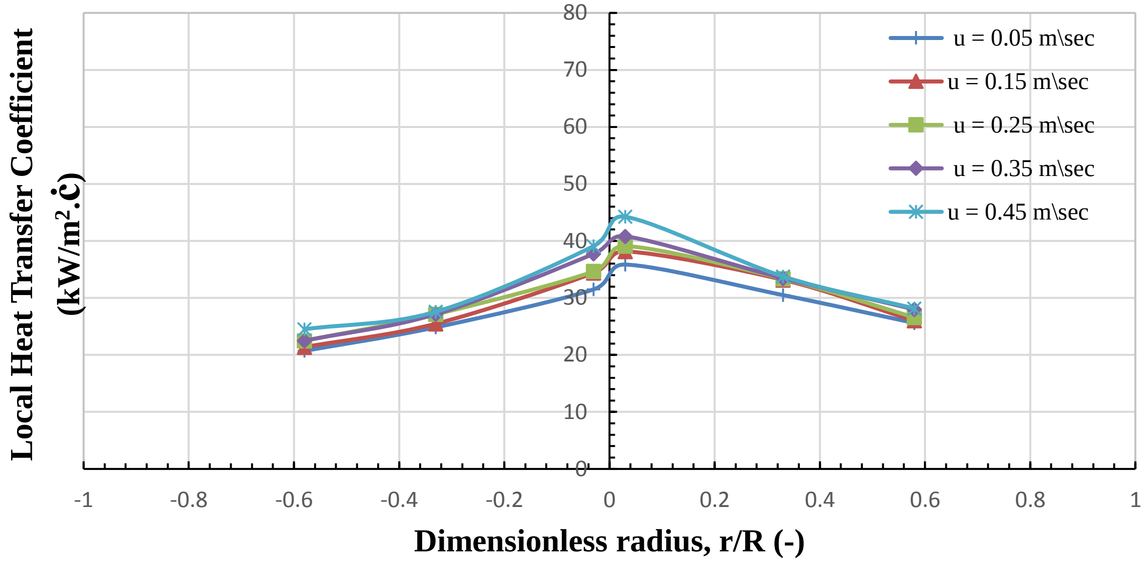

Figure 6: Diametrical profiles of the local heat transfer coefficients at axial heights (Z/D=2.7)

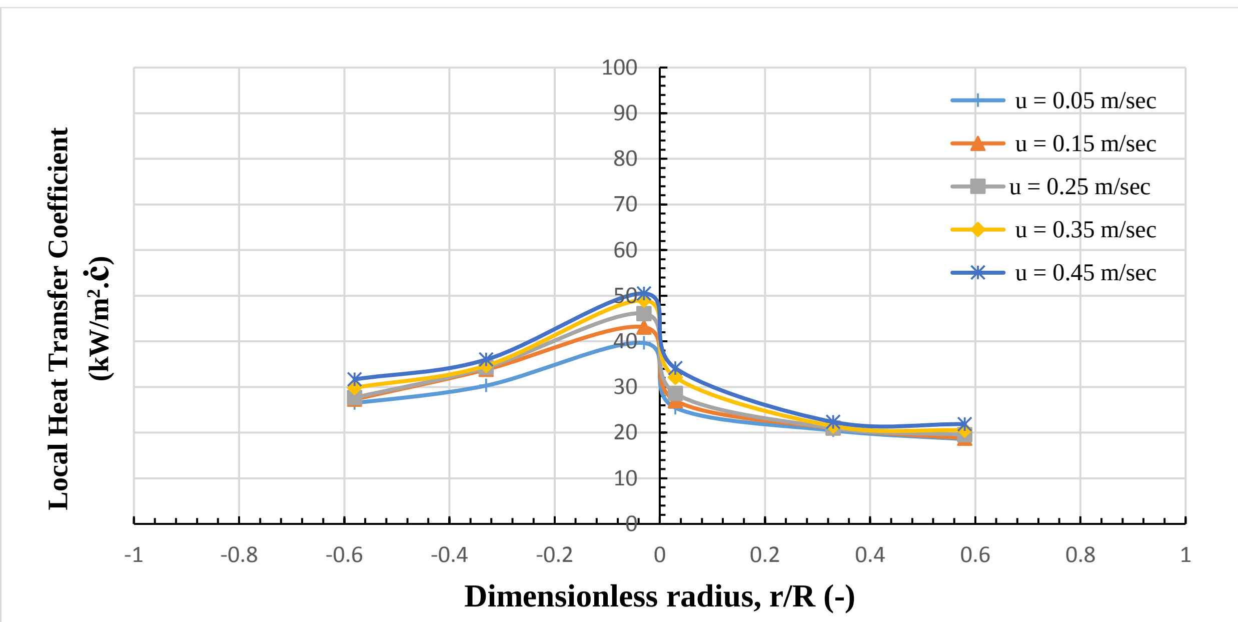

Figure 7: Diametrical profiles of the local heat transfer coefficients at axial heights (Z/D=5)

2.2. Effects of superficial gas velocity on local heat transfer coefficients

At various axial and radial positions, the effects of superficial gas velocity were investigated on the LHTCas shown in **Figure 8** and **Figure 9**. The column's HTCs were measured axially at (Z/D=2.7, Z/D=5) and radially at (±0.58, ±0.33, and ±0.03) along the column with a wide range of superficial gas velocities varying from 0.05 to 0.45 m/s. The impact of the superficial gas velocity on the HTCs may be shown to vary between the bubbly and churn-turbulent flow regimes. It can be noticed from thee figure that the values of the HTCs in the central and wall regions rise rapidly with a rise in the superficial gas velocity in the bubbly flow regime towards the transition regime. While at the churn-turbulent flow regime displays a lower range of increase in the value of HTCs. However, the HTCs reach the maximum value at higher superficial gas velocities[15]. This is because the fact that in the bubbly flow regime, small bubble sizes form at low superficial gas velocity. The size of the bubbles gradually increases as the superficial gas velocity increases. The increase in the superficial gas velocity (from 5 cm/s (bubbly flow regime) to around 45 cm/s (churn-turbulent flow regime) causes a significant increase in the HTCs. When the superficial gas velocity is larger than 35 cm/s, bubbles coalesce and disintegrate at the same rate, resulting in a plateau in bubble size. Increased liquid velocity, decreased liquid back-mixing, and a large increase in bubble break-up rate are all caused by dense heat exchange internals. There is a significant influence on mixing intensity and heat transfer rates when vertical tube bundles are present in the column, as well as a restriction on radial bubble motion and the confinement of the bubble size distribution. LHTCis very dependent on hydrodynamics, such as being improved by local turbulence. In this case, significant liquid recirculation creates more bubble-wake-induced turbulence, which makes the HTC better. According to [22], significant turbulence lowers the thickness of the thermal boundary thickness film, increasing the HTC. According to Saxena and Patel[32], the availability of internals can assist promote better mixing in BCs by restricting the maximum stable size of the bubbles. The HTC rose fast with the superficial gas velocity at low velocities due to improved liquid mixing in the column, which reduces the residence time of liquid components visiting the surface of heat exchange tubes and increases heat transfer rates.

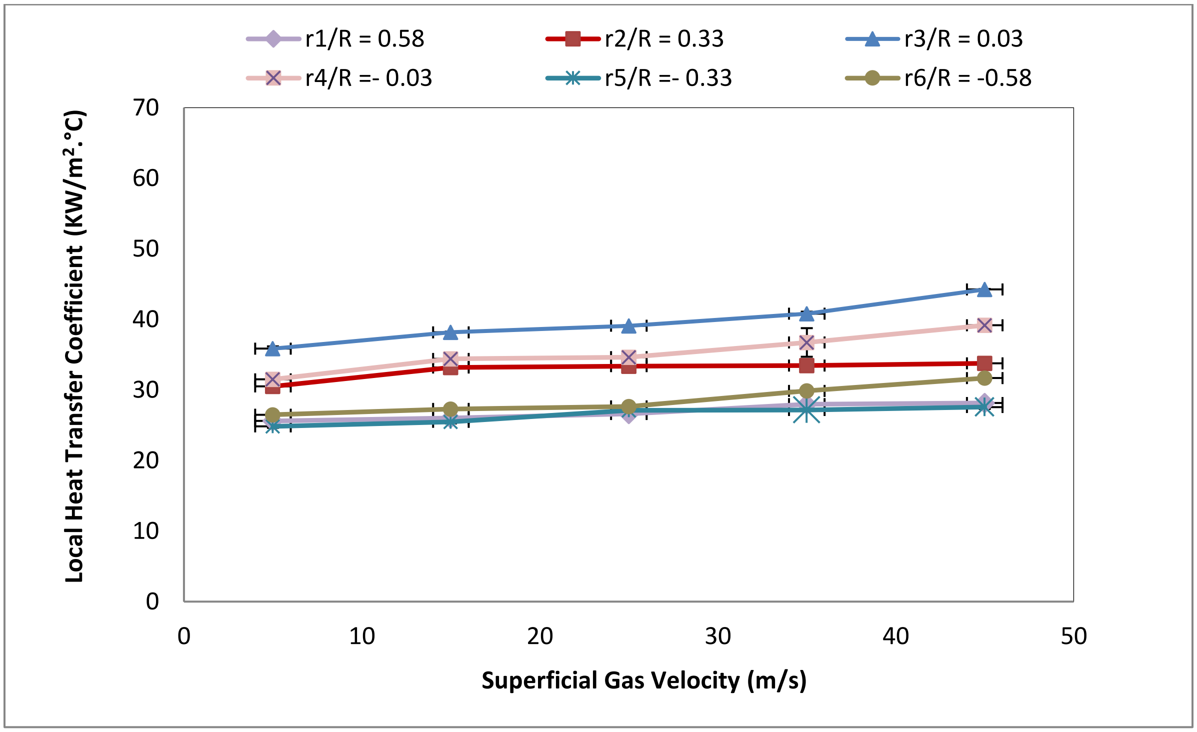

Figure 8: Impact of superficial gas velocity on local heat transfer coefficient at (Z/D=2.7)

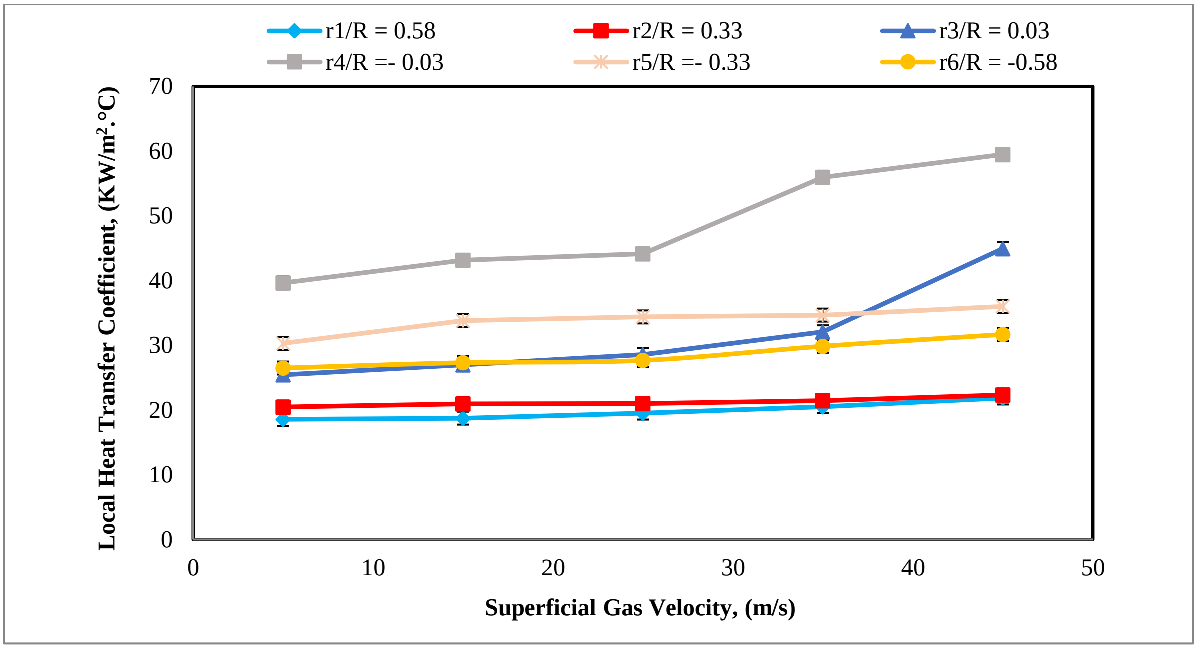

Figure 9: Impact of superficial gas velocity on local heat transfer coefficient at (Z/D=5)

Figure 9 compares the experimental findings of the LHTC with previous studies. The LHTC was evaluated in the center region with a wide range of superficial gas velocities. Furthermore, the experimental results for LHTC rise consistently with increasing superficial gas velocity, following the same trends as Rahman[33] and Kagumba[25]. It is worth noting that the LHTC values from the previous study are lower than the values from our study due to various reasons such as column diameter, probe shape, different tube configurations, and the height of the heat transfer probe from the distributor, as well as variations in cartridge heater dimensions in both cases.

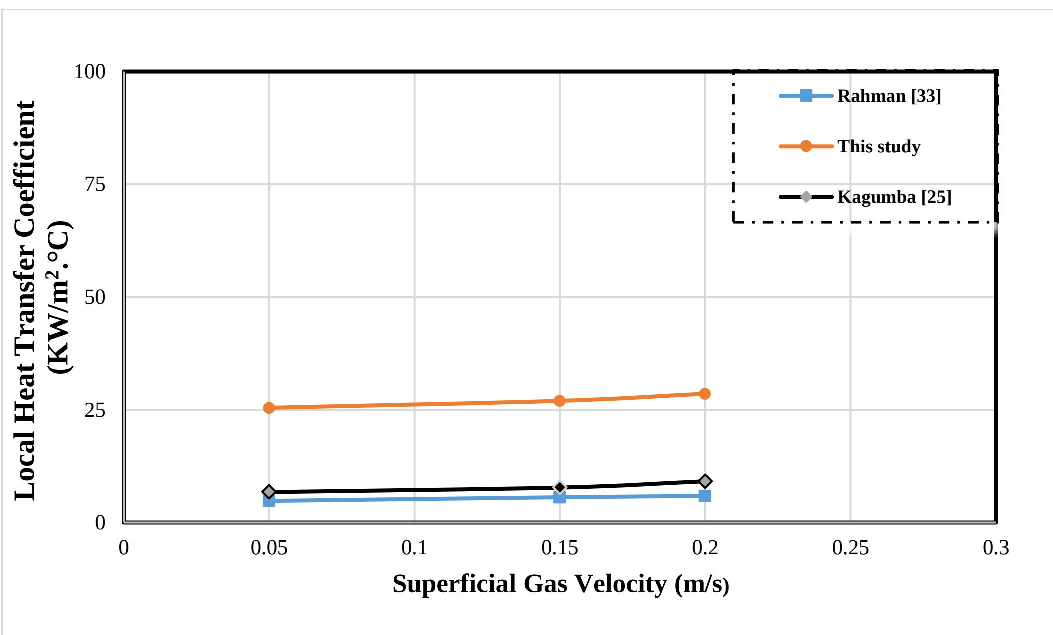

Figure 9: Comparison with existing data using different tubes arrangemant in the center region at different superficial gas velocities

3. Conclusion

The influence of the presence of bundle of heat exchanging tubes and their arrangement on LHTCs were evaluated using an advanced heat transfer technique in a 13 cm diameter bubble column. Additionally, the effect of superficial gas velocity, tube arrangement (i.e., triangular tube arrangement), radial location, and axial height on the LHTC was investigated over a wide range of superficial gas velocity (5-45 cm/s).The conclusions are summarized as follows:

1. The LHTCs increase as superficial gas velocity increases, and greater HTC values were obtained at the core of the column compared to the wall region.
2. Using a triangular tube configuration for arraigning tubes inside the BC causes distinct unsymmetrical HTC profiles along the diameter of the BC.
3. Unlike parabolic HTC profiles obtained in a BCwithout heat exchanging tubes, steeper HTC profiles are obtained in the BC when this column is equipped densely with a bundle of HETs.
4. The axial height was discovered to significantly affect the LHTC here high HTCs where high values of HTCs were obtained at fully developed flow region (Z/D=5) compared to gas distributor region (Z/D=2.7).

From the industrial point of view and according to the obtained results using a triangular tube arrangement causes a distinguished unsymmetrical (nonuniform distribution) HTC profiles; therefore, further investigations are needed to examine many tube arrangement deigns to choose the proper design toward reaching uniform distribution and consequently will improve the performance of such reactor.

Acknowledgement

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Nomenclature

A   A probe heat transfer area m^2

Z   The distance between the tubes and the gas distributor, m

Z/D   Axial distance above the gas distributor

h Local heat transfer coefficient between the heat flux sensor and the bulk of bubble column, $W/m^2.$ °C

$q^{"}$ The heat flux passed through the heat flux sensor, W/m^2

T_s Surface temperature, °C

T_b Bulk temperature, °C

h_i Instantaneous local heat transfer coefficient, $W/m^2.$ °C

$q^{"}_i$ Instantaneous heat flux, W/m^2

T_{si} Instantaneous surface temperature, °C

T_{bi} Instantaneous bulk temperature, °C

$h_{av.}$ Average heat transfer coefficient, $W/m^2.$ °C

N Total number of acquired data

r Radial location in the column, m

R Radius of column, m

LHTC Local heat transfer coefficient

HTC Heat transfer coefficient

HETs Heat exchanging tubes

BC Bubble column reactor

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