

Study of Mass Transfer Coefficient in a Wetted Wall Column

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Abstract

Gas absorption is the unit operation in which one or more soluble components of gas mixture are dissolved in a liquid. The absorption may be a purely physical phenomenon or may involve chemical reaction with one or more constituents in the liquid solution. In order to obtain the highest rate of absorption, gas and liquid streams flow in opposite directions in counter-current flow. The unit in this work has been designed to help grasp the basic principles of the chemical and physical aspects involved in absorption. This study unit is made of borosilicate transparent glass in order to show the water spread in the column and get the visual distribution of fluids behavior which helps to fully understand the phenomenon. In the spray wetted wall columns, an efficient contact between the phases is achieved by atomizing through fixed or rotary nozzles. The nozzles are arranged along the periphery and the fluids are fed in a counter-current flow. This obstruction-free operation makes this type of process suitable to treat flow rate containing a great number of solid particles. In this work, the wetted wall column is used to determine gas/liquid mass transfer coefficients, which is essential to design absorption towers. This study investigates the absorption of oxygen from air into deoxygenated water (prepared by nitrogen sparging) in liquid film-controlled absorption experiment. The liquid film mass transfer coefficient is calculated at various mass flow rates of water and air. This work also studies the effect of water flow and air flow on oxygen concentration in the oxygenation and de-oxygenation process.

Keywords: Absorption; wetted wall; mass transfer coefficient; oxygenation; deoxygenation.

1. Introduction

The removal of one or more selected components from a mixture of gases by absorption into a suitable liquid is the second major operation of chemical engineering that is based on interphase mass transfer controlled largely by rates of diffusion. The gas-liquid absorption process may be treated as a physical process; the chemical reaction doesn't hold considerable effect. However when nitrogen oxides are absorbed in water to produce nitric acid, or when carbon dioxide is absorbed in a solution of sodium hydroxide, a chemical reaction occurs, which effects the actual rate of absorption. Absorption processes are therefore conveniently divided into two groups, those in which the process is solely physical and those where a chemical reaction is af-

fecting the process. In considering the design of equipment to achieve gas absorption, the main requirement is that the gas should be brought into intimate contact with the liquid, and the effecting of the equipment will mainly be determined by the contact degree reached between the two phases. In absorption, usually the gas is fed at the bottom of the column, and the solvent is fed at the top. The solvent and absorbed gas leave at the bottom, and the unabsorbed components leave as gas from the top. The essential difference between distillation and absorption is that in the former the vapour has to be produced in each stage by partial vaporization of the liquid at its boiling point, whereas in absorption the liquid is well below its boiling point. In distillation there is a diffusion of molecules in both

directions, so that for an ideal system equimolecular counter diffusion takes place, though in absorption gas molecules are diffusing into the liquid, with negligible transfer in the reverse direction, in general, the ratio of the liquid to the gas flow rate is considerably greater in absorption than in distillation with the result that layout of the trays is different in the two cases [1].

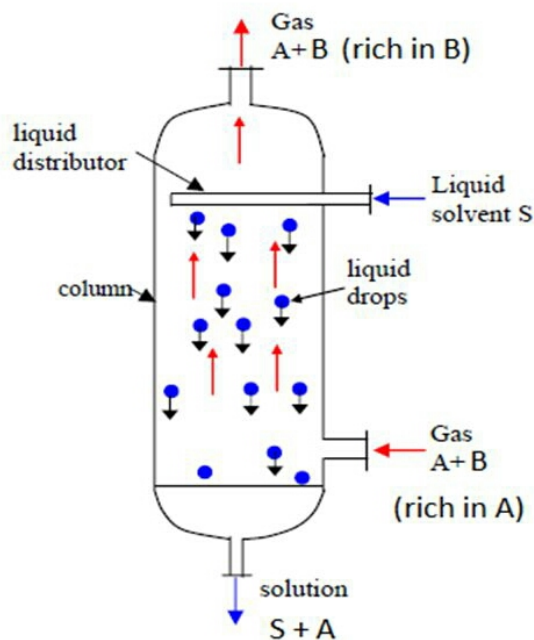


Figure 1.1: Spray column used in gas absorption [2].

The equipment used for continuous gas/liquid contact can be a tower filled with solid packing material, an empty tower into which the liquid is sprayed and through which the gas flows, or a tower that contains a number of bubble-cap, sieve or plates. Other typical absorption operations are carried out in spray columns, wetted wall columns, and stirred vessels. In general the gas and the liquid stream counter current to each other in order to obtain the greatest rate of absorption.

In this work an absorption spray column is used, where the contact surface between the phases is obtained by atomizing through fixed nozzles. The nozzles are arranged along the periphery and the fluids are fed in counter-current flow. Obstruction free operation makes this type of columns particularly suitable to treat flow rate containing a great

amount of solid particles.

Some of the spray columns advantages are Continuous contact, Low pressure drop, Low cost, Gas phase controlling and Considered as one stage.

The main goal in this experimental work is to study of mass transfer coefficient in wetted wall columns, and to investigate the effects of water and air flow rates on the mass transfer coefficient [2].

2. Mythology and Experimental work

Wetted wall gas absorption columns can be used to estimate the mass transfer coefficients between gases and liquids, essential in the design of absorption towers. This aspect is the most important one to determine the size of such towers, since they serve as a basis from which correlations have been developed for absorption towers.



Figure 2.1: Wetted wall gas absorption column.

As seen in Figure 2.1, a wet film absorption column (or wetted wall gas) contains, essentially, in a

vertical tube through which a liquid inclines; temporarily a gas rises through it. The gas, when contacting the liquid, is partially spread in it by means of the mass transfer. This process is usually used to study the mass transfer between two components in two different phases due to the fact that there is an interfacial film between such phases in the wet film column, dissimilar other processes. It will be assumed that such superficial area corresponds to the inner surface of such tube, so that the liquid can be in the shape of a thin laminar film [5].

3. Experimental Description

The operating principle of the unit is very simple. The feeding pump (2) draws water from tank (1) to the oxygenation column (3), where it is sprayed by a special nozzle onto the internal wall of the cylinder in order to obtain a wetted wall. The air pump (9) pumps air in a counter-current at flow to the flowing water in the column. Oxygen is continuously absorbed from the flowing air by the seeping water on the wall. The water is drawn from the bottom of the column by the pump P2 (4) and sent to flow meter (5) and to the sampling vessel 1 (6) where probe 1 measures the saturation of the treated water. Afterwards, the oxygenated water is sent to the de-oxygenation column (7), where it is sprayed on the internal wall of the cylinder. Nitrogen is pumped inside the column in counter-current flow to extract the oxygen from the water.

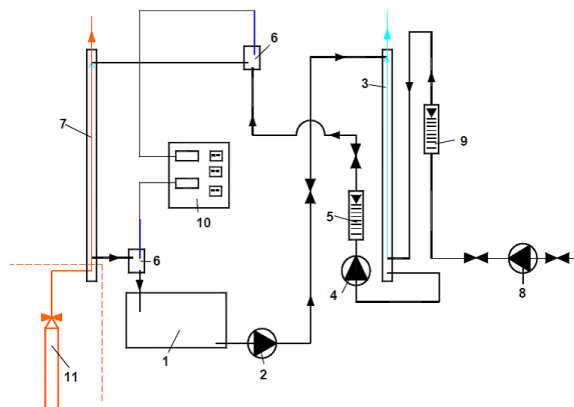


Figure 3.1: Flow chart of the plant [2].

The system chosen for the experiment is the absorption of oxygen into oxygen free water. In this system the solubility and enthalpy of the solution

are small and by saturating the inlet air with water, humidification effects are eliminated. Thus it is possible to maintain reasonably isothermal conditions throughout the column [5]. Experimental procedure allows a power-law relationship to be calculated and a comparison is made between this and published relationships such as:

$$Sh = (Sc)^{0.5} (Ga)^{0.17} (Re)^n \quad (3.1)$$

That is, for a given gas/liquid system:

$$(Sh)_L \propto (Re)_L^n$$

$$\frac{K_L Z}{D_L} \propto \frac{\rho u d}{\mu}$$

Thus, construction of a logarithmic graph:

$$\frac{K_L Z}{D_L} \text{ vs } (Re)_L$$

for various flow rates of oxygen (in the form of air) a power law can be determined and compared to published values.

Inter diffusion coefficient in dilute solutions can be calculated as follows:

$$D_{AB} = \frac{1.17 \times 10^{-13} (\zeta_B M W_B)^{0.5} T}{V A^{0.6} \mu} \quad (3.2)$$

Recommended values for the association factor are:

2.6 of water. Oxygen → Water
solvent B = H₂O , solute A=O₂

$$V_A = 2 \times 7.4 \times 10^{-3} \\ = 0.0148 \frac{m^3}{kgmol}$$

$$D_{AB} = \frac{1.17 \times 10^{-13} (2.6 \times 18)^{0.5} \times 298.15}{(0.0148)^{0.6} \times 8.96 \times 10^{-4}} \\ = 3.336 \times 10^{-6} \frac{m^2}{s}$$

Reynolds Number can be estimated by following equation:

$$Re_L = \frac{\rho_L u d}{\mu_L} \quad (3.3)$$

Column surface area

$$A = \pi (r)^2 \quad (3.4)$$

$$\pi (0.016)^2 = 0.804 \times 10^{-3} m^2$$

Calculation of velocity

$$u = Q/A \quad (3.5)$$

$$u = \frac{1.389 \times 10^{-6}}{0.804 \times 10^{-3}} = 1.727 \times 10^{-3} \frac{m}{s}$$

$$Re = \frac{996.28 \times 1.727 \times 10^{-3} \times 0.032}{8.96 \times 10^{-4}}$$

$$= 61.449$$

Table 3.1: Data of Reynolds number

$Q \left(\frac{m^3}{s} \right)$	$A \left(m^2 \right)$	$u \left(\frac{m}{s} \right)$	$\rho_L \left(\frac{kg}{m^3} \right)$	$\mu_L \left(\frac{kg}{m.s} \right)$	Re_L
1.4×10^{-6}	0.8×10^{-3}	1.72×10^{-3}	996.3	8.96×10^{-4}	61
2.8×10^{-6}	0.8×10^{-3}	3.5×10^{-3}	996.3	8.96×10^{-4}	123
4.2×10^{-6}	$\times 10^{-3}$	5.2×10^{-3}	996.3	8.96×10^{-4}	184
5.6×10^{-6}	0.8×10^{-3}	6.90×10^{-3}	996.3	8.96×10^{-4}	246
6.9×10^{-6}	0.8×10^{-3}	8.6×10^{-3}	996.3	8.96×10^{-4}	307

Calculation of liquid flow rate

$$\Gamma = \frac{Q}{h} \times \rho \quad (3.6)$$

$$\Gamma = \frac{1.389 \times 10^{-6}}{0.9} \times 996.28$$

$$= 1.537 \times 10^{-3} \frac{kg}{m.s}$$

$$B_F = \left(\frac{3ur}{\rho^2 g} \right)^{\frac{1}{3}} \quad (3.7)$$

$$B_F = \left(\frac{3 \times 1.727 \times 10^{-3} \times 1.537^{-3}}{(996.28)^2 \times 9.81} \right)^{\frac{1}{3}}$$

$$= 9.351 \times 10^{-5}$$

Calculation of mass transfer coefficient

$$K_L = 0.422 \sqrt{\frac{D_L \Gamma}{\rho B F^2}} \quad (3.8)$$

$$K_L = 0.422 \sqrt{\frac{3.336 \times 10^{-6} \times 1.537 \times 10^{-3}}{996.28 \times (9.351 \times 10^{-5})^2}}$$

$$= 0.01 \frac{m}{s}$$

Calculation of Sherwood number

$$Sh = \frac{K_L Z}{D_L} \quad (3.9)$$

$$= \frac{0.01 \times 0.9}{3.336 \times 10^{-6}} = 2697.84$$

Table 3.2: Data of Reynolds number

$u \left(\frac{m}{s} \right)$	$Q \left(\frac{m^3}{s} \right)$	$\Gamma \left(\frac{kg}{m.s} \right)$	B_F	$K_L \left(\frac{m}{s} \right)$	$\frac{K_L Z}{D_L}$
1.72×10^{-3}	1.4×10^{-6}	1.6×10^{-3}	9.4×10^{-4}	0.01	2698
3.5×10^{-3}	2.8×10^{-6}	3.1×10^{-3}	1.5×10^{-4}	0.014	3777
5.2×10^{-3}	4.2×10^{-6}	4.6×10^{-3}	2.0×10^{-4}	0.017	4856
6.90×10^{-3}	5.6×10^{-6}	6.2×10^{-3}	2.4×10^{-4}	0.02	5396
8.6×10^{-3}	6.9×10^{-6}	7.7×10^{-3}	2.7×10^{-4}	0.023	6205

$$Sh = 0.32 Sc^{0.5} Ga^{0.17} Re^{0.5} \quad (3.10)$$

Calculation of Schmidt number

$$Sc_L = \frac{\mu}{\rho D_L} \quad (3.11)$$

$$= \frac{8.96 \times 10^{-4}}{996.28 \times 3.336 \times 10^{-6}} = 0.27$$

Calculation of Galileo number

$$Ga_L = \frac{dp^3 g \rho^2}{\mu^2} \quad (3.12)$$

$$= \frac{(0.032)^3 \times 9.81 \times (996.28)^2}{(8.96 \times 10^{-4})^2}$$

$$= 0.397 \times 10^9$$

$$Sh = 0.32 \times (61.679)^{0.5} (0.27)^{0.5} (0.397 \times 10^9)^{0.17}$$

$$= 37.618$$

Table 3.3: Data of Sherwood and Reynolds number

Sh	Re	$\frac{Sh}{Sc.Ga}$
2.50	62	37.6
3.54	123	53.2
4.33	185	65.1
5.00	247	75.1
5.60	308	84.0

Calculation of flooding gas velocity

$$U_f = F_1 F_2 \left(\frac{\sigma}{\rho g} \right)^{0.5} \quad (3.13)$$

The data covered column sizes up to 50-mm (2-in) diameter; the correlation should be use l with caution for larger columns.

$$F_2 = \left(\frac{G}{L} \right)^{0.25} \quad (3.14)$$

$$L = Q\rho \quad (3.15)$$

$$L = 6.944 \times 10^{-6} \times 996.28$$

$$= 6.9 \times 10^{-3} \frac{kg}{s}$$

$$G = Q\rho \quad (3.16)$$

$$G = 8.33 \times 10^{-4} \times 1.186$$

$$= 9.88 \times 10^{-4} \frac{kg}{s}$$

$$F_2 = \left(\frac{9.88 \times 10^{-4}}{6.918 \times 10^{-3}} \right)^{0.25} = 0.615$$

Calculation of Surface Tension

$$\sigma = A(1 - T_r)^{(B+CT_r+DT_r^2+ET_r^3)} \quad (3.17)$$

A = 0.18548 , B = 2.717 , C = -3.554 , D = 2.047 , E = 0

$$T_r = \frac{T}{T_c} \quad (3.18)$$

$$= \frac{298.15}{647.13} = 0.46$$

$$\sigma = 0.185(1 - 0.46)^{(2.7+(-3.5)(0.46)+(2.04)(0.46)^2+(0)(0.46)^3)}$$

$$= 0.0729 \frac{N}{m}$$

$$F_1 : 1.22 \text{ when } 3.2 \frac{d_i}{\sigma} > 1.0$$

As $3.2 \frac{0.032}{0.0729} = 1.404$
 $F_1 = 1.22$

$$U_f = 1.22 \times 0.615 \left(\frac{0.0729}{1.186} \right)^{0.5} = 0.186 \frac{m}{s}$$

4. Results and Discussion

Theoretical and experimental data of mass transfer coefficient at different Reynolds numbers or air velocities were compared. The plotted data in Figures 4.1 and 4.2 show the comparison at various Reynolds numbers. A close fit between the predicted and the experimental data was found in Figures 4.1 and 4.2. These findings indicate that the mass transfer coefficient equation developed in this work has a sufficient degree of accuracy. Generally, it was found that the discrepancy was lower at low Reynolds but it increases as Reynolds number increases. Also the work shows that Sherwood number increases proportionally with Reynolds number.

$$Sh = 0.32(Re)^n (Sc)^{0.5} (Ga)^{0.17} \quad (4.1)$$

In Figure 4.1, it is observed that the oxygen concentration is highly dependent on Reynolds number and it increases linearly as Reynolds number increases. Generally, all curve trends show Sherwood number is increasing linearly with Reynolds number, and they can be correlated as follows:

$$Sh = 0.32(Re)^{0.5} (Sc)^{0.5} (Ga)^{0.17} \quad (4.2)$$

In Figure 4.2 clearly shows that, the deviation between the calculated and experimental values is increasing as Reynolds number increases. At low Reynolds number the deviation is around 35%, while at high Reynolds number it is about 45%, because of the effect of air high velocities on oxygen concentration.

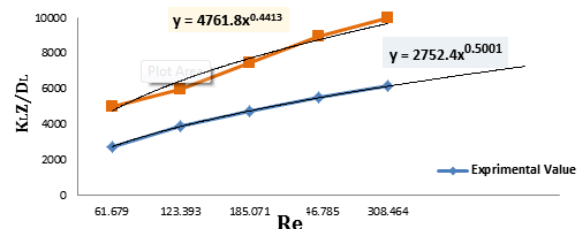


Figure 4.1: Comparison between the experimental data & published data

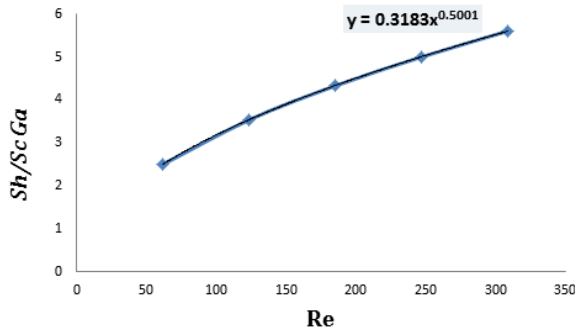


Figure 4.2: Relationship between Sherwood number & Reynolds number

Figure 4.3 to 4.6 illustrate the experimental correlation between the air flow rate and oxygen concentration with a constant counter water flow rate of $(1.389 \times 10^{-6} \text{ m}^3/\text{s})$ within a time interval of (2 min). In general, these figures show a gradual increase in oxygen concentration as the air flow rate increases, which is due to the oxygen absorption in the water. The oxygen absorption rate, itself, gradually decreases till the water reaches its saturation state, and the oxygen oxygen absorption stops.

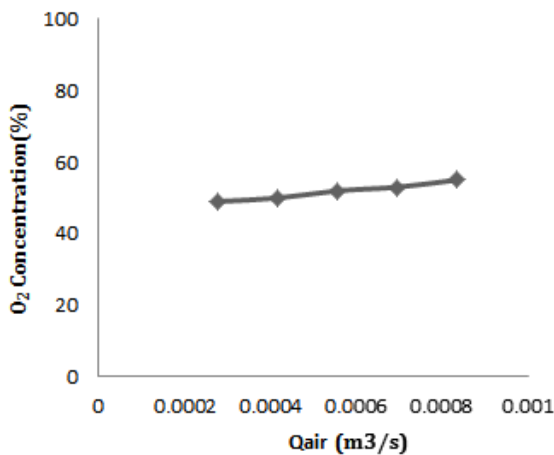


Figure 4.3: . Relation between air flow rate & oxygen concentration rate in Probe 1 at water flow rate $(1.389 \times 10^{-6} \text{ m}^3/\text{s})$.

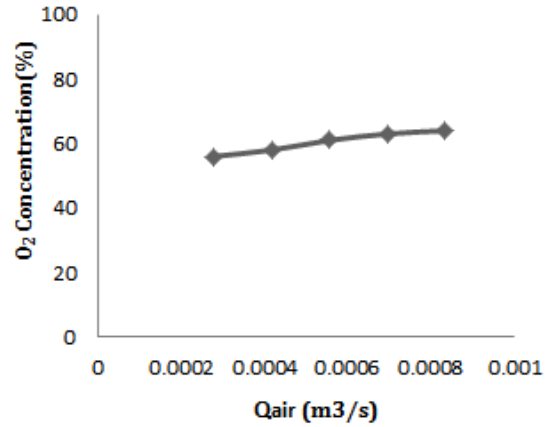


Figure 4.4: Relation between air flow rate & oxygen concentration rate in Probe 1 at flow rate water $(2.778 \times 10^{-6} \text{ m}^3/\text{s})$.

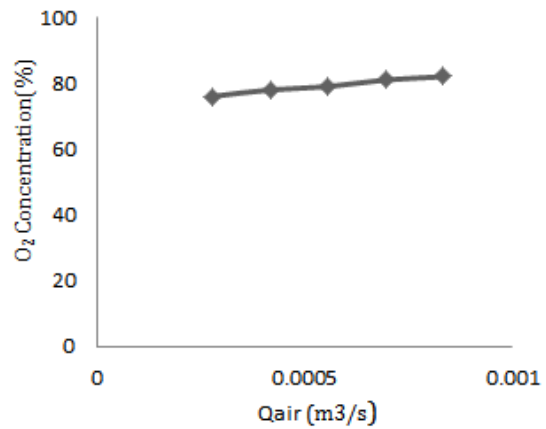


Figure 4.5: Relation between air flow rate & oxygen concentration rate in Probe 1 at water flow rate $(4.167 \times 10^{-6} \text{ m}^3/\text{s})$.

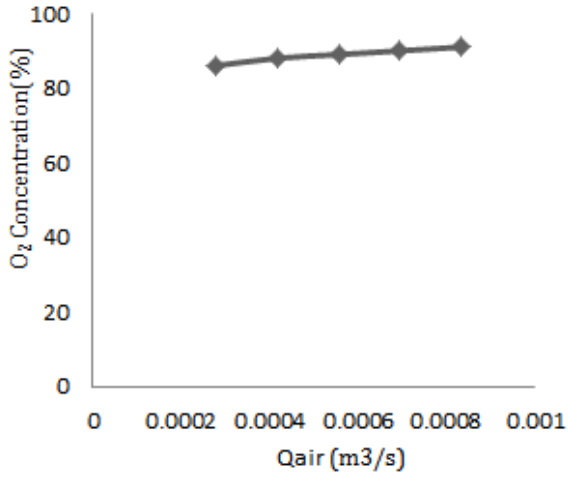


Figure 4.6: Relation between air flow rate & oxygen concentration rate in Probe 1 at water flow rate ($5.555 \times 10^{-6} \text{m}^3/\text{s}$).

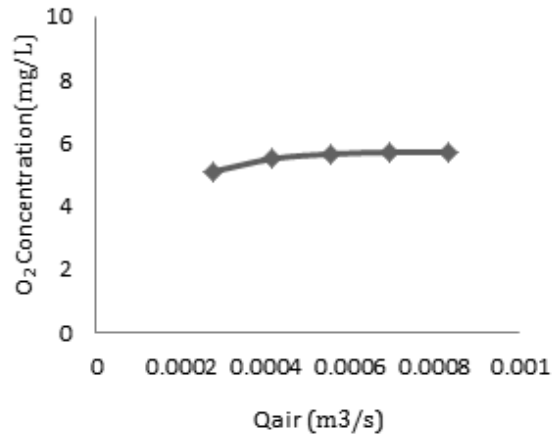


Figure 4.8: Relation between air flow rate & oxygen concentration rate in Probe 2 at flow rate water ($2.778 \times 10^{-6} \text{m}^3/\text{s}$).

The curves trends in Figures 4.7 and 4.8, show that, at same constant water flow rate, the oxygen concentration in (probe 2) are slightly increasing with the increase of air flow rates. This hardly noticeable effect is due to the fact that the water is either at, or is approaching its oxygen saturation state.

Figures 4.9 and 4.10 show the effect of water flow rate on the oxygen concentration. The oxygen concentration decreases as the water flow rate increases. This is due to the water turbulence flow in the column. During the turbulence flow, the oxygen absorption rate drops significantly because of smaller mass transfer areas and less times of exposure as opposed to the smooth laminar flow.

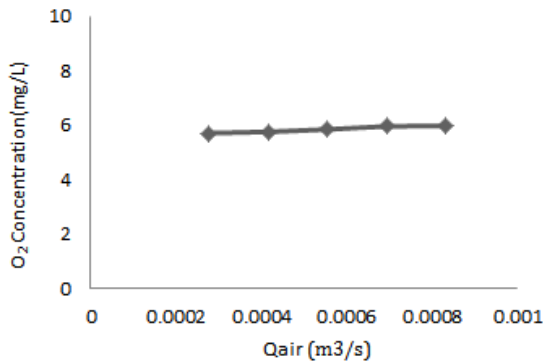


Figure 4.7: Relation between air flow rate & oxygen concentration rate in Probe 2 at water flow rate ($1.389 \times 10^{-6} \text{m}^3/\text{s}$).

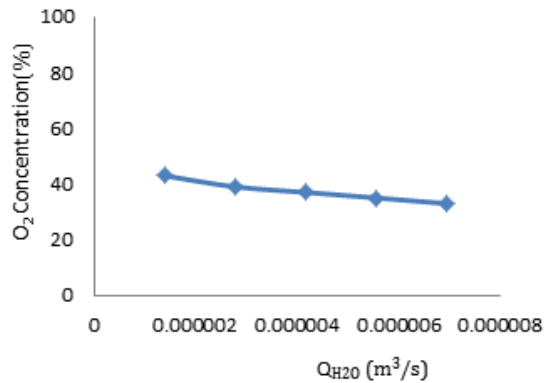


Figure 4.9: . Relation between water flow rate & oxygen concentration rate in Probe 1 at air flow rate ($2.778 \times 10^{-4} \text{m}^3/\text{s}$).

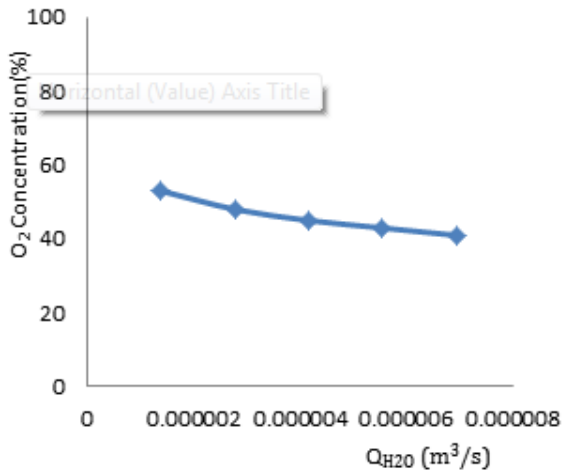


Figure 4.10: Relation between water flow rate & oxygen concentration rate in Probe 1 at air flow rate ($4.166 \times 10^{-4} m^3/s$).

Figures 4.11, and 4.12 show that the oxygen concentration in (probe 2) declines tiredly with the increase of water flow rate at some constant air flow rate which is caused by the gradual increase of oxygen concentration.

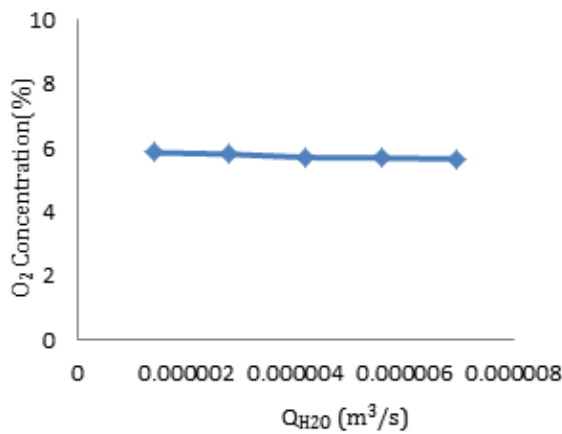


Figure 4.11: Relation between water flow rate & oxygen concentration rate in Probe2 at air flow rate ($2.778 \times 10^{-4} m^3/s$).

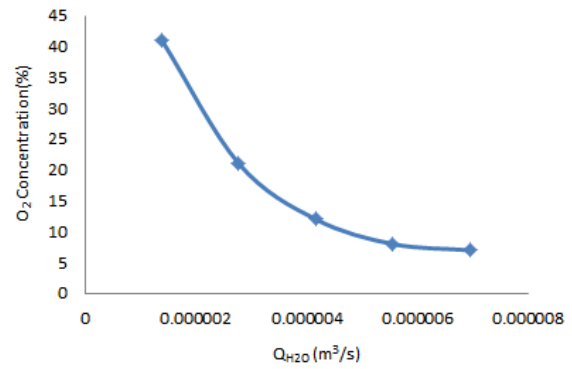


Figure 4.13: Relation between water flow rate & oxygen concentration rate in Probe 1 at nitrogen flow rate ($250 m^3/s$).

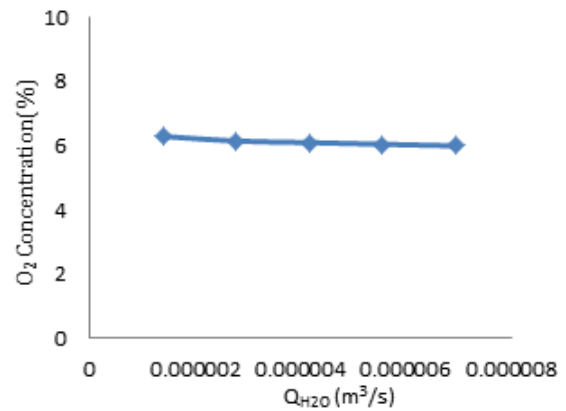


Figure 4.12: Relation between water flow rate & oxygen concentration rate in Probe2 at air flow rate ($6.944 \times 10^{-4} m^3/s$).

In De-oxidation process, the air pump has to be switched off. The oxygen concentrations are obtained at different water flow rates, and then plotted in Figure 4.13. The oxygen concentrations at probe1 drop significantly with the increase of water flow rate at the beginning of the trend. However, the trend declines at a smaller gradient in the rest of the curve.

5. Conclusion and recommendation

- Good agreement between the previously published and the experimental data was found indicating that the models used in this work to estimate the

mass transfer coefficient have a sufficient degree of accuracy.

- Some of the plotted correlations indicate that the oxygen concentration at probe2 increases slightly with the increase of air flow rate at constant water flow.
- The oxygen concentrations at probe1 drop significantly with the increase of water flow rate at the beginning of the trend.
- Nitrogen has a significant influence as a reduction factor to extract the oxygen from the oxygenated water in the de-oxidation process.
- For future studies, the temperature effect on oxygen concentration can be investigated in wetted wall gas absorption. In addition, graphical correlations of mass transfer coefficients of some other substances can be thoroughly studied, instead of O_2

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