PERFORMANCE OF A NEW PACKING ELEMENT FOR PACKED COLUMN USING AIR-WATER SYSTEM

by

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16101

Dissertation submitted in partial fulfillment of
the requirements for the
Bachelor of Engineering (Hons)
(Chemical Engineering)

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Universiti Teknologi PETRONAS
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CERTIFICATION OF APPROVAL

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Approved by,

____

(Prof Dr Duvvuri Subbarao)

UNIVERSITI TEKNOLOGI PETRONAS

BANDAR SERI ISKANDAR, PERAK

January 2015

CERTIFICATION OF ORIGINALITY

I hereby certify that I am responsible for the work submitted in 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 undertaken or done by unspecified sources or persons to the extent of my knowledge and information.

(ABDUL SHARIB BIN MOHAMED)

ABSTRACT

Packed tower is a continuous contact equipment widely used for gas absorption, distillation and liquid-liquid extraction. It consists of a cylindrical shell filled with a suitable packing material to provide a large interfacial area of contact between the phases. Since its inception, packing has shown great progress and improvement in its design and performance. The aim of this experiment is to develop a new type of packing element for packed tower. The design concept for the new packing is by making a rigid structure that holds the soft, flexible structure. This flexible structure should be fine and thin in order to give maximum mass transfer area while the rigid structure is to provide the strength to the packing element. The new packing is developed by using simple apparatus consist of plastic tightener attached to a metal rod. The metal rod provides the strength to the packings while the plastic tightener provides the mass transfer area. Physical characteristics of the developed packing were measured and used to calculate the geometric surface area, void fraction and equivalent spherical diameter. After the new packing is completed, experiments were carried on self-developed pilot plant using air and water as the medium. Water is fed from the top of the column while air is fed from the bottom. Air and water will counter-currently in contact. Two methods were used to analyze the pressure drop and mass transfer performance; pressure drop and mass transfer test. For pressure drop, two test was conducted, the dry pressure drop and the wet pressure drop. The mass transfer performance was analyzed by evaluating the change in moisture content of the outlet gas. The entire test was set against the result of same experiment for 10 spherical marbles as reference. For the experiment set-up, air-water counter current flow system that replicates a real packed column was constructed to test the new packing element using pipe. The packing characteristics of the developed packing such as geometric surface area, void fractions, and equivalent spherical diameter of packing particle was compared with other packing elements used in the industry. Data from experiments conducted shows that packing is able to gives low pressure drops and increase mass transfer. Based on these results, it can be concluded that the developed has potential for further research.

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INTRODUCTION

1.1 Background of study

1.1.1 Packed Tower

Ludwig (1994) states that packed tower are used as contacting equipment for gas-liquid and liquid-liquid system. It consists of a cylindrical shell filled with a suitable packing material to provide a large interfacial area of contact between the phases. Liquid is distributed at the top of the packing and trickles down through the bed. Gas or vapor is fed from the bottom. It flows up through the void spaces of the bed and comes in contact with liquid flowing down the packing surface.

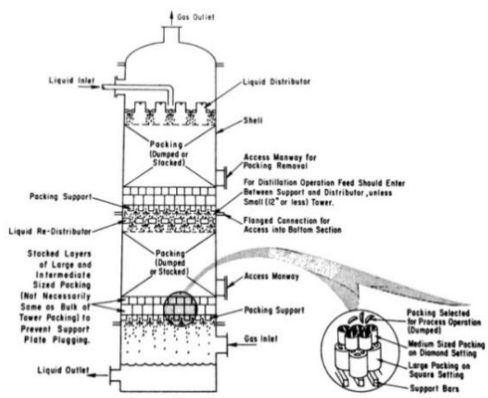

Figure 1.1.1 Cross Section of a typical packed tower (Ludwig, 1994)

Ludwig (1994) also states that for a typical packed bed absorber, the basic unit should consist of:

1. Shell
2. Packing
3. Packing Support
4. Liquid Distributor
5. Intermediate supports and redistributors
6. Gas and liquid entrance and exit nozzle.

Packed tower are preferred for gas/liquid absorption processes is because they generate subsequent exchange surface between phases with limited pressure (Fourati, Roig and Raynal 2012). Distributor and packing are of particular importance in determining the performance of this particular equipment. A good understanding of packing operational characteristic and its effect on the performance of packed tower is essential in ensuring appropriate and suitable selection of packing. (Ludwig, 1994).

1.1.2 Packing Elements

A variety of packing differing in shape, size and performance are available and can be classified into two categories:

1. Random packing
2. Structured packing
3. Grid packing

The following discussions will focuses on the development of random and structured packing.

1. Random Packing:

Discrete, individually shaped particle designed to provide contacting surface between down-flowing liquid and up-flowing vapor/gas. Example of the earlier generation of type of category is Raschig ring and Berl Saddle. Raschig ring is the oldest type of packing introduced by German chemist F. Raschig in 1907. This ring is made by cutting tubes of suitable sizes. Berl Saddle was developed in the 1930s. It has larger specific surface area and smaller voidage than Rashig ring.

Figure 1.1.2 : Raschig Ring (Left) and Berl Saddle (Right)

Random packings, as the name implied, are simply dumped into packed column during installation. The fall however should be as gentle as possible to avoid broken packing that will lead to increase in pressure drop.

2. Structured Packing

Usually composed of pack “pads” fabricated by shaping/crimping, bending, etc sheets of thin gauge metal or wire. Examples of structured packing are Intalox and Metal Max-Pak.

The installation of structured packings are generally more expensive than random packings due to it is a hand operation. Bennet and Kovac (2010) revealed that since the 1980s structured packings have been applied successfully in industrial distillation and absorption columns, especially with the development of Optiflow in 1994. This is primarily because structured packings usually offer less pressure drop and have higher efficiency and capacity than random packings. The high initial cost of structured packing is compensated by the lesser operating cost due to lesser pressure drop across the bed.

<u>Material for Packing Element</u>

Packing elements are made using a variety of materials ranging from ceramic, plastic, carbon or metal particles, sheets or wires depending on its service application. According to Dutta (2007), ceramic packing are favored for hugh corrosive service and operation at elated temperature. Ceramic packings however are prone to breakage. Metal random packing offer higher capacity and efficiency due to smaller wall thickness. It have higher compression resistance but have less wettability than ceramic packings. Packings made of thinner sheets, wires provide more surface area per volume as well as higher voidage thus providing a better mass transfer and lesser pressure drop. Plastic packing are cheap, light and corrosion – resistance. However, plastic packings have poor wettability, brittle at low temperature and have tendency to degrade in an oxidative environment.

1.2 Problem Statement

The development of packing element for packed columns has shown great progress since breakthrough into the industries. Through research and development, the structure of packing changes from a rigid structure to a flexible structure where large mass transfer area is available.

Based on the trend, future packings will be made of thinner wires. Thinner structures made of wires may not be strong enough to support the weight of other packing elements. It is proposed to develop a new packing with finer wires supported on a vertical support rod.

1.3 Objective of Study

1. To design and fabricate new structured packing element design for packed column.
2. To study the characteristics and performance of the developed packing element using air-water system.

1.4 Scope of study

To achieve the objective set for this research, the following scope of study will be emphasized throughout the project. The most crucial scope for this research is to develop new packing elements. The packing element will then be analyzed to understand its characteristics. From here, the study specifically set its parameters to investigate the pressure drop produced by the packing element across the packed column. This scope also set to understand the efficiency of mass transfer between the liquid and gas for the new packing element.

CHAPTER 2

LITERATURE REVIEW

2.1 Pressure Drop and Ergun's Equation

The liquid that come into the column drops to the bottom due to gravity. Gas that enters the column is pressure-driven and generated by equipment such as blower or compressor. As gas flow upward, it experience pressure drop due to frequent change in the flow direction and expansion and contraction. (Dutta, 2007). As liquid simultaneously flows through the bed in counter-current direction, a part of open space of the bed is occupied by liquid. This is known as liquid-up and thus, decreasing the area available for gas flows. This explains why pressure drop increases with increasing liquid output.

Pressure drop along the packed bed is one of the important parameters that determine the performance and feasibility of the packing element. Low pressure drop during process or operation is favored because it provides stability in the system and also reduces the energy consumption of the compressor to move gas long the packed column.

Measurement for dry pressure drop in packed columns is made in the absence of liquid flow. It is always lower than the wet pressure drop measured. Measurement for wet pressure drop experience is higher because the liquid flowing through the column changes the bed structure due to liquid hold-up as explained earlier. (A. Zakeri et al, 2011)

<u>Pressure Drop Model Estimation</u>

The estimation for Equation that is typically used to estimate the pressure drop along the packed bed column is the Ergun's equation (1952). The Ergun's equation was derived by the Turkish chemical engineer Sabri Ergun.

By assuming k_1=150 and k_2 = 1.75, (Allen, Backström, and Kröger., 2013) the equation expresses the friction factor, f_p, in a packed column as a function of the Reynold's number; f_p = $\frac{150}{Gr_p} + 1.75$ (1)

Where

$$f_p = \frac{\Delta p D_p}{L\rho V^2}\left(\frac{\varepsilon^3}{1-\varepsilon}\right) \quad (2)$$

$$Gr_p = \frac{D_p V_s \rho}{(1-\varepsilon)\mu} \quad (3)$$

From the above, the pressure drop across the packed bed is:

$$\Delta p = \frac{150\mu(1-\varepsilon)^2 V_s L}{D_P^2 \varepsilon^3} + \frac{1.75\rho V_s^2 L(1-\varepsilon)}{D_P\ \varepsilon^3} \quad \text{[kg/m]} \quad (4)$$

Where

Δp	-	the pressure drop across the packed bed
L	-	the length of the packed bed
D_p	-	the equivalent spherical diameter of the packing
ρ	-	the density of the fluid
μ	-	the dynamic viscosity of the fluid
V_s	-	the superficial velocity
ε	-	the void fraction of the bed

From Equation 4, it is favoured to have low value of $\frac{\Delta P}{L}$. In order to do so, V_s value needs to be low, and D_P value needs to be big. But V_s is high for improved mass transfer and larger capacity, and D_P needs to be smaller for in order to hav elarger surface area per volume. To solve this, $\frac{(1-\varepsilon)}{\varepsilon^3}$ needs to be small as possible, meaning ε should be as high as possible approaching 1.

In other word, pressure drop across a packed bed is inversely proportional to the void fraction of the bed, ε, and equivalent spherical diameter of the packing element.

Also, the pressure drop across a packed bed is also directly proportional to the superficial velocity of fluid, density of fluid, and the length of packed bed in the column. Consequently, a column with long packed bed will have a higher pressure drop compared to column with shorter packed bed. Besides that, operation at high liquid and gas loading will cause high pressure drop across the packed bed.

This pressure drop equation is only applicable for gas flow only. The gas used for this project is air. The dynamic viscosity of air is 0.00001938 kg/m.s at 22.3 ˚C, which is the air temperature.

$$\left[\frac{\Delta p}{L}\frac{D_p}{\rho V_s^2}\right]\left[\frac{\varepsilon^3}{(1-\varepsilon)^2}\right]\left[\frac{D_p V_s \rho}{\mu}\right] = \left[\frac{D_p V_s \rho}{(1-\varepsilon)\mu}\right] k_2 + k_1 \qquad (5)$$

The constant k_2 describes the turbulence flow relation with the pressure loss across the packed bed, while k_1 describes the laminar flow relation of the pressure loss across the packed bed. These two values can be calculated and compared for different packing elements. Common value for k_2 ranges between 1.5 and 1.8, and common value for k_1 ranges between 150 and 180.

2.2 Mass Transfer

Based on the formula for mass transfer rate:

$N_A \quad = \quad k_C A \Delta C_A \quad$ [mol s^{-1}] (6)

Maximizing mass transfer coefficient, k_C, effective mass transfer area, A, and driving force concentration difference, ΔC_A, will be able to reach highest mass transfer rate. It should be known that the driving force concentration difference, ΔC_A, , is dependent on the process and is not affected by the packing in the packed tower. Therefore, the only parameters that can be affected by the design of packing are mass transfer coefficient, and effective mass transfer area, A.

Model for the prediction of liquid phase mass transfer for random packed columns for gas-liquid systems was develop by Jerzy Mackowiak in 2011 explaining the volumetric mass transfer coefficient is $\beta_L a_e$. According to Mackowiak, the equation was derived on the assumption that the liquid flows down the packed bed mainly in the form of droplets and the effective interfacial area per unit volume, a_e. depends only on the hold up in the packed bed. By combining the liquid phase mass transfer coefficient, L and the effective interfacial area per unit volume, a_e., the volumetric mass transfer coefficient can be formed.

$N_A \quad = \quad k_C A \Delta C_A \quad = \quad \beta_L \alpha_e V \Delta C_A \quad$ [mol s^{-1}] (7)

The effective mass transfer area, A in the above equation is the same as the product of the effective interfacial area for mass transfer per unit volume, and the volume occupied by the packing, V. The effective mass transfer area per unit volume, is identical to the droplet surface, while the total liquid hold up, h_L, corresponds to the liquid hold-up of the droplets. The interfacial area per unit volume can be determined by using the following equation:

$\alpha_e = 6\frac{h_L}{d_T} \quad [{m^2}/{m^3}]$ (8)

For random packing, the specific liquid hold-up, h_L

$h_L = 0.57(\frac{\mu_L^2 \alpha}{g})^{1/3} \quad [{m^2}/{m^3}]$ (9)

Thus, the effective interfacial areas per unit volume, a_e is directly proportional to the geometric surface area of packing per unit volume, a. Therefore, a packing design with high surface area will provide a higher effective interfacial area for mass transfer.

The mean droplet diameter in accordance to the Sauter mean of the droplets can be determined using

$$d_T = \sqrt{\frac{\sigma_L}{\Delta\rho g}} \qquad \text{[m]} \qquad (10)$$

Higbie (1935) states that the formula for determining liquid phase mass transfer coefficient can be described by:

$$\beta_L = \frac{2}{\sqrt{\pi}}\sqrt{\frac{D_L}{\tau}} \qquad \text{[m/s]} \qquad (11)$$

According to Schultes (2011) this equation can be used if the contact time of the droplet to cover the distance, l, between two contact-points within the packing

$$\tau = \frac{l}{\bar{U}_L} \qquad \text{[s]} \qquad (12)$$

Where $\bar{U}_L$ is the absolute droplet velocity . Mackowiak (2010) expressed a correlation for the contact path, l. This correlation is expressed as:

$$l = 0.155(1-\varphi_p)^{2/3} d_h^{1/2} \qquad \text{[m]} \qquad (13)$$

For the hydraulic diameter,

$$d_h = \frac{4\varepsilon}{\alpha} \qquad \text{[m]} \qquad (14)$$

The volumetric mass transfer coefficient can be found by utilizing the following formula,

$$\beta_l a_e = \frac{N_A}{V\Delta C} = \frac{Q_g\left(y_{out} - y_{in}\right)}{V\left(p_v - yP\right)/RT} \qquad (15)$$

2.3 Packing Design Development

Several improvement in the design of packing took place in the last quarter of the 20th century and the process is continuing (Dutta, 2007). Based on study by Larson and Kister (1997) and Schultes (2003) manage to identify 4 generation of the evolutionary process of random packing.

Table 2.3.1 History of Development of Packing

Generation	Period	Example	Voidage
In the beginning	Before 1900s	Stone, Gravel	0.3-0.5
First	1907 to mid 1950s	Raschig ring, Lessing ring, Berl-Saddle, Spiral ring	0.5-0.7
Second	Mid 1950s to mid 1970s	Pall ring (plastic and metal), modified version of Pall Ring ie Flexiring Intalox Saddle	0.7 to 0.9
Third	Mid 1970s to late 1990	IMT (Norton) Nutter ring Jaeger Tripac Koch Flexisaddle	0.8 to 0.95
Fourth	Late 1990-current period	Raschig Super Ring	>0.95

According to Kister (1992), there are few desirable characteristic for packings:

1. Large surface area
   Interfacial area of contact between gas and liquid is created in a packed bed by spreading of the liquid on the surface of the packing.
2. Void volume
   A packed bed should have a high fractional voidage so as to keep the pressure drop low. Thus, the thinner the metal sheet/wire gives higher voidage.
3. Mechanical Strength
   The packing material should have sufficient material strength so that it does not break or deform during filling or during operation under weight of bed.

CHAPTER 3

METHODOLOGY

3.1 Research Methodology

For this research, the following steps are taken in finding the said objective.

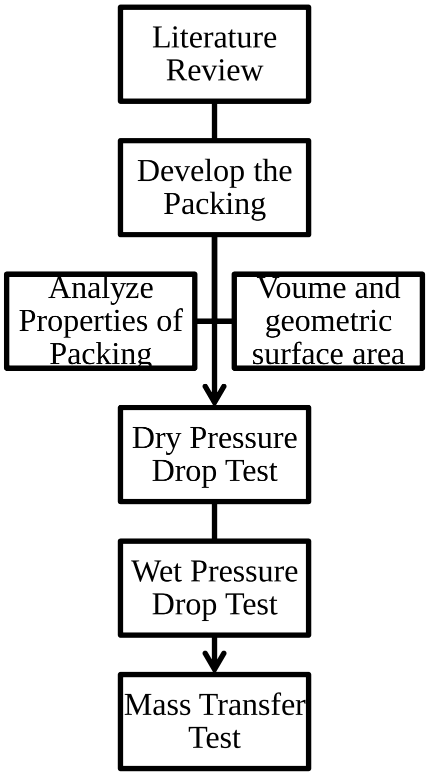

Figure 3.1.1: Experiment Flow

3.2 Development and fabrication of the new packing element

This section explores and discusses the theory for the development of the packing that is used in this research

Lee and Hwang (1989) provide the basis for the design of the new packing element. Rigid structure is expected to provide the strength to hold the fine flexible strands together, whereas, the strands provide the surface area for mass transfer. Providing counter current flow between the fluids can give a longer time of contact for more mass transfer.

The first reference for the new design was based on previous study by Aiman (2014). In his research, the packing has combination of rigid structure and flexible structure. The flexible structure of the strand in this design contributes much of the surface area in this design. Modification was made by using larger, sturdier plastic wire in order to increase the surface area.

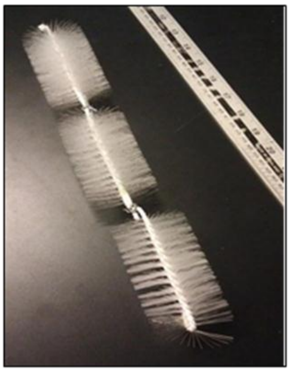

Figure 3.2.1: Mirv-1 packing element developed by Aiman (2014)

The second reference was made from study by Ee Ping. In his study, Ee Ping used a thick plastic rod that act as support for his packing. This gives the packing the mechanical strength required as well as cheap to produce. Modification made from this to explore using metal rod instead of plastic rod. This is because metal rod is stronger to be a support rod with smaller diameter size. Both criteria tally with the desired characteristic of a good packing as proposed Kister (1992) that was discussed earlier.

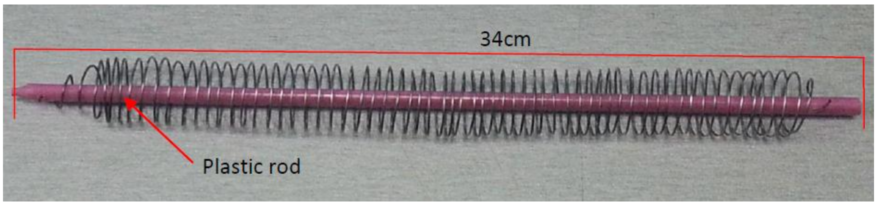

Figure 3.2.2: Helix Prime developed by Ee ping (2014)

In order to compare the characteristic of the developed packing, another packing was used as a reference. In this case, spherical marble was selected. Marble was selected for the convenience due to its shape and readily available.

Listed are the tools required for the development of the packing

Table 3.2.1: Apparatus for Development of Packing Element

Hardware	Raw Material	Software
Digital thermometers Measuring Tape	Air Water Metal Rod Plastic tightener	Microsoft Excel - used mainly for the calculation, making datasheet and graphs for analysis

Basis for the packing design is to have the desirable characteristic of packing as mentioned by Kister (1992) and combining with recommendation made by Aiman (2014) and Ee Ping (2014). For that, the material for the selected for the packing is metal rod and plastic wire from plastic tightener. The plastic tighetener would be attached to the metal rod in a helical pattern. The strong supporting rod made of metal and the plastic tightener is expected to that provide the mass transfer for the packing.

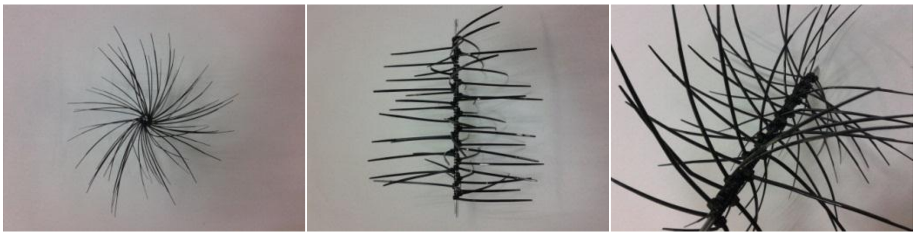

Figure 3.2.3: The developed packing element

Finding the Geometric Surface Area and Volume of the New Packing Element

In order to find the exact volume of the developed packing, water displacement method was used. In this method, a 100.0ml beaker was placed in a transparent plastic container. The beaker was fully illed with water. Next, the packing element would be fully immersed in the beaker. The water spilled into the transparent plastic container is then collected and measured using measuring cylinder.

Full beaker with water

Packing is totally immersed

Water discharge from beaker is measured

Figure 2.4: Water displacement method

Table 3.2.2 Water displacement method result

Trial	**Volume of Water Collected (mL)**
1	**15**
2	**17**
3	**16.5**

Average volume of packing

$$= \frac{15 + 17 + 16.5}{3}$$

$$= 16.2 \text{ mL}$$

$$= 16.2\ mL \times \frac{1L}{1000mL} \times \frac{1m^3}{1000L}$$

$$= 0.0000162\ m^3$$

The **total surface area** for the developed packing was calculated using manual calculation method as below.

For 1 unit of the Plastic Tightener

Length = 0.08 m

Surface area = 2(0.001 x 0.8) + 2(0.0001 x 0.8)

= 0.000176 m^2

For 55 units of plastic tightener around the supporting rod

Surface area = $\underline{0.00968\ m^2}$

Cylindrical Metal Rod

Rod Length = 0.19 m

Rod Diameter = $1\ x\ 10^{-3}$ m

Rod Dimension = $\pi(\frac{D}{4})^2$

= $1.96\ x\ 10^{-7}$ m

Surface area of rod = 2πrh+$2\pi r^2$

= $\underline{0.000598\ m^2}$

Total Surface Area, SA = 0.010278 m^2

Data above shall be used to investigate other important characteristic of the packing.

Geometric Surface Area per unit Volume,

α = $9\frac{SA}{Vc}$

= $9\,\frac{0.010278}{4.196\text{x}\ 10^{-4}}$

= $220.4\ \frac{m^2}{m^3}$

Void Fraction,

$$\boldsymbol{\varepsilon} = \frac{Vc - Vp}{Vc}$$

$$= \frac{4.196\text{x } 10^{-4} - 0.0000162}{4.196\text{x } 10^{-4}}$$

$$= 0.9614$$

<u>Equivalent Surface Diameter,</u>

$$D_p = \frac{6VP}{SA}$$

$$= \frac{6(0.0000162)}{0.010278}$$

$$= 0.009457$$

Table 3.2.3 Characteristic of the developed packing element

Total surface area, SA	0.010278
Total Volume, VP	0.0000162
Geometric surface area per unit volume, α	220.4
Void fraction, ε	0.9614
Equivalent spherical diameter, Dp	0.00957
Length Of Packing (m)	0.19

3.3 Pressure Drop Test

Determination of dry pressure drop is a preliminary tool for characterizing structured packings. Dry pressure drop was measured by closing the liquid valve and air was inserted to the system at 0.23 m/s.

Evaluation of pressure drop when liquid is flowing in counter current with air was also conducted.

The pressure drop for the orifice is measured based on the difference in water height using a simple manometer made of transparent tube filled with water at specific velocity of air. The following equation is used to calculate the pressure difference from manometer;

$$\Delta p = (\frac{\Delta h_{column}}{100})(\rho_{air})(g)$$

This will later be compared with Ergun's pressure drop. In order to find the Ergun's pressure drop across the packed bed equation, the following assumption was used (Allen, Backström, and Kröger., 2013). By assuming k1=150 and k2 = 1.75, the equation expresses the friction factor in a packed column as a function of the Reynold's number.

$$\Delta p = \frac{150(1-\varepsilon)^2 \mu V_s L}{D^2 \varepsilon^3} + \frac{1.75 \rho V_s^2 L (1-\varepsilon)}{D \varepsilon^3}$$

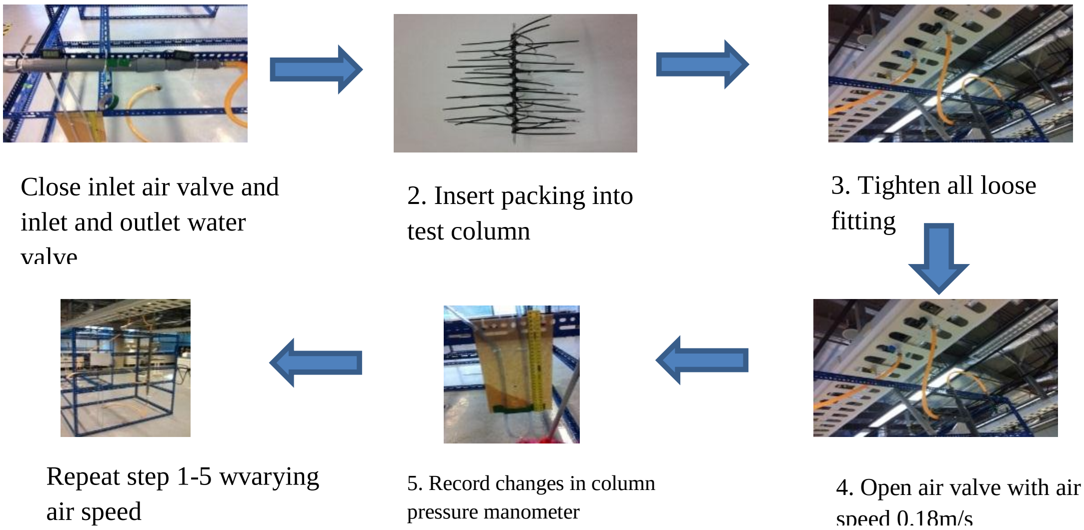

Figure 3.3.1 The Dry Pressure Drop Experiment Procedure

The experiment procedure was referred from Aiman (2014) and Ee Pin (2014)

2.3.1. Dry Pressure Drop Experiment Procedure

4. Close the water outlet valve.
5. Open the air inlet valve until the water height in the orifice flow meter pressure difference manometer increase by 0.2cm
6. Measure and record the water height increment in the column pressure drop manometer.
7. Repeat step 2 and 3 with water height of 0.4cm, 0.6cm, 0.8cm, 1.0cm, 2.0cm, 3.0cmand 3.5cm in the orifice flow meter pressure difference manometer.
8. Close the water outlet valve.
9. Open the air inlet valve until the water height in the orifice flow meter pressure difference manometer increase by 0.2cm
10. Measure and record the water height increment in the column pressure drop manometer.
11. Repeat step 2 and 3 with water height of 0.4cm, 0.6cm, 0.8cm, 1.0cm, 2.0cm, 3.0cmand 3.5cm in the orifice flow meter pressure difference manometer.

3.4 Mass Transfer Test

Mass transfer calculation was made by contacting air with water. Water that comes from top of the packed column will be in contact with air from the bottom and such some of the water will evaporate and transfer into the air causing the air humidity to increase. The humidity of the inlet and outlet air is analyzed by using the dry-bulb and wet-bulb temperature for both the inlet and outlet flow.

Himmelblau in Basic Principles and Calculation in Chemical Engineering 6th Edition states that the wet bulb temperature is the temperature of bulb with wet porous cotton cloth (wick) at equilibrium. With 2 known parameter (Dry Bulb Temperature and Wet Bulb Temperature), the other parameter can obtained from the psychometric chart. In this case, emphasis is given in finding the Relative Humidity of the inlet and outlet air of the column.

With these temperatures, the amount of water in the air can be determined with a **psychometric chart**. By calculating the humidity difference between the inlet and outlet gas, we can calculate the amount of water transferred into the air. Multiplying the amount of water evaporated with the mass flow rate, we can determine the rate of mass transfer.

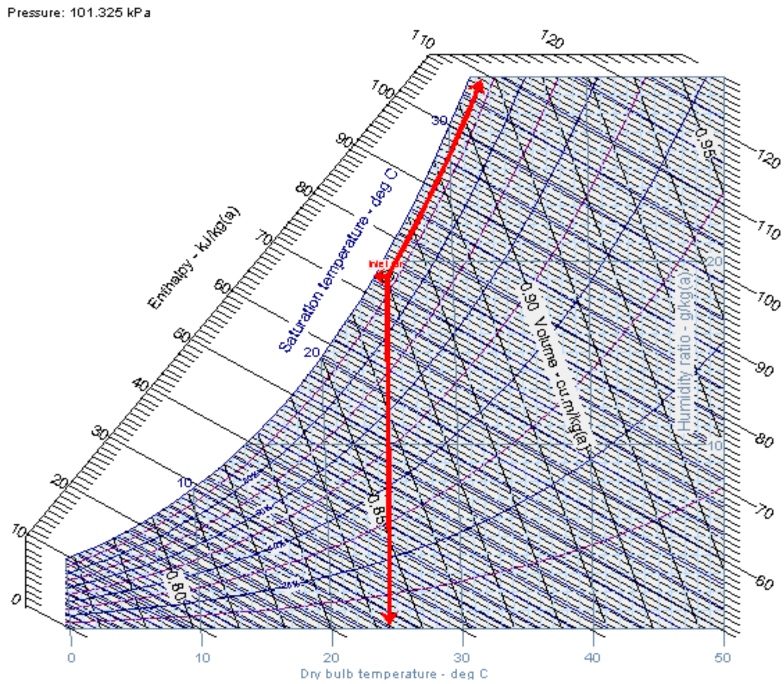

Figure 3 4.1: Finding the Relative Humidity using Psychometric Chart

3.4.1 Mass Transfer Experiment Procedure

1. Open the water outlet valve until it is fully open.
2. Fully open the water inlet valve for 10 minutes to make sure that the packing element is fully wetted.
3. Close the water inlet partially to reduce the water flow rate.
4. Collect the amount of water flowing out of the column in 10 seconds using a measuring cylinder and record the amount.
5. Close the water outlet valve partially to prevent air from escaping through the water outlet valve.
6. Attach wet tissue papers to one of the 2 digital thermometers probes that are located at the gas flow inlet and outlet respectively.
7. Open the gas inlet valve partially until the water height in the orifice flow pressure manometer increase by 0.2 cm.
8. Let the equipment run for 5 minutes and then record the wet-bulb and dry-bulb temperature of both inlet and outlet gas flow.
9. Record the water height increment in the column pressure drop manometer.
10. Repeat step 7 to 10 with water height of 0.4cm, 0.6cm, 0.8cm, 1.0cm, 2.0cm, 3.0cmand 3.5cm .

3.5 Experiment Set-Up

The dry pressure drop and mass transfer coefficient experiment will be conducted using an air-water counter current flow. The flow diagram of the experimental setup for this research is as per Figure 8.

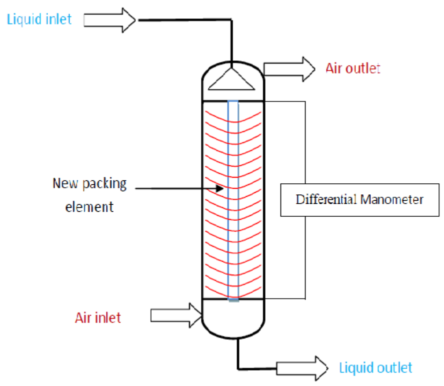

Figure3.5.1. Flow diagram for the experiment arrangement

Air enters the system through air inlet and flow across the orifice meter. Air is then channelled through the packed bed. Simultaneously, water is released into the system and enters from the bottom. Air and water are mix in the packed bed and water flow to the water outlet while air flow through the air outlet.

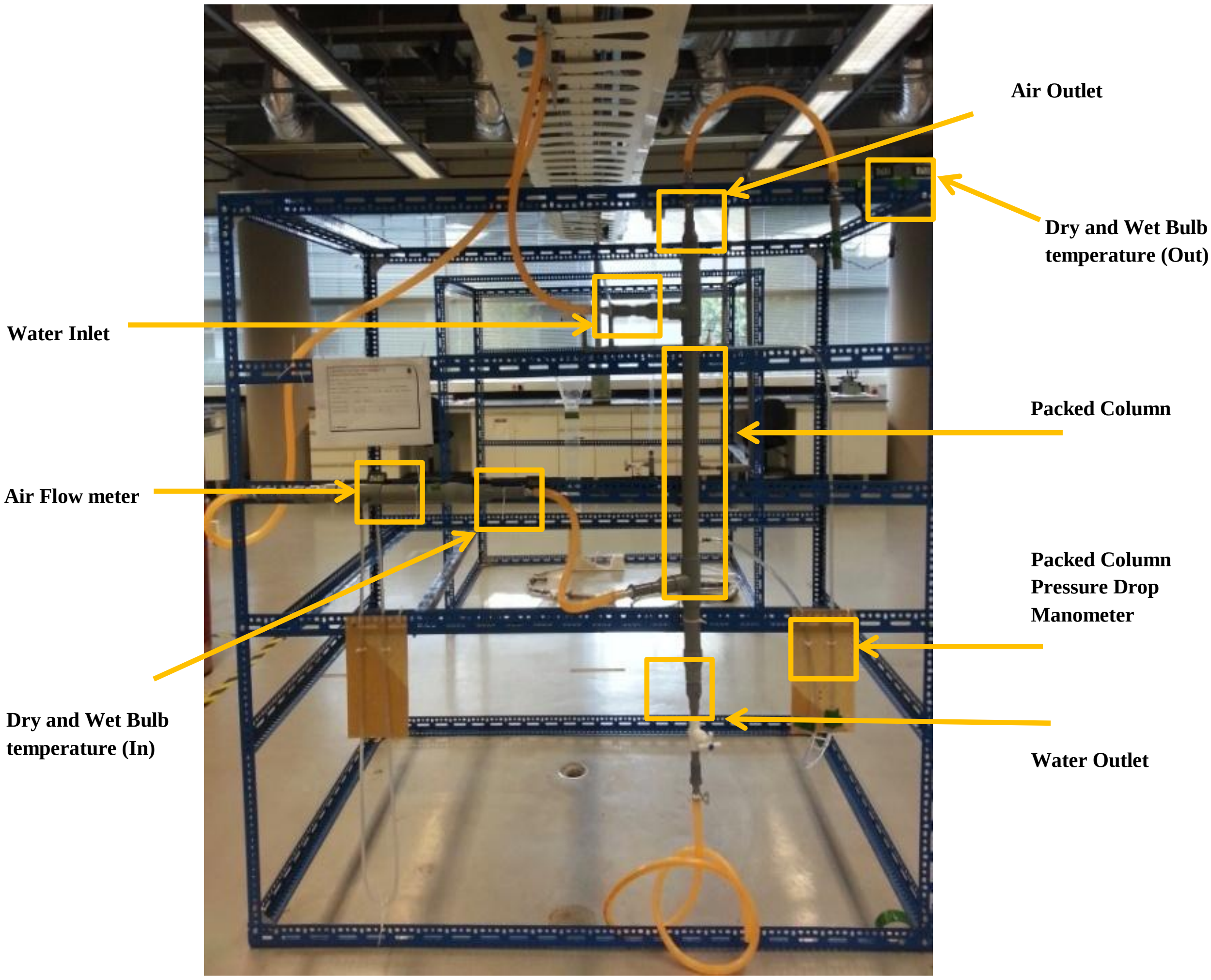

Figure 3. 5.1: The Experiment Setup

3.5.1 Orifice Flow Meter Design

For this experiment, an orifice flow meter was self -developed in order to measure the air flow rate entering the packed column. The pressure difference for the orifice is measured based on the difference in water height using a simple manometer made of transparent tube filled with water. The basis of design for the designed orifice flow meter is summarized in Table 3.5.1:

Table 3.5.1 The orifice flow meter design specification

Pipe (inlet) diameter upstream of orifice Di, cm	3.8
Pipe area upstream of orifice Ai, m2	0.001134
Orifice diameter DO, cm	1.3
Orifice area AO, m2	0.0001327
Water density, kg/m3	1000
Gravitational constant, m/s2	9.81
Flow coefficient, Cf	0.7

Figure3.5.2: Orifice flow metre pressure difference manometer

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CHAPTER 4

RESULT AND DISCUSSION

4.1 Packing Characteristic

Table 4.4.1.1 Characteristics of the developed packing element

Total surface area, SA	0.010278
Total Volume, VP	0.0000162
Geometric surface area per unit volume, α	220.4
Void fraction, ε	0.9614
Equivalent spherical diameter, Dp	0.00957
Length Of Packing (m)	0.19

Table 4.1.1 shows that although the developed packing has a higher void fraction and geometric surface area per unit volume, it has very low equivalent spherical diameter of packing. The high void fraction means it has a very low resistance to gas and liquid flow inside the column. This may lead to the pressure drop inside the absorber column to be very low during operation.

4.2 Pressure Drop Experiment

The following result was obtained for the pressure drop across the column of the developed packing element was obtained through the hydrodynamic tests during the operation.

The Ergun's constants are assumed to be k_1= 150. and k_2 = 1.75. Figure 13 shows the result of the hydrodynamic test.

Table 4.2.1 Dry Pressure Drop Test Result

No.	Gas Flow Rate (m/s)	Pressure inside column(kPa)
1	0.23	0.11
2	0.33	0.22
3	0.41	0.34
4	0.47	0.45
5	0.52	0.56
6	0.74	1.11
7	0.91	1.66
8	0.98	1.93

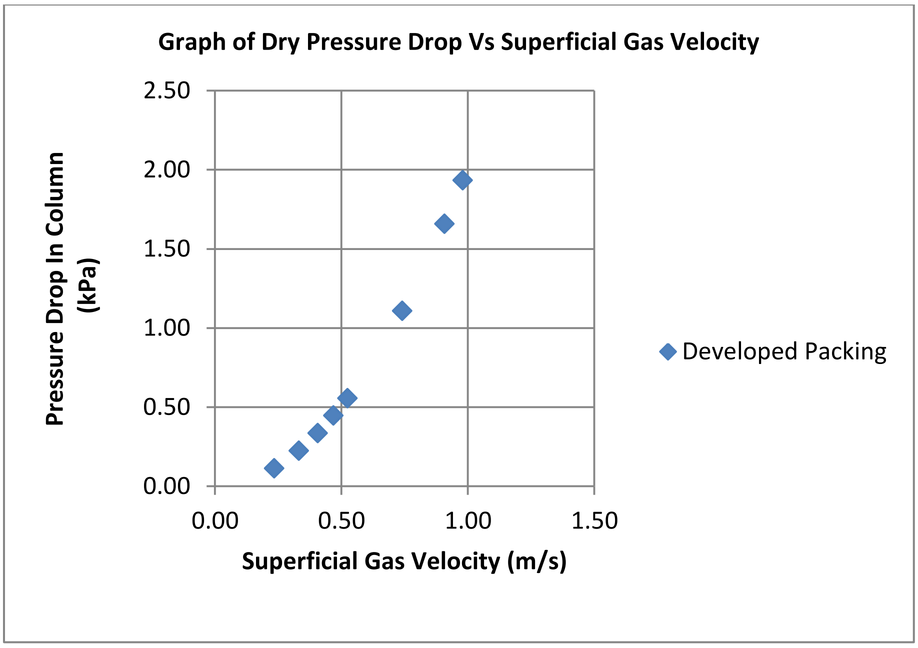

Figure 4.2.1 Graph of Pressure Drop versus Superficial Gas Velocity

Based on Figure 4.2.1, the pressure drop per meter of packing element for the developed packing element increases exponentially as the superficial gas velocity increases. At highest tested superficial velocity of 0.981 m/s, the pressure drop of developed packing is 1.93 kPa. However, it should be noted that for the last 3 reading it shows a very large increase in the pressure drop and deviate from initial reading. This is suspected due to it has exceed its loading point. This means that liquid start to accumulate in the packing.

The high pressure drop of the packing element is due to small equivalent spherical diameter. The pressure drop across packed bed is inversely proportional to equivalent spherical diameter of packing element.

Table 4.2.2 Wet Pressure Drop Test Result

No.	Gas Flow Rate (m/s)	Pressure inside column(kPa)
1	0.23	9.50
2	0.33	9.81
3	0.41	9.81
4	0.47	19.62
5	0.52	29.43
6	0.74	49.05
7	0.91	68.67
8	0.98	78.48

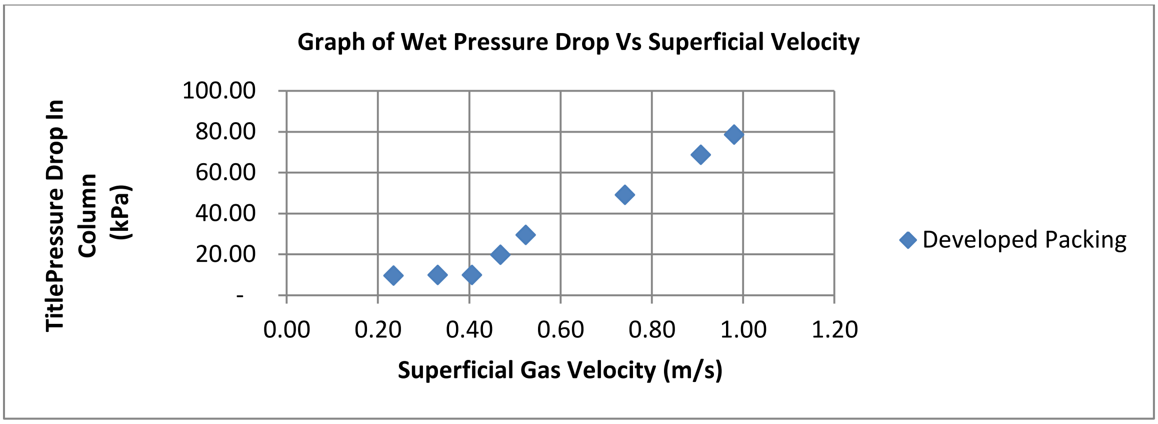

Figure 4.2.2 Graph of Pressure Drop versus Superficial Gas Velocity

The first wet pressure test result shows increase in pressure drop across the column. For all points at the same gas velocity, the pressure drop is higher for wetted packings compared to dry packings.

4.3 Mass Transfer Test

Table 4.3.1 shows the result for the mas transfer test result for the developed packings. Results shows that the volumetric mass transfer coefficient, $\beta_L.a_e$, increases as the air flow rate increases. However, it is observed there is one point lies out of range. This is expected due to technical error during conducting the experiment

Table 4.3.1 Mass Transfer Test Result

No.	Gas Flow Rate (m/s)	Inlet Gas						Outlet Gas					
		Dry Bulb Temperature (^0C)	Wet Bulb Temperature (^0C)	Relative Humidity	Partial Pressure Of Water	Mol fraction of water	Moisture Content	Dry Bulb Temperature (^0C)	Wet Bulb Temperature (^0C)	Relative Humidity	Partial Pressure Of Water	Mol fraction of water	Moisture Content
1	0.23	25.1	24.4	94.5	0.3234	0.0032	0.01910	25.5	25.3	98.4	0.3213	0.00317	0.0200
2	0.33	25.0	24.4	95.2	0.3018	0.0030	0.01910	25.4	25.2	98.4	0.3194	0.00315	0.0200
3	0.41	25.0	24.2	93.7	0.2969	0.0029	0.01880	25.3	25.1	98.4	0.3175	0.00313	0.0200
4	0.47	25.0	24.1	92.9	0.2944	0.0029	0.01860	25.2	24.9	97.6	0.3131	0.00309	0.0198
5	0.52	24.9	24.1	93.7	0.2951	0.0029	0.01870	25.1	24.7	96.8	0.3087	0.00305	0.0190
6	0.74	24.8	24.0	94.7	0.2933	0.0029	0.01850	24.8	24.3	96.0	0.3001	0.00296	0.0190
7	0.91	24.8	23.9	92.9	0.2908	0.0029	0.01840	24.5	23.9	95.2	0.2928	0.00289	0.0185

No.	Volumetric Gas Flowrate (m3/hr)	Difference in Inlet & Outlet Moisture Content of Gas	Partial Pressure of Air in Inlet Water	Average Partial Pressure of water in air	T (K)	(Pv-Pavg)/(RT)	Volumetric Mass Transfer Coefficient
1	0.94	0.0009	101.0016	0.32235	297.55	0.040697712	34.58803535
2	1.35	0.0009	101.0232	0.3106	297.55	0.040711193	49.65785692
3	1.67	0.0012	101.0281	0.3072	297.35	0.040741933	81.84301321
4	1.92	0.0012	101.0306	0.30375	297.25	0.040758047	94.0577604
5	2.12	0.0003	101.0299	0.3019	297.25	0.040758513	25.96356452
6	3.02	0.0005	101.0317	0.2967	297.15	0.040775063	61.61803425
7	3.72	1E-04	101.0342	0.2918	297.05	0.040791786	15.17384879

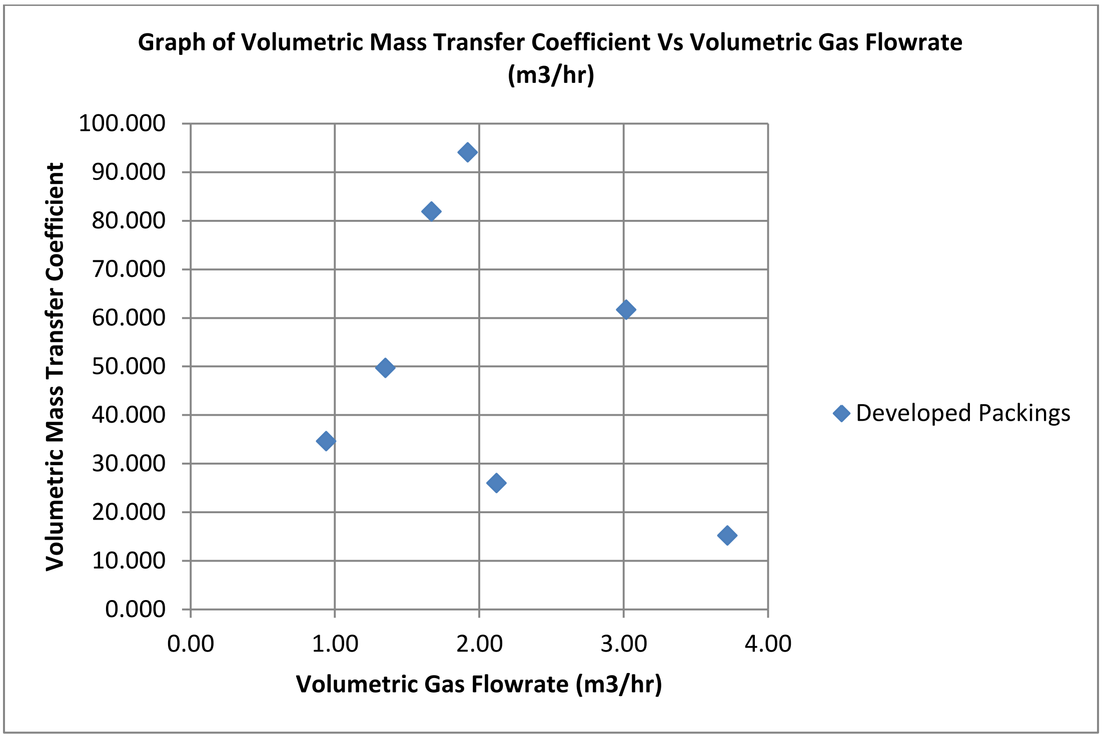

Figure 4.3.1: Graph Volumetric Mass Transfer Coefficient Vs Volumetric Gas Flowrate (m3/hr).

CHAPTER 5

CONCLUSION AND RECOMMENDATION

5.1 Conclusion

In this study, the main objectives of this study have been achieved by the successful design and fabrication of new structured packing and its performance have been analysed and studied.

For pressure drop experiment, it is evident the developed packing is able to produce pressure drop inside the packed column. For the mass transfer, the developed packing also shows capacity to perform mass transfer. Based on these results, it can be concluded that the packing have potential for extensive research to improve its performance.

Clearly, data and result obtained from this study is vital for future reference in producing a more commercially and technically competitive packing element.

5.2 Recommendation and Suggestion for future work

Recommendation for future study would be to understand the actual flow of fluid across the packing element using Computational Fluid Dynamics (CFD). CFD can be used to perform the calculations required to simulate the interaction of liquids and gases with surfaces defined by boundary conditions.

It is highly advised to explore few more structured packing designs before this preceding this research to the next stage i.e. Proceed the analysis of the packing element at the pilot plant level. It would be highly recommended to produce and fabricate future packing element using 3D printing technology.

The experimental setup should be re-built to obtain a more accurate measurement devices to measure mass transfer rate, pressure drop across packed bed, air flow rate, and liquid flow rate.

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APPENDICES

Appendix - A

Packing Column and Packing Element Characteristics and Dimension

Example calculation of the dimension of packing column

Diameter, D = 0.038m , R= 0.019m

Height, H = 0.53m

Cross Sectional Area of Column,

Ac = $\pi(\frac{D}{4})^2$

= $\pi(\frac{0.038}{4})^2$

= 0.001134 m^2

Surface Area of Column,

As = $2\pi RH$

= 0.04417 m^2

Volume of Column,

Vc = $\pi R^2 H$

= 4.196x 10^{-4} m^3

Example calculation of the characteristics and properties of the developed packing element

<u>Plastic Wire</u>

(1 unit)

Length = 0.08 m

Surface area = 2(0.001 x 0.8) + 2(0.0001 x 0.8)

= 0.000176 m^2

Volume = (0.001 x 0.8) x (0.0001 x 0.8) x (0.001 x 0.0001)

= $6.4 \text{ x } 10^{-15}\ m^3$

(55 units)

Surface area = $\underline{0.00968\ m^2}$

<u>Cylindrical Metal Rod</u>

Rod Length = 0.19 m

Rod Diameter = $1\ x\ 10^{-3}$ m

Rod Dimension = $\pi(\frac{D}{4})^2$

= $1.96\ x\ 10^{-7}$ m

Surface area of rod = $2\pi rh+2\pi r^2$

= $\underline{0.000598\ m^2}$

<u>Total Surface Area, SA</u> = 0.010278 m^2

<u>Geometric Surface Area per unit Volume,</u>

$$\alpha = 9\frac{SA}{Vc}$$

$$= 9\,\frac{0.010278}{4.196\text{x}\ 10^{-4}}$$

$$= 220.4\ \frac{m^2}{m^3}$$

<u>Void Fraction,</u>

$$\boldsymbol{\varepsilon} = \frac{Vc-Vp}{Vc}$$

$$= \frac{4.196\text{x}\ 10^{-4} - 9.5\ x\ 10^{-8}}{4.196\text{x}\ 10^{-4}}$$

$$= 0.9997$$

<u>Equivalent Surface Diameter,</u>

$$D_p = \frac{6VP}{SA}$$

$$= \frac{6(\ 9.5\ x\ 10^{-8})}{0.010278}$$

$$= 0.00005545$$

Appendix - B

(Mass Transfer)

Example of calculation of moisture content for the developed packing element

Inlet gas relative humidity, RH(%)	=	22.22
Outlet gas relative humidity, RH(%)	=	100
Inlet Gas Dry- Bulb Temperature ($°C$)	=	26.0
Outlet Gas Dry- Bulb Temperature ($°C$)	=	27.5
Volumetric Flow Rate of air, Q_{Volume}	=	0.0006623

Assuming 1 mol of air occupy 0.0224 m^3 of air and

Total pressure of the system is 101.3 kPa

Example of calculation for effective interfacial area for mass transfer

Void Fraction

ε = 0.9997

Geometric surface area per unit volume

$\frac{m^2}{m^3}$ = 220.4

Form Factor

$\varphi\rho$ = 0.208

Gravitational Acceleration

g = 9.81 m / s^2

Surface Tension

σ_L = 0.7275 kg / s^2

$\Delta\rho$ = 1023.633 kg / m^3

The mean Droplet Diameter, d_t

$$d_t = \sqrt{\frac{\sigma_L}{\Delta\rho.g}}$$

$$= \sqrt{\frac{0.7275}{1023.633\ X\ 9.81}}$$

$$= 0.00269 \text{ m}$$

Specific Liquid Hold-Up, h_l

$$h_l = 0.57\left(\frac{u_L^2\ X\ \alpha}{g}\right)^{\frac{1}{3}}$$

$$= 0.57\left(\frac{0.001^2\ \ X\ 105.53}{9.81}\right)^{\frac{1}{3}}$$

$$= 0.012588\ \frac{m^2}{m^3}$$

The effective interfacial area for mass transfer at the specific liquid loading of 0.001 m/s

$$a_e = 6\ \frac{h_l}{d_t}$$

$$= 6\ \left(\frac{0.012583}{0.00269}\right)$$

$$= 28.05\ \frac{m^2}{m^3}$$

To find effective interfacial area, vary the specific liquid load for the system.

Example of calculation for volumetric mass transfer coefficient , $\beta_L a_e$

Hydraulic diameter, d_h

$$d_h = \frac{4\varepsilon}{a}$$

$$= \frac{4\ x\ 0.9997}{220.4}$$

$$= 0.0181$$

$$\beta_L \alpha_e = \frac{15.1}{(1-\varphi_p)^{1/3} d_h^{1/4}} \left(\frac{D_L \Delta\rho g}{\sigma_L}\right)^{1/2} \left(\frac{a}{g}\right)^{1/6} u_L^{5/6}$$

Appendix - C

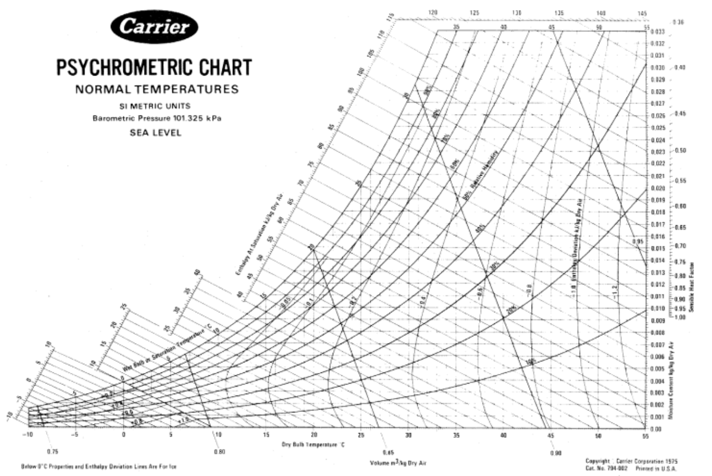
Steam Table (Koretsky, 2004)

TABLE B.1 Saturated Water: Temperature Table 2

T °C	P kPa, MPa	$\hat{v}_l$ m³/kg	$\hat{v}_v$ m³/kg	$\hat{u}_l$ kJ/kg	$\Delta\hat{u}_{lv}$ kJ/kg	$\hat{u}_v$ kJ/kg	$\hat{h}_l$ kJ/kg	$\Delta\hat{h}_{lv}$ kJ/kg	$\hat{h}_v$ kJ/kg	$\hat{s}_l$ kJ/kg K	$\Delta\hat{s}_{lv}$ kJ/kg K	$\hat{s}_v$ kJ/kg K
0.01	0.6113	0.001000	206.132	0.00	2375.3	2375.3	0.00	2501.3	2501.3	0.0000	9.1562	9.1562
5	0.8721	0.001000	147.118	20.97	2361.3	2382.2	20.98	2489.6	2510.5	0.0761	8.9496	9.0257
10	1.2276	0.001000	106.377	41.99	2347.2	2389.2	41.99	2477.7	2519.7	0.1510	8.7498	8.9007
15	1.7051	0.001001	77.925	62.98	2333.1	2396.0	62.98	2465.9	2528.9	0.2245	8.5569	8.7813
20	2.3385	0.001002	57.790	83.94	2319.0	2402.9	83.94	2454.1	2538.1	0.2966	8.3706	8.6671
25	3.1691	0.001003	43.359	104.86	2304.9	2409.8	104.87	2442.3	2547.2	0.3673	8.1905	8.5579
30	4.2461	0.001004	32.893	125.77	2290.8	2416.6	125.77	2430.5	2556.2	0.4369	8.0164	8.4533
35	5.6280	0.001006	25.216	146.65	2276.7	2423.4	146.66	2418.6	2565.3	0.5052	7.8478	8.3530
40	7.3837	0.001008	19.523	167.53	2262.6	2430.1	167.54	2406.7	2574.3	0.5724	7.6845	8.2569
45	9.5934	0.001010	15.258	188.41	2248.4	2436.8	188.42	2394.8	2583.2	0.6386	7.5261	8.1647
50	12.350	0.001012	12.032	209.30	2234.2	2443.5	209.31	2382.7	2592.1	0.7037	7.3725	8.0762
55	15.758	0.001015	9.568	230.19	2219.9	2450.1	230.20	2370.7	2600.9	0.7679	7.2234	7.9912
60	19.941	0.001017	7.671	251.09	2205.5	2456.6	251.11	2358.5	2609.6	0.8311	7.0784	7.9095
65	25.033	0.001020	6.197	272.00	2191.1	2463.1	272.03	2346.2	2618.2	0.8934	6.9375	7.8309
70	31.188	0.001023	5.042	292.93	2176.6	2469.5	292.96	2333.8	2626.8	0.9548	6.8004	7.7552
75	38.578	0.001026	4.131	313.87	2162.0	2475.9	313.91	2321.4	2635.3	1.0154	6.6670	7.6824
80	47.390	0.001029	3.407	334.84	2147.4	2482.2	334.88	2308.8	2643.7	1.0752	6.5369	7.6121
85	57.834	0.001032	2.828	355.82	2132.6	2488.4	355.88	2296.0	2651.9	1.1342	6.4102	7.5444
90	70.139	0.001036	2.361	376.82	2117.7	2494.5	376.90	2283.2	2660.1	1.1924	6.2866	7.4790
95	84.554	0.001040	1.982	397.86	2102.7	2500.6	397.94	2270.2	2668.1	1.2500	6.1659	7.4158
100	0.10135	0.001044	1.6729	418.91	2087.6	2506.5	419.02	2257.0	2676.0	1.3068	6.0480	7.3548
105	0.12082	0.001047	1.4194	440.00	2072.3	2512.3	440.13	2243.7	2683.8	1.3629	5.9328	7.2958
110	0.14328	0.001052	1.2102	461.12	2057.0	2518.1	461.27	2230.2	2691.5	1.4184	5.8202	7.2386
115	0.16906	0.001056	1.0366	482.28	2041.4	2523.7	482.46	2216.5	2699.0	1.4733	5.7100	7.1832
120	0.19853	0.001060	0.8919	503.48	2025.8	2529.2	503.69	2202.6	2706.3	1.5275	5.6020	7.1295
125	0.2321	0.001065	0.77059	524.72	2009.9	2534.6	524.96	2188.5	2713.5	1.5812	5.4962	7.0774
130	0.2701	0.001070	0.66850	546.00	1993.9	2539.9	546.29	2174.2	2720.5	1.6343	5.3925	7.0269
135	0.3130	0.001075	0.58217	567.34	1977.7	2545.0	567.67	2159.6	2727.3	1.6869	5.2907	6.9777
140	0.3613	0.001080	0.50885	588.72	1961.3	2550.0	589.11	2144.8	2733.9	1.7390	5.1908	6.9298
145	0.4154	0.001085	0.44632	610.16	1944.7	2554.9	610.61	2129.6	2740.3	1.7906	5.0926	6.8832
150	0.4759	0.001090	0.39278	631.66	1927.9	2559.5	632.18	2114.3	2746.4	1.8417	4.9960	6.8378
155	0.5431	0.001096	0.34676	653.23	1910.8	2564.0	653.82	2098.6	2752.4	1.8924	4.9010	6.7934
160	0.6178	0.001102	0.30706	674.85	1893.5	2568.4	675.53	2082.6	2758.1	1.9426	4.8075	6.7501
165	0.7005	0.001108	0.27269	696.55	1876.0	2572.5	697.32	2066.2	2763.5	1.9924	4.7153	6.7078
170	0.7917	0.001114	0.24283	718.31	1858.1	2576.5	719.20	2049.5	2768.7	2.0418	4.6244	6.6663

Appendix - D

(Psychometric Chart)



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