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# Experimental Study of Volumetric Mass Transfer Coefficients in Slurry Bubble Column Reactor

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## Abstract

Scaling up of Fisher-Tropsh requires suitably accurate estimations of hydrodynamic and mass transfer parameters as a function of column size and slurry concentration. The present study focuses on gas holdup, volumetric mass transfer and local mass transfer coefficients in a slurry bubble column employing a $C_9$-$C_{11}$ Iraqi paraffin oil as a liquid phase, alumina and silica particles as a solid phase and oxygen was used as a gas phase because the properties of the paraffin oil are similar to those of Fisher-Tropsch wax under actual operating conditions in the industrial slurry bubble column and alumina and silica serve as carrier for the active cobalt catalyst utilized in the Fischer-Tropsch process. The experimental work was carried out using two rectangular (0.1 m length, 0.02 m width and 0.95 m height) and (0.1 m length, 0.02 m width and 2.6 m height) slurry bubble columns. The superficial gas velocity was varied in the range of (1-6 cm/s) for short column and (7-12 cm/s) for long column. For all experiments the height of liquid phase was maintained at (75 cm) for short column and (160 cm) for long column from the gas distributor and solid loading varied in 0, 5, 10, 15% vol. The experimental results showed that the gas holdup increases linearly with superficial gas velocity at both homogeneous and heterogeneous regimes but the rate of increasing is slower at the heterogeneous flow and also the volumetric mass transfer coefficient increases with superficial gas velocity for both regimes. And the results showed that the gas holdup and volumetric mass transfer coefficient decreased with increasing solid loading.

**Keywords:** Slurry bubble column; Hydrodynamics; Mass transfer coefficient

## Introduction

The use of Bubble columns (BCs) is widely spread through a number of industries and will become especially important in the future in large scale conversion of natural gas and synthesis gas to fuels and chemicals. It is the future use of BCs that will severely test the current know-how applied to their design and operation. Hence, a more fundamental understanding of the fluid dynamics and transport processes in BC is highly desirable in order to reduce the uncertainties in scale-up and optimize the design and performance of these reactors. As one of the key reactor design parameters, the volumetric gas-liquid mass transfer coefficient, $K_La$, is directly affected by the hydrodynamics, phase mixing, and physical properties. In the ongoing effort to reduce uncertainty, there has been a large body of mass transfer research covering various specific topics of Luo et al. [1], Fan et al. [2], Behkish [3] and Vandu and Krishna [4]. Al-Zaharani and Daous [5] measured the volumetric mass and heat transfer coefficient inside a bubble column employing a single gas nozzle was measured and the effect of adding the solid phase was investigated. They showed that the use of a single nozzle helps to obtain fine and almost mono sized bubbles, and they investigate the effect of gas superficial velocity, solid concentration and static liquid height on mass and heat transfer coefficient in a bubble column using air-water and a cation resins as the solid phase. It was found that both volumetric mass and heat transfer coefficient increased with superficial gas velocity. An addition of 5% wt of suspended solids into the bubble column enhanced the volumetric mass transfer coefficient was observed when the superficial gas velocity greater than 0.056 m/s did not contribute to any further change in the values of this coefficient.

Vandu et al. [6] reported the results of an experimental study of the gas holdup, $\varepsilon_g$, and volumetric mass transfer coefficient, $K_La$, in a bubble column slurry reactor of 0.1m diameter operated at ambient temperature and pressure conditions. The superficial gas velocity U was varied in the range (0-0.4 m/s), Air was used as the gas phase. The liquid phase used was $C_9$-$C_{11}$ paraffin oil of porous catalyst (alumina catalyst support). With increasing slurry concentrations, $\varepsilon_G$ is significantly reduced due to enhanced bubble coalescence.

The objective of this study is to investigate the hydrodynamics and mass transfer parameters in a rectangular slurry bubble column reactor simulating the Fischer-Tropsch synthesis under actual conditions using Iraqi paraffin oil via hydrodynamics effect and their influence on superficial gas velocity and volumetric mass transfer coefficient.

### Experimental work

The experiments were carried out using two rectangular slurry bubble columns, which were made of Perspex to enable visual observation and photographic recording of the bubbles. One of them has dimensions of 0.1 m length, 0.02 m width and 0.95 m height and, the other of (0.1 m length, 0.02 m width and 2.6 m height) (Figure 1). The base plate of the column has one off-center orifice for liquid or slurry outflow and a central orifice for gas inflow through a distributor, which was supplied by oxygen cylindrical through check valve and a humidifier. The two columns had two pressure tapes located along the column, for short column distance between two tapes is 45cm, and for long column is 140 cm. The two pressure taps were connected to pressure difference transmitter by a plastic tube of 1cm inside diameter

placed at the bottom of the column. Normal Iraqi paraffin oil ($C_{10}$-$C_{13}$) mixture cut supplied by Arab Company for Detergent Chemicals is used as the liquid phase. Alumina and silica powders manufactured by "GMBH", Germany were used as solid phases. The properties of the catalyst carrier are similar to those envisaged for used in the commercial Fischer Tropsch reactor. Oxygen gas is used as a gas phase; with a purity of 97%. Nitrogen gas with a purity of 99% is employed to flash out the dissolved oxygen. Oxygen dissolved meter (type; LTT-Lutron, DO-5512 SD, Taiwan), and a high speed video camera (Sony, model No: HDR-XR550E, wide-angle is 26.3mm, Japan) were connected online. Pressure difference method was used to determine the pressure drop between two taps on the column by using a pressure transducer type (ST- 3000 Transmitter- "YAMATAKE", Japan). The slurry concentration, $\varepsilon_s$ was varied in the range 0, 5, and 10% vol. All experiments are conducted at ambient pressure and temperature conditions, and in a batch mood operation with respect to the liquid phase. The sensor constant value corresponds to an inherent delay in readings obtained as a result of the fact that the oxygen sensor has a finite response time and it is obtained as previously described Han and Al-Dahhan [7]. Sufficient time was given in each experimental run for the oxygen saturation concentration in the liquid, $C_L^*$ to be reached. When saturated concentration is achieved, the volumetric mass transfer coefficient $k_La$ can be calculated using eq. below:

$$K_L a = K_L a_L (1 - \varepsilon_g)(1 - f_s \varepsilon_s) \qquad (1)$$

where: $K_L a_L$ = the volumetric mass transfer coefficient per unit volume of liquid, $\varepsilon_g$ = gas holdup, $f_s$ = the volume fraction of the solid particles. $\varepsilon_s$ = solid holdup. Windows Media Player program was used to examine the flow pattern inside the column.

## Results and Discussion

### Effect of superficial gas velocity and solid loading on $K_L a$

The effect of superficial gas velocity on the volumetric mass transfer coefficient, $K_L a$ at different solid concentration is shown in Figure 2 and 3 and Table 1 for short and long columns and two types of solid loading. These figures indicate that the volumetric mass transfer coefficient, $K_L a$ increases rapidly from 0.01 to 0.12 sec$^{-1}$ at
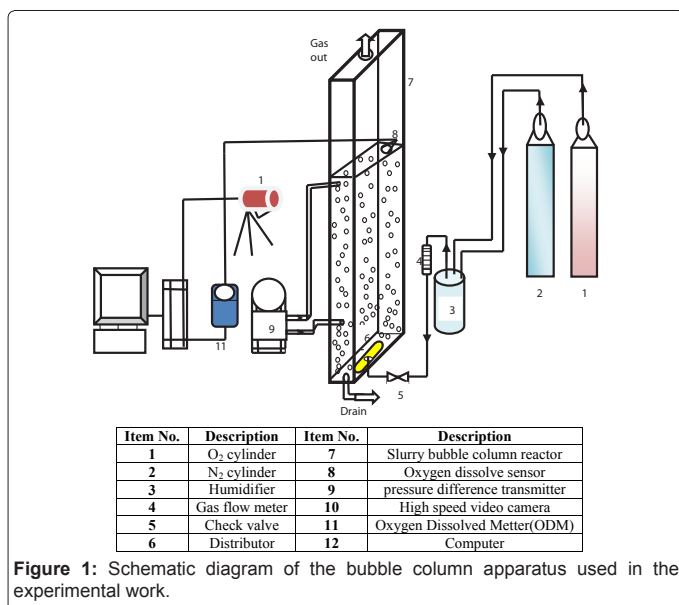


**Figure 1:** Schematic diagram of the bubble column apparatus used in the experimental work.

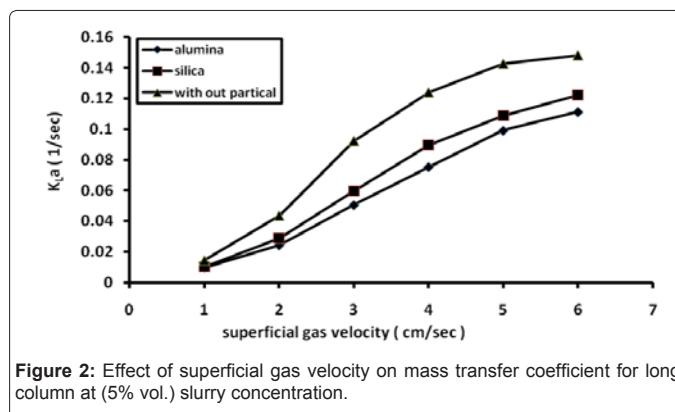| Item No. | Description | Item No. | Description |
|---|---|---|---|
| 1 | $O_2$ cylinder | 7 | Slurry bubble column reactor |
| 2 | $N_2$ cylinder | 8 | Oxygen dissolve sensor |
| 3 | Humidifier | 9 | pressure difference transmitter |
| 4 | Gas flow meter | 10 | High speed video camera |
| 5 | Check valve | 11 | Oxygen Dissolved Metter(ODM) |
| 6 | Distributor | 12 | Computer |



**Figure 2:** Effect of superficial gas velocity on mass transfer coefficient for long column at (5% vol.) slurry concentration.

zero loading with increase of superficial gas velocity (1-4) cm/sec, a less increase was realized in the case of using silica particles in the same range of velocity increasing (0.028-0.088 sec$^{-1}$), and alumina exhibited the lowest value increase with velocity graduation (0.01-0.074 sec$^{-1}$) but the increasing trend was reduced at high superficial gas velocities where it reached just 0.15, 0.12 and 0.107 (all in sec$^{-1}$) for no loading, silica and alumina respectively at 6 cm/sec. The reason for this increasing is mainly attributed to the increase in the interfacial area. As the superficial gas velocity increases, the mean bubble diameter decreases. However, the bubble size decreases up to a certain point and then remains constant even if the superficial gas velocity is increased further. Thus, the increase in the interfacial area can be explained mainly as a result of the higher superficial gas velocity. An increase in the superficial gas velocity also enhances the turbulence induced by the gas flow, which increases $K_L$. The increase in the interfacial area and $K_L$ at high superficial gas velocities predominates over the decrease in the mass-transfer coefficient because of shorter gas-liquid contacting time and results in an increase in $K_L a$. These results are in agreement with results of Al-Zahrani and Daous [5], Behkish [3], Abdul-Rahman and Alazzi [8] and Asgharpour et al. [9]. The volumetric mass transfer coefficient, $K_L a$ decreases also in the range of (0.108- 0.0983) sec$^{-1}$ with increasing the alumina concentration from 5-10%, this behavior can be attributed to the bubble size distribution in the column under these conditions. Although the volume fraction of gas bubbles is reduced at lower solid concentrations, this reduced volume mainly consists of a large population of small gas bubbles, contributing enormously to the gas-liquid interfacial area. When increasing solid concentration above certain value, however, the relative change of the volume fraction of small gas bubbles slightly decreases, whereas the population of these small bubbles sharply decreases due to coalescence, resulting in a sharp decrease of the gas-liquid interfacial area and subsequently $K_L a$. These results are in agreement with results of Behkish [3], Vandu and Krishna [4] and Abdul-Rahman and Alazzi [8] and in disagreement with results of Vandu et al. [6] and Hashemi et al. [10]

### Effect of superficial gas velocity and solid loading on gas holdup ($\varepsilon g$)

The effect of superficial gas velocity on the gas holdup, $\varepsilon_g$ at different solid concentration is shown in Figure 4 and 5 and Table 1 for short column and long column. These figures indicate that the gas holdup, $\varepsilon_g$ increases with increasing of superficial gas velocity for both columns, the gas holdup increases sharply as $U_g$ increases. A decrease in the slope of variation curve signifies the onset of bubble clustering and hence the

| Type of column | $U_g$ (cm/sec) | Pressure drop (mbar) | Gas holdup ( - ) | $K_L a_L$ (1/sec) | $K_L a$ (1/sec) |
|---|---|---|---|---|---|
| Silica, short column | 1 | 67 | 0.034586 | 0.003484 | 0.008396 |
| | 2 | 65 | 0.0625 | 0.025331 | 0.021373 |
| | 3 | 64 | 0.090909 | 0.049638 | 0.040613 |
| | 4 | 63 | 0.112426 | 0.090606 | 0.072378 |
| | 5 | 62 | 0.132948 | 0.118559 | 0.092517 |
| | 6 | 61 | 0.152542 | 0.133584 | 0.101886 |
| Alumina, short column | 1 | 80 | 0.034586 | 0.00415 | 0.003606 |
| | 2 | 79 | 0.0625 | 0.02005 | 0.016917 |
| | 3 | 77 | 0.090909 | 0.04229 | 0.034601 |
| | 4 | 76 | 0.112426 | 0.0796 | 0.063586 |
| | 5 | 75 | 0.132948 | 0.10846 | 0.084636 |
| | 6 | 74 | 0.152542 | 0.12899 | 0.098382 |
| Silica, long column | 7 | 142 | 0.116022 | 0.05774 | 0.045937 |
| | 8 | 140 | 0.130435 | 0.080335 | 0.062871 |
| | 9 | 136 | 0.139785 | 0.13289 | 0.102883 |
| | 10 | 134 | 0.148936 | 0.16665 | 0.127647 |
| | 11 | 132 | 0.162304 | 0.20004 | 0.150815 |
| | 12 | 130 | 0.175258 | 0.24998 | 0.185552 |
| Alumina, long column | 7 | 172 | 0.111111 | 0.05333 | 0.042664 |
| | 8 | 169 | 0.123288 | 0.0741 | 0.058468 |
| | 9 | 166 | 0.135135 | 0.1158 | 0.090136 |
| | 10 | 163 | 0.144385 | 0.1546 | 0.11905 |
| | 11 | 161 | 0.153439 | 0.18839 | 0.143535 |
| | 12 | 159 | 0.157895 | 0.2011 | 0.152413 |

**Table 1:** Experimental results for 10% loading in long and short column using alumina and silica.

onset of the churn-turbulent bubble regime. As $U_g$ further increases, bubble collisions intensify, leading to more bubble clustering. Larger bubble clusters rise faster and tend to aggregate in the center of the bubble column. As they rise, the momentum of these clusters is transferred to smaller bubbles and hence increases their rising velocity. The clustering effect contributes to a decrease in the rate of increase of the gas holdup with increasing $U_g$. This maximum point corresponds to the onset of bubble coalescence. These larger bubbles have a much higher rise velocity, causing a decrease in the gas holdup. As the gas velocity further increases, the gas holdup increases solely due to the higher through flow of the gas. At ambient pressure, the sharp increase in gas holdup at low $U_g$ is not observed. The regime transition is believed to occur at $U_g$ lower than the minimum measurement condition. Therefore, these figures show that the gas holdup is mainly dependent on the superficial gas velocity and solid concentration. These results are in agreement with results of Vandu et al. [6], Behkish [3], Hashemi et al. [10], Abid and Jameel [11], Sulaymon et al. [12]
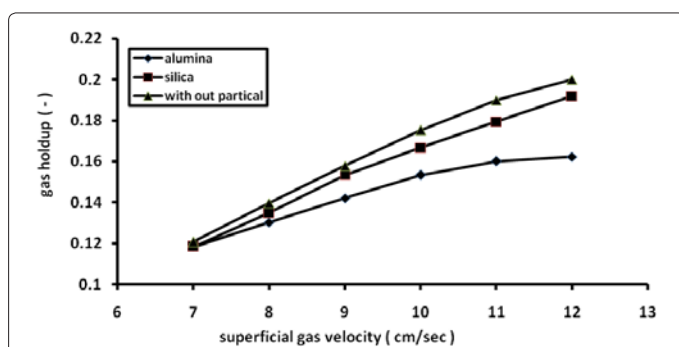


**Figure 3:** Effect of superficial gas velocity on gas holdup for long column at (5% vol.) slurry concentration.
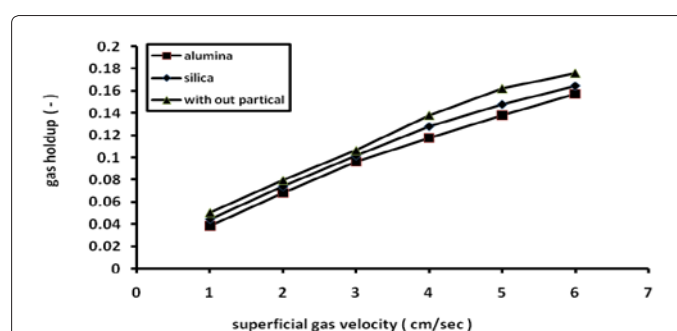


**Figure 4:** Effect of superficial gas velocity on gas holdup for short column at (5% vol.) slurry concentration.

and Asgharpour et al. [9]. These figures show also that the gas holdup, $\varepsilon_g$ decreases with the increase in the solid concentration for both columns. As seen from these figures that this decreasing is more rapid at high solid concentration and high superficial gas velocity. The reason is mainly due to the increase in the apparent viscosity. Actually, the influence of increasing liquid viscosity and solid concentration on the hydrodynamics is the same qualitatively; this increase is accompanied by significant increase of average bubble size which results in an increase in bubble rise velocity and decrease in the gas holdup. These results are in agreement with results of Li and Prakash [13], Mena et al. [14], Vando and Krishna [4] and Vandu et al. [6] and Alwasiti et al. [13]

## Conclusions

The gas holdup increases from (0.01315 to 0.1758) with increasing superficial gas velocity from (1 to 6 cm/s) and increases from (0.101124 to 0.2) with increasing superficial gas velocity from (7 to 12 cm/s), and
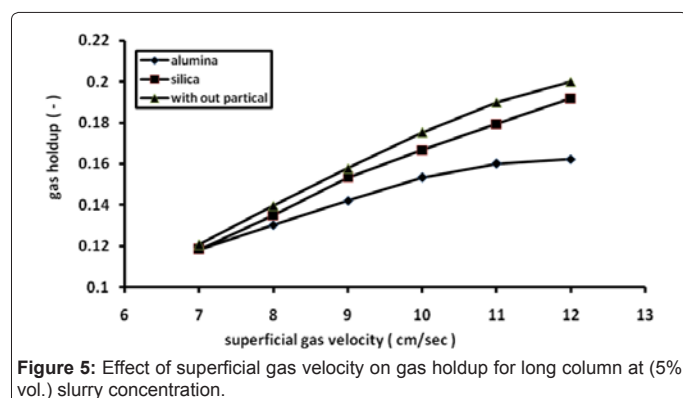
**Figure 5:** Effect of superficial gas velocity on gas holdup for long column at (5% vol.) slurry concentration.

decreases with increasing solid concentration. The volumetric mass transfer coefficient increases from (0.002826 to 0.148043 $s^{-1}$) with increasing superficial gas velocity from (1 to 6 cm/s) and increases from (0.024593 to 0.239051 $s^{-1}$) with increasing superficial gas velocity from (7 to 12 cm/s), and decreases with increasing solid concentration and it is higher for silica loading than alumina loading.

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