A study on the effectiveness of gas absorption in oxygen-water system by using modified wetted-wall column

By

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Dissertation submitted in partial fulfillment of

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1) Absorption
2) Gases -- Absorption and adsorption

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Approved by,

(Associate Professor Ir Abdul Aziz Omar)
Supervisor

UNIVERSITI TEKNOLOGI PETRONAS

TRONOH, PERAK

May 2005

CERTIFICATE OF ORIGINALITY

This is to certify that I am responsible for the work submitted for this project, that the original work is my own except as specified in the references and acknowledgements, and that the original work contained herein have not been taken or done by unspecified sources or persons.

Atifah

NOR ATIFAH BINTI MOHD HADZIR

CHAPTER 1

INTRODUCTION

1.1 Background of Study

Absorption, also known as gas absorption, gas washing and gas scrubbing is a unit operation used in the chemical industry to separate gases by washing or scrubbing a gas mixture with a non-volatile and suitable liquid. One or more constituents of the gas mixture is or are selectively dissolved or is absorbed in the liquid and can thus be removed from the mixture. Thus, the species of interest in the gas mixture may be all components, only the component(s) not transferred, or only the component(s) transferred (Seader and Henley, 1998). In some systems, this gaseous constituent forms a physical solution with the liquid or the solvent, and in other cases, it reacts with the liquid chemically. The purposes of absorption may be for *gas purification* (i.e. removal of air pollutants from exhaust gases, contaminations and catalyst poisons from gases that will be further processed), *product recovery*, or *production of solutions of gases for various purposes* (Kirk-Othmer, 1992). Several examples of applied absorption processes are shown in *Figure 1* in *Appendices.*

From environmental point of view, gas scrubbing plays an important role for hazardous gas abatement, such as Carbon Monoxide (CO), Sulfur Dioxide (SO_2), hydrocarbons or Volatile Organic Carbon (VOC), particulate matter (PM), Nitrogen Oxides (NO), Ground level Ozone and Lead, which have adverse effects on human health and welfare and for which the Environmental Protection Agency (EPA) has set air quality standards. Those gases are particularly are the consequences of excessive emission of pollutants, insufficient ventilation leading to poor atmospheric dispersal of pollutants, a very dense population, a very high concentration of industries and the presence of temperature inversion (EPA,2004). Furthermore, the concept of gas absorption is quite pronounced in the applications of removal VOCs, radioactive gas, carbon dioxide and oxidation of iron and manganese from contaminated groundwater by utilizing desorption process, which is the reverse of absorption process (American Water Works Association, 1990).

For industrial purposes, it also has been used widely in product recovery and chemical solution production, as shown in *Figure 1* in *Appendices*. In ammonia-water system which is mainly used in refrigeration system, the gas absorption principles also is being applied in such a way by emphasizing thermal balance between heat input and output and mass transfer in refrigeration cycles for cooling purposes. The same goes in lithium bromide-water system, in which water acts as refrigerant for cooling purposes. In gas purification process in petrochemical industries especially in ammonia production from steam reforming product (hydrogen), carbon dioxide gas needs to be removed because it is poisonous to catalyst. Monoethanolamine (MEA) and Diethanolamine (DEA) are being used for scrubbing carbon dioxide due to their high mass transfer rate and favours energy intensive regeneration process.

In food processing, an example of gas absorption is found in hydrogenation of oils, in which the hydrogen gas is bubbled through the oil with which it reacts. Generally, there is a catalyst presents also to promote the reaction. The hydrogen is absorbed into the oil, reacting with the unsaturated bonds in the oil to harden it. Another example is in the carbonation of beverages. Carbon dioxide under pressure is dissolved in the liquid beverage, so that when the pressure is subsequently released on opening the container, effervescence occurs. An example of desorption is found in the steam stripping of fats and oils in which steam is brought into contact with the liquid fat or oil, and undesired components of the fat or oil pass out with the steam. This is used in the deodorizing of natural oils before blending them into food products such as margarine, and in the stripping of unwanted flavours from cream before it is made into butter. The equilibrium conditions arise from the balance of concentrations of the gas or the volatile flavour, between the gas and the liquid streams.

In the gas absorption process, sufficient time must be allowed for equilibrium to be attained so that the greatest possible transfer can occur and, also, opportunity must be provided for contacts between the streams to occur under favourable conditions (nzifst).This study shall focus on the application of gas absorption as a tool for oxygen absorption. This study concentrates on the absorption of oxygen in water and parameters involved for determining the effectiveness of the gas absorption.

1.2 Problem Statement

The effectiveness of gas absorption is much depends on several factors; such as type of packings, operating temperature and pressure, flow rates, absorbent concentrations, humidity, solubility as well as chemical addition. In absorption process, gas flow is components from the gas to the fluid and it is much related with the transition of components of the gas phase to the liquid phase. The extent in which is possible to transfer gaseous components to the fluid phase depends on solubility of these components in the fluid. For instance, the balance concentration at the vapor stage which corresponds to a certain concentration at the fluid stage depends on the temperature; a higher temperature of the fluid phase, the higher balance concentration at the mist stage. In addition, it much relies on the creation of large surface areas through the use of variety of mechanical methods. These methods include hydraulic spray, impingement tray, bubble cap tray, sieve trays, packing (modular and dump-type), grids and a variety of combination devices all purposely to create this high liquid surface area in as small a volumetric space as possible. These techniques can be classified in two basic categories which are; (1) those which flow the liquid over some type of media (packing, meshes, grids, etc.) and (2) those which create a spray of droplets (Schifftner and Hesketh, 1996).This study shall focus on the effectiveness of gas absorption with random packing of 15 mm plastic Raschig rings for oxygen-water system by using a modified wetted-wall column. The type of packing is fixed and parameters such as flow rates and temperature are varied to study on the absorption rate of oxygen in water.

1.3 Objectives and Scope of Study

This study holds a few objectives, which are:

1. To study on the effectiveness gas absorption by varying the operating parameters of modified wetted-wall column.
2. To study on the heat and mass transfer of oxygen-water absorption.

However, due to tight time-frame, the scope of study is restricted on the study of mass transfer of oxygen-water absorption in term of mass transfer flux as well as contributing parameters for gas absorption efficiency such as packing addition, liquid hold up in the column and flooding mass velocity at different water and air flow rates. Also, the study takes into account direct effect of different flow rates of water supply, air and different inlet water temperature based on the value of dissolved oxygen (DO) in the outlet stream. Relationship between dimensionless number such as Reynolds number, Sherwood number and Nusselt number are also being studied.

CHAPTER 2

LITERATURE REVIEW AND THEORY

2.1 Oxygen

2.1.1 Physical and Chemical Properties

In General

Oxygen is by far the most common element found in nature. For example, oxygen makes up by weight:

- 46% of the Earth's crust (in the form of oxides, silicates, etc.)
- 89% of the Earth's water (in the form of molecules)
- 21% of the air we breathe
- 62% of the human body (in the form of molecules)

In its most well-known form (it constitutes 21% of the atmosphere), it is a tasteless, odorless and colorless gas essential to life which reacts strongly in the presence of other chemical substances.

SUPPLY MODE:

Oxygen can be supplied in cylinders, liquefied gas tank, by on site generator or by pipeline.

Molecular Weight

- Molecular weight : 31.9988 g/mol

Solid phase

- Melting point : -219 °C
- Latent heat of fusion (1,013 bar, at triple point) : 13.9 kJ/kg

Liquid phase

- Liquid density (1.013 bar at boiling point) : 1141 kg/m^3
- Liquid/gas equivalent (1.013 bar and 15 °C (59 °F)) : 854 vol/vol
- Boiling point (1.013 bar) : -183 °C
- Latent heat of vaporization (1.013 bar at boiling point) : 212.98 kJ/kg

Critical point

- Critical temperature : -118.6 °C
- Critical pressure : 50.43 bar
- Critical density : 436.1 kg/m^3

Triple point

- Triple point temperature : -218.8 °C
- Triple point pressure : 0.00152 bar

Gaseous phase

- Gas density (1.013 bar at boiling point) : 4.475 kg/m^3
- Gas density (1.013 bar and 15 °C (59 °F)) : 1.354 kg/m^3
- Compressibility Factor (Z) (1.013 bar and 15 °C (59 °F)) : 0.9994
- Specific gravity (air = 1) (1.013 bar and 21 °C (70 °F)) : 1.105
- Specific volume (1.013 bar and 21 °C (70 °F)) : 0.755 m^3/kg
- Heat capacity at constant pressure (Cp) (1 bar and 25 °C (77 °F)) : 0.029 kJ/(mol.K)
- Heat capacity at constant volume (Cv) (1 bar and 25 °C (77 °F)) : 0.021 kJ/(mol.K)
- Ratio of specific heats (Gamma:Cp/Cv) (1 bar and 25 °C (77 °F)) : 1.393365
- Viscosity (1.013 bar and 0 °C (32 °F)) : 0.0001909 Poise
- Thermal conductivity (1.013 bar and 0 °C (32 °F)) : 24.24 mW/(m.K)

Miscellaneous

- Solubility in water (1.013 bar and 0 °C (32 °F)) : 0.0489 vol/vol
- Concentration in air : 20.94 vol %

(Source: airliquide, 2005)

Vapor Pressure graph is shown in Appendices, Figure 1.

2.1.2 Applications

Industries	**Applications**
Chemicals	Oxygen is used to improve the yield of a large number of petrochemical processes. Oxygen can be used pure in chemical oxidation reactions such as the production of ethylene oxide (EO), propylene oxide (PO), ethylene dichloride (EDC), vinyl acetate monomer (VAM), titanium dioxide (TiO_2), ferric sulfate and also for the debottlenecking of air-based processes such as those in the production of acrylonitrile and purified terephtalic acid (PTA). O_2 is also used in the production of synthesis gas (H_2/CO).
Pharmaceuticals	Oxygen is used in chemical synthesis, for enrichment of air during fermentation, for treatment of wastewater and flame sealing of glass ampuls for finished products.
Food and Beverage	Oxygenation of fish-breeding tanks
Glass, Cement and Lime	Mainly used for the glass melting and generally for all oxy-combustion process.
Healthcare	Treatment of respiratory insufficiencies and resuscitation, in hyperbaric oxygen changes for treatment of carbon monoxide poisoning.
Metals industry	As in the iron and steel industry (Decarburization of hot metal to produce steel, and to enrich blast furnace air), oxygen is used in non ferrous primary production, secondary smelting etc.
Laboratories & analysis	Oxygen is used in calibration gas mixtures for petrochemical industry; environmental emission monitoring, industrial hygiene or safety monitors and trace impurity analyzers. Oxygen is used in bomb calorimeters to measure the PCI of hydrocarbons or coal and in oxidation reactions.

Industries	Applications
Oil and Gas	Oxygen is used in raffinery to enrich air of regeneration of Fluid Cracking Catalytic units (FCC) (up to 28 % in O_2).
Pulp and paper	Environment-friendly paper pulp bleaching : Oxygen is mainly used in the delignification step, O_2 participates in the boosting of bleaching operations like alkaline extraction (Eo), in white or black liquors oxidation, polysulfure liquors production as well as combustion (lime burning kiln, boilers boosting). Oxygen is also used in the waste treatment and as precursor of ozone.
Electronics	Ultra-pure oxygen is used to oxidize certain materials, such as Si to SiO_2, or ashing of photoresists and to achieve chemical vapor deposition of oxides. It is also used to make ozone for oxidations or cleaning.
Space and Aeronautics	Oxygen is used in their liquid states as ergols for the propulsion of the cryogenic stages of the Ariane rockets.
Environment	In a biological basin, oxygen enhances the waste water treatment (BOD, sludges, odors, energy). Oxygen also improves waste treatment, decreasing the amount of incineration emissions by a factor of up to 7.
Other industries	Biological water purification, clean waste incineration, ozone synthesis

(Source: airliquide, 2005)

2.2 Absorption Theory

2.2.1 In General

Generally, gas scrubbing is always carried out in vertical countercurrent columns (*Figure 2.1*). The gas and liquid streams are commonly counter-current for a more effective mass transfer. The solvent is fed at the top of the absorber, whereas the gas mixtures enter from the bottom. Then, the absorbed substance is washed out by the solvent and leaves the absorber at the bottom as liquid solution. Then solvent undergoes recovery step in a subsequent stripping or desorption operation.

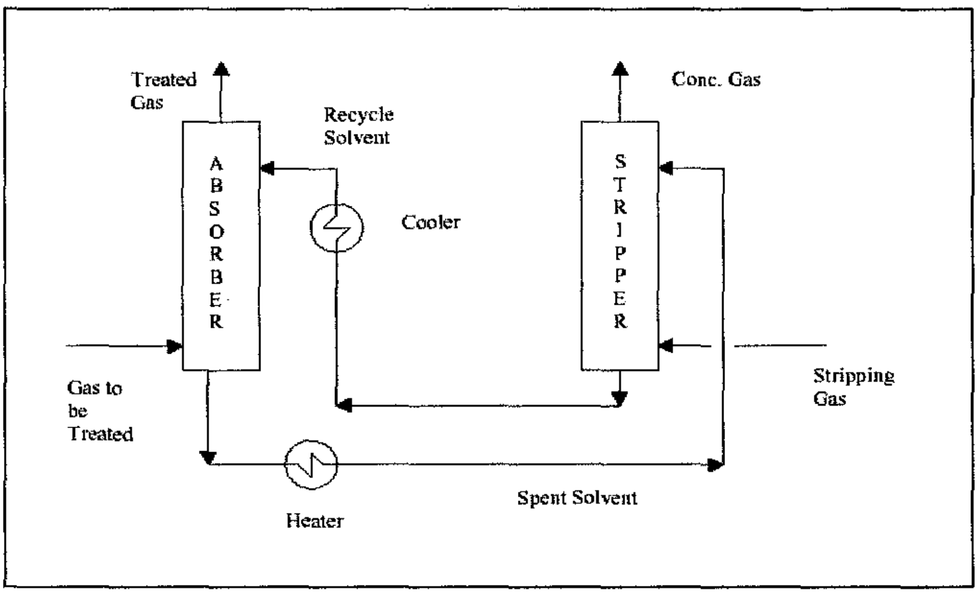


***Figure 2.1:** Flow sheet of absorption process*

This process is essentially the reverse of absorption and involves countercurrent contacting of the liquid loaded with solute using an inert gas or water vapour purposely to selectively remove components by mass transfer from the liquid to the gas phase (Seader and Henley,1998). The absorber may be packed column, plate tower, or simple spray column, or a bubble column. The packed column is a shell either filled with randomly packed elements or having a regular solid structure designed to disperse the liquid and bring it and the rising gas into close contact. Various dumped-type packing elements (*Figure 2.2*) and construction materials are commonly utilized, which are intended to create large internal surface but a small pressure drop in order to facilitate mass transfer between the two streams.

***Figure 2.2**: Random packing materials.* (Source: Seader, J.D and Henley, E.J, *Separation Process Principles*, John Wiley &Sons, Inc., (1998))

Structured or arranged packing may be made of corrugated metal or plastic sheets providing a large number of regularly arranged channels (*Figure 2.3*), but range of other geometry exists. In plate towers, liquid flows from plate to plate in cascade trend and gases bubble through the flowing liquid at each plate through a mass of dispersers (e.g. holes in sieve tray, slits in bubble-cap tray) or through a cascade of liquid as in a shower deck tray (Kirk-Othmer,1992).

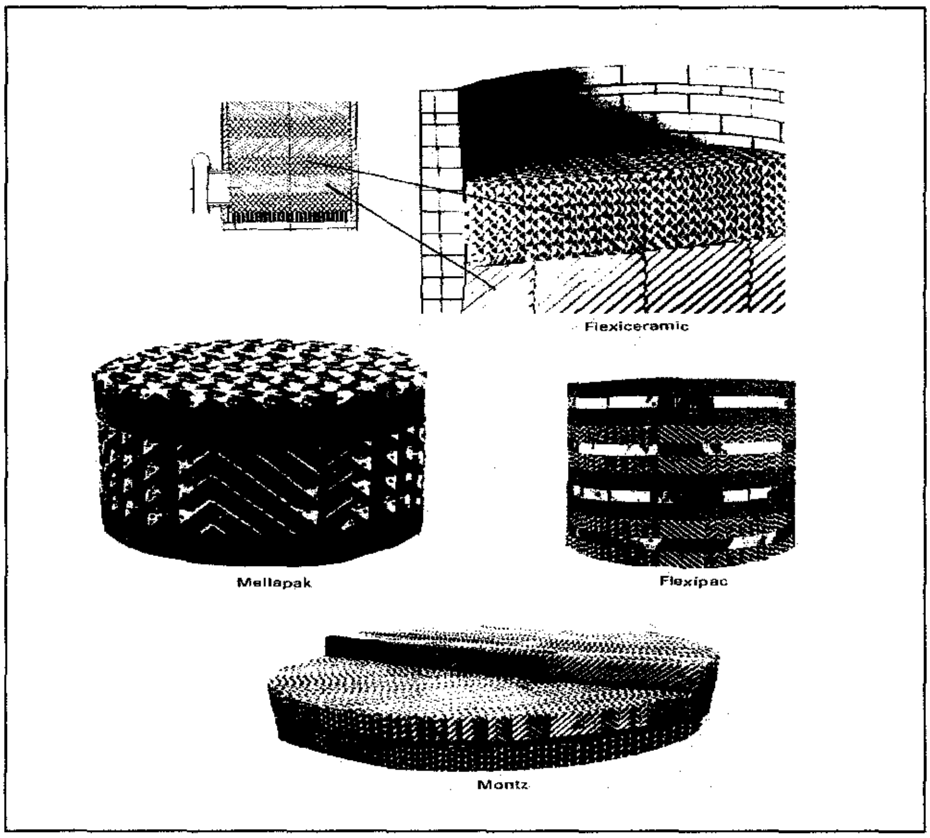


***Figure 2.3**: Structured packing materials.* (Source: Seader,J.D and Henley,E.J, *Separation Process Principles*, John Wiley &Sons, Inc., (1998))

There are two types of absorptions which are *chemical* and *physical.* In *chemical absorption,* the liquid solvent reacts with the gas stream and remains in solution. In *physical absorption,* the solute in the gas is more soluble in the liquid solvent and, therefore, the solute is transferred to the liquid. Chemical is usually preferred over physical because the equilibrium for chemical absorption is much favourable for the separation. However, physical absorption is important since it can be applied when chemical absorption is not possible (Dahdal, et al.).

However, there are limitations regarding to absorption and stripping process which are:

1. **Absorption and air stripping:**
    - For high VOC (volatile compounds) concentration above 1000 mg/l and different VOC
    - Solids <2%

2. **Absorption and steam stripping:**
   - VOC highly soluble in water like alcohol and ketones (acetone, ethanol, etc)
   - $T_b > 150°C$
   - Excess VOC (>10%)
   - Suspended solids higher than 2% tend to polymerize
   - If phenols cannot be treated, use extraction.

More specific applicability of absorption and stripping process are:

1. **Absorption and air stripping:**
   - Remove of VOC at low concentration (<200mg/l) from contaminated ground water.
2. **Absorption and stream stripping**
   - Remove of H_2S and ammonia before biological treatment.
   - Best available technology for an array of organic compounds, plastic and synthetic fibres (OCPSF) category like benzene.
   - Higher VOC concentrations as with air stripping (100mg/l and more).
   - Pyridines, cresol, monomers and halogenated solvents.
   - Elimination of flow VOC concentration from high volume flow of waste stream.
   - Recovery of thermally unstable materials (low boiling points.)

In design part, the ideal absorbent should be:

- Have a high solubility for the solute(s).
- Have a low volatility to reduce loss of absorbent
- Be noncorrosive
- Have a low viscosity to provide a low pressure drop
- Be non-toxic
- Be available and not expensive

(Seader and Henley,1998).

2.2.2 Parameters affecting mass transfer

Gas absorption involves transportation of elements from gas phase to liquid phase and this can be related with heat and mass transfer. In mass transfer, matter can move spontaneously from one place to another through a number of mechanisms, including:

1. *Molecular diffusion*, which results from the thermal motion of molecules, limited by collisions between molecules;
2. *Convection*, or bulk flow, which occurs under a pressure gradient or other imposed external force;
3. *Turbulent mixing*, where macroscopic packets of fluid, or eddies, move under inertial forces.

(King,1980)

There are a few factors contribute to the rate of heat and mass transfer, which are;

2.2.2.1 Type of packing

Absorption and stripping are frequently conducted in packed columns, particularly when;

1. The required column diameter is less than 2 feet;
2. The pressure drop must be low, as for a vacuum service;
3. Corrosion considerations favour the use of ceramic or polymeric materials;
4. Low liquid hold-up is desirable.

(Seader and Henley,1998).

The advantages of packed columns include simple and, usually cheaper construction, as long as the tower diameter is not too large. These columns are preferred for corrosive gases because these packing can be made from ceramic or plastic materials. This type of packing are also used in vacuum applications due to the pressure drop, especially for regularly structured packing, is usually less than through plate columns (Kirk-Othmer,1992).

There are two major types of packings; random and regular. Random packings are simply dumped into the tower during the installations and allowed to fall at random. The Raschig Ring first patented by Dr, Fritz Raschig in Germany in 1907, was the first standardized packing. Until the sixties, packed columns were mostly filled with Raschig rings or Berl saddles, known as *first-generation* packings. Then development of more advanced packings with higher separation efficiency al low pressure drop accelerated. Today, Pall rings (*second-generation*) and exotically shaped saddles made of ceramics, metals, or plastics (*third-generation*) are widely used as packings (Benitez, 2002).

The applications of packings are always related with dispersion of liquids in columns. The corresponding parameters related with packings which determine the mass transfer coefficient are:

1. Liquid distribution
2. Liquid hold-up
3. Pressure drop

1. Liquid distribution

Adequate initial distribution of the liquid at the top of the packing is very important. Otherwise, s significant portion of the packing near the top of the tower will remain dry and results in ineffective mass transfer. In random packings, the packing density (i.e. the number of packing pieces per unit volume) is ordinarily less in the immediate vicinity of the tower walls, and this leads to a tendency of the liquid to segregate towards the walls and the gas to flow in the centre of the tower and create channelling phenomena. This condition greatly reduces the extent of vapour-liquid contact. This tendency is much less pronounced when the nominal diameter of the individual packing pieces (d_p) is smaller than one-eight the tower diameter, D (Seader and Henley,1998). It is recommended that the ratio $d_p/D = 1/15$ (Treybal, 1980). In order to reduce the effect of channelling, liquid redistributors should be installed at intervals varying from 3 to 10 times the tower diameter, but at least every 6 or 7 meters. The wall in a packed bed affects the packing density resulting in void fraction variations in the radial direction. Voidage variations of packed-beds in the near wall region influence the pressure drop, bed permeability, fluid hold-up, linear velocity, and residence time distribution. At small column to particle diameter ratios, typically less than ten, this effect becomes more prominent (Klerk, 2003).

Variance of bed voidage values of a randomly packed bed of spheres at large column to particle diameter ratio is ascribed to the packing mode and has been discussed by authors like Haughey and Beveridge (1969) and McWhirter et al.(1997). Four random packing modes for spheres are distinguished:

a) Very loose random packing ($\varepsilon \approx 0.44$):obtained by gradual defluidization of a fluidized bed or by sedimentation.
b) Loose random packing ($\varepsilon \approx 0.40 - 0.41$):obtained by letting sphere roll individually in place, or by dropping the spheres into the container as a loose mass.
c) Poured random packing ($\varepsilon \approx 0.375 - 0.391$):obtained by pouring spheres into a container.
d) Dense random packing ($\varepsilon \approx 0.359 - 0.375$):obtained by vibrating or shaking down the packed bed.

Mueller (1992) developed the following equation to predict the radial void fraction distribution in a cylindrical tower packed with equal-sized spheres;

$$\varepsilon = \varepsilon_b + (1-\varepsilon_b)\, J_o(ar^*)\, \exp(-\beta r^*)$$

$\alpha = 7.45 - [3.15/(D/d_p)]$ for $2.02 \leq D/d_p \leq 13.0$

$\alpha = 7.45 - [11.25/(D/d_p)]$ for $D/d_p \geq 13.0$

$\beta = 0.315 - [0.725/(D/d_p)]$ $\quad \epsilon_b = 0.365 + (0.220/D/d_p)$

$r^* = r/d_p$ $\quad 0 \leq r^* \leq D/2d_p$

J_o = Bessel function of the first kind of order zero

r = radial distance measured from the wall

From *Figure 2.4*, it shows that wide fluctuations of void fraction near the wall, decaying gradually as we move toward the centre of the bed. According to Govindarao and Froment (1986), when D/d_p >10, the radial void fraction approaches a constant asymptotic value (ε_b) at a distance from the wall of approximately 5 particle diameters, consistent with the graph shown in *Figure 2.4.*

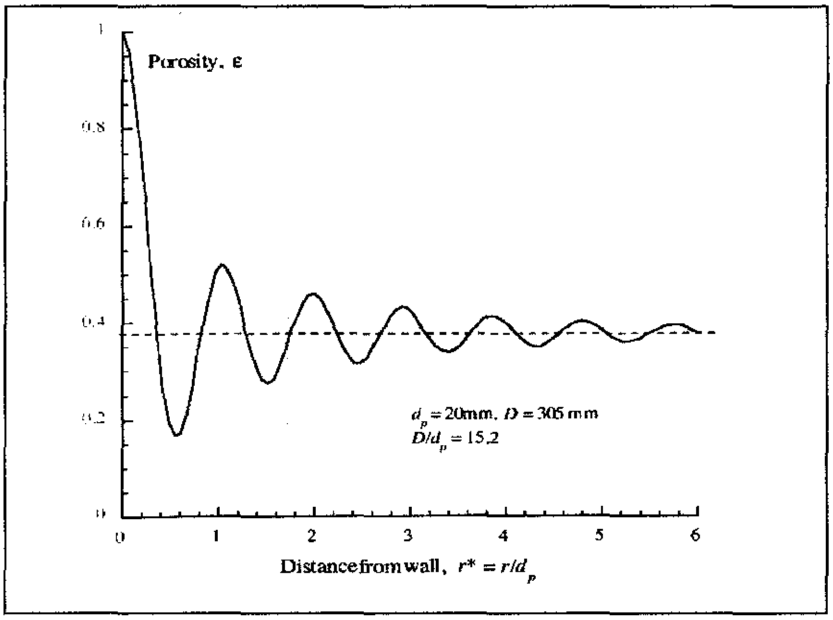
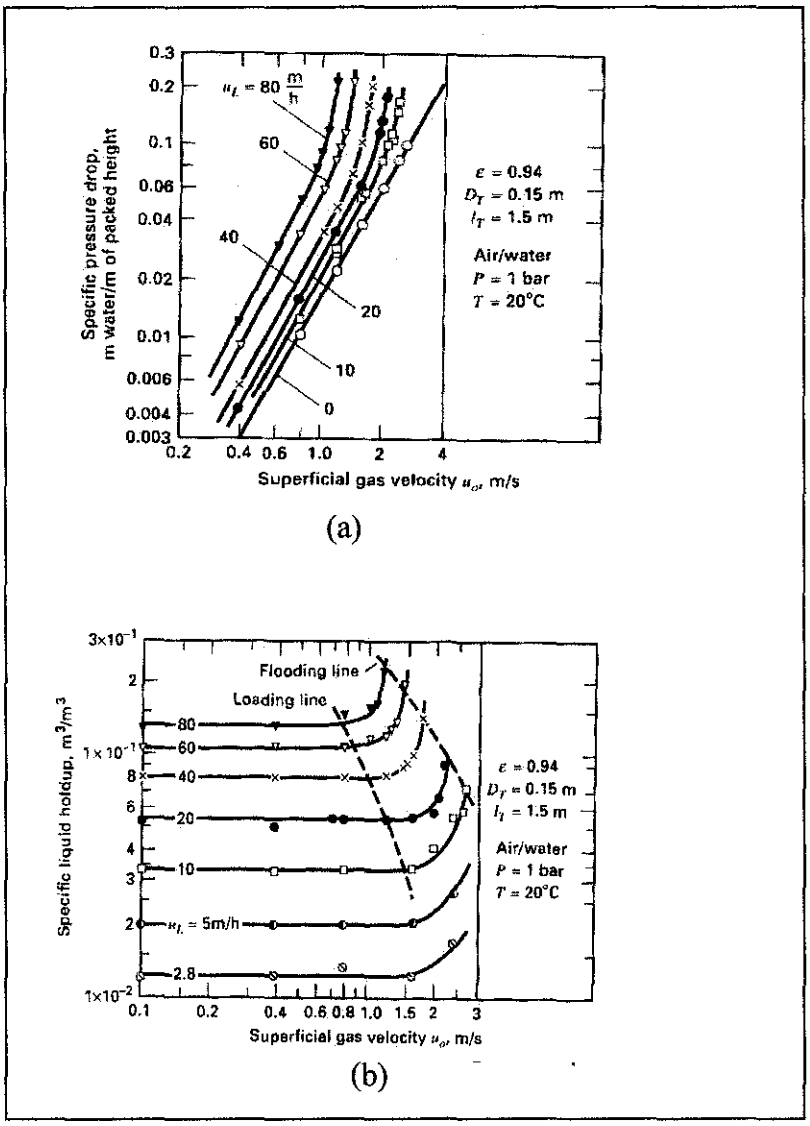


***Figure 2.4**: Oscillatory variation of void fraction near the walls of a packed bed.* (Source: Benitez, Jaime, *Principles and Modern Applications of Mass Transfer Operations*, John-Wiley & Sons, Inc. (2002))

2. Liquid hold-up

Liquid hold-up (i.e. the quantity of liquid contained in the packed bed) is directly related with pressure drop in the column. From experimental curves by Billet (1989), and Stichlmair, Bravo, and Fair (1989), shown in *Figure 2.5*, give a relationship between specific pressure drop (meters of water head per meter of packed bed) and specific liquid hold-up (cubic meters per cubic meter of packed bed) as the function of superficial gas velocity for different values of superficial water velocity.



(a)

(b)

***Figure 2.5**: (a) Specific pressure drop for dry and irrigated 25-mm metal Bialecki rings (b) Specific liquid hold-up for irrigated 25-mm metal Bialeck rings.*

(Source: R.Billet, *Packed Column Analysis and Design*, Ruhr-University Bochum (1989) with permission)

Loading point is the upper limit to the gas velocity for a constant liquid hold-up at a given liquid velocity. After the loading point, any increase in liquid hold-up will decrease the void fraction causing an increased pressure drop. Below this point, the gas phase is the continuous phase. Above this point, liquid begins to accumulate or load the bed, replacing gas hold-up and causing a sharp increase in pressure drop. Finally, a gas velocity is reached at which the liquid surface is continuous across the top of the packing and the column is flooded. At the *flooding point*, the pressure drop increases infinitely with increasing gas velocity (Seader and Henley,1998). The loading region is between the loading point and the flooding point wherein significant liquid entrainment is observed, liquid hold-up increases sharply, mass transfer efficiency decreases, and column operation is unstable. The superficial gas velocity at the loading point is approximately 70% of that the flooding point (Billet, 1989). Most packed columns are designed to operate below the loading point, which is in the *preloading region.*

From extensive experiments by Billet and Schultes (1995), specific liquid hold-up in the preloading region has been found for a wide variety of random and structures packings and for a number of gas-liquid systems. According to the dimensionless expression, the specific liquid hold-up depend on packing characteristics, and the viscosity, density, and superficial velocity of the liquid.

$$h_L = [\,12\, Fr_L/Re_L]^{1/3}[a_h/a]^{2/3}$$

h_L = specific liquid hold-up (m^3 hold-up/m^3 packed bed)

Re_L = liquid Reynolds number = $\dfrac{\text{inertial force}}{\text{viscous force}}$

$= \upsilon_L\rho_L/a\mu_L = \upsilon_L/a\nu_L$

υ_L = superficial liquid velocity (m/s)

a = specific surface area of spacing (m^2/m^3)

Fr_L = liquid Froude number = $\upsilon_L^2 a/g$

g = acceleration of gravity

a_h = hydraulic, or effective, specific are of packing

The ratio of specific areas is given by,

$a_h/a = C_h\, Re_L^{0.5}\, Fr_L^{0.1}$ *for* $Re_L < 5$

$a_h/a = 0.85 C_h\, Re_L^{0.25} Fr_L^{0.1}$ *for* $Re_L \geq 5$

Values of a and C_h are characteristic of the particular type and size of packing.

Regarding to Perry and Green (1998), three modes of liquid hold-up in packed columns are recognized, which are:

1. Static, h_s
2. Total, h_t
3. Operating, h_o

Static hold-up is the amount of liquid remaining on packing that has been fully wetted and then drained. Total hold-up is the amount of liquid on the packing under dynamic conditions. Operating hold-up is the amount of liquid attributed to operation and is measured experimentally as the difference between total and static hold-up.

i. Static, h_s

$$\boxed{h_s = 2.79\,\frac{C_1 \mu_L^{C2} \sigma^{C3}}{\rho_L^{0.37}}}$$

where μ_L= liquid viscosity (mPa.s)
σ = surface tension (mN/m)
ρ_L = liquid density (kg/m^3)

C_1, C_2 and C_3 are constant (refer to Perry's Chemical Engineer's Handbook, page 14-47) and only available for 1 in. carbon and ceramic Raschig rings and 1 in. ceramic Berl saddles.

ii. Operating, h_o

$$h_o = 2.2\,(\mu'_L u_L / g\,\rho_L d_p^2)^{1/3} + 1.8\,(u_L^2 / g d_p)^{1/2}$$

where μ'_L = liquid viscosity (Pa.s)
u_L = liquid superficial velocity (m/s)
g = gravitational constant (m/s^2)
ρ_L = liquid density (kg/m^3)
d_p = nominal packing size (m)

iii. Total, h_t

$$h_t = h_o + h_s$$

(Perry and Green, 1998)

Due to Al Dahdan et al. (1997), there are five limiting cases to describe the effect of gas flow rate and pressure on liquid hold-up, which are:

1. Internal liquid hold-up is the liquid hold-up contained in a porous particle in the packed bed. For nonporous particles there will be no internal liquid hold-up.
2. External liquid hold-up is the liquid hold-up not contained in particles in the packed bed. For nonporous particles the external liquid hold-up will be the same as the total liquid hold-up.
3. Residual liquid hold-up is the part of the external liquid hold-up that remains in the packed bed after the packed bed was completely wetted and then drained.
4. Dynamic (or free-draining or operative) liquid hold-up is the part of the external liquid hold-up that collects at the bottom of the column after a sudden shutoff of the liquid feed.
5. Static liquid hold-up is the internal liquid hold-up plus the residual liquid hold-up. For a bed nonporous particles, static hold-up and residual hold-up are the same.

Further explanation of the relationship of gas capacity factor and liquid superficial velocity on the total liquid hold-up can be seen from *Figure 2.6* (Iliuta, et al., 2003);

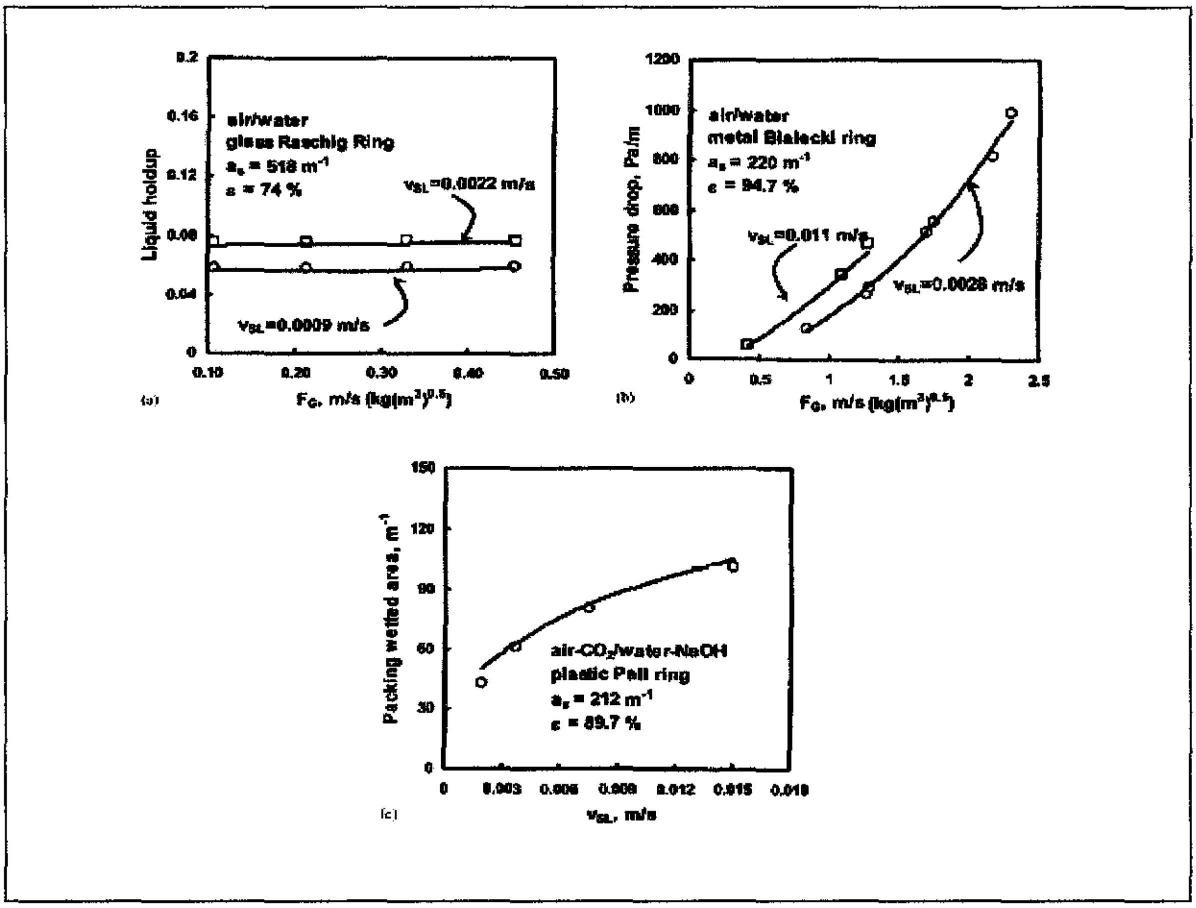


Figure 2.6: *Effect of gas capacity factor and liquid superficial velocity on the total liquid holdup (a), the irrigated pressure drop (b), the packing wetted area (c).*

Lines show simulated behavior using specific equations* and the symbols refer to experimental data points.

* refer to Iliuta et al (2003), *Two-fluid model for counter-current dumped packing-containing columns*, Chemical Engineering Science, pg 1376.

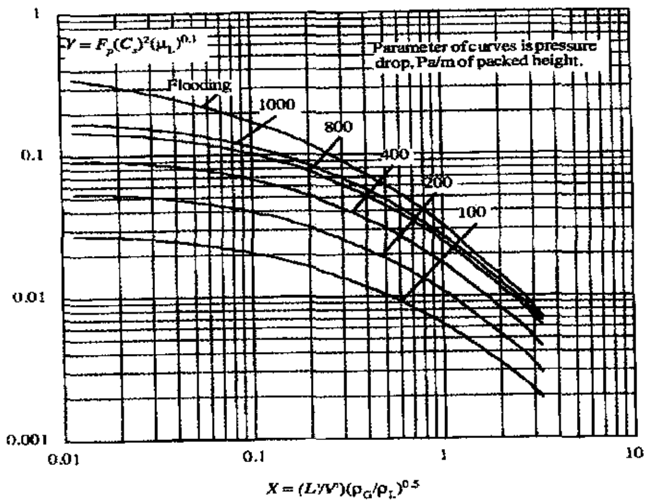
3. Pressure Drop

From empirical expression developed by Kister and Gill (1991), it has been found that the pressure drop at flooding is strongly dependent on the packing factor for both random and structured packings.

$$\Delta P_{flood} = 0.115 F_p^{0.7}$$

where ΔP_{flood} has units of Pa per meter of packed height and F_p has units of ft^2/ft^3

Leva (1954) used experimental data on ring and saddle packings to extend the Sherwood et al. (1938) flooding correlation to include lines of constant pressure, with the resulting chart becoming known as the *generalized pressure drop correlation* (GPDC) (Benitez,2002) refer to *Figure 2.7.*



L = liquid flow rate, kg/s
ρ_G = gas density, kg/m^3
C_S = $v_G[\rho_G/(\rho_L - \rho_G)]^{1/2}$
F_p = packing factor, ft^2/ft^3
V' = gas flow rate, kg/s
ρ_L = liquid density, kg/m^3
v_G = superficial gas velocity, m/s
μ_L = liquid viscosity, Pa-s

***Figure 2.7:** Generalized pressure drop correlation for packed beds.*
(Generated using the Packed Column Calculator, version 1.1, Katmar Software, 1998) (Source: Benitez, Jaime, *Principles and Modern* Applications of Mass Transfer Operations, John-Wiley & Sons, Inc. (2002))

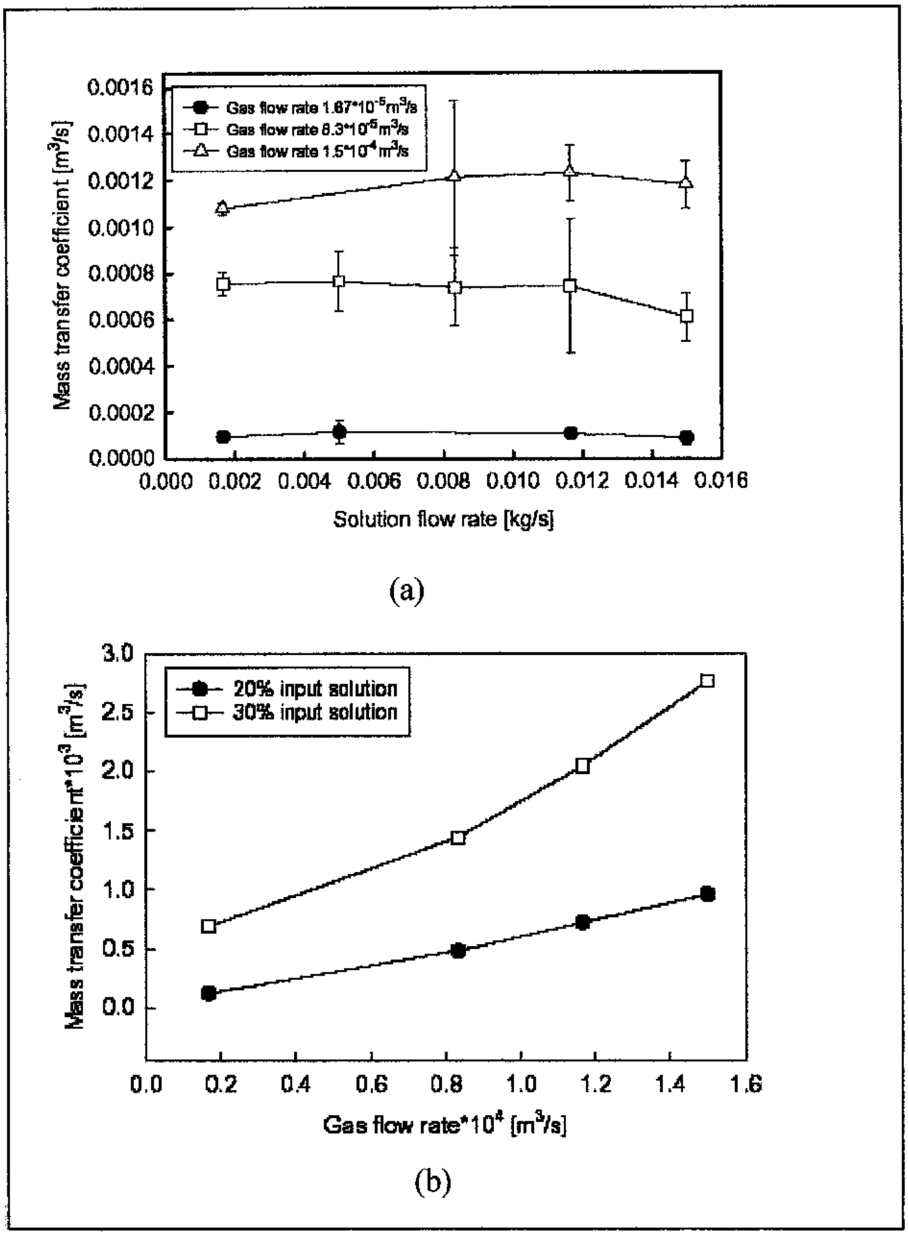
As packing size increases, mass transfer efficiency and pressure drop decrease. Therefore, an optimal packing size exists that represents a compromise between these two factors; since low pressure drop and high mass transfer rates are both desirable.

2.2.2.2 Temperature

The balance concentration at the vapor stage which belongs to a certain concentration at the fluid stage depends on the temperature, a higher temperature of the fluid phase results in a higher balance concentration at the vapor stage. Lowering of the temperature has therefore also a favorable impact on the output (Crystec). The correlation for absorption factor, A is governed by this formula; $A = L/KV$ for a specific component. K is equilibrium ratio between vapor and liquid component.
K-value for many solutes varies exponentially with the temperature and is inversely proportional to pressure, this reduction will result in lower absorption rate. According to Dahdal et al, the temperature of entering liquid affect absorption by affecting the flow rate of liquid required for the separation with a given number of stages (tray tower). Increasing the temperature of the entering solvent increases the liquid flow rate required.

2.2.2.3 Flow rates

Lee et al. (2002) carried out an experimental an analysis for ammonia/water in bubble mode in a plate-type absorber. They found that higher solution and gas flow rate increase the heat and mass transfer. *Figure 2.8* shows the effect of gas and solution flow rate on mass transfer coefficient and heat generation.



(a)

(b)

***Figure 2.8**: Mass transfer coefficient as a function of solution flow rate and gas flow rate*

They also relate Reynolds number for gas at different concentration of inlet solution with Nusselt and Sherwood numbers. The relationship of those dimensionless numbers is shown in *Figure 2.9*.

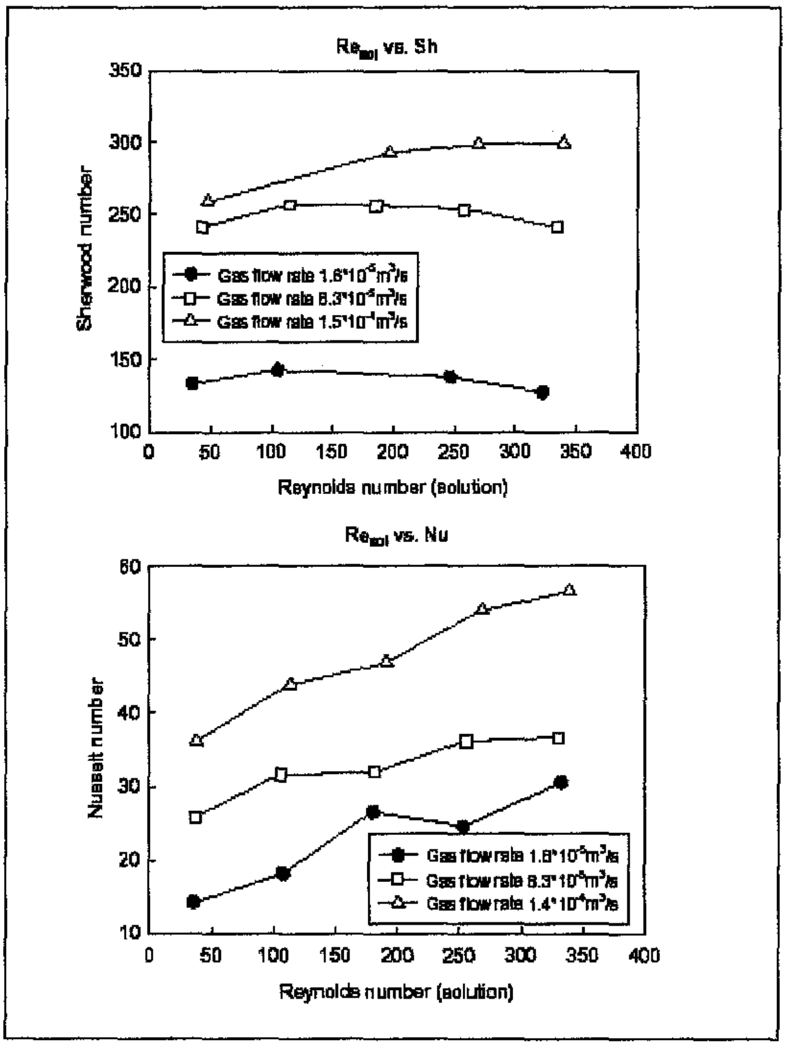


***Figure 2.9**: Effect of solution Reynolds number on Nusselt and Sherwood numbers*

The absorption rate is expressed as the following equations using the overall mass transfer coefficient, K. The mass transfer in the vapour phase is assumed to be little compared with the mass transfer in the liquid phase (Lee et al., 2002)

$$m_{abs} = K_p A_{abs} \Delta x_{lm,l}$$

m_{abs} = absorption rate

K = overall mass transfer coefficient (m/s)

A_{abs} = area of absorption (m^2)

$\Delta x_{lm,l}$ = log mean concentration gradient for liquid

$$\Delta x_{lm,l} = [\,(x_{in}^{eq} - x_{in}) - (x_{out}^{eq} - x_{out})]/\ln[(x_{in}^{eq}-x_{in})/(x_{out}^{eq}-x_{out})]$$

x_{in}^{eq} = inlet liquid concentration at equilibrium

x_{in} = inlet liquid concentration

x_{out}^{eq} = outlet liquid concentration at equilibrium

x_{out} = outlet liquid concentration

From numerical and experimental study for mass transfer for ammonia gas/ammonia aqueous solution by Lee et. al (2003), it shows that ammonia gas absorption is sensitive to the amounts of the inputs gas and solution, temperature and concentration of solution, and direction of flow. As the flow rate of the input gas increases, the absorption region of gas also increases. When the gas and solution are countercurrent, and temperature and concentration of the input solution are keep low, the absorption region of the gas decreases. If the ratio of the liquid to gas stream rate inlet is too low, the solute build up will occur in the upper portion of the column causing a higher temperature profile in the top of the column. As a result, internal cooling maybe necessary for lower liquid to gas ratios.

In spite of the effect of gas and liquid flow rates, air sparger flow rate also can affect the absorption rate. Air sparger is a device for introducing a stream of gas in the form of small bubbles into a liquid. Generally, bubble mode absorption is used for high liquid hold-up. If the vessel diameter is small, the sparger, located at the bottom of the vessel, may simply be an open tube through which the gas issues into the liquid. The purpose of sparging may be contacting the sparged gas with the liquid, or it may simply be a device for agitation. Air sparger is usually used collaborately with tray towers. The bubble absorption mode is strongly recommended for ammonia-water absorption systems because the low wettability in the thin film mode is critical to the performance in falling film absorption (Kang et al, 2000). The bubble mode provides not only a high heat transfer coefficient but also good wettability and mixing between the liquid and the vapour. In the bubble absorption mode, the bubble dynamics such as bubble diameter and bubble velocity play important roles in the enhancement of absorption performance (Kang et al, 2002). *Figure 2.10* shows the bubble absorption process.

The study reveals that the departing bubbles become hemispherical as the vapour velocity increases. The higher the liquid concentration, the lower the absorption driving potential, which results in a larger bubble diameter.

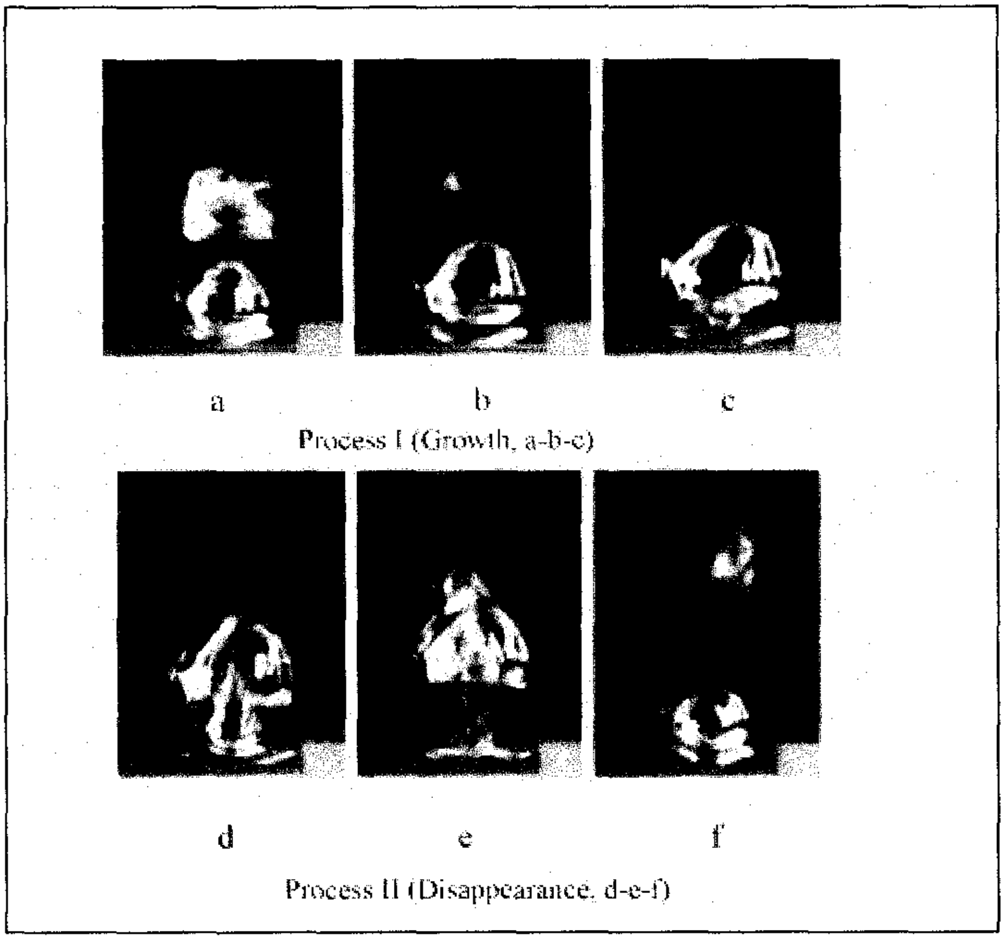


Figure 2.10: *Visualization of bubble absorption process* ($x_l = 0.1$, $d_o = 3{:}8$ *mm*, $Re_v = 1300$). (Source: Kang et al, *Mass transfer correlation of* NH_3-H_2O *bubble absorption*, International Journal of Refrigeration(2002), pg 881)

According to Benitez, 2002, for low liquid velocities, the bubble size may be taken as that produced at the orifices of the sparger, governed by the following correlations to estimate the size of the bubbles, as they leave the orifices of the sparger (Leibson, et al., 1956);

$d_p = 0.0287 d_o^{1/2} Re_o^{1/3}$ for $Re_o \leq 2{,}100$

$d_p = 0.0071 Re_o^{-0.05}$ for $10{,}000 \leq Re_o < 50{,}000$

d_p = bubble size(m) d_o = orifice diameter(m)

$Re_o = 4m_G / \Pi d_o \mu_G$ m_G = gas inlet (m/s)

For high liquid velocities, the bubble size may be altered by turbulence break-up and coalescence of bubbles. For example, for air-water in the range φ_G = 0.1 to 0.4 and $v_l/(1-\varphi_G)$ = 0.15 10 15 m/s, the bubble size is approximated by (Petrick,1962);

$$d_p = 0.002344/[v_l/(1-\varphi_G)]^{0.67}$$

d_p = bubble size(meter) v_L = liquid velocity (m/s)

Those correlations can be further visualized from *Figure 2.11*;

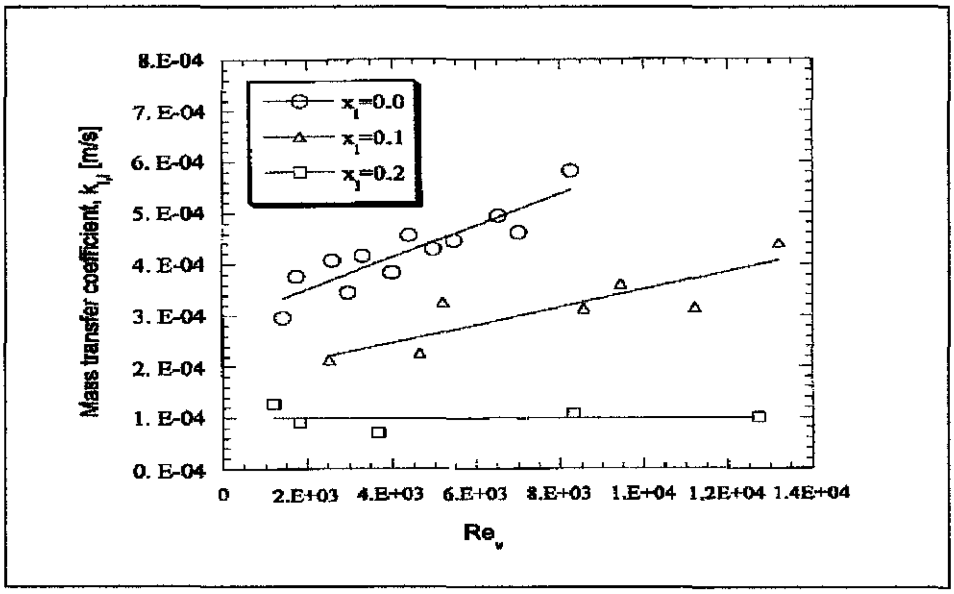


***Figure 2.11**: Mass transfer coefficient versus Re_v for the growth process*
(Source: Kang et al, Mass transfer correlation of NH_3-H_2O bubble absorption, International Journal of Refrigeration(2002), pg 883)

$$Re_v = \rho_v u_v d_v/\mu_v$$

Re_v = vapour Reynolds number ρ_v = vapour density

u_v = vapor velocity d_v = vapour diameter

μ_v = vapor dynamic viscosity

Mass transfer coefficient, k_l is defined as;

$$\dot{m}_{a,l} = k_{l,i}A_i\rho_l(x_l^{eq}-x_l)$$

2.2.2.4 Absorbent or absorbate concentration

According to the study done by Issa et al (2002), it shows that with an increase in ammonia initial concentration in an ammonia-water liquid mixture, the mass absorption rate decreases until there is almost no absorption when initial concentration is about 60%. The affinity between ammonia vapour and water liquid to form ammonia aqueous is considerably high, therefore, it is suggested that the equilibrium constant of the absorption reaction, which is defined as the concentration of the products over that of reactants at equilibrium, has a great value,i.e, the reversible absorption reaction is favourable in the direction of producing ammonia aqueous. *Figure 2.12* shows the relationship between absorbate concentration in liquid stream and ammonia absorption.

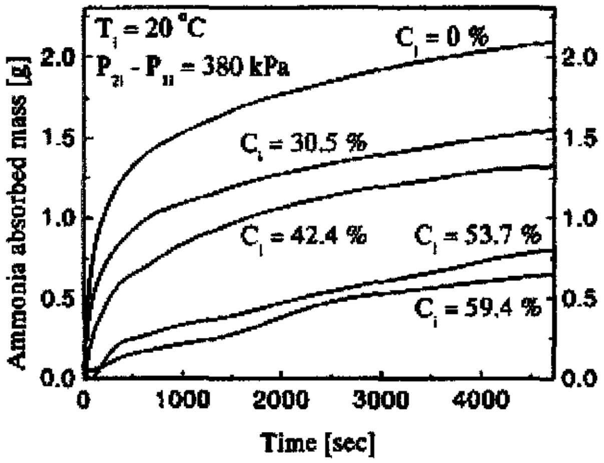


***Figure 2.12**: Ammonia absorption rates estimated by the ideal gas equation in all cases of different C_i and for ΔP_i = 380 kPa.*

Other considerable factors affecting gas absorption are;

2.2.2.5 Humidity of the gas stream

Inlet gases of the absorber with high humidity at high temperature affect the capability of the gas to consume latent heat hindering the absorption process.

Therefore, dehumidification of the inlet gas should be considered for absorbers with large heat effects (Dahdal et al).

2.2.2.6 Flooding mass velocity

This parameter is utilized to represents the maximum capacity condition for a packed column. According to Schifftner and Hesketh(1996), the flooding mass velocity is governed by corresponding formula;

$$G_F = (32.2\, y\, \rho_G\, \rho_L / F_p\, \mu_L^{0.2})^{0.5}$$

$$x = L_M/G_M\, [\rho_G/\rho_L - \rho_G)]^{0.5}$$

where

ρ_G = gas density (lb/ft3) ρ_L= liquid density (lb/ft^3)

F_p = packing factor (ft^2/ft^3) μ_L = liquid dynamic viscosity (lb.s/ft^2)

y = variable (*refer to Flooding Velocity Graph*)

Source : Schifftner and Hesketh, 1996

x = variable L_M = liquid flow rate

G_M = gas flow rate G_F = flooding mass velocity

The *Flooding Velocity Graph* is shown below in *Figure 2.13.*

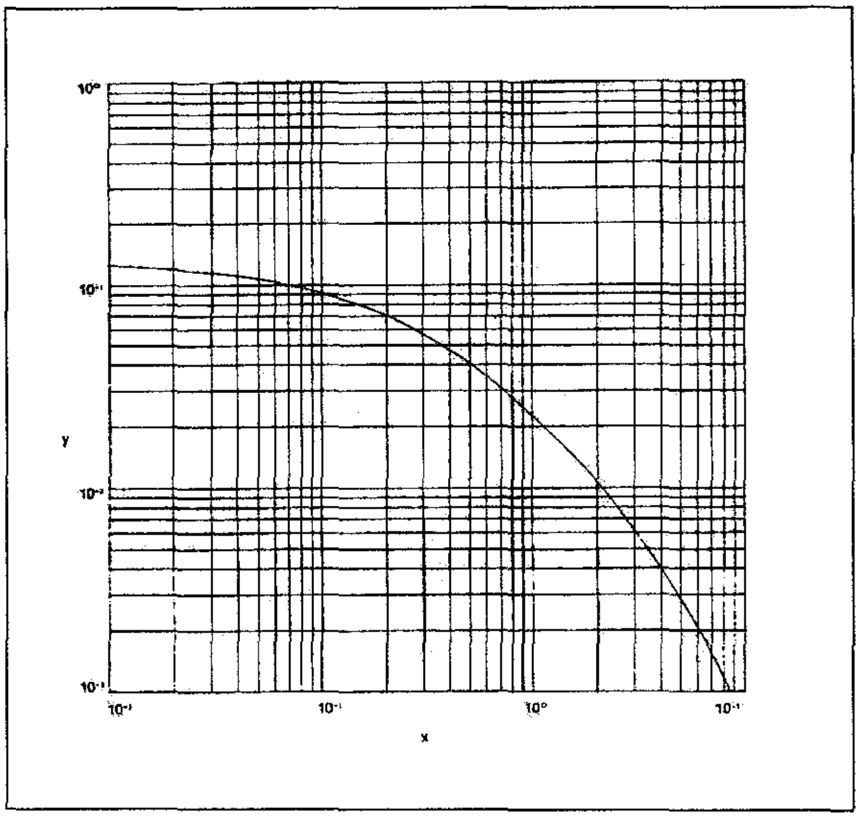


***Figure 2.13**: Flooding velocity graph.* (Source: Schifftner, Kenneth C., and Hesketh, Howard E.,*Wet Scrubber*, Second Edition, Technomic Publishing Co.,Inc. (1996))

From the equation, it shows that the flooding velocity is indirectly proportional to gas flow rate and liquid flow rate. It suits with the above explanation saying that flooding point occurs after loading region, wherein the gas velocity increasing at a given liquid velocity.

2.2.2.7 Chemical addition

By adding chemicals to the carrier fluid in which absorbed components are converted, the load can increase. Adding of chemicals that can react with the absorbed gases has a favorable impact on the absorption output has. Beside water also organic fluids are used as absorption means. In many cases chemicals or micro-organism are added to the carrier fluid to put or neutralize the gases which are solved in the fluid (for instance in conditioned scrubber). By this conversion the concentration in water becomes lower and more of the gasses can solve (according to the law of Henry).

2.3 Dissolved Oxygen (DO)

The dissolved oxygen (DO) is oxygen that is dissolved in water.With the exception of the food and beverage industries (using production water) and aquaculture, the presence of natural levels of dissolved oxygen in water for industrial operations generally is undesirable. It is accepted that industries incorporate conditioning processes to provide the quality levels necessary for the water supply, based on their own needs. Therefore, dissolved oxygen criteria for industrial water uses have not been developed (wlapwww.gov.bc.ca).

DO is more pronounced for environmental conservation especially for water treatment both for domestic and industrial. The oxygen dissolves by diffusion from the surrounding air; aeration of water that has tumbled over falls and rapids; and as a waste product of photosynthesis. An simplified formula is given below:

Photosynthesis (in the presence of light and chlorophyll):

Carbon dioxide + Water ------------> Oxygen + Carbon-rich foods
CO_2 H_2O O_2 $C_6H_{12}O_6$

Fish and aquatic animals cannot split oxygen from water (H_2O) or other oxygen-containing compounds. Only green plants and some bacteria can do that through photosynthesis and similar processes. Virtually all the oxygen we breath is manufactured by green plants. A total of three-fourths of the earth's oxygen supply is produced by phytoplankton in the oceans.

The effect of the temperature

If water is too warm, there may not be enough oxygen in it. When there are too many bacteria or aquatic animal in the area, they may overpopulate, using DO in great amounts.

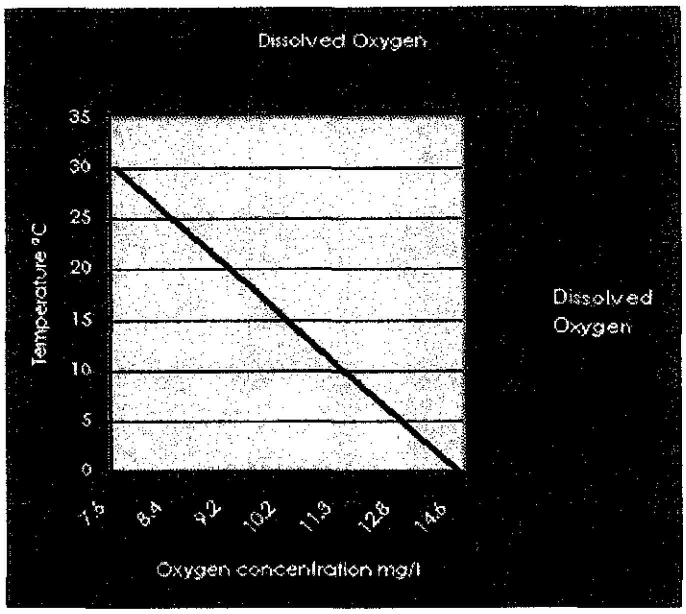


Figure 2.14: Effect of the temperature in the DO.

(Source: http://www.lenntech.com/homenl.htm)

Environmental Impact:

Total dissolved gas concentrations in water should not exceed 110%. Concentrations above this level can be harmful to aquatic life. Fish in waters containing excessive dissolved gases may suffer from "gas bubble disease"; however, this is a very rare occurrence. The bubbles or emboli block the flow of blood through blood vessels causing death. External bubbles (emphysema) can also occur and be seen on fins, on skin and on other tissue. Aquatic invertebrates are also affected by gas bubble disease but at levels higher than those lethal to fish. Adequate dissolved oxygen is necessary for good water quality. Oxygen is a necessary element to all forms of life. Natural stream purification processes require adequate oxygen levels in order to provide for aerobic life forms. As dissolved oxygen levels in water drop below 5.0 mg/l, aquatic life is put under stress. The lower the concentration, the greater the stress. Oxygen levels that remain below 1-2 mg/l for a few hours can result in large fish kills.

Biologically speaking, however, the level of oxygen is a much more important measure of water quality than feacal coliform. Dissolved oxygen is absolutely essential for the survival of all aquatic organisms (not only fish but also invertebrates suach as crabs, clams, zooplankton, etc). Moreover, oxygen affects a vast number of other water indicators, not only biochemical but esthetic ones like the odor, clarity and taste. Consequently, oxygen is perhaps the most well-established indicator of water quality.

Polution in the rivers:

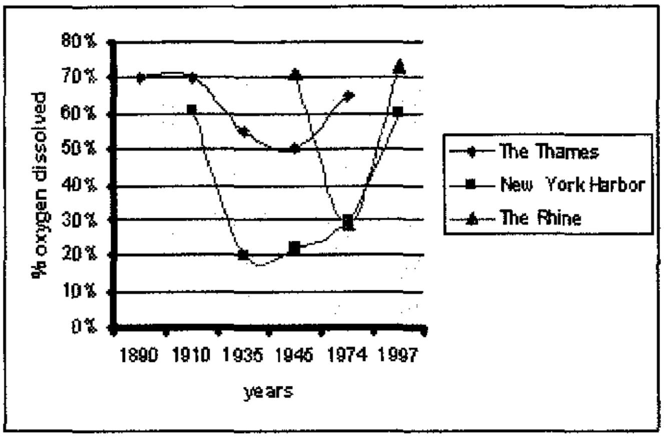


Figure 2.15:*The percentage levels of Oxygen dissolved in the river "The Thames" in the period (1890-1974), The New York harbor in the period (1910-1997), and the river "The Rhine" in the period (1945-1997).*

(Source: *The Skeptical environmentalist; measuring the real state of the world.* Author:Bjøn Lomborg)

From the graph, it shows how the oxygen levels for some of the majors rivers have returned to the previous high levels after decades of low levels. This has consequences for both marine organisms and humans. The increased levels of percentage of dissolved oxygen have improved the posibilities of aquatic live.

How Dissolved Oxygen Affects Water Supplies

A high DO level in a community water supply is good because it makes drinking water taste better. However, high DO levels speed up corrosion in water pipes. For this reason, industries use water with the least possible amount of dissolved oxygen. Water used in very low pressure boilers have no more than 2.0 ppm of DO, but most boiler plantoperators try to keep oxygen levels to 0.007 ppm or less (http://www.lenntech.com).

Aeration process is another best example for gas absorption involving dissolved oxygen for wastewater treatment. In this process, air and water are brought into intimate contact with each other to transfer volatile substances to or from the water. The removal of a gas from water is classified as desorption, or stripping. In the case of iron and manganese, the air causes these minerals to precipitate out of solution. The water can then move through a filter to trap the iron and manganese particles (http://www.uri.edu).The US Environmental Agency (USEPA) has identified air stripping as the one of the best available methods for the VOCs removal from contaminated groundwater especially for industrial wastewater treatment.

The principle uses for aeration in water treatment include:

- To reduce the concentration of taste-and-odor-causing substances and, to a limited extent, for oxidation of organic matter
- To remove substance that may in some way interfere with or add to the cost of subsequent water treatment. A prime example is removal of carbon dioxide from water before lime softening
- To add oxygen to water, primarily for oxidation of iron and manganese so that they may be removed by further treatment
- To remove radon gas
- To remove VOCs considered hazardous to public health

There are several types of aeration units such as;

- Waterfall aeration
    - spray aerators
    - multiple-tray aerators
    - Cascade aerators
    - Cone aerators
    - Packed column
- Diffusion-type aeration
- Mechanical aeration

In wastewater management systems, aeration is used in sewers and treatment plant head works to control hydrogen sulfide formation, to strip volatile organic and inorganic compounds from wastewater, to supply oxygen for aerobic biological wastewater treatment, to supply oxygen for aerobic biological wastewater treatment, to raise treated effluent dissolved-oxygen concentrations to level acceptable for discharge, and, in some cases, to increase the oxygen concentration of receiving waters. The latter case should be viewed as an emergency procedure and not as a solution to an environmental quality problem. (Tcobanoglous, et al,1987).

For packed tower aeration (PTA) as shown in *Figure 2* in *Appendices*, is designed slightly the same like packed column gas scrubber except its function, process and gas used, both use packing material to enhance the gas absorption. It is a waterfall aeration process that trickles raw water over a medium (packing) within a cylinder to mix water with air. The packing is usually composed of numerous hard plastic spheroid or box-type shapes, configured for maximum surface area. This medium is designed to break the water into tiny droplets, a process enhanced by the introduction of air blown from underneath the packing in the tower. As the air passes the water droplets, the organic contaminants are volatilized or “stripped” from the water and carried into the atmosphere. This technology has achieved removal rates of 95% or better for many of the volatile organic chemicals. The water is usually disinfected immediately following air stripping, because exposure to the atmosphere may introduce bacteria into the water. Water with high iron or manganese levels may tend to foul the plastic media, necessitating its periodic cleaning. One disadvantage of the packed tower process is the cost of the additional electricity required to run the blower. Another disadvantage is the physical size of the installation: towers may reach up to 8 feet in diameter and 30 feet in height, which could represent a significant visual impact. Additionally, packed tower exhaust gases may require treatment to meet air emissions regulations (depending on location), which can significantly increase the costs of this technology (http://www.dhs.state.or.us).

The rate at which a volatile compound is removed by air stripping in packed tower aeration (PTA) depends on the following factors:

- Air-to-water ratio(A ratio)
- Height of packing in the column
- Available surface area for mass transfer
- Water loading rate
- Air and water temperatures
- Physical chemistry of the contaminants to be removed

(American Water Works Association, 1990).

Predicting oxygen transfer rates in aeration system is nearly always based on oxygen rate model;

$$r_{O2} = K_L\, a\, (C_s\text{-}C_{O2})$$

where

r_{O2} = rate of oxygen mass transfer, g/cm^3.s

$K_L\, a$ = overall oxygen mass transfer coefficient, s^{-1}

C_s = saturation concentration of oxygen in bulk liquid, g/m^3

C_{O2} = concentration of oxygen in bulk liquid, g/m^3

The overall oxygen mass transfer coefficient is usually determined in full-scale facilities or in test facilities. Oxygen mass transfer coefficient, $K_L\, a$ is a function of temperature, intensity of mixing (and hence of the type of aeration device used and the geometry of the mixing chamber), and constituents in the water (Ford et al, Municipal Wastewater Treatment Plant Design and Strenstrom et al). The temparature effects are treated in the similar manner as they were treated in setablishing the BOD rate coefficient-by usingan exponential function the Van't Hoff-Arrhenius relationship;

$$K_L a_{(T)} = K_L a_{(20°C)} \theta^{T-20}$$

where

$K_L a_{(T)}$ = oxygen mass transfer coefficient at temperature, T, s^{-1}

$K_L a_{(20°C)}$ = oxygen mass transfer coefficient at 20°C, s^{-1}

Values for θ vary with test conditions and typically are in the range of 1.015 to 1.040 (American Society of Civil Engineers and Ford et al).

Effects of mixing intensity and tank geometry are difficult to deal with on a theoretical basis but must be considered in the design process because aeration devices are often chosen on the basis of efficiency. Efficiency is strongly related to the $K_L a$ value associated with a given aeration unit. A correction factor, α, is used to estimate the $K_L a$ value in the actual system:

$$\alpha = \frac{K_L a \text{ (wastewater)}}{K_L a \text{ (tap water)}}$$

where α is the correction factor. Values of α vary with the type of aeration device, the basin geometry, the degree of mixing, and the wastewater characteristics. Values of α varying from 0.3 to 1.2 have been reported (Stenstrom, et al,1981).

A second correction factor, β, is used to correct the test-system oxygen transfer rate for differences in oxygen solubility due to constituents in the water such as salts, particulates, and surface active substances:

$$\beta = \frac{C_s \text{ (wastewater)}}{C_s \text{ (tap water)}}$$

Values of β vary from about 0.7 to 0.98. A β value of 0.95 is commonly used for wastewater. Because the determination of β is within the capability of most wastewater treatment plant laboratories, experimental verification of assumed values is recommended (Tcobanoglous, et al,1987).

In PTA, the air flow required depends on the Henry's law coefficient for the compounds to be removed from the water. Packing height is a function of the required VOC removal efficiency. In general, an increase in packing height results in higher VOC removal. The air-to-water ratio is a column is a function of water temperature and desired level of contaminant removal. This ratio determines the size of the blower, the primary component of operating cost for PTA systems. Air-to-water ratio typically ranges from 30:1 to 100:1. Water loading rate, the amount of water passing through the column, usually ranges from 25 to 30 gpm/ft3. Column diameter is selected to accommodate the desired water loading on the column. Packed tower aeration removal effectiveness usually increases with an increase in water temperature, but it has been found that heating the influent water to increase removal effectiveness is not generally cost-effective (American Society of Civil Engineers and Ford et al).

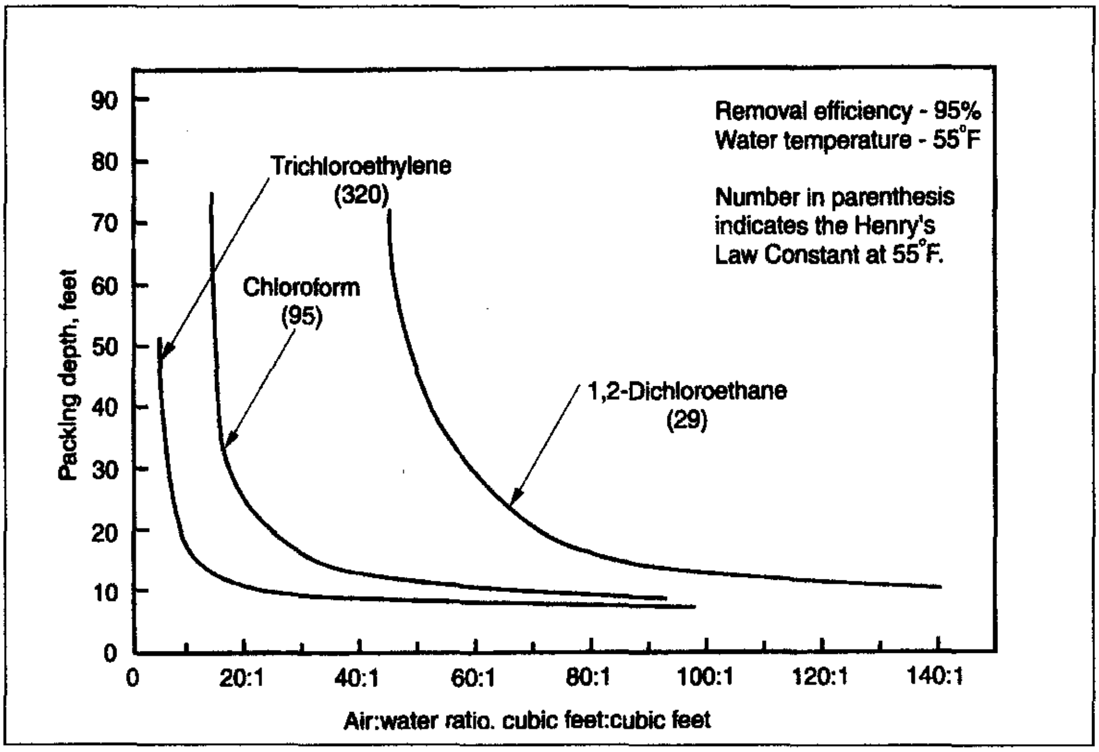


***Figure 2.16:** Effect of type of VOC on packed column design.*

(Source: AWWARF/KIWA Report, 1983)

From *Figure 2.16*, it shows the effect that the type of compound to be removed has on packing depth and air-to-water ratio. An air-to-water ratio of about 20:1 is required to achieve 85% removal of trichloroethylene (TCE) with 15 ft (14.6 m) of packing medium that is 1 in. (2.5 cm) in diameter. For 95%removal of a less volatile compound such as1,2-dichloroethane, an air-to-water ratio of about 120:1 is required for a column with the same size and depth of packing.

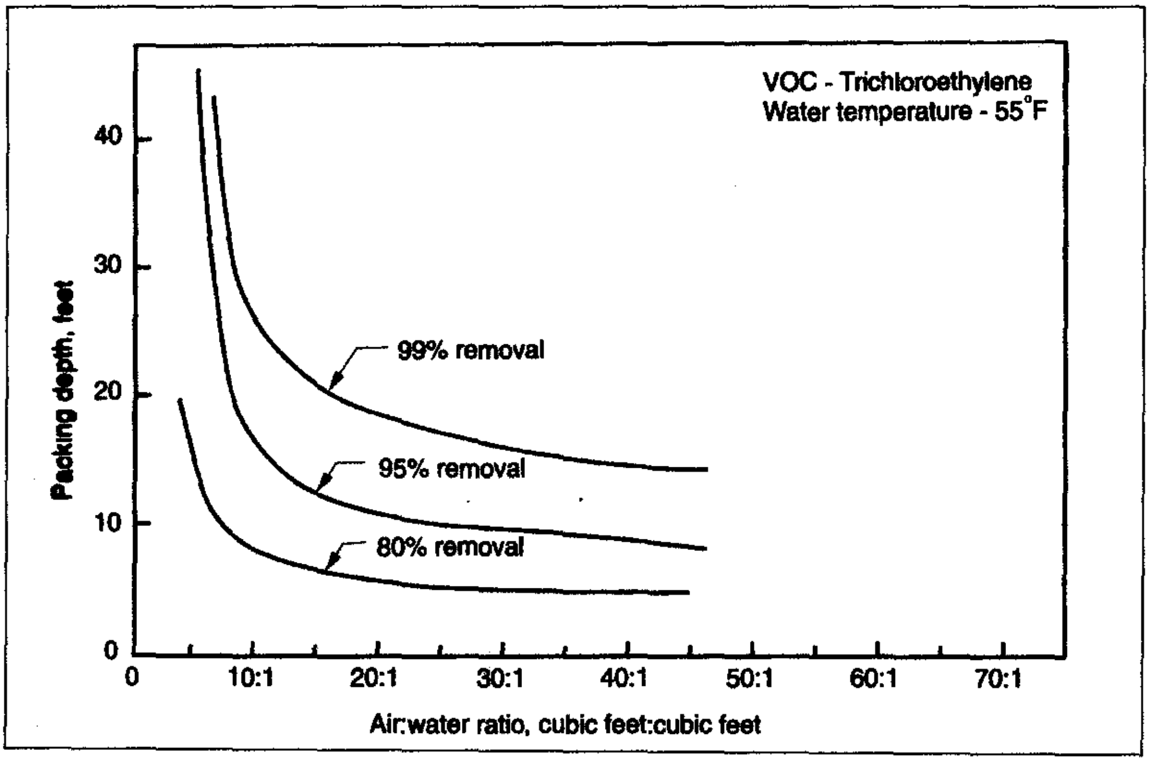


***Figure 2.17**: Effect of removal efficiency on packed column design.*
(Source: AWWARF/KIWA Report, 1983)

In *Figure 2.17*, the effect of desired removal efficiency on the design of a packed column is shown. It illustrates the relationship between air-to-water ratio and packing depth to achieve various efficiencies for TCE removal. About 6 ft (2m) of 1 in. (2.5 cm) packing medium is required to achieve 80% removal of TCE with an air-to-water ratio of 20:1. to achieve 99% removal with the same packing and air-to-water ratio, about 20 ft (6.1 m) of packing would be required.

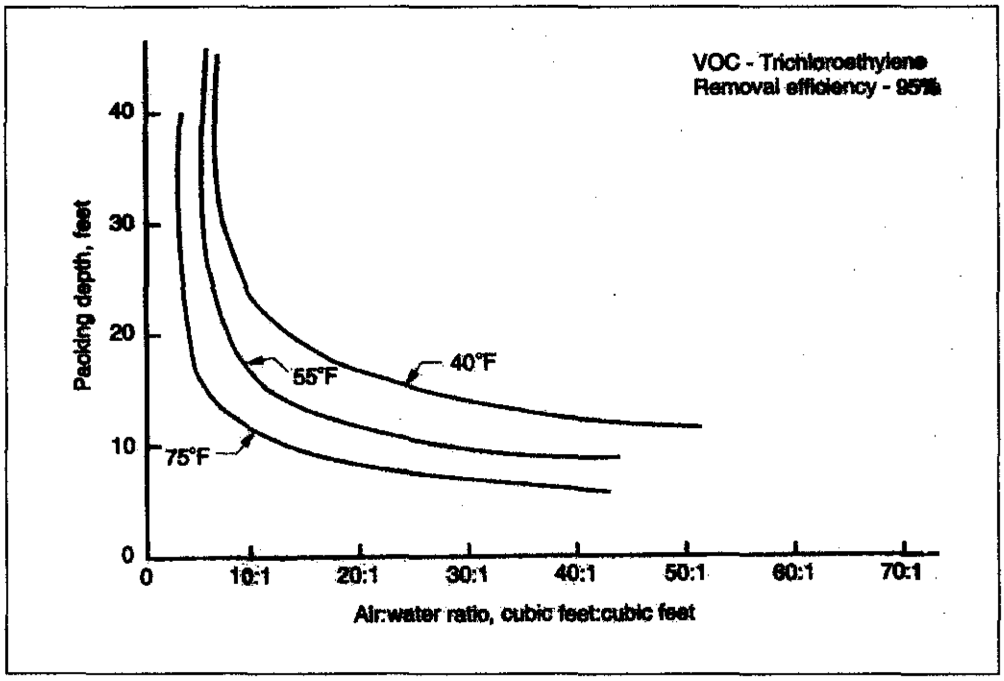


***Figure 2.18:** Effect of water temperature on packed column design*
(Source: AWWARF/KIWA Report, 1983)

The effect of water temperature is illustrated in *Figure 2.18*. For 95% TCE removal efficiency, it shows that for high water temperature, it favours lower packing depth as compared to lower water temperature at the same ratio of air to water.

CHAPTER 3

METHODOLOGY/ PROJECT WORK

3.1 Oxygen absorption in water by modified wetted-wall column

A series of experiments are done to study on the effectiveness of gas scrubber for ammonia absorption in ammonia-water system. The study is carried out in several sections, which are:

- Study the effect of water flow rate on oxygen absorption
- Study the effect of air flow rate on oxygen absorption
- Study the effect of water inlet temperature on oxygen absorption

For water flow rate and air flow rate study, average mass transfer coefficient is calculated by using Microsoft Excel. Heat transfer coefficient based on the result for water inlet temperature is calculated. Graphs for both parameters are plotted against the corresponding water and air flow rates as well as the inlet temperature. Furthermore, a further study on gas absorption effectiveness is done based on calculation liquid hold up in the column and flooding mass velocity at different water and air flow rates. Relationship with dimensionless number is studied by calculating Reynolds, Sherwood and Nusselt number and the characteristic of the absorption process.

However, for the convenience of this study, some modifications are done on the wetted-wall column. 15 mm Plastic Raschig rings are filled in the wetted-wall column and an external heater, which is circulation water bath, is installed to vary the water inlet temperature into the second column. *Figure 3.1* shows the experimental set-up of modified wetted-wall column.

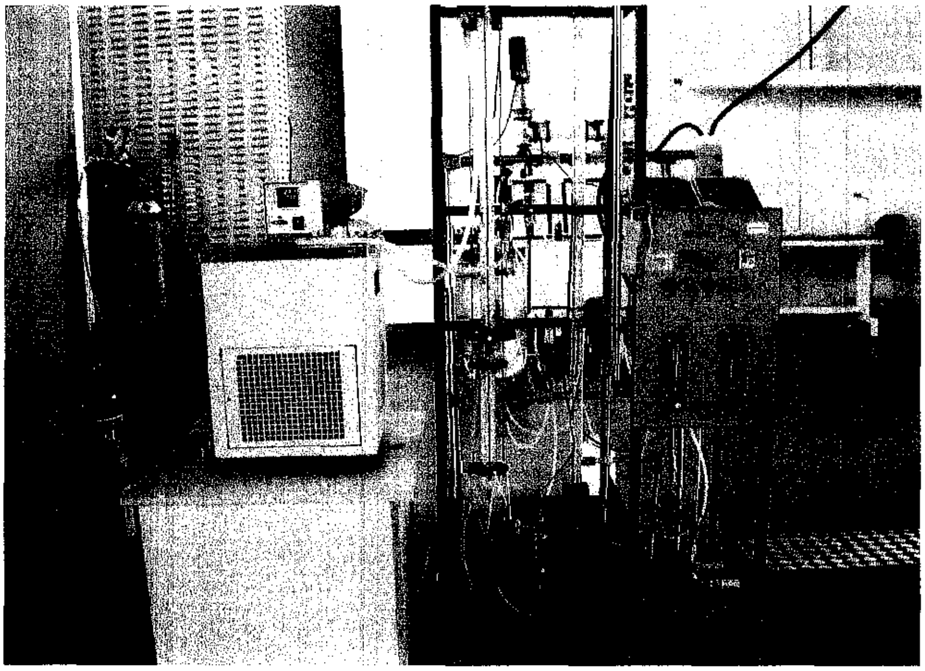


***Figure 3.1:** Experimental set-up of modified wetted-wall column.*

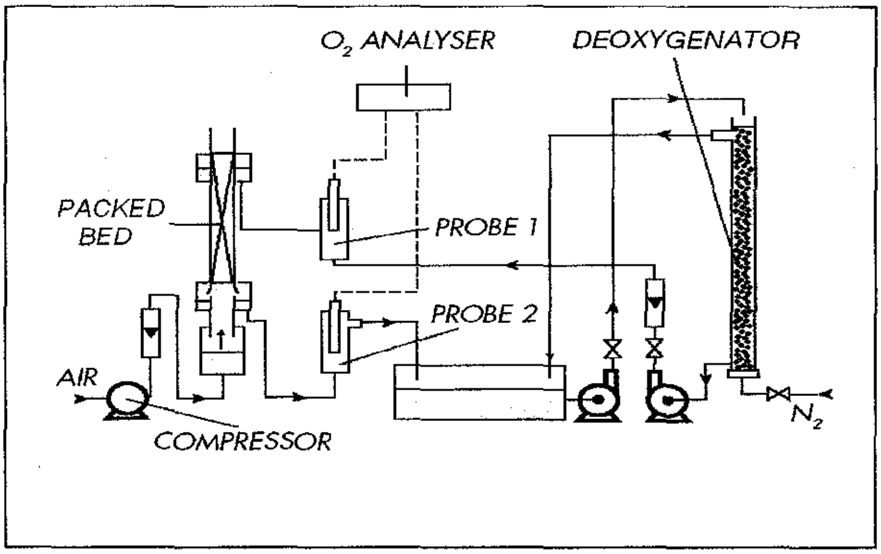


***Figure 3.2:** Schematic diagram of modified wetted-wall column*

In operation, water is sparged with nitrogen in the deoxygenator before entering the top of the modified wetted wall column. Air is pumped by the integral diaphragm type air pump into the base of the column. The air passes the packing in the column, giving up the oxygen to the water. Dissolved oxygen at inlet and outlet can be measured in rapid succession. The water drains into the storage tank to be recycled to the deoxygenator.

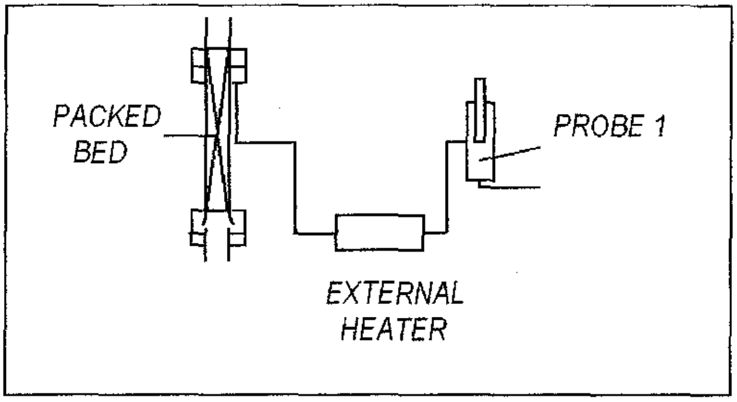
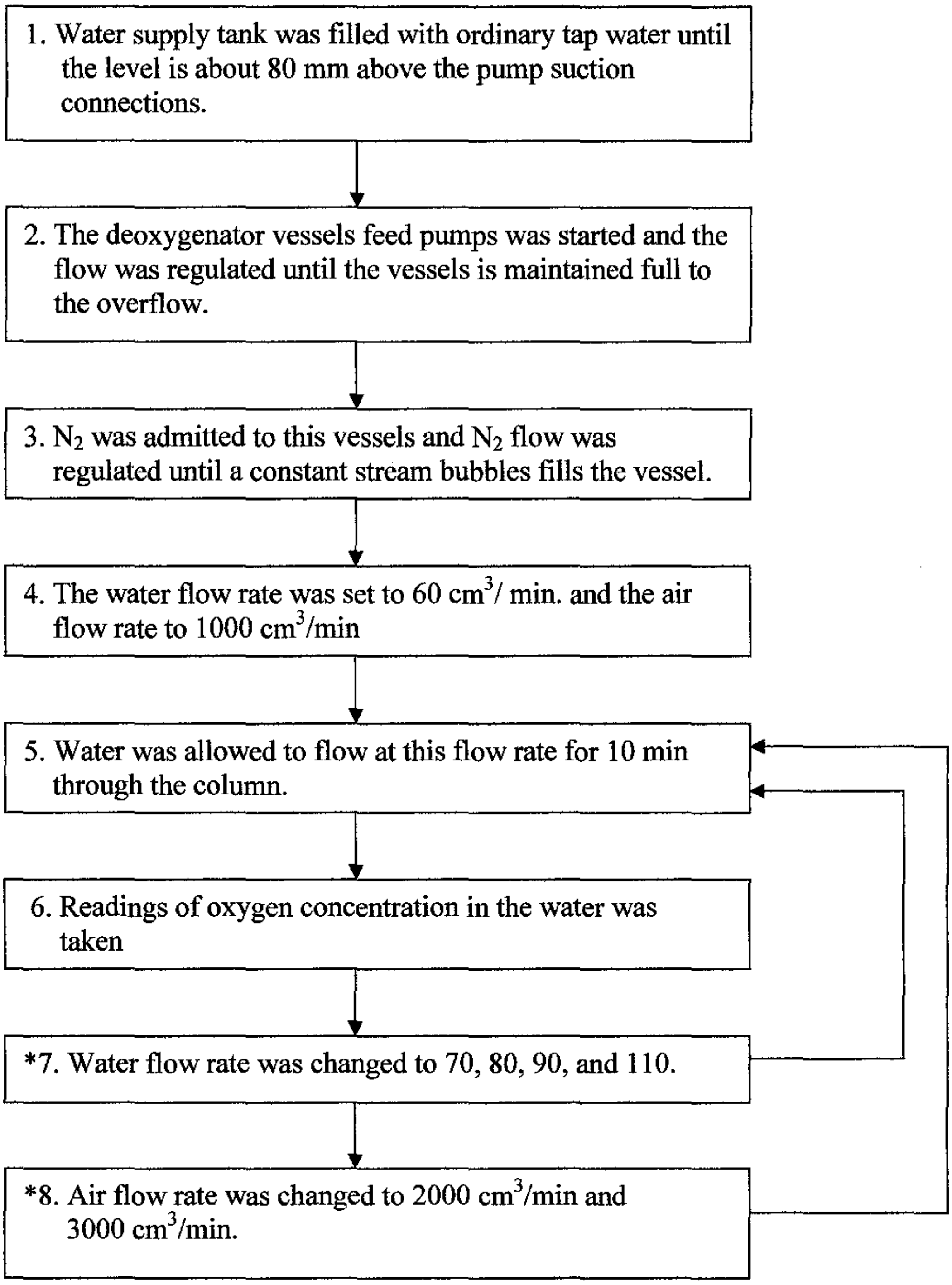


Figure 3.3: *Schematic diagram for installed external heater*

An external heater is installed temporarily on the modified wetted-wall column by bypassing the connection between outlet Probe 1 to the inlet of modified wetted-wall column. The bypass line connecting the outlet of DO meter to the circulation water bath and the outlet tube of the water bath is connected to the inlet tube of the column.

3.2 Experimental procedures:



1. Water supply tank was filled with ordinary tap water until the level is about 80 mm above the pump suction connections.

2. The deoxygenator vessels feed pumps was started and the flow was regulated until the vessels is maintained full to the overflow.

3. N_2 was admitted to this vessels and N_2 flow was regulated until a constant stream bubbles fills the vessel.

4. The water flow rate was set to 60 cm^3/ min. and the air flow rate to 1000 cm^3/min

5. Water was allowed to flow at this flow rate for 10 min through the column.

6. Readings of oxygen concentration in the water was taken

*7. Water flow rate was changed to 70, 80, 90, and 110.

*8. Air flow rate was changed to 2000 cm^3/min and 3000 cm^3/min.

* correspond to any changes regarding to the study purposes

- **Study the effect of water flow rate on oxygen absorption.**
  * Water flow rates vary 60,70,80,90 and 110 cm^3/ min at air flow rate of 1000, 2000 and 3000 cm^3/ min.

- **Study the effect of air flow rate on oxygen absorption.**
  * Air flow rates vary at 1000, 2000, 3000 and 4000 cm^3/ min at water flow rates of 70, 90 and 110 cm^3/ min.

- **Study the effect of water inlet temperature on oxygen absorption.**
  * Water inlet temperatures vary at 30°C, 35°C, 40°C and 45°C at air flow rates of 1000, 2000, 3000 and 4000 cm^3/min. Water flow rates are kept constant due to the existence of secondary pump in the external heater, which is cannot be adjusted. Thus, the effect of water inlet temperature with different water flow rates cannot be studied.

    The temperature of outlet water from the modified wetted-wall is measured and collected for further analysis of heat transfer.

3.3 Formulas for calculations

3.3.1 Mass transfer calculations

3.3.1.1 Calculations for average mass transfer coefficient:

These calculations are carried based on predetermined values which are water and air flow rates and excluding data obtained from the experiments.

Dwivedi and Upadhyay (1977) proposed a single correlation for both gases and liquids in packed and fluidized beds in terms of the j-factor as

$$\varepsilon j_{Mpb} = \frac{0.765}{\left(Re^{*}_{pb}\right)^{0.82}} + \frac{0.365}{\left(Re^{*}_{pb}\right)^{0.386}}$$

ε = porosity (void fraction) which is valid for $0.01 \le Re^*_{pb} \le 15{,}000$. The terms j_{Mpb} and Re^*_{pb} are defined by

$$j_{Mpb} = (\langle kc \rangle / \upsilon_o)\, Sc^{2/3}$$

j_{Mpb} = Chilton-Colburn j-factor for mass transfer for packed beds

$\langle kc \rangle$ = average mass transfer coefficient *(m/s)*

υ_o= superficial velocity

$= Q / A$

Q = volumetric flow rate

A = total cross-sectional area of the bed

$= \pi / r^2$

Schmidt number, $Sc = v / D_{AB}$

v = kinematic viscosity (m^2/s)

D_{AB} = diffusion factor (m^2/s)

D_{AB} for air-H_2O system at 313 K (40°C) is $2.88 \times 10^{-5}\ m^2/s$

$$D_{AB} \propto \frac{T^{3/2}}{P}$$

$$Re^*_{pb} = \frac{Dp\upsilon_o\rho}{\mu}$$

Dp = particle diameter (m)

μ = viscosity (kg/m.s)

(Tosun, İsmail,2002)

3.3.1.2 Calculation for mass transfer coefficient:

This calculation is done based on the concentration of inlet and outlet of oxygen in water which are obtained from the experiments.

$$k_L = \frac{j}{A\Delta C_{LM}}$$

k_L = liquid film mass transfer coefficient, m/s

j = change in concentration of O_2 in the water passing through the column x volumetric flow rate of water

A = area of mass transfer

ΔC_{LM} = log mean concentration difference

$$\Delta C_{LM} = \frac{(100 - O2\text{ in})\ (100 - O2\text{ out})}{\ln\left[\frac{(100 - O2\text{ in})}{(100 - O2\text{ out})}\right]} \quad \text{x} \quad 0.09\ \text{p.p.m x } 10^{-3}\ \text{kg/ m}^3$$

0.09 p.p.m =conversion factor for saturation of water at 20 °C

(Chemical Engineering Lab 2 Manual,2005)

3.3.2 Heat transfer calculations

Calculation for average heat transfer coefficient:

Whitaker (1972) proposed the following correlation for heat transfer in packed beds:

$$Nu_{pb} = (0.4\, Re_{pb}^{1/2} + 0.2 Re_{pb}^{2/3})\, Pr^{0.4}$$

$$\text{Nusselt number, } Nu_{pb} = \langle h \rangle \frac{Dp}{k} \frac{\varepsilon}{1-\varepsilon}$$

k = thermal conductivity (W/m.K)

$$Re_{pb} = \frac{D p \upsilon_0 \rho}{\mu} \frac{1}{1-\varepsilon}$$

This equation only valid when

$$3.7 \leq Re_{pb} \leq 8000$$

$$0.34 \leq \varepsilon \leq 0.74$$

$$Pr \approx 0.7$$

All properties used in the formulas are evaluated at the average fluid temperature in the packed bed.

(Tosun, İsmail,2002)

3.3.3 Specific Liquid Hold-up

$$h_L = [\,12\, Fr_L/Re_L]^{1/3}[a_h/a]^{2/3}$$

h_L = specific liquid hold-up (m^3 hold-up/m^3 packed bed)

Re_L = liquid Reynolds number = $\upsilon_L \rho_L / a\mu_L$

υ_L= superficial liquid velocity, (m/s)

a = specific surface area of spacing (m^2/m^3)

Fr_L = liquid Froude number = $\upsilon_L{}^2 a/g$

g = acceleration of gravity

a_h = hydraulic, or effective, specific are of packing

The ratio of specific areas is given by,

$a_h/a = C_h\, Re_L{}^{0.5}\, Fr_L{}^{0.1}$ $\quad$ $for\ Re_L < 5$

$a_h/a = 0.85 C_h\, Re_L{}^{0.25} Fr_L{}^{0.1}$ $\quad$ $for\ Re_L < 5$

Values of a and C_h are characteristic of the particular type and size of packing.

(Billet and Schultes, 1995)

3.3.4 Dimensionless numbers

For packing beds, the modified dimensionless numbers are:

$$Re_{pb} = \frac{Dp\,\upsilon_0 \rho}{\mu} \frac{1}{1-\varepsilon}$$

$$Nu_{pb} = \langle h \rangle \frac{Dp}{k} \frac{\varepsilon}{1-\varepsilon}$$

$$Nu_M = Sh_{pb} = \langle Kc \rangle \frac{Dp}{D_{AB}}$$

CHAPTER 4

RESULTS AND DISCUSSION

4.1 FINDINGS

The rate of oxygen absorption in water is measured by means of average mass transfer coefficient, $\langle kc \rangle$, which consider dimensionless number correlations and the flow rates, and liquid transfer coefficient, k_L, which considers DO percentages inlet and outlet. Higher mass transfer coefficient indicates better oxygen absorption due to flow rates, inlet water temperatures and packings. From the results obtained, it shows that higher water and air flow rates as well as packings enhance the mass transfer of oxygen into the water. However, the mass transfer of oxygen into water decreases rapidly as the inlet water temperature is increased. Furthermore, liquid hold-up also increases when water flow rates increase. Comparison of mass transfer coefficient for wetted-wall column without packing and the modified column shows that rate of oxygen absorption in packed bed is higher than that of in column without packings. Relationship between Reynolds number and both Sherwood and Nusselt numbers shows that both *Sh* and *Nu* are directly proportional to the *Re*.

4.2 LABORATORY EXPERIMENTS

- **Study on water flow rates effects on oxygen absorption in water**

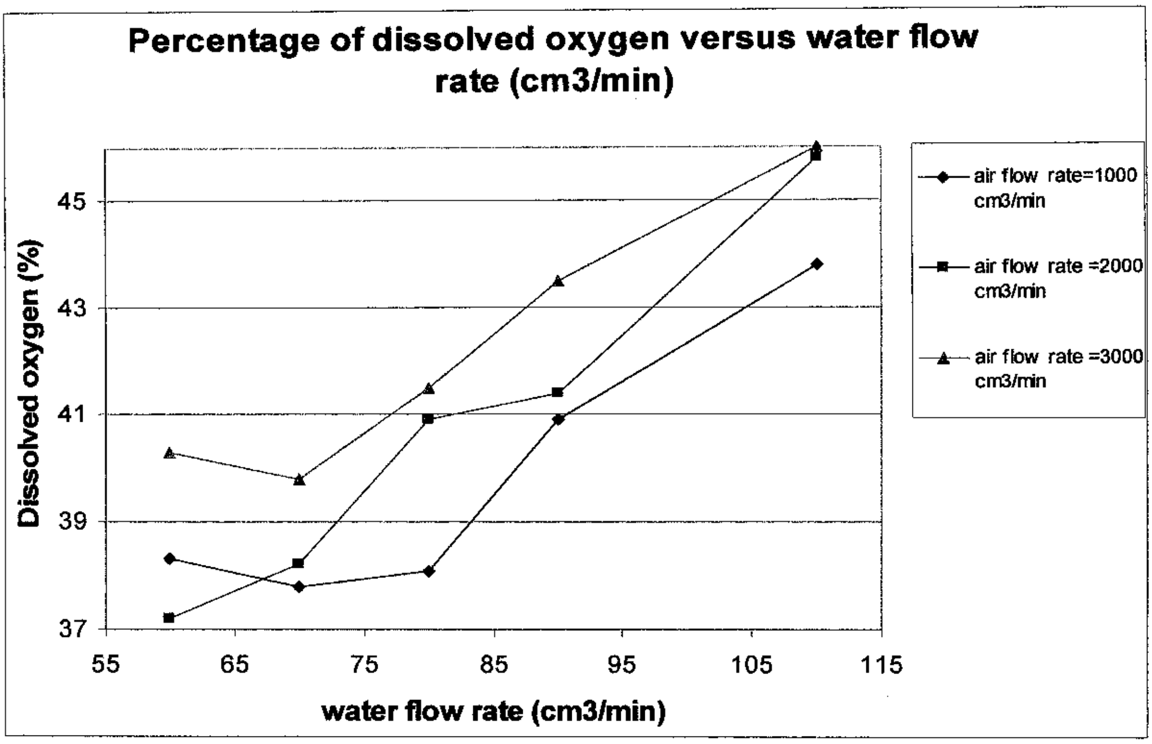


***Figure 4.1:** Percentage of dissolved oxygen in outlet water as a function of water flow rates (cm^3/min)*

From *Figure 4.1,* it shows that percentage of oxygen content in the outlet water increases as the water flow rates are increased. Although the trends are quite unstable for 1000 and 2000 cm^3/min air flow rates due to the DO meter high sensitivity, both are still favour better absorption of oxygen in the water as the water flow rates are increased. Significant increase in DO percentage occurs from 70 m^3/min water flow rate. Higher air flow rates also favour better mass transfer, especially at 2000 m^3 air/min where the slope of the graph is higher compare to the other two trend lines.

However, in ammonia-water system in bubble mode plate type absorber (Lee et al, 2002), (refer to *Figure 2.8 (a)*) the effects of solution flow rates on the mass transfer coefficient is not very significant. The mass transfer coefficient tends to be constant and it starts to decrease at about 0.12 kg solution/s. In this system, the solution used is aqueous ammonia solution with fixed concentration of ammonia throughout the experiment. Thus, it can be concluded that for this experimental condition, the system is not liquid-controlled but more on gas-controlled.

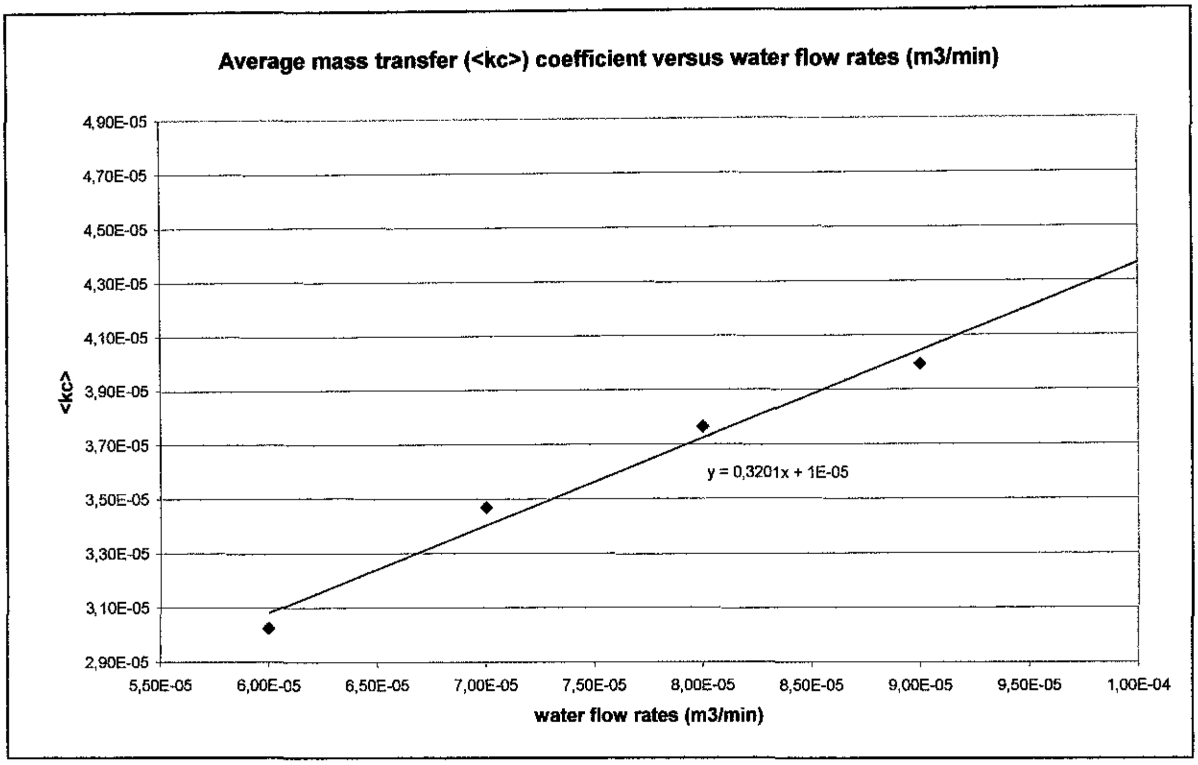


Figure 4.2: *Average mass transfer coefficient, $\langle kc \rangle$ as a function of water flow rates. The $\langle kc \rangle$ calculation is only based on water flow rates by using mass transfer correlations of dimensionless number.*

The values of $\langle kc \rangle$ are calculated by utilizing mass transfer correlations proposed by Dwivedi and Upadhyay (1977). Those correlations use modified dimensionless number to model the transport phenomena of the flow in packed beds. The calculations only consider the predetermined values of water and air flow rates. From *Figure 4.2*, it shows that $\langle kc \rangle$ increases as the water flow rates increase. As the water flow rates used are very low, the values of $\langle kc \rangle$ also are very low.

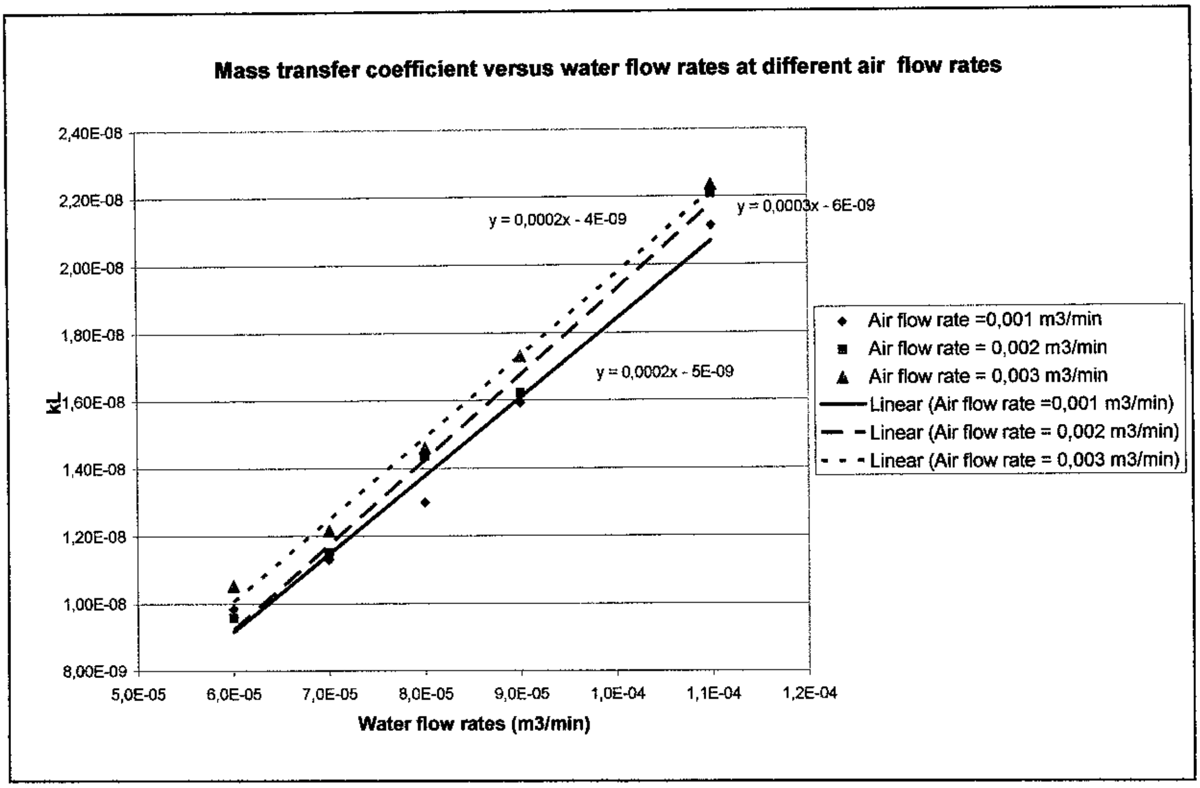


Figure 4.3: *Relationship between liquid mass transfer coefficient, k_L and water flow rate (m^3/min). k_L values are calculated based on DO inlet and outlet obtained from the experiments.*

Liquid mass transfer coefficients, k_L, are calculated by using the DO inlet and outlet values gathered from the experiments. The similar trend in *Figure 4.1* is obtained in the *Figure 4.3*, where the k_L increases as the water flow rates increase. Only k_L is calculated because the system can be considered as liquid-controlling system as any changes in DO percentages are much depend on any variations in water flow rates rather than air flow rates. Variations in air flow rates still show some differences in the amount of oxygen dissolved but not much pronounced as compared to variations in water flow rates.

- **Study on air flow rates effect on oxygen absorption in water**

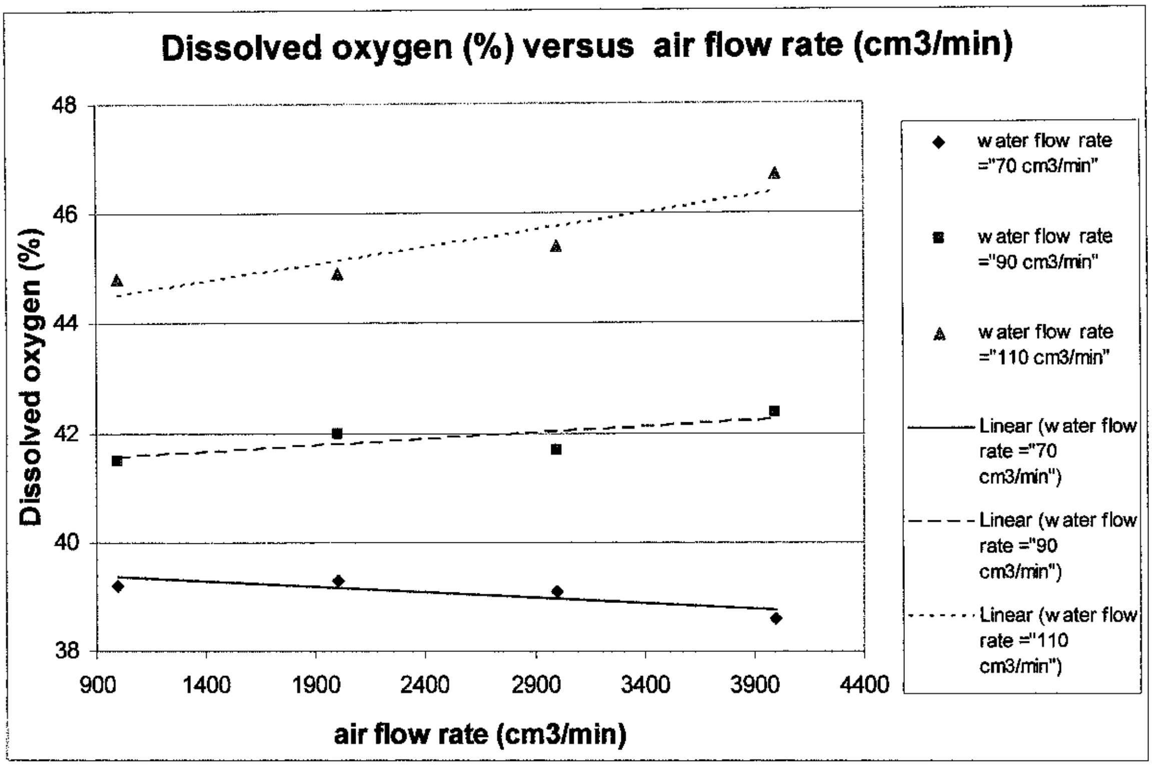


Figure 4.4: *Percentage of dissolved oxygen as a function of air flow rates (cm^3/min) at different water flow rates.*

Figure 4.4 shows the relationship between percentages of DO in the outlet water with air flow rates. At low water flow rates, the DO percentage seems to decline as the air flow rates increase. For 90 cm^3 water/min, the DO percentages increase but not very significant and tend to fluctuate. However, DO percentage increase is very significant at 110 cm^3 water/min with the increasing air flow rates. It also indicates that variations in air flow rates not very facilitating oxygen absorption in water as compared to changes in water flow rates. Furthermore, it shows that the best oxygen absorption only occur at high water and air flow rates. Compare to a study done by Lee et al, 2002, on ammonia-water system (refer to *Figure 2.8 (b)*), a very significant increase of mass transfer occurs as the ammonia gas flow rates are increased. As the affinity between ammonia vapor and water liquid to form ammonia aqueous is considerably high, any increase in water vapor flow rates will result in high mass transfer coefficient.

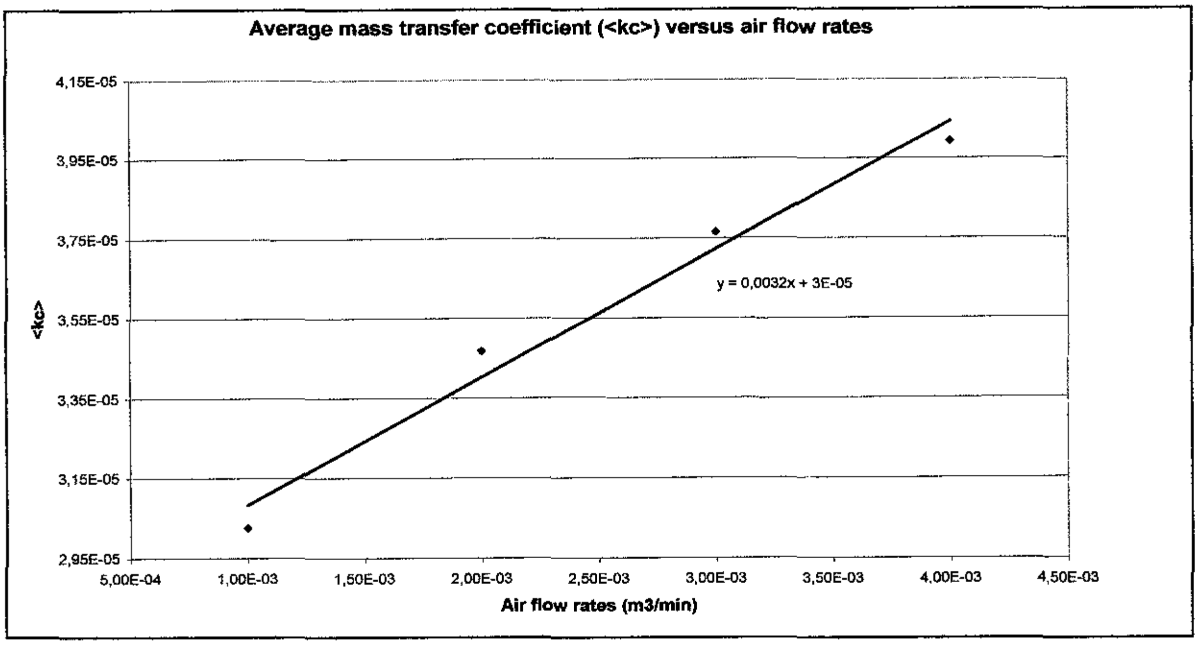


Figure 4.5: *The effect of air flow rates on average mass transfer coefficient,* $\langle kc \rangle$*. The values are determined by mass transfer correlations involving dimensionless numbers.*

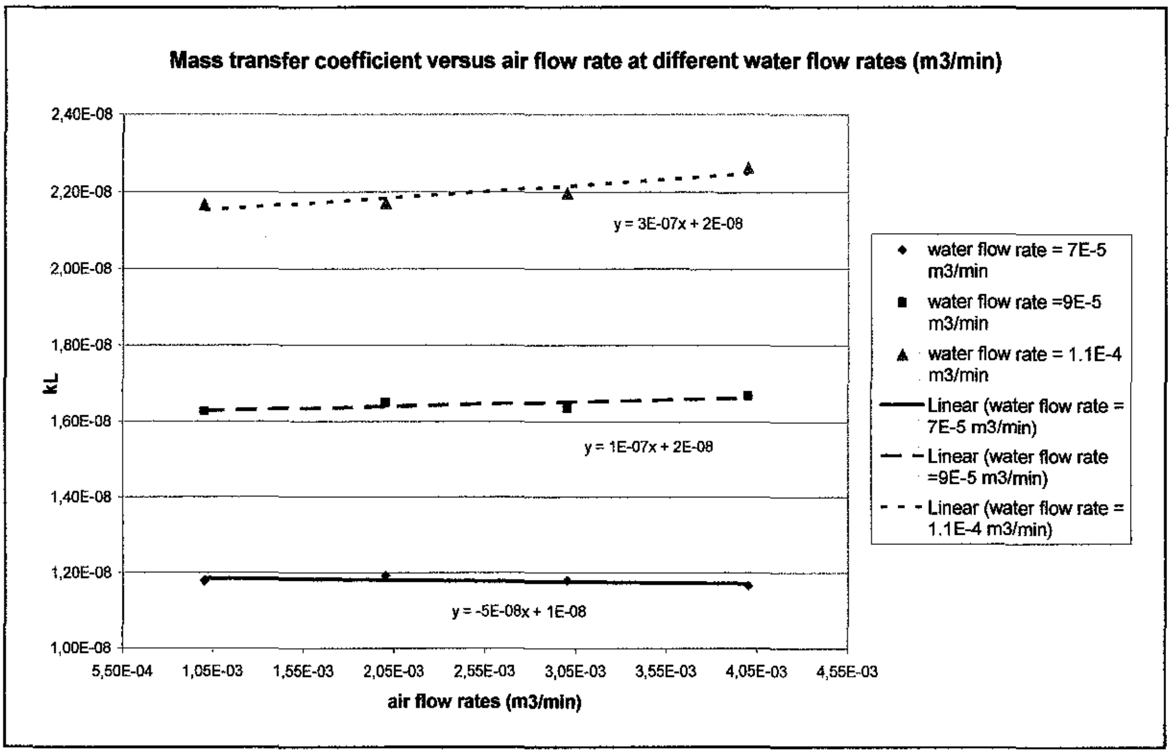


Figure 4.6: *The effect of air flow rates on liquid mass transfer coefficient,* k_L*, at different water flow rates.*

In *Figure 4.5*, the similar method of calculation is applied for determining $\langle kc \rangle$ values as in *Figure 4.2*. As the air flow rates increase, the $\langle kc \rangle$ values also increase. Similar graph trend as in *Figure 4.4* can be seen in *Figure 4.6*, indicating slight difference of k_L as the air flow rates change. In oxygen-water system, air flow rates not much affecting the rate of oxygen absorption and it tends to decrease when the associating water flow rates in operation is very low due to low affinity between oxygen and water.

- **Study the effect of inlet water temperature on oxygen absorption in water**

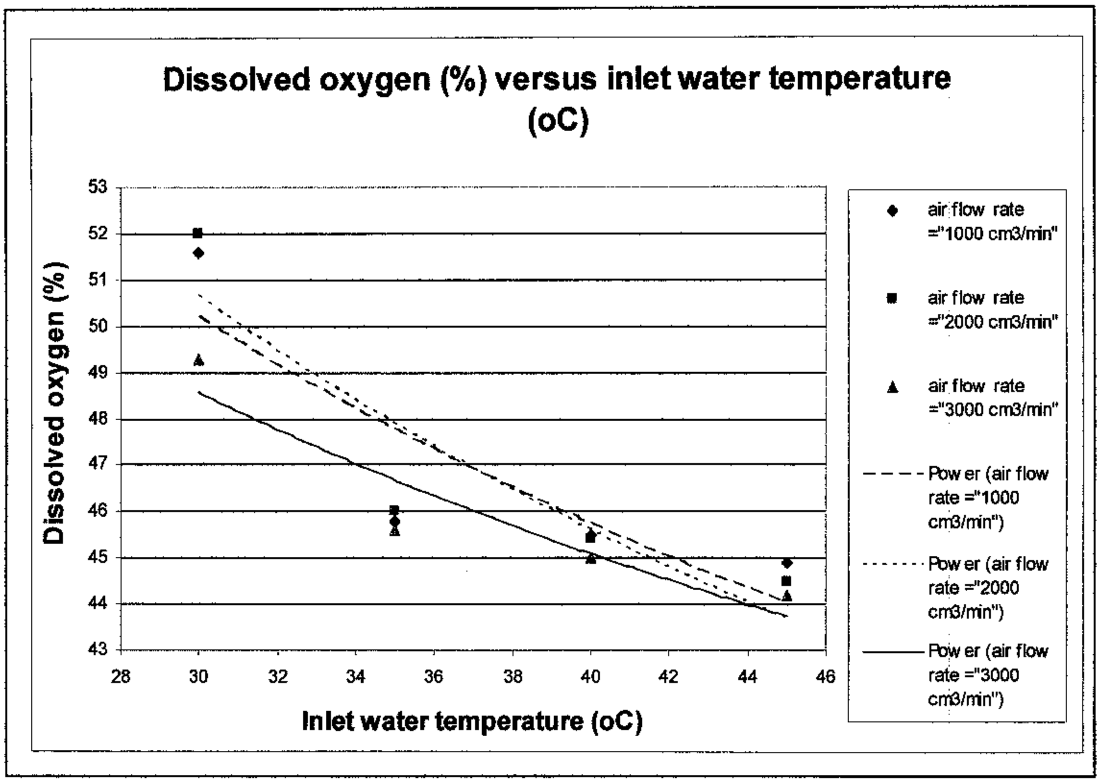


Figure 4.7: The percentage of dissolved oxygen as a function of inlet water temperature at different air flow rates.

Higher inlet water temperature will decrease the percentage of DO in water and it is much pronounced at high flow rate, which is at 0.003m^3 air/min as shown in *Figure 4.7*. Higher flow rates of air associating with increasing temperature results in high reduction in DO percentage. As shown in *Figure 2.14*, DO percentages decrease gradually with increase in water temperature. This can be seen in solubility curve for oxygen gas, plotted as milligrams of oxygen dissolved per 1000 g of water, that shows the solubility of oxygen at 0°C is about twice its solubility at 30°C. As the temperature of the water goes up, the lower the concentration of dissolved oxygen gas. Simply stated, the water temperature helps determine the maximum amount of oxygen gas that water can dissolve.

However, from Table 2-140, Oxygen-Temperature relationship extracted from Perry's Chemical Engineer's Handbook (1998), it shows that higher temperature favors higher solubility. The temperature here refers to the oxygen gas temperature, at which oxygen solubility increases when its temperature increases. As the oxygen molecules have more energy to move randomly and absorbing in water, the percentage of oxygen dissolved becomes higher which gives better solubility. Nevertheless, for this case, the inlet water is increased which gives resistance for the gas to absorb into the water as temperature gradient occurs in the system.

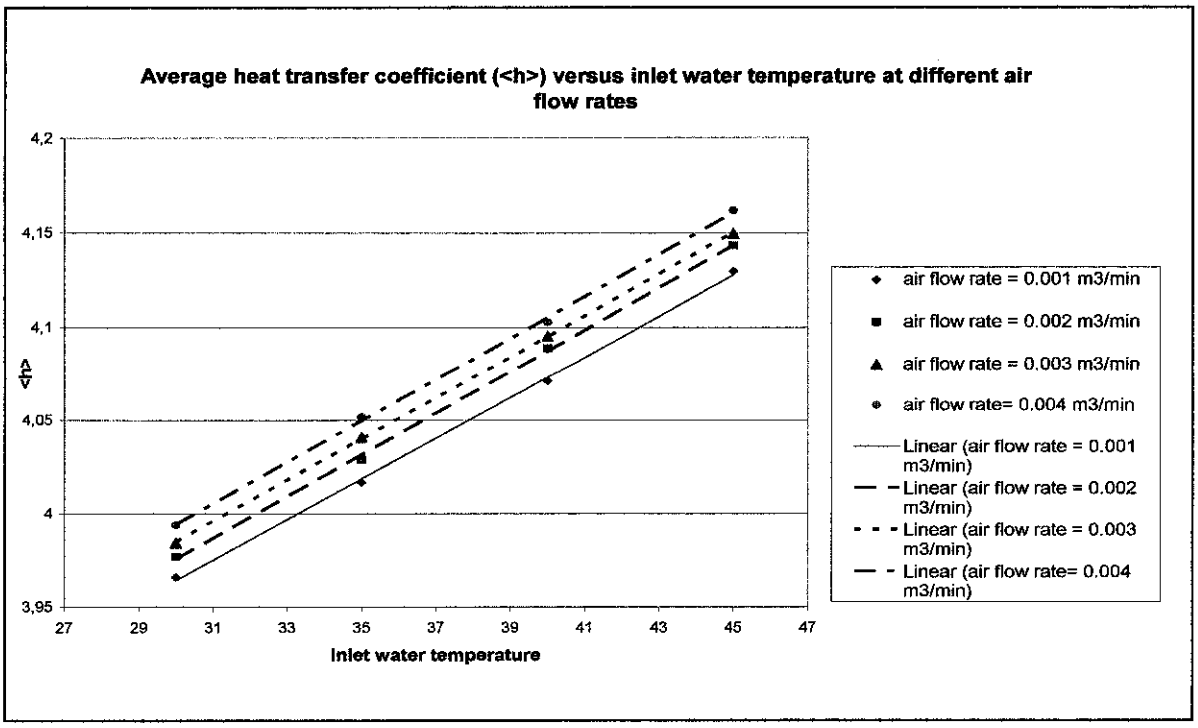


Figure 4.8 *Relationship between average heat transfer coefficient, $\langle h \rangle$ and inlet water temperature.*

Better heat transfer is obtained as the inlet water temperature is increased as shown in *Figure 4.8*. The calculation considers the average temperature of bed by averaging both inlet and outlet temperature. As heat transport occurs from the water to the air, the outlet water is lower than the inlet by neglecting heat loss in atmosphere since the system is an open system. Higher air flow rate yields better heat transfer demonstrated by the average heat transfer coefficient, $\langle h \rangle$. For inlet water temperature effect study, the only parameter that is varied is the air flow rate due to restrictions on the external heater. The heater has its own pump and the flow rates of water outlet of the heater cannot be varied due to unavailability of flow meter on the external heater. So, the water flow rates entering the absorption column are always constant throughout the experiment. Thus, this study is restricted by only considering air flow rates effect on heat transfer.

- **The effect of water flow rates on specific liquid hold-up (h_L)**

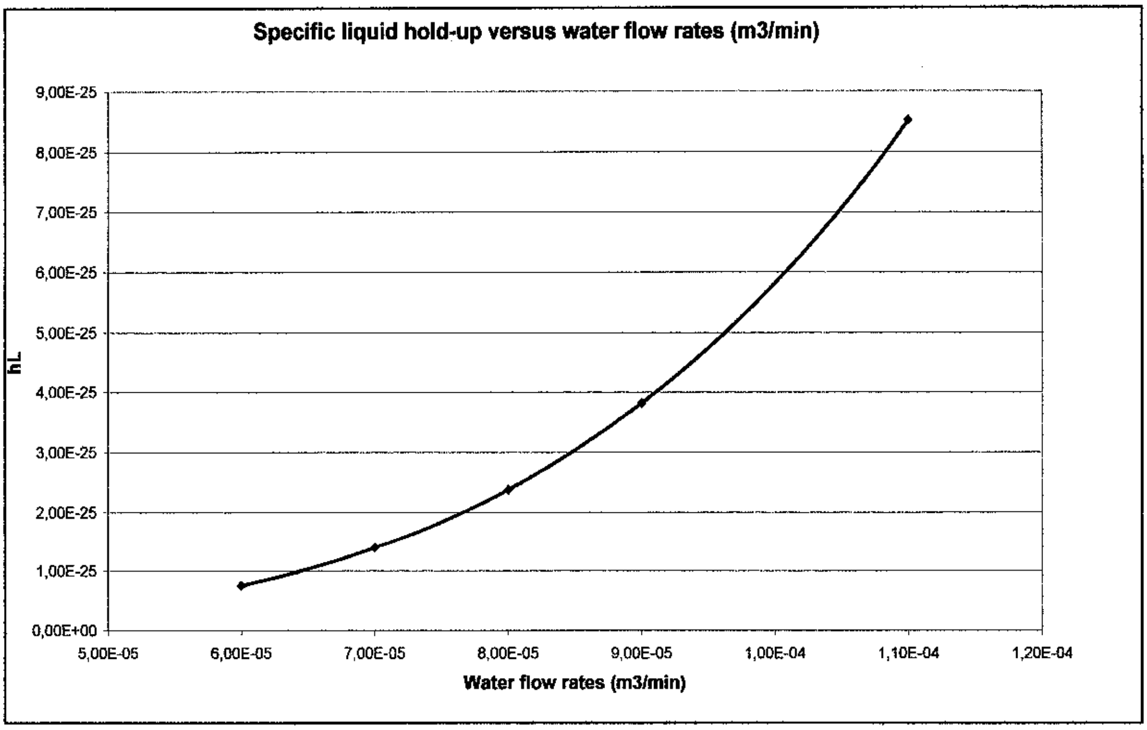


Figure 4.9: *The effect of water flow rates on specific liquid hold-up (h_L)*

The relationship between specific liquid hold-up in the packed bed with water flow rates can be observed in *Figure 4.9*. The h_L increases gradually as the water flow rates increase. Liquid hold-up is defined as the quantity of liquid contained in the packed bed and it is a function of pressure drop. In this system, the pressure drop is very minimal due to low flow rates of water and air used. Because of that, the values of h_L are very small and not very significant. As the liquid hold-up increment is in control, the loading region is not reached and flooding does not occur during the experiment. Regarding to Seader and Henley, 1998, the loading region is between the loading point and the flooding point wherein significant liquid entrainment is observed, liquid hold-up increases sharply, mass transfer efficiency decreases, and column operation is unstable. From Billet, 1989, the superficial gas velocity at the loading point is should be approximately 70% of that the flooding point to avoid flooding in packed column.

The liquid hold-up is a function of void fraction or porosity, ϵ, and other packing constants as listed in Table 6.8, Separation Process Principle (1998). From *Figure 4.9,* it shows that at low liquid velocities, liquid hold-up becomes so small that the packing is no longer completely wetted. When this occurs, packing efficiency decreases dramatically, particularly for aqueous systems of high surface tension (Seader and Henley,1998).

In a study carried out by Wammes et al. (1991a), by using 3-mm glass spheres in a water-nitrogen system, they obtained residual liquid saturation values on the order of 0.035-0.050 for a packed bed with a porosity of 0.39. For a similar system with bed porosity of 0.375-0.385, Levec et al. (1986) reported a residual liquid hold-up of 0.022. This low value was explained in terms of the possible poor wetting properties of the glass used (Wammes et al.,1991a). From *Figure 2.6 (a)*, there is a relationship between liquid hold-up with gas flow rate in air-water system by using glass Raschig rings. It shows that the liquid hold-up is constant although there is an increment in gas flow rates. However, at high superficial water velocity, the liquid hold-up increases. Thus, it can be concluded that liquid hold-up is much influenced by the liquid flow rates. From the observations and literature reviews, it can be concluded that mass transfer efficiency are depends on type of material, size, shape, porosity (voidage) and orientation of the packing particles.

- **Relationship between dimensionless number**

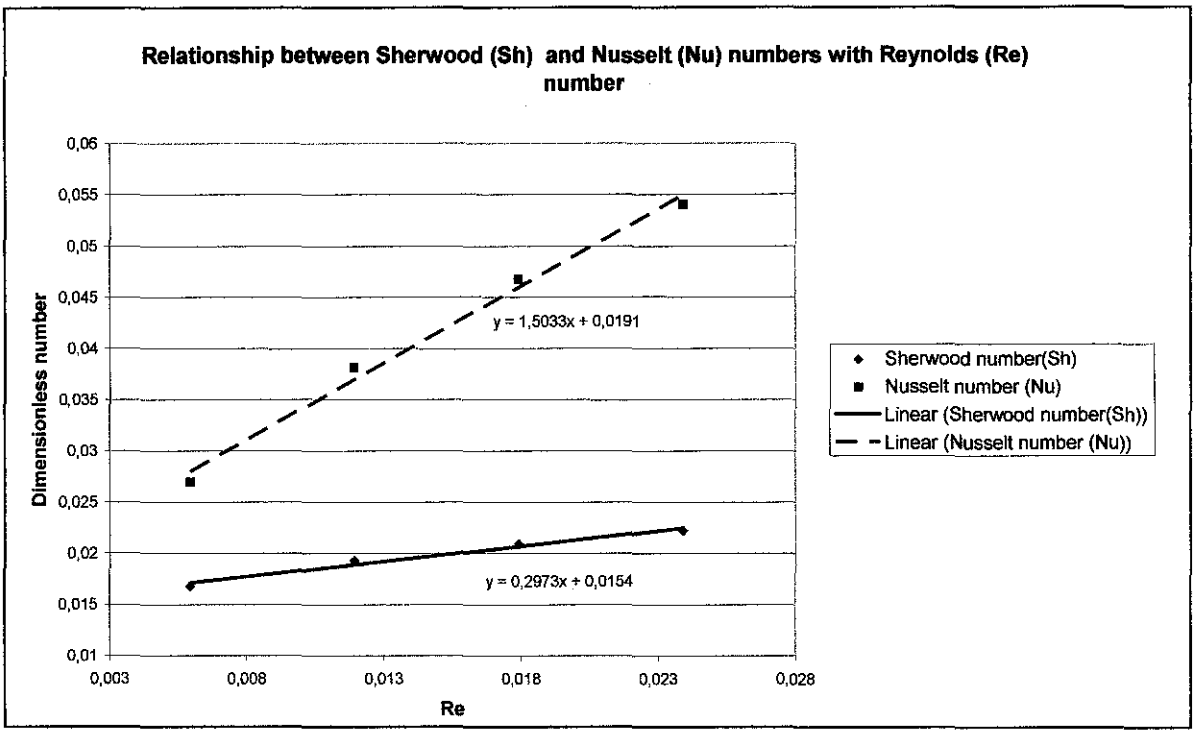


***Figure 4.10:** Relationship between Reynolds number and Sherwood and Nusselt number at 30°C at different air flow rates.*

Dimensionless numbers are used to characterize flow behaviour as well as heat and mass transfer. Basically, Reynold number is used to characterize flow behaviour (i.e laminar, transaction and turbulent) and Sherwood and Nusselt numbers are used for characterizing mass transfer with forced convection and heat transfer with forced convection respectively. From *Figure 4.10*, the relationship between *Re* and both *Sh* and *Nu* numbers are plotted at various air flow rates, which are at 1000 ,2000,3000 and 4000 cm^3/min and at 30°C. *Re* and *Nu* numbers are functions of temperature while *Sh* number is a function of average mass transfer coefficient, $\langle kc \rangle$. Nusselt number increases very significantly with increasing *Re* number. As compared to *Sh* number, it only increases a little and not very significant. As both *Re* and *Nu* numbers are related with temperature variations, both are also related directly as well and it shows that more turbulence the flow is, the more heat transfer by convection. For *Sh* number, the correlation between the number with *Re* number is not very significant as $\langle kc \rangle$ is calculated by using Re^* for packed bed which is slightly different. However, the graph trend shows that the more turbulence the flow, the more mass transfer and heat transfer can occur due to forced convection.

- **Study the effect of packing on mass transfer**

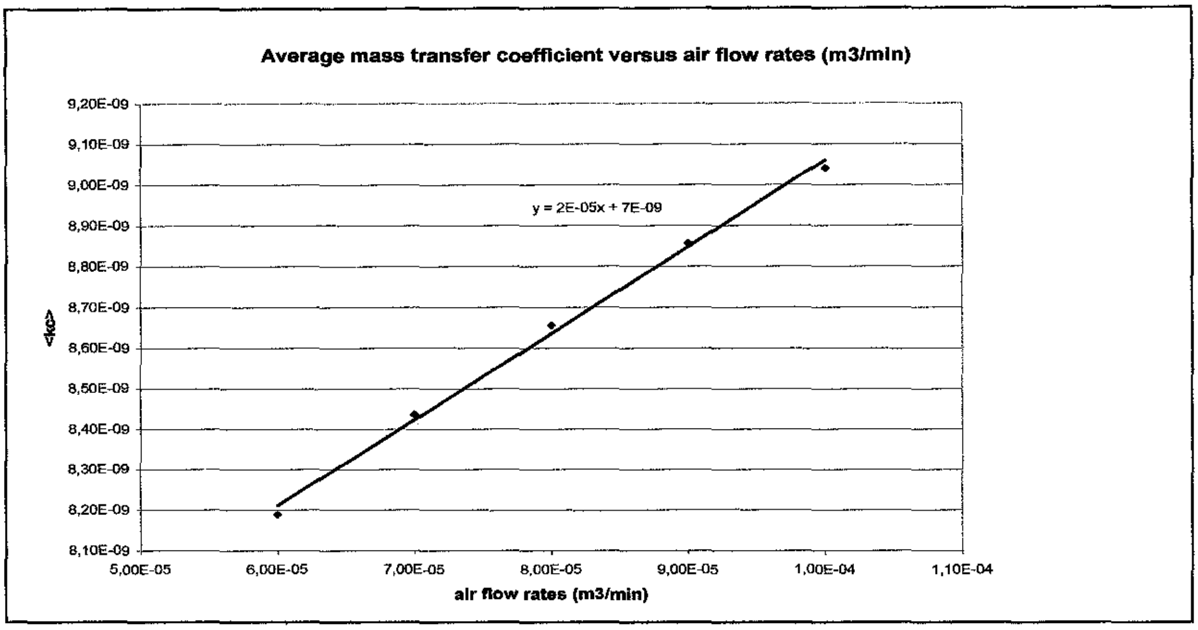


Figure 4.11: *Relationship between average mass transfer coefficient,* $\langle kc \rangle$ *and air flow rates for wetted-wall column without packing*

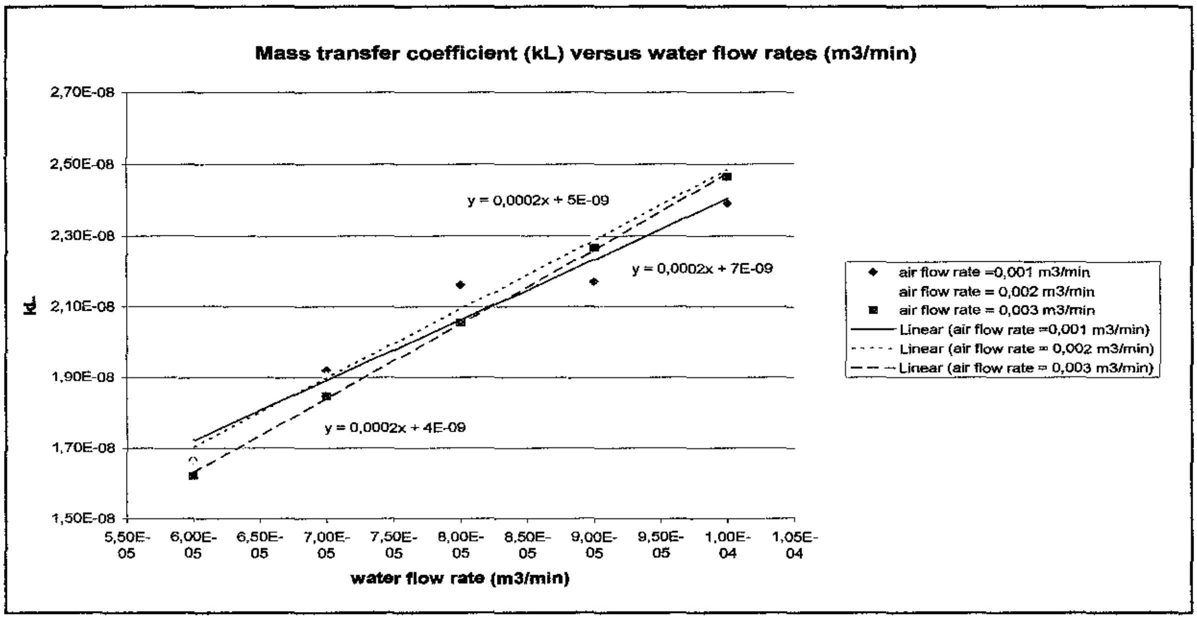


Figure 4.12: *The effect of water flow rates on liquid mass transfer coefficient,* k_L, *for wetted-wall column without packing.*

For this study, data for wetted-wall column without packing is obtained from Wetted-Wall Absorption Column experiment, Chemical Engineering Laboratory 2, with permission. The comparison of the mass transfer coefficient is done based on $\langle kc \rangle$ and k_L values calculated for water flow rates effect. For packed-bed column, from *Figure 4.2*, the slope of the graph is 0.3201, and from *Figure 4.3*, the slope is 2×10^{-4} and 3×10^{-4}. As compared to non-packed bed in *Figure 4.10* and *Figure 4.11*, both values of $\langle kc \rangle$ and k_L are 2×10^{-5} and 2×10^{-4} respectively. Higher value in slope indicates that the mass transfer increment is better compared to the lower ones. From the observations, it shows that mass transfer in packed-bed is better than in wetted-wall column. However, if k_L is considered solely for this comparison, the performance of both type of column cannot be distinguished better as both columns have slightly the same value of k_L.

4.3 ERRORS AND RECOMMENDATION

4.3.1 Errors

There are many problems occur during the experiment which leads to errors in the data gathered, which are:

1. Probe for DO meter is very sensitive with any changes in position and temperature. The probe is made of membrane that is very sensitive in temperature and it is originally designed for isothermal system. Sets of experiments have to be repeated due to inconsistent DO readings and should be done at the same condition and position of the probe. The system also takes considerably long period to stable before the experiment can be carried on.
2. Due to the limitations of the equipment, the plastic Raschig rings are put from the bottom of the column up to the top of the absorption area. In other words, the packing is put excessively from the absorption area and this might affect the flow and amount of air into the absorption area. Some of oxygen from the air might be absorbed

even before the air reaches the absorption area and the oxygen-rich water does not flow through the probe but it is constantly being drained out.

4.3.2 Recommendations

1. Put divider or plate to separate absorption area from another part of column to ensure the effectiveness of the absorption.
2. Since the probe always giving fluctuating value, it should be serviced more often such as replacing new membrane and put it at the right position.
3. Instead of using recycled water from the column, the effectiveness of the absorption can be improved by using fresh water from tap.
4. The current system is put in an open system and the effect of pressure drop slightly can be reduced. However, putting the system in closed-system will be better because the real situation and problems can be observed during the experiment when pressure drop occurs more intensely as well as can reduce the heat loss to surrounding. The effect of pressure drop on liquid hold-up and flooding can be studied better.

CHAPTER 5

CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

Objectives of this project successfully achieved which are to study on the effectiveness of gas absorption which is particularly oxygen absorption in water by means of modified wetted-wall column. From the experimental works and literature researches, it can be concluded that;

1. Mass transfer rate is directly related with flow rates of gas and liquid. Higher flow rates favour higher mass transfer rate and it is more pronounced in water flow rate variations as compared to air flow rates variations in oxygen-water system.
2. Increase in inlet liquid temperature can decrease the mass transfer rate especially in oxygen-water system, but it significantly results in better heat transfer especially at higher gas flow rates.
3. Liquid hold-up in packed bed increases as water flow rates increases and it shows that better wettability of the packing structures. Nevertheless, it should be controlled to prevent flooding that can reduce mass transfer efficiency.
4. Dimensionless number is a powerful tool to characterizing the flow of the gas and liquid in the system as well as to relate with heat and mass transfer in the gas-liquid system. Turbulent flow enhances the absorption rate by increasing mass transfer as well as heat transfer.
5. The use of packing can favour better gas absorption by improving the mass transfer in gas-liquid system.

5.2 Problems and Recommendations

5.2.1 Problems faced

Early stage of study

In the early stage of the study, the objective is to determine the effectiveness of ammonia-water absorption by using gas scrubber. However, due to the gas scrubber problem, with lack of proper operating manual and trainings, added with the problems of the equipment itself such as leakage of ammonia gas tube and flow meter malfunction, the study is terminated and is changed to this new topic. Due to the tight time-frame, this problem really gives a big burden and many difficulties to the student as she needs to redo everything that she has done for the sake of the new study.

5.2.2 Recommendations

5.2.2.1 Project management

First and foremost, project given to student should consider the availability and flexibility of any related infrastructure to the project. Equipments, apparatus, chemical and software should be available and can be utilized by students to help producing a quality research. Any problems involving those infrastructures really demoralize and burdening the student. Good communications between the respective personnel are very essential to ensure the success of the project. In addition, health and safety measurement should be taken into great consideration, for instance the existence of confined space during laboratory works due to malfunction of sliding door in the environment laboratory.

5.2.2.2 Project improvement

This study has many areas that can be improved and expanded. Since this topic covers wide scope of absorption, this study is recommended to be continued by other researchers by narrowing any area of interest such as the study on the packing only by considering the angle and orientation of the packing particles, porosity and size effects and type of material used. The expansion of this study will be more interesting and might reveal new discoveries for further meaningful applications for the sake of human welfare and development.

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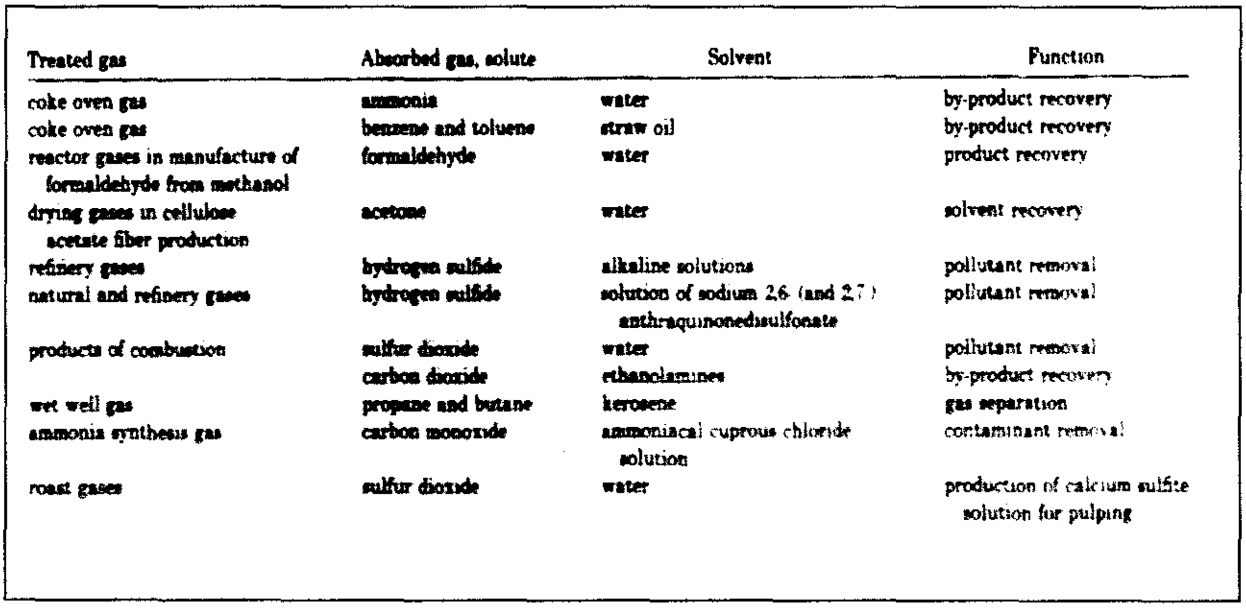
APPENDICES



Treated gas	Absorbed gas, solute	Solvent	Function
coke oven gas	ammonia	water	by-product recovery
coke oven gas	benzene and toluene	straw oil	by-product recovery
reactor gases in manufacture of formaldehyde from methanol	formaldehyde	water	product recovery
drying gases in cellulose acetate fiber production	acetone	water	solvent recovery
refinery gases	hydrogen sulfide	alkaline solutions	pollutant removal
natural and refinery gases	hydrogen sulfide	solution of sodium 2,6 (and 2,7) anthraquinonedisulfonate	pollutant removal
products of combustion	sulfur dioxide	water	pollutant removal
	carbon dioxide	ethanolamines	by-product recovery
wet well gas	propane and butane	kerosene	gas separation
ammonia synthesis gas	carbon monoxide	ammoniacal cuprous chloride solution	contaminant removal
roast gases	sulfur dioxide	water	production of calcium sulfite solution for pulping

Figure 1: Typical Commercial Gas Absorption Processes (Source: Seader,J.D and Henley, E.J, Separation Process Principles, John Wiley &Sons, Inc., (1998))

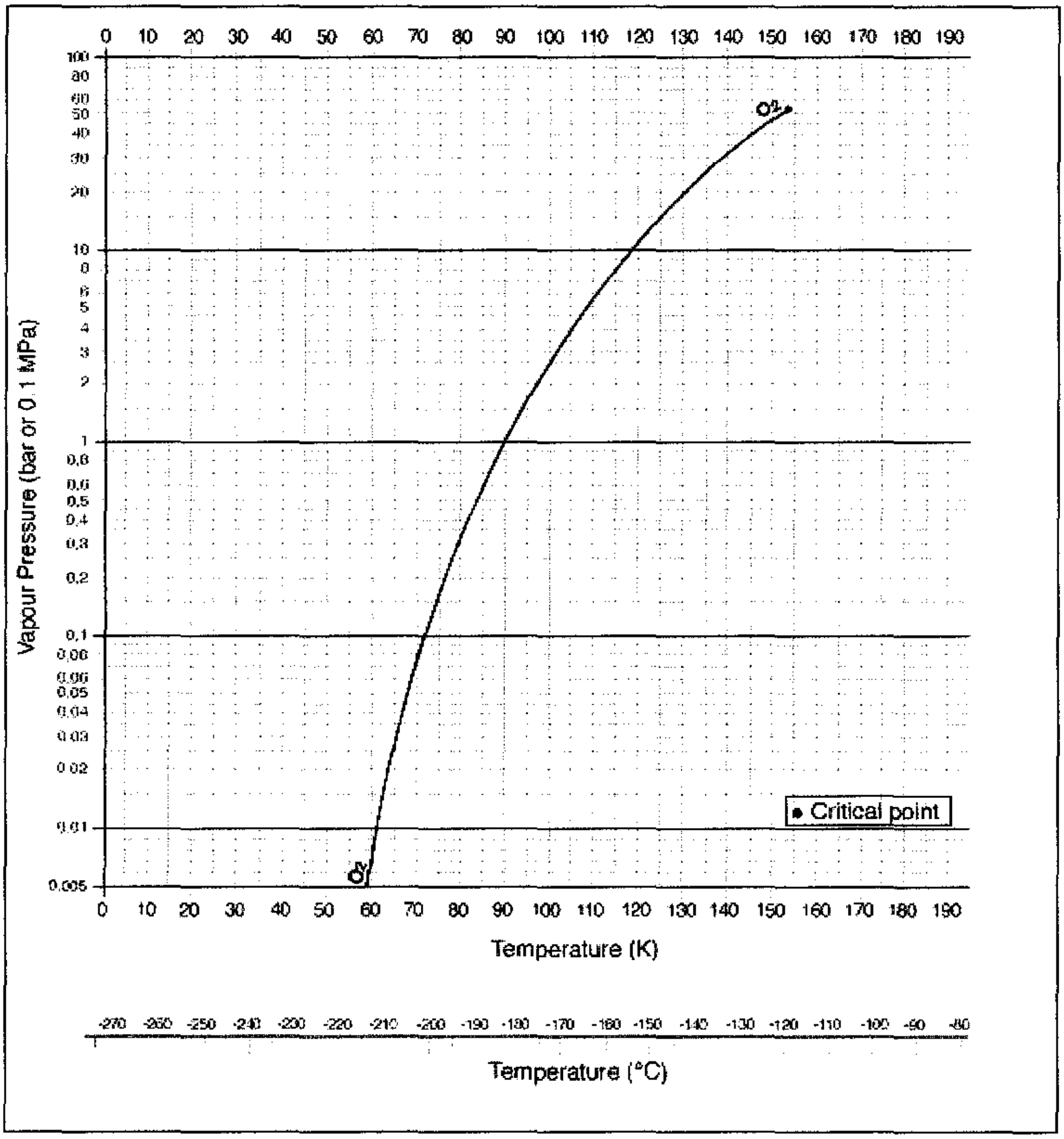


Figure 2: Vapor Pressure graph (Source: airliquide, 2005)

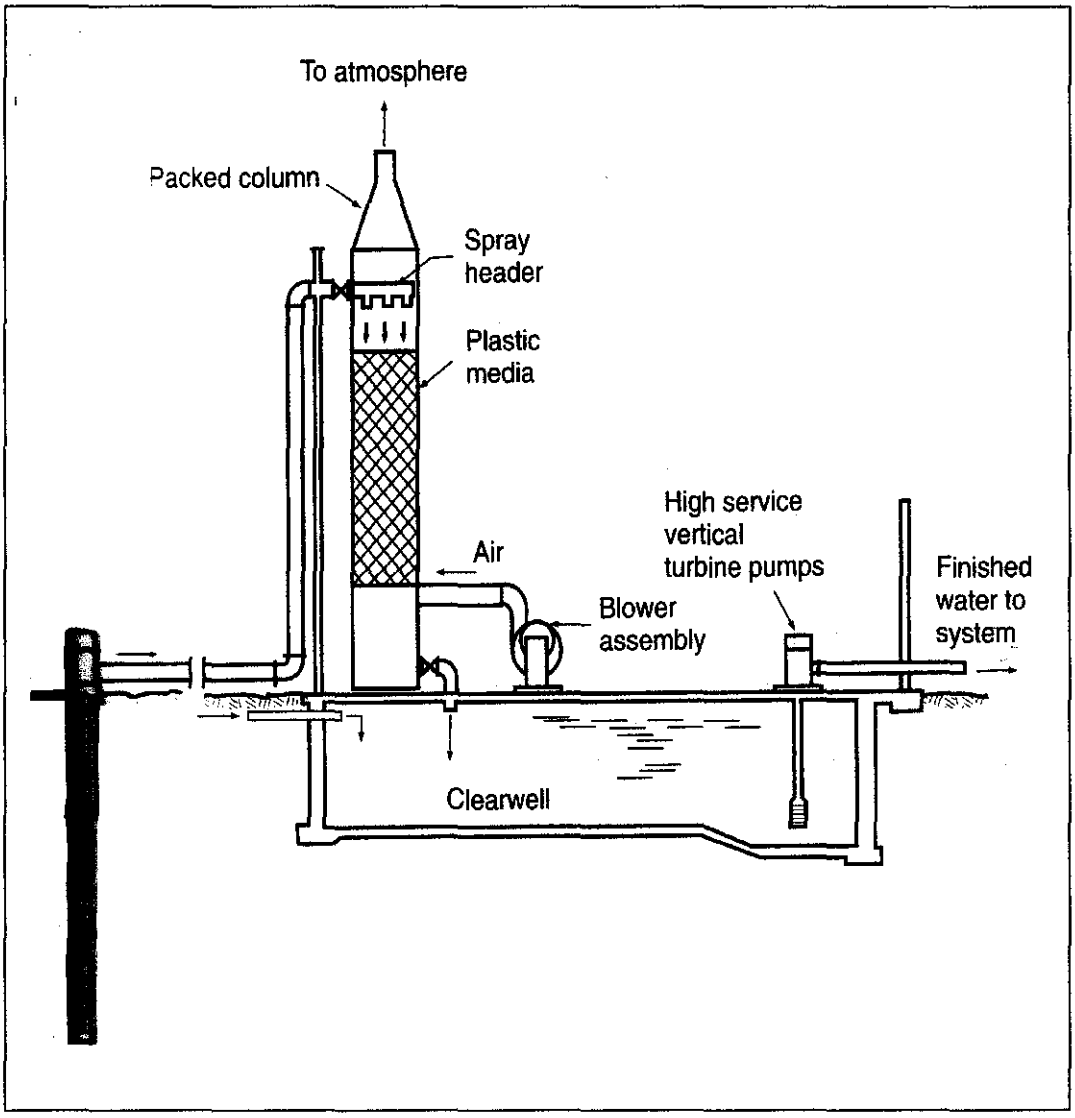


Figure 3: Packed tower aeration system. (Source: Cook College operator training course)

EXPERIMENTAL RESULTS

Table 1: Experimental results for study of the effect of water flow rates on oxygen absorption in water.

	Air flow rate (cm^3/min)					
Water flow ate (cm^3/min)	1000		2000		3000	
	DO inlet (%)	DO outlet (%)	DO inlet (%)	DO outlet (%)	DO inlet (%)	DO outlet (%)
60	13.7	38.3	13.5	37.2	13.6	40.3
70	13.7	37.8	13.6	38.2	13.5	39.8
80	13.8	38.1	13.5	40.9	13.5	41.5
90	13.8	40.9	13.7	41.4	13.5	43.5
110	13.7	43.8	13.8	45.8	13.6	46.0

Table 2: Experimental results for study of the effect of air flow rates on oxygen absorption in water.

	Water flow rate (cm^3/min)					
Air flow rate (cm^3/min)	70		90		110	
	DO inlet (%)	DO outlet (%)	DO inlet (%)	DO outlet (%)	DO inlet (%)	DO outlet (%)
1000	13.8	39.2	13.7	41.5	13.7	44.8
2000	13.6	39.3	13.7	42.0	13.7	44.9
3000	13.7	39.1	13.7	41.7	13.7	45.4
4000	13.6	38.6	13.7	42.4	13.7	46.7

Table 3: Experimental results for study of the effect of water inlet temperatures on oxygen absorption in water.

	Air flow rate (cm^3/min)							
Inlet water temperature (°C)	1000		2000		3000		4000	
	DO inlet (%)	DO outlet (%)	DO inlet (%)	DO outlet (%)	DO inlet (%)	DO outlet (%)	DO inlet (%)	DO outlet (%)
30	14.7	51.6	14.5	52.0	14.4	50.0	14.5	49.3
35	14.6	45.8	14.5	46.0	14.5	45.5	14.5	45.6
40	14.5	45.5	14.5	45.4	14.5	45.0	14.5	45.0
45	14.5	44.9	14.5	44.5	14.5	44.4	14.5	44.2

CALCULATION

1. Mass transfer

- **Average mass transfer coefficient, $\langle kc \rangle$,calculations:**

1. Physical properties:

Calculate for diffusion coefficient of air, D_{AB};

$$D_{AB} \propto \frac{T^{3/2}}{P}$$

$P = 1$ atm

D_{AB} for air-H_2O system at 313 K (40°C) is 2.88×10^{-5} m^2/s

$$(D_{AB})_{300} = (D_{AB})_{313}\,(300/313)^{3/2}$$
$$= 2.70 \times 10^{-5}\ m^2/s$$

For air at room temperature (27°C): $v = 15.60 \times 10^{-6}\ m^2/s$

$Sc = v\ /\ D_{AB}$

$= 15.60 \times 10^{-6} / 2.70 \times 10^{-5}$

$= 0.577$

2. Assumptions:

i. Steady-state conditions prevail.

ii.The system is isothermal at room temperature, 27°C.

3. Analysis:

System: air and water in packed bed

$$Re^*_{pb} = \frac{Dp\upsilon_o\rho}{\mu}$$

Dp = diameter of one packing material = 15 mm

Total cross sectional area, $A = \pi / r^2 = 3.142 / (0.075)^2$

$= 558.51\ m^2$

υ_o (superficial velocity) = Q / A

$\mu_{water} = 1.02 \times 10^{-3}$ kg/m.s

$\mu_{air} = 1.8462 \times 10^{-5}$ kg/m.s

$\rho_{water} = 1000$ kg/m3

$\rho_{air} = 1.774$ kg/m3

(**Note:** Q depends on respective water flow rates and air flow rates For water flow rates study with fixed air flow rates, only consider Q_{water} consistently and vice versa for air flow rates study.)

$$Re^*_{pb} = \frac{\underline{Dp\upsilon_o}}{\mathrm{v}}$$

Calculate for $\epsilon j_{\mathrm{Mpb}}$,

$$\epsilon j_{\mathrm{Mpb}} = \frac{0.765}{(\mathrm{Re}^*_{\mathrm{pb}})^{0.82}} + \frac{0.365}{(\mathrm{Re}^*_{\mathrm{pb}})^{0.386}}$$

ϵ (void fraction) for 15 mm Raschig rings is 0.690 $\mathrm{m}^3/\mathrm{m}^3$.

Calculate for average mass transfer coefficient, $\langle kc \rangle$;

$$j_{Mpb} = (\langle kc \rangle / \upsilon_o)\, Sc^{\,2/3}$$

Table 4: Final values for calculation of $\langle kc \rangle$ for water flow rate study

Water flow rate (m^3/min)	Parameters			
	υ_o	Re^*_{pb}	$\epsilon j_{\mathrm{Mpb}}$	$\langle kc \rangle$
6,00E-05	1,07E-07	1,58E-03	1,56E+02	8,19E-09
7,00E-05	1,25E-07	1,84E-03	1,38E+02	8,44E-09
8,00E-05	1,43E-07	2,11E-03	1,24E+02	8,66E-09
9,00E-05	1,61E-07	2,37E-03	1,13E+02	8,86E-09
1,10E-04	1,97E-07	2,90E-03	9,57E+01	9,21E-09

Table 5: Final values for calculation of $\langle kc \rangle$ for air flow rate study.

Air flow rate (m^3/min)	Parameters			
	v_o	Re^*_{pb}	ϵj_{Mpb}	$\langle kc \rangle$
0,001	1,79E-06	2,58E-03	1,05E+02	3,02E-05
0,002	3,58E-06	5,16E-03	6,02E+01	3,47E-05
0,003	5,37E-06	7,74E-03	4,36E+01	3,76E-05
0,004	7,16E-06	1,03E-02	3,47E+01	3,99E-05

- **Mass transfer coefficient calculations**

$$k_L = \frac{j}{A \Delta C_{LM}}$$

A = 3.16 x 10-2 x п x 0.90

= 0.089 (constant variable)

$$\Delta C_{LM} = \frac{(100 - O2\,\mathrm{in})\ (100 - O2\,\mathrm{out})}{\ln\left[\frac{(100\ -O2\ \mathrm{in})}{(100\ - O2\ \mathrm{out})}\right]} \quad \mathrm{x} \quad 0.09\ \mathrm{p.p.m\ x}\ 10^{-3}\ \mathrm{kg/\ m^3}$$

j = change in concentration of O2 in the water passing through the column x volumetric flow rate of water

Table 6: Values of k_L calculated for water flow rate study

Air flow rate (m^3/min)			
Water flow rate (m^3/min)	0,001	0,002	0,003
	k_L		
0,0000600	9,8484E-09	9,579E-09	1,0531E-08
0,0000700	1,1299E-08	1,151E-08	1,2157E-08
0,0000800	1,2983E-08	1,435E-08	1,4595E-08
0,0000900	1,5938E-08	1,624E-08	1,7309E-08
0,0001100	2,1147E-08	2,209E-08	2,236E-08

Table 7: Values of k_L calculated for air flow rate study

Water flow rates (m^3/min)			
Air flow rate (m^3/min)	0,00007	0,00009	0,00011
	k_L		
0,001	1,2E-08	1,6E-08	2,2E-08
0,002	1,2E-08	1,7E-08	2,2E-08
0,003	1,2E-08	1,6E-08	2,2E-08
0,004	1,2E-08	1,7E-08	2,3E-08

2. Heat transfer

- **Average heat transfer coefficient, $\langle h \rangle$, calculations:**

1. Physical properties:

υ_0 for Q at 1000, 2000, 3000 and 4000 cm^3/min or 0.001, 0.002, 0.003 and 0.004 m^3/min.

□ (void fraction) for 15 mm Raschig rings is 0.690 m^3/m^3.

2. Assumptions:

i. Steady-state condition prevails.

3. Analysis:

Calculate for Reynolds number for packed beds,

$$Re_{pb} = \frac{Dp\,\upsilon_0\rho}{\mu}\frac{1}{1-\varepsilon}$$

μ and ρ are function of temperature (30°C, 35°C, 40°C and 45°C)

Calculate for Prandtl number, Pr;

$$Pr = \frac{\upsilon}{\alpha}$$

α = thermal diffusivity (m^2/s)

Calculate for Nusselt number, Nu;

$$Nu_{pb} = (0.4\,Re_{pb}^{1/2} + 0.2Re_{pb}^{2/3})\,Pr^{0.4}$$

Calculate for $\langle h \rangle$;

$$Nu_{pb} = \langle h \rangle \frac{Dp}{k} \frac{\varepsilon}{1-\varepsilon}$$

Table 8: Values of $\langle h \rangle$ calculated based on air flow rate study

	Air flow rate (cm^3/min)			
Average water temperature (°C)	0,001	0,002	0,003	0,004
	$\langle h \rangle$			
29,3	3,965904	3,976867	3,984319	3,993753
34	4,016874	4,029065	4,040985	4,051611
39	4,071094	4,08887	4,095466	4,102913
44,4	4,12965	4,143234	4,149944	4,161852

- **Calculation for Specific Liquid Hold-up**

$$h_L = [\, 12\ Fr_L/Re_L]^{1/3}[a_h/a]^{2/3}$$

$$Re_L = \upsilon_L/a\nu_L$$

$$Fr_L = \upsilon_L^{2}a/g$$

$$a_h/a = C_h\ Re_L^{0.5}\ Fr_L^{0.1} \qquad \text{for } Re_L < 5$$

$$a_h/a = 0.85C_h\ Re_L^{0.25} Fr_L^{0.1} \qquad \text{for } Re_L \geq 5$$

(**Note:** a and C_h from Table 6.8, Seader and Henley, Separation Process Principles)

Table 9: Calculated values for h_L

Water flow rate (m^3/min)	Re_L	Fr_L	a_h/a	h_L
0,0000600	0,0003999	3,67E-13	7,85E-09	7,54E-26
0,0000700	0,0004666	5,00E-13	9,89E-09	1,40E-25
0,0000800	0,0005332	6,53E-13	1,21E-08	2,38E-25
0,0000900	0,0005999	8,26E-13	1,44E-08	3,82E-25
0,0001100	0,0007332	1,23E-12	1,95E-08	8,52E-25

- **Calculation for dimensionless numbers**

$$Re_{pb} = \frac{Dp\upsilon_0\rho}{\mu}\frac{1}{1-\varepsilon}$$

$$Nu_{pb} = \langle h\rangle \frac{Dp}{k}\frac{\varepsilon}{1-\varepsilon}$$

$$Nu_M = Sh_{pb} = \langle kc\rangle \frac{Dp}{D_{AB}}$$

Table 10: Values of dimensionless numbers

Air flow rate (m^3/min)	v_o	$\langle kc \rangle$	Re_{pb}	Sh_{pb}	Nu_{pb}
0,001	1,79E-06	3,02E-05	0,005945858	0,016805	0,026952
0,002	3,58E-06	3,47E-05	0,011915209	0,01927	0,038159
0,003	5,37E-06	3,76E-05	0,017903762	0,020914	0,046784
0,004	7,16E-06	3,99E-05	0,023889411	0,022185	0,054054

Table 11: Values of $\langle kc \rangle$ for wetted-wall column (non-packing)

Water flow rate (m^3/min)	Parameters			
	v_o	Re^*_{pb}	ϵj_{Mpb}	$\langle kc \rangle$
6,00E-05	1,07E-07	1,58E-03	1,56E+02	8,19E-09
7,00E-05	1,25E-07	1,84E-03	1,38E+02	8,44E-09
8,00E-05	1,43E-07	2,11E-03	1,24E+02	8,66E-09
9,00E-05	1,61E-07	2,37E-03	1,13E+02	8,86E-09
1,00E-04	1,79E-07	2,63E-03	1,03E+02	9,04E-09

Table 12: Values of and k_L *for wetted-wall* column (non-packing)

Air flow rate (m^3/min)			
Water flow rate (m^3/min)	0,001	0,002	0,003
	k_L		
0,0000600	1,7E-08	1,7E-08	1,6E-08
0,0000700	1,9E-08	1,9E-08	1,8E-08
0,0000800	2,2E-08	2,1E-08	2,1E-08
0,0000900	2,2E-08	2,3E-08	2,3E-08
0,0001000	2,4E-08	2,4E-08	2,5E-08