

University of Southern Queensland  
Faculty of Engineering and Surveying

## Evaluation of Wet Scrubber Systems

A dissertation submitted by

Yap Lee Jiuan  
(0050027395)

In fulfillment of the requirements of

Courses ENG4111 and 4112 Research Project

towards the degree of

Bachelor of Engineering (Mechanical)

Submitted: 27 October, 2005

## ABSTRACT

Packed bed wet scrubber is an air pollution control device which uses liquid to remove pollutant from the process air streams. It is widely used in many industries in Malaysia to remove soluble gaseous pollutants. It is also capable of removing particles with low particles loading. The common designs of the packed bed scrubber are cross flow and counter current flow. In this project, the efficiencies of cross flow and counter current flow packed bed wet scrubbers used in Penang, Malaysia are studied and compared. Design requirements for these industry scrubbers are also investigated from Department of Environment Penang. Factors affecting the scrubber efficiency are also included. For this project, the scrubber efficiency is determined empirically in which the efficiency of packed bed scrubber is found from experimented and proven efficiency data based on the designed packing depth. A survey is also done for this project among several local consultants of packed bed wet scrubber in Penang so that practical information regarding the scrubber is traceable. This project is expected to be useful towards the understanding of packed bed scrubber system used in Penang, Malaysia.

University of Southern Queensland  
Faculty of Engineering and Surveying

**ENG4111 & 4112 *Research Project***

**Limitations of Use**

The Council of the University of Southern Queensland, its Faculty of Engineering and Surveying, and the staff of the University of Southern Queensland, do not accept any responsibility for the truth, accuracy and completeness of material contained within or associated with this dissertation.

Persons using all or any part of this material do so at their own risk, and not at the risk of the Council of the University of Southern Queensland, its Faculty of Engineering and Surveying or the staff of the University of Southern Queensland.

This dissertation reports an educational exercise and has no purpose or validity beyond this exercise. The sole purpose of the course pair entitled “Research Project” is to contribute to the overall education within the student’s chosen degree program. This document, the associated hardware, software, drawings and other material set out in the associated appendices should not be used for any other purpose: if they are so used, it is entirely at the risk of the user.

Prof G Baker  
Dean  
Faculty of Engineering and Surveying

## Certification

I certify that the ideas, designs and experimental work, results, analyses and conclusions set out in this dissertation are entirely my own effort, except where otherwise indicated and acknowledged.

I further certify that the work is original and has not been previously submitted for assessment in any other course or institution, except where specifically stated.

**Yap Lee Jiuan**

**Student Number: 0050027395**

---

Signature

---

Date

## Acknowledgements

The author is thankful to her USQ supervisors, Dr. Wenyi Yan and Dr. Fok Sai Cheong for their valuable comments, assistance and guidance given during project implementation. Appreciation is also given to Mr. Teh Chee Seng, the local project supervisor for his support and contribution of helpful information for the project. The author is grateful to officers of Department of Environment Penang, Mr. Mohamad Fitri and Mr. Razman for their cooperation and assistance. Apart from that, it is the author pleasure to have the willingness of local consultants to contribute their valuable time for the survey. Lastly, the author is also thankful to her family and friends for their supports.

# Table of Contents

<b>Abstract</b>	i
<b>Acknowledgements</b>	iv
<b>List of Figures</b>	viii
<b>List of Tables</b>	ix
<b>Nomenclature</b>	x
<b>Acronyms</b>	xiii
<b>Chapter 1 Introduction</b>	1
1.1 Introduction	1
1.2 Objective and Scope of Work	2
1.3 Outline of Project	2
<b>Chapter 2 Literature Review</b>	3
2.1 Introduction	3
2.2 Working Principle	4
2.3 Working Mechanisms	5
2.3.1 Gas Removal	5
2.3.2 Particle Removal	8
2.4 Packed Bed Wet Scrubbers	9
2.4.1 Counter Current Flow	14
2.4.2 Cross Flow	16

<b>Chapter 3</b>	<b>Efficiency of Packed Bed Scrubber</b>	19
3.1	Introduction	19
3.2	General Emissions Standard	20
3.3	Basic Requirements of DOE	24
3.4	Factors Influencing Efficiency	26
3.4.1	Irrigation Area	26
3.4.2	Scrubbing Liquid	29
3.4.3	Bed Depth	30
3.4.4	Liquid Flow Rate	31
3.4.5	Temperature	31
3.4.6	Material of Construction	32
3.4.7	Packing	33
3.4.8	Maintenance	34
3.4.9	Liquid to Gas Ratio	35
3.4.10	Heat Effect	35
3.5	Theoretical Study	36
3.5.1	Removal Efficiency	36
3.5.2	Bed Depth	40
3.5.2.1	Number of Transfer Units	42
3.5.2.2	Overall Height of Transfer Unit	44
3.6	Empirical Approach	47
3.6.1	Efficiency of Counter Current Flow Packed Bed Scrubber	48
3.6.2	Efficiency of Cross Flow Packed Bed Scrubber	55
<b>Chapter 4</b>	<b>Results and Discussion</b>	58
4.1	Introduction	58
4.2	Scrubber Design	59
4.3	DOE Requirements	60
4.4	Type of packing	61
4.5	Packing Size	63
4.6	Packing depth	63

4.7 Scrubbing Liquid	65
4.8 Space Constraint	66
4.9 Application and Capacity	67
4.10 Orientation	67
<b>Chapter 5 Conclusion and Recommendation</b>	<b>69</b>
5.1 Conclusion	69
5.2 Recommendation for Improving Scrubber Performance	70
5.3 Recommendation for Future Work	71
<b>References</b>	<b>72</b>
<b>Appendix A Project Specification</b>	<b>76</b>
<b>Appendix B #2 Type-R Tellerette Packing Characteristic</b>	<b>79</b>
<b>Appendix C Tables of Contaminant</b>	<b>81</b>
<b>Appendix D Mass Transfer Efficiency Data</b>	<b>84</b>
<b>Appendix E Questionnaire</b>	<b>90</b>
<b>Appendix F Survey Endorsement &amp; Verification</b>	<b>107</b>
<b>Appendix G Authorized Letter</b>	<b>111</b>



## List of Figures

	<u>PAGE</u>
Figure 2.1 Mechanism of absorption (Joseph et al. 1998)	6
Figure 2.2 Equilibrium lines for a pollutant in air and water (Davis 1999)	7
Figure 2.3 Mechanism of impaction (Joseph et al. 1998)	8
Figure 2.4 Mechanism of diffusion (Joseph et al. 1998)	9
Figure 2.5 Types of packing available for packed bed wet scrubber (Joseph et al. 1998)	11
Figure 2.6 Chevron Type mist eliminator (Joseph et al. 1998)	13
Figure 2.7 Counter current flow packed bed scrubber	16
Figure 2.8 Cross flow packed bed scrubber	18
Figure 3.1 Generalized pressure drop correlation (Joseph et al. 1998)	27
Figure 3.2 Colburn diagram (Joseph et al. 1998)	43
Figure 3.3 <i>HTU</i> of type-R Tellerette packing for counter current flow scrubber of gaseous hydrochloric acid-air-water system (Ceilcote Air Pollution Control 2005)	50

## List of Tables

		<u>PAGE</u>
Table 2.1	Suggested scrubbing liquid and scrubber material for certain gases (Croll-Reynolds 1990)	12
Table 3.1	General emission standards for gaseous substances (Environmental Quality (Clean Air) Regulations Malaysia 1978)	20
Table 3.2	Effluent discharge standards (Environmental Quality (Sewage and Industrial Effluents) Regulations Malaysia 1979)	23
Table 3.3	Table of contaminant for counter current flow packed bed scrubber in which the efficiency of scrubber is determined based on the designed packing depth (Ceilcote Air Pollution Control 2005) (Refer Appendix C for additional description)	52
Table 3.4	Table of contaminant for cross flow packed bed scrubber in which the efficiency of scrubber is determined based on the designed packing depth (Ceilcote Air Pollution Control 2005) (Refer Appendix C for additional description)	56

## Nomenclature

Symbol	Description	Unit
$a$	total surface area of packing per unit volume of bed	$\text{m}^2/\text{m}^3$
$A$	cross sectional area of scrubber	$\text{m}^2$
$AF$	absorption factor	-
$b$	constant	-
$B$	ratio of blow down flow to scrubber inlet liquid flow	-
$c_1$	constant	-
$c_2$	constant	-
$cfm$	cubic feet per minute	-
$f$	the percent of flooding velocity	-
$F$	packing factor	-
$g_c$	gravitational constant	$\text{m/s}^2$
$G$	gas flow rate	$\text{kg/s}$
$G'$	superficial gas mass flow rate	$\text{kg/m}^2.\text{s}$
$G_c$	molar flow rate of carrier gas	$\text{kmol/s}$
$G_m$	gas molar flow rate	$\text{mol/s}$
$G_{\text{flooding}}$	gas mass velocity unit of cross sectional area, at the flooding condition	$\text{kg/s.m}^2$
$G_{\text{operating}}$	gas mass velocity in actual operating condition	$\text{kg/s.m}^2$
$H$	Henry's law constant	$\text{N/m}^2$
$HTU$	overall height of transfer unit	$\text{m}$
$HTU_G$	height of gas transfer unit	$\text{m}$
$HTU_L$	height of liquid transfer unit	$\text{m}$
$k_x$	mass transfer coefficient in the liquid phase	$\text{mol/s.m}^2$
$k_y$	mass transfer coefficient in the gas phase	$\text{mol/s.m}^2$
$K_G$	overall mass transfer coefficient in the gas phase	$\text{mol/m}^2.\text{s}$
$L$	liquid flow rate	$\text{kg/s}$
$L'$	superficial liquid mass flow rate	$\text{kg/m}^2.\text{s}$

$L_s$	molar flow rate of scrubbing liquid	mol/s
$L_m$	liquid molar flow rate	mol/s
$m$	slope of equilibrium curve	-
$NTU$	number of transfer units	-
$p$	partial pressure of pollutant	N/m <sup>2</sup>
$ppm$	parts per million	-
$Sc_L$	liquid Schmidt number	-
$Sc_G$	gas Schmidt number	-
$x_{en}$	mole fraction of pollutant in entering liquid	-
$x_i$	mole fraction of the pollutant entering the scrubber in the liquid	-
$x_o$	mole fraction of the pollutant exiting the scrubber in the liquid	-
$X_i$	inlet liquid mol ratio of pollutant to unpolluted scrubbing liquid	-
$X_o$	outlet liquid mol ratio of pollutant to unpolluted scrubbing liquid	-
$y^*$	pollutant concentration in gas in equilibrium	ppm
$y_i$	mole fraction of pollutant in entering gas	-
$y_{in}$	inlet pollutant concentration	ppm
$y_i^*$	mole fraction of pollutant in gas phase in equilibrium with mole fraction of the pollutant entering in the liquid phase	-
$y_o$	mole fraction of pollutant in exiting gas	-
$y_o^*$	mole fraction of pollutant in gas phase in equilibrium with mole fraction of the pollutant exiting in the liquid phase	-
$Y_i$	inlet gas mol ratio of pollutant to unpolluted carrier gas	-
$y_{out}$	outlet pollutant concentration	ppm
$Y_o$	outlet gas mol ratio of pollutant to unpolluted carrier gas	-
$z$	vertical dimension of scrubber	m
$Z$	depth of packing	m

*Greek*

---

$\rho_g$	density of the gas	kg/m <sup>3</sup>
$\rho_l$	density of the liquid	kg/m <sup>3</sup>
$\varepsilon$	ordinate value from Figure 3.1	-
$\phi$	ratio of water density to liquid density	-
$\phi_p$	packing constant	-
$\mu$	viscosity of liquid	kg/m.s or centipoise
$\eta$	packed bed scrubber efficiency	-
$\lambda$	constant	-
$\xi$	packing constant	-
$\alpha$	packing constant	-
$\beta$	packing constant	-
$\gamma$	packing constant	-

## Acronyms

DOE	-	Department of Environment
EPA	-	United States Environmental Protection Agency
FRP	-	Fiber Reinforced Plastic
PVC	-	Polyvinyl Chloride
SS	-	Stainless Steel

# Chapter 1

## Introduction

### **1.1 Introduction**

Packed bed wet scrubber is an air pollution control device which uses liquid to remove pollutants. It is commonly utilized by many industries in Malaysia to remove the gaseous pollutants in the exhaust gas stream before discharging them to the atmosphere. Therefore, proper functioning of the packed bed wet scrubber system is vital for air pollution control.

The efficiency of a packed bed wet scrubber system can be defined as the effectiveness of the scrubbing process for fume removal. The scrubbing efficiency is the key performance of the packed bed scrubber system. A high efficiency scrubber is critical to ensure that the discharged air stream is harmless to human and environment. Efficiency of packed bed scrubber is significantly influenced by several factors. For instance, scrubber design, packing depth, scrubber sizing, selection of scrubbing liquid, type of packing used, and scrubbing liquid distribution rate can seriously affect the scrubbing process.

There are three types of flow configurations associated with packed bed wet scrubber designs namely counter current flow, concurrent flow as well as cross flow. Only the counter current flow and cross flow arrangements will be discussed in this project. Generally, cross flow arrangement is found to be less efficient than counter current flow arrangement. Both of these flow arrangements adopt the working principle of mass transfer. Absorption, an operation of mass transfer, serves as a cleaning mechanism for gases removal. The working mechanisms for particle removal consist of impaction and Brownian diffusion. In this project, theoretical study and comparison between cross flow and counter current flow packed bed scrubbers are conducted. The efficiency for these two flow configurations is also investigated.

## **1.2 Objective and Scope of Work**

Efficiency of a scrubber is important for air pollution control. Therefore, factors influencing scrubber efficiency are critical to ensure an effective scrubber design. The aim of this project is to study and compare the efficiencies of cross flow and counter current flow packed bed scrubber used in Penang, Malaysia.

In the project, packed bed wet scrubber as an air pollution control device is reviewed. A theoretical study is conducted for the cross flow and counter current flow packed bed wet scrubber systems. The design requirements of Department Environment (DOE) Penang for these scrubbers are investigated. General emission standard for these scrubbers are collected from DOE and all related data are analyzed to determine the factors influencing the scrubber efficiency. The data as well as relevant curves are used to determine the efficiencies for the cross flow and counter current flow packed bed scrubbers. These determined efficiencies are compared. A survey is also done for the project among several local consultants of packed bed wet scrubber, including DOE Penang. From the results, it is hoped that the appropriateness for each of these two scrubbers in term of applications, constraints, etc. could be determined. Finally, recommendation based on the results is provided to improve the scrubber performance.

## **1.3 Outline of Project**

Chapter 1 introduces general idea of this project which consists of project background, objectives as well as project description. Chapter 2 presents the fundamental design and specific background of the packed bed wet scrubber. In chapter 3, the factors influencing the efficiency of packed bed wet scrubber both for cross flow and counter current flow configurations are discussed. There will be a theoretical study and efficiency calculation with comparison for these scrubbers. The results and discussion are documented in Chapter 4. Project is concluded in chapter 5 with recommendation to improve the scrubber performance.



## Chapter 2

### Literature Review

#### **2.1 Introduction**

Since early 1900s, packed bed scrubber was introduced as a pollutant-solvent system in industries to remove offensive gases from the air streams. This wet scrubbing technology is usually adopted when a gaseous pollutant cannot be easily removed in a dry form. The system is particularly useful with the presence of soluble gases. According to United States Environmental Protection Agency (EPA), packed bed wet scrubber can be referred as acid gas scrubber when it is used to control inorganic gases. Packed bed wet scrubber is also known as packed tower. It is called an absorber when chemical reaction is involved with the scrubbing process.

This air cleaning device is applicable for a wide range of pollutants. The pollutants include inorganic fumes, volatile organic compound, particulate matter as well as hazardous air pollutant. However, high concentration of the solid particles tends to clog the packed bed when it is used for particulate control. This affected the absorption efficiency. Besides, solid particles are insoluble in water. As a result, EPA states that packed bed scrubbers are mainly capable of removing solid particles with low particles loading.

Packed bed wet scrubber has been widely used by many industries in Penang, Malaysia to limit the discharge of air pollutants. Typically, the applications are plating operations, chemical processing, pharmaceutical processing, chlorination processing, and fertilizer processing and so on. In Penang, packed bed wet scrubber can be found at the Prai industrial area, Bayan Lepas free trade zone, Juru industrial area and so on.

Hydrochloric acid is used to analyze tin concentration in the plating solution. Acidic fumes emitted during the analysis are channeled by ducts to the packed bed scrubber for cleaning. A horizontal cross flow packed bed scrubber which has a capacity of 11000 cfm was installed in Fairchild Semiconductor for this particular purpose. The removal efficiency of the acidic fume was estimated to be 95%.

Similarly, a 7000 cfm of acid scrubber was installed in Qdos Flexcircuits. It is a counter current flow packed bed scrubber. This scrubber cleans fume generated from boric acid, which is used to prepare the product's surface for further plating process. The estimated removal efficiency for the scrubber was 95%

In Lumileds Lighting, a 7000 cfm counter current flow packed bed scrubber was installed. Lumileds Lighting is a manufacturer of LED product. The scrubber functions to scrub acidic fumes which are produced from etching process in the production of LED parts. The scrubber removal efficiency was expected to be 95%.

## **2.2 Working Principle**

Packed bed wet scrubber involves mass transfer operation. Mass transfer of the packed bed wet scrubbers is defined as the transfer of gas molecules to the liquid. The operation of mass transfer occurs between a soluble gas and a liquid solvent where the gaseous pollutant is transferred from the process stream (gas phase) to the scrubbing liquid (liquid phase).

The mass transfer rate is important for the performance of the packed bed scrubbers because it greatly influences the rate at which the pollutant is removed. A simple expression of mass transfer operation for packed bed scrubber is given in equation (2.1).

$$G_c(Y_i - Y_o) = L_s(X_o - X_i) \quad (2.1)$$

Where

- $G_c$  = molar flow rate of carrier gas, mol/s  
 $Y_i$  = inlet gas mol ratio of pollutant to unpolluted carrier gas  
 $Y_o$  = outlet gas mol ratio of pollutant to unpolluted carrier gas  
 $L_s$  = molar flow rate of scrubbing liquid, mol/s  
 $X_i$  = inlet liquid mol ratio of pollutant to unpolluted scrubbing liquid  
 $X_o$  = outlet liquid mol ratio of pollutant to unpolluted scrubbing liquid

This expression states that total number of mol of contaminant collected by scrubbing liquid is equivalent to total number of mol of contaminant lost by the gas stream in the packed bed wet scrubber.

## 2.3 Working Mechanisms

### 2.3.1 Gas Removal

Absorption, an operation of mass transfer is the mechanism used in packed bed scrubber to remove gaseous contaminant from the exhaust gas stream. Absorption is said to occur when the gaseous pollutants dissolve in the scrubbing liquid droplets. The driving force for absorption is the concentration difference of the contaminants between the gas and liquid phases. Absorption will cease if the concentration of contaminants in the gas phase are in equilibrium with the pollutant's concentration in the liquid phase. Solubility of pollutant in the liquid is a factor controlling the concentration difference. A gas which is more soluble tends to be absorbed faster.

Absorption is classified into physical absorption and chemical absorption. Physical absorption occurs when the absorbed gas is simply dissolved into the liquid solvent. When there is a reaction between the absorbed gas and the liquid solvent, it is a chemical absorption. Chemical absorption provides efficient scrubbing for insoluble gases such as chlorine and sulphur dioxide.

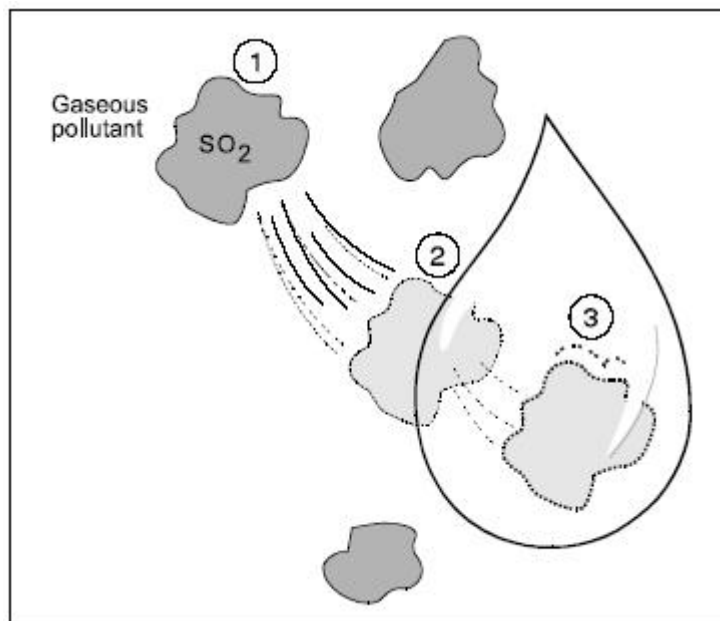


Figure 2.1 Mechanism of absorption (Joseph et al. 1998)

There are three stages associated with gas absorption. Figure 2.1 shows the gaseous contaminant of sulphur dioxide diffuses to the interface between the gas and liquid from the bulk area of the gas phase. The gaseous molecule transfers rapidly to the liquid phase across the interface in the second stage. The molecule is then diffuse to the bulk area of the liquid in the final stage (Joseph et al. 1998).

The principle of absorption is governed by the equilibrium line. This is shown in Figure 2.2. The equilibrium lines are plotted based on the solubility data of a pollutant obtained at equilibrium conditions.

There are three equilibrium lines shown in Figure 2.2. Each line has temperature which increases from the right bottom corner to the left upper corner. The absorption will result if a coordinate  $(x, P)$  lies above the equilibrium line at a particular temperature. This implies there will be mass transfer from the gas to liquid. Mass transfer will cease if the coordinate lies on the equilibrium line.

Equilibrium solubility of a gas liquid system can be expressed by Henry's Law. The expression of Henry's law is given in equation (2.2).

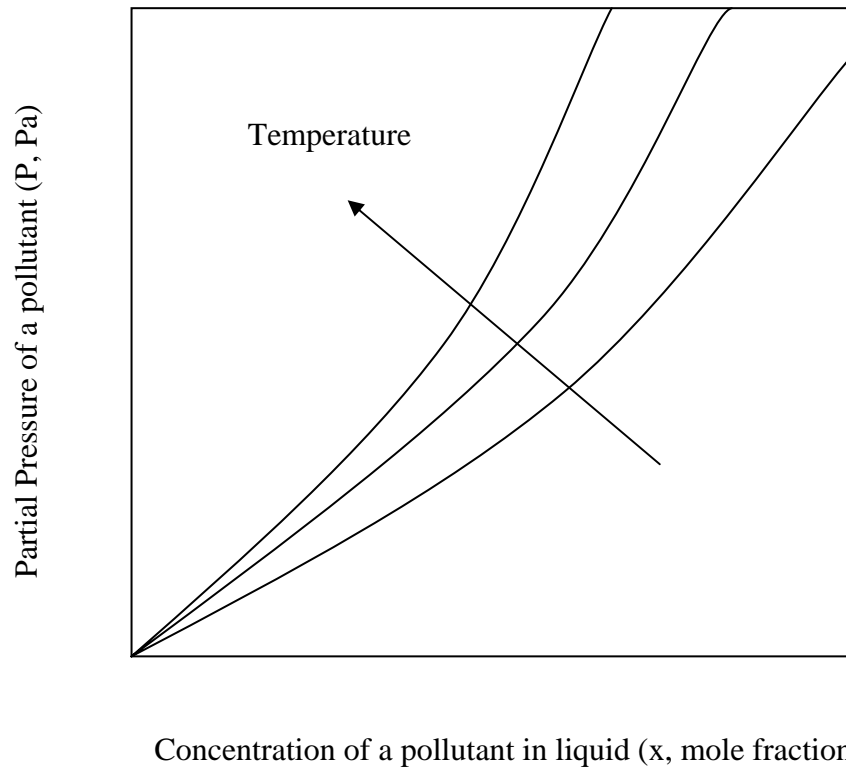


Figure 2.2 Equilibrium lines for a pollutant in air and water (Davis 1999)

$$p = Hx \quad (2.2)$$

Where

$p$  = partial pressure of pollutant at equilibrium,  $\text{N/m}^2$

$H$  = Henry's law constant,  $\text{N/m}^2$

$x$  = mole fraction of pollutant in the liquid

Henry's law can be used to predict solubility provided the equilibrium line is straight. If the pollutant concentration is very dilute, the equilibrium line is usually straight.

In addition, performance of gas absorption is affected by other factors. For instance, temperature of the exhaust gas stream, construction material of the scrubber,

selection of scrubbing liquid, viscosity and so on. These factors which form some parts in influencing scrubber removal efficiency will be discussed in other sections.

### 2.3.2 Particle Removal

There are two primary working mechanisms associated with particle removal from the process stream in packed bed scrubber, namely impaction and Brownian diffusion.

Impaction results when dust particles cannot follow the curving streamlines around a scrubbing liquid droplet. The particle continues to move towards the droplet along a less curvature path due to inertia and finally it separates from the streamlines and hit the liquid droplet. Mechanism of impaction is shown in Figure 2.3.

The rate of impaction depends on the diameter of the particle and the relative velocity between the liquid droplet and the particle. Impaction is usually significant with larger particle and with increased velocity. A particle size that is more than  $1\mu\text{m}$  is generally collected by impaction (Davis 1999).

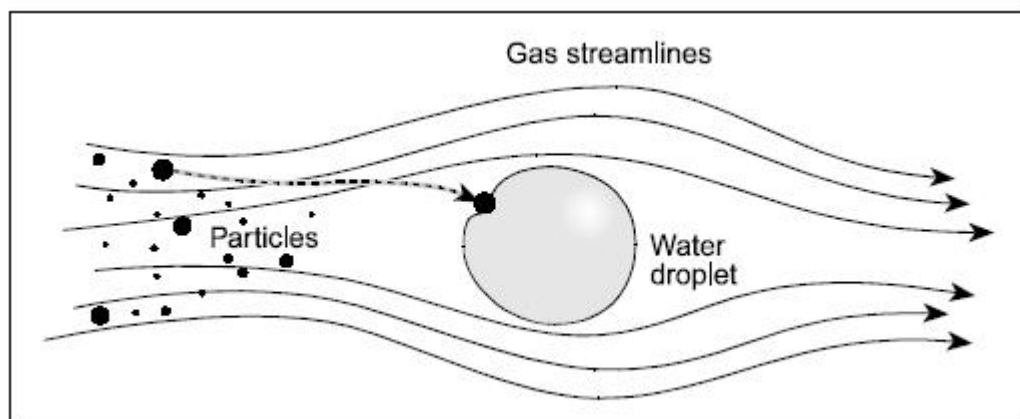


Figure 2.3 Mechanism of impaction (Joseph et al. 1998)

Brownian diffusion occurs when small particles in the exhaust gas stream have random motion and they do not move along the streamlines. This irregular movement causes the particles to collide with the liquid droplets and gaseous molecules. As a result they are captured by the liquid droplets. Mechanism of diffusion is shown in Figure 2.4.

The rate of diffusion is dependent on the size of liquid droplet, particle diameter and the relative velocity between the particle and the liquid droplet. Diffusion increases with decreased particle size and liquid droplet size. It decreases with increased relative velocity. This mechanism is able to remove particle which is less than  $0.1\ \mu\text{m}$  (Davis 1999).

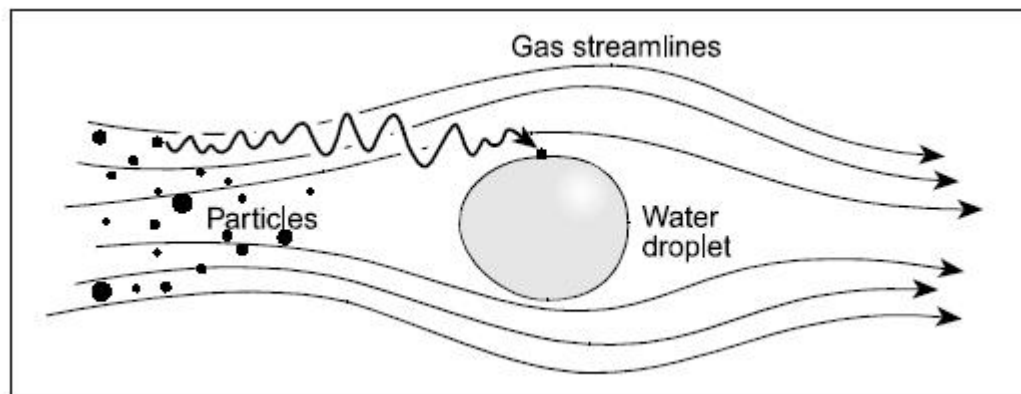


Figure 2.4 Mechanism of diffusion (Joseph et al. 1998)

## 2.4 Packed Bed Wet Scrubbers

There are a variety of wet scrubbers used in industries. Each type of wet scrubber differs in geometries as well as gas-liquid contacting techniques. The operating variables associated with wet scrubber design consist of liquid to gas flow rate ratio (which is also known as reflux ratio), location of liquid distribution, liquid distribution rate, water temperature, gas temperature, gas velocities, gas solubility, gas residence time, particle loading and so on.

Typically, a wet scrubber system's components consist of scrubbing shell, fan system, duct work, scrubbing liquid treatment, entrainment separator, exhaust stack and pumping system. Examples of wet scrubber are spray tower, venturi scrubber, packed bed scrubber, wet cyclone scrubber, plate scrubber and others.

According to Stone (1998), components of a packed bed wet scrubber consist of shell, packing, packing support, mist eliminator and liquid distribution system. Hankinson (1928) discussed the scrubber vessel which should be designed with sufficient cross sectional area to provide the acceptable air velocity. Besides, an appropriate depth of packing is required to provide the necessary surface area to distribute the scrubbing liquid. The liquid distribution system should be designed to supply the desired volume of liquid throughout the packing. Furthermore, a mist eliminator should be used to prevent the scrubbing liquid from entering the exhaust stack (Hankinson 1928).

In brief, operation of packed bed wet scrubber consists of two primary stages. In the first stage, liquid is discharged by nozzles onto packing. As gas moves through the packing, the gas contacts a liquid film that is distributed evenly over the packed bed. The process will transfer the pollutants from the gas to the liquid. In the second stage, the gas is passed through a mist eliminator or entrainment separator as the gas exits the packed bed. The function of a mist eliminator is to remove the entrained droplets and other particles which have not been removed by the packed bed. Finally, cleaned gas is then channeled to the atmosphere by a fan through a chimney or exhaust stack.

A packed bed scrubber is randomly filled with packing up to a certain depth or height. The purpose of using packing is to provide large surface area of scrubbing liquid which allow sufficient gas residence time for contact. It promotes turbulent mixing between gas and liquid phases. Packing is available in market in a variety of forms. It is made from a range of material such as plastic, polypropylene, metal and carbon steel. Raschig ring, Tellerette packing, Intalox saddles and spiral rings are examples of packing (Davis 1999) as shown in Figure 2.5.



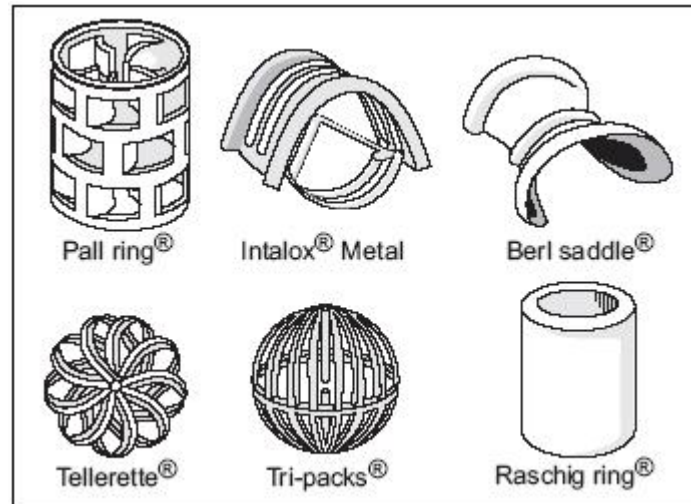


Figure 2.5 Types of packing available for packed bed wet scrubber  
(Joseph et al. 1998)

Water is a common choice of scrubbing liquid for removal of inorganic contaminants such as phosphorus, sulphur, nitrogen oxide and halogen. Most of these gaseous pollutants are water soluble. In addition, water is inexpensive and readily available. Davis (1999) reported that there are other choices of scrubbing liquid that can be used to provide wet film for packing. He also said that literature for choosing the liquid needed to be reviewed to ensure a practical absorption process. The scrubbing liquid chosen should be inexpensive and have low viscosity and high solubility for the gases.

Problems of erosion and corrosion are common to wet scrubbing equipment. Croll-Reynolds (1990) provides a list of selection of scrubber material and scrubbing liquid for a certain range of gases (Table 2.1) to minimize the cost and maintenance problem.

Table 2.1 Suggested scrubbing liquid and scrubber material for certain gases  
(Croll-Reynolds 1990)

<b>Gas</b>	<b>Scrubbing Liquid</b>	<b>Scrubber Material</b>
Ammonia	Water	Cast iron, steel, FRP, PVC, Ni-Resist
Chlorine	Water	Fiberglass, Haveg, PVC
Chlorine	Caustic	FRP, PVC, Kynar
Carbon Dioxide/ Air	Caustic	Cast iron, steel, Ni-Resist
Hydrogen Chloride	Water / Caustic	FRP, PVC, Kynar
Hydrogen Fluoride	Water	FRP (with Dynel Sheild), rubber lined steel, graphite lined, Kynar
Hydrogen Sulfide	Caustic	FRP, 316 SS, PVC
Hydrogen Sulfide	Sodium Hydrochloride	FRP, PVC, Kynar, Teflon
Nitric Acid	Water	FRP, 316 SS, 304 SS
Sulfur Dioxide	Caustic/ Lime Slurry	FRP, 316 SS (tends to pit)
Sulfur Acid	Water	FRP, Alloy 20

In packed bed wet scrubber, Chevron type mist eliminator is usually used to remove entrained droplets. This component can be made from stainless steel and FRP material. As shown in Figure 2.6, liquid droplets in the gas stream impinge on the blade surfaces as they move through the mist eliminator. As a result the liquid droplets fall back to the scrubber vessel. Excess emission will result if the liquid droplets are allowed to escape. Generally, droplet size of 5 $\mu$ m can be captured by this mist eliminator.

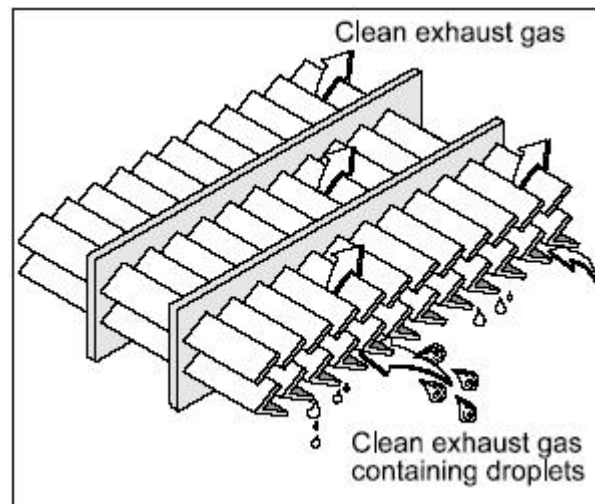


Figure 2.6 Chevron Type mist eliminator (Joseph et al. 1998)

Pollutants transferred to the scrubbing liquid are required to be removed before the liquid is reused (Davis 1999). Hence, an integral sump is used to keep the absorbed pollutant with the liquid while additive is added into the sump for neutralization. For example, caustic solution will be the additive used if the pollutant is acidic. The integral sump is usually located at the floor situated at the bottom of the packed bed and the gas inlet.

Apart from that, duct work is important to provide connections for the gas scrubbing process. The dirty air streams are channeled to the scrubber by duct. Similarly, duct work is needed to discharge the gas stream to the atmosphere. Duct is usually attacked by the pollutant. Consequently abrasion results on the duct going to the scrubber. Corrosion can also occur at duct outlet when temperature of the gas stream is below the dew point of the acidic or electrolytic compound from the gas stream (Joseph 1998). Therefore, proper material selection is important. Normally, construction material of duct is always chosen based on the nature of the pollutant.

A fan system is needed to force the exhaust gas from the packed bed scrubber through the duct work. Fan has a range of capacity. Scrubber removal efficiency can be optimized with a correct fan sizing. Besides, selection of fan material is also important since location of a fan can be placed before or after the scrubber. When a fan is placed before the scrubber, it is also known as positive pressure fan and this

position of fan is subjected to abrasion and accumulation of solid particles. For a fan which located after the scrubber, it is normally named as negative pressure fan. The negative pressure fan is subjected to corrosion problem that caused by acidic compound from the gas stream. In general, centrifugal fan is usually used in wet scrubber system (Joseph et al. 1998).

A pump is needed in packed bed scrubber to transport sludge produced from the scrubbing process to the waste treatment plant. Besides, it is also used to transport the scrubbing liquid into the scrubber vessel during the scrubbing process. The pump is selected based on the designed liquid flow rate and the pumping material. Additionally, maintenance and inspection are required for the pump since it will be corroded by the fume. Furthermore, it may be clogged by solid material leading to pumping failure.

Packed bed wet scrubber needs maintenance to ensure a consistent wet scrubbing process. Hankinson (1928) reported that regular inspection is suggested for packing, nozzles and mist eliminator. This is because packed bed and nozzles have the potential to be plugged by solid particles in the gas stream and in the liquid. These situations can affect the scrubber removal efficiency. Apart from that, fresh water should be added continuously to the integral sump (Hankinson 1928). This is because addition of fresh water will help to dilute the pollutant in the sump.

#### **2.4.1 Counter Current Flow**

Counter current flow is the most common type of flow arrangement for packed bed scrubber. With this arrangement, exhaust gas stream enters a scrubber at the bottom of a bed of packing and the gas moves vertically upwards through the packed bed. Scrubbing liquid is distributed downwards by nozzles or sprays at the top of the packed bed to encounter the gas stream in the opposite direction.

The exhaust stream is forced in the direction of winding as it moves through the packing so that both the liquid and exhaust streams have intimate mixing between each other. After that, the gas stream moves through an entrainment separator which

is situated at the top of nozzles. This is to prevent entrained droplets and hazardous particulate from escaping. Packing support is used to carry the weight of packing and it needs to be tough. A typical counter current flow configuration scrubber is shown in Figure 2.7.

Stone (1998) reported that shell of counter current flow packed bed scrubber can be economically constructed as a cylinder. The shell is usually made from PVC or FPR. According to Ceilcote Air Pollution Control (2005), this designed unit is compact and is ideal where floor space is at a premium. Besides, it has maximum corrosion resistance and high collection efficiency.

In theory, counter current flow arrangement has the highest efficiency as compared to cross flow and concurrent flow configurations. In this flow arrangement, the most dilute gas is contacted with the purest scrubbing liquid as the gas move vertically upwards through the packing resulting maximum driving force (concentration difference) for absorption. Besides, the scrubbing liquid is introduced at the top of the packed bed and therefore the gas has the freshest scrubbing liquid as it exits packed bed. Counter current flow arrangement has characteristic of high pressure drop (Kinematics 2002) requiring high irrigation rate (Stone 1998). Better droplet formation results with high pressure drop and this leads to high removal efficiency (ICAC, n.d.).

EPA reported that this flow arrangement has height limitation. Furthermore, high concentration of particles in the air stream tends to plug the packing for this arrangement. Apart from that, flooding may results in the counter current flow arrangement if the variation gas flow rate or liquid distribution rate is very high. Joseph et al. (1998) reported that flooding results where liquid does not drain out through the packing and is held at the void spaces between packing. This condition can significantly affect the scrubber operation (Joseph et al. 1998).

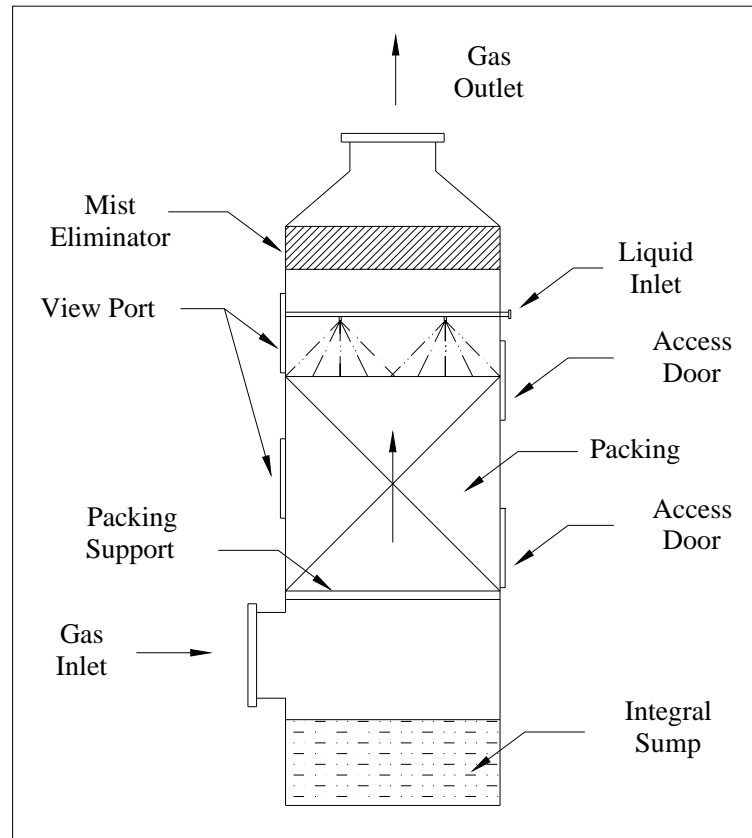


Figure 2.7 Counter current flow packed bed scrubber

### 2.4.2 Cross Flow

Cross flow packed bed wet scrubber has a horizontal profile. For cross flow arrangement, exhaust gas stream flows horizontally through a bed of packing. Scrubbing liquid is introduced at the top of the packed bed at right angle to the gas stream to provide wet film for packing and to wash away collected material.

At the front of the packed bed, there are nozzles or sprays to scrub the entering gas and the face of the packed bed. The purpose is to ensure an absolute wetting of the packing. As the gas stream leaves the packed bed, it flows through an entrainment separator. The entrainment separator is located subsequent to the packed bed so that entrained droplets and particle matter in the gas stream are completely captured before they are discharged to the atmosphere.

Apart from that, the packed bed is sloped at the leading face in the direction of the oncoming gas stream. The sloping can reduce plugging of particles and allow the scrubbing liquid to be able to flow down to the bottom of the packed bed before it is pushed back by the entering gas. As a consequence of this, the front packing can be absolutely wetted by the front nozzles. This process increases removal efficiency (Ceilcote Air Pollution Control 2005). A typical cross flow packed bed wet scrubber is shown in Figure 2.8.

According to Stone (1998), shell of a cross flow packed bed scrubber is usually rectangular in cross section and two grids are used to hold the packing. Ceilcote Air Pollution Control (2005) reported that cross flow arrangement is also efficient for removing gas. It has characteristics of low pressure drop and low liquid irrigation rates. Apart from that, it is ideal to use when roof mounting is necessary and ceiling height is limited. Theoretically, in cross flow arrangement, concentration gradient exists in two directions in the scrubbing liquid which is from front to rear and from top to bottom.

According to Kinematics (2000), this unit has greater particles handling capacity and can provide rapid chemical reaction if there is chemical absorption between the gas and liquid phase. A unit of cross flow packed scrubber filled with Tellerette packing is used by phosphate fertilizer industry to remove solid particulate (Ceilcote Air Pollution Control 2005). Cross flow can be very effective when using a caustic solution to scrub an acid gas (Jaeger Product 1996). Monroe Environmental (2002) reported that multi stages are available for cross flow design. This allows multiple scrubbing liquids to be used in series (Monroe Environmental 2002).

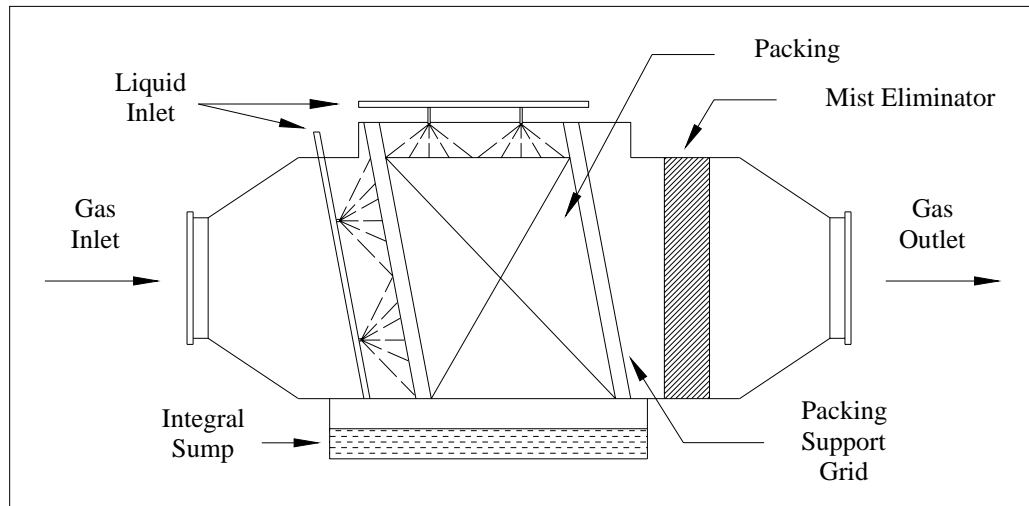


Figure 2.8 Cross flow packed bed scrubber



## Chapter 3

# Efficiency of Packed Bed Scrubber

### 3.1 Introduction

In this chapter, a number of factors affecting the removal efficiency of packed bed scrubber are investigated. These factors are determined based on design requirements for the scrubber from DOE Penang. In designing a packed bed scrubber, these factors should be taken into consideration to avoid scrubber operation problem. From an economic point of view, these factors help to minimize the operating, installation and the maintenance cost.

Theoretical study of scrubber efficiency calculation is presented after the factors influencing the scrubber efficiency are introduced. This study helps to provide the theoretical basis for finding the scrubber removal efficiency. After the theoretical studies, an illustration of determining the scrubber efficiency is presented. The scrubber efficiency is found by using an empirical approach in the illustration, both for cross flow and counter current flow packed bed scrubbers. In the empirical approach, efficiency of packed bed scrubber is determined from experimented and proven efficiency data based on the designed packing depth.

Two important parameters, number of transfer units ( $NTU$ ) and overall height of transfer unit ( $HTU$ ) are needed in determining the packing depth. By multiplying the  $NTU$  and  $HTU$ , packing depth that required for a packed bed scrubber can be obtained. Thus, theoretical study of these parameters is also included in this chapter.

### 3.2 General Emission Standard

The requirements of DOE for packed bed scrubber are governed by Environmental Quality (Clean Air) Regulations Malaysia 1978. Under this regulation, general emission standards for gaseous substances are defined. The general emission standard is shown in Table 3.1. The scrubber efficiency calculation in a later section is conducted with reference to this standard in order to limit the discharge of gas emission.

There are three standards of compliance in Table 3.1, namely A, B and C. According to the Environmental Quality (Clean Air) Regulations, every new scrubber shall comply with Standard C. Every existing scrubber shall comply with Standard A within two years and comply with Standard B within three years from the date the regulations come into force. Emission of particles, dust and other solid particles from the scrubber outlet shall not exceed emission level of  $0.04 \text{ g/Nm}^3$ .

Apart from that, effluents discharged from the scrubber shall comply with Environmental Quality (Sewage and Industrial Effluents) Regulations 1979. The effluents shall be channeled to the waste water treatment system and comply with Standard A or B under Environmental Quality (Sewage and Industrial Effluents) Regulations. The general effluent discharge standard is shown in Table 3.2.

Table 3.1 Emission standards for gaseous substances (Environmental Quality (Clean Air) Regulations Malaysia 1978)

Substance Emitted	Sources	Standards
(a) Acid gases	Manufacture of sulphuric acid	<ol style="list-style-type: none"> <li>1. Equivalent of: Standard A: 7.5 Standard B: 6.0 Standard C: 3.5g of sulphur trioxide/ <math>\text{Nm}^3</math> of effluent gas,</li> <li>2. Effluent gas free from persistent mist</li> </ol>

Table 3.1 General emission standards for gaseous substances (Environmental Quality (Clean Air) Regulations Malaysia 1978)

Substance Emitted	Sources	Standards
(b) Sulphuric acid mist or sulphur trioxide or both	Any source other than combustion process and plant for manufacture of sulphuric acid as in (a) above	1. Equivalent of: Standard A: 0.3 Standard B: 0.25 Standard C: 0.2g of sulphur trioxide/ Nm <sup>3</sup> of effluent gas, 2. Effluent gas free from persistent mist
(c) Chlorine gas	Any source	Equivalent of: Standard A: 0.3 Standard B: 0.25 Standard C: 0.2g of hydrogen chloride/ Nm <sup>3</sup>
(d) Hydrogen chloride	Any source	Equivalent of: Standard A: 0.6 Standard B: 0.5 Standard C: 0.4g of hydrogen chloride/ Nm <sup>3</sup>
(e) Fluorine, hydrofluoric acid, or inorganic fluorine compound	Manufacture of aluminum from alumina	Equivalent of: Standard C: 0.02g of hydrofluoric acid/ Nm <sup>3</sup> of effluent gas

Table 3.1 Emission standards for gaseous substances (Environmental Quality (Clean Air) Regulations Malaysia 1978)

Substance Emitted	Sources	Standards
(f) Fluorine, hydrofluoric acid, or inorganic fluorine compound	Any source other than manufacture of aluminum from alumina as in (e) above	Equivalent of: Standard A: 0.15 Standard B: 0.125 Standard C: 0.100g of hydrofluoric acid/ Nm <sup>3</sup> of effluent gas
(g) Hydrogen sulphide	Any source	Equivalent of: Standard A: 6.25 Standard B: 5.00 Standard C: 5.00 of parts per million volume for volume
(h) Oxide of nitrogen	Manufacture of nitric acid	Equivalent of: Standard A: 4.60 Standard B: 4.60 Standard C: 1.7 and effluent gas substantially colourless gramme of sulphur trioxide/ Nm <sup>3</sup>
(i) Oxides of nitrogen	Any source other than combustion processes and manufacture of nitric acid as in (h) above	Equivalent of: Standard A: 3.0 Standard B: 2.5 Standard C: 2.0g of sulphur trioxide/ Nm <sup>3</sup>

Table 3.2 Effluent discharge standards (Environmental Quality (Sewage and Industrial Effluents) Regulations Malaysia 1979)

Parameter		Unit	Standard	
			A	B
(i)	Temperature	°C	40	40
(ii)	pH value	-	6.0-9.0	5.5-9.0
(iii)	BOD <sub>5</sub> at 20°C	mg/l	20	50
(iv)	COD	mg/l	50	100
(v)	Suspended Solids	mg/l	50	100
(vi)	Mercury	mg/l	0.005	0.05
(vii)	Cadmium	mg/l	0.01	0.02
(viii)	Chromium, Hexavalent	mg/l	0.05	0.05
(ix)	Arsenic	mg/l	0.05	0.10
(x)	Cyanide	mg/l	0.05	0.10
(xi)	Lead	mg/l	0.10	0.5
(xii)	Chromium, Trivalent	mg/l	0.20	1.0
(xiii)	Copper	mg/l	0.20	1.0
(xiv)	Manganese	mg/l	0.20	1.0
(xv)	Nickel	mg/l	0.20	1.0
(xvi)	Tin	mg/l	0.20	1.0
(xvii)	Zinc	mg/l	1.0	1.0
(xviii)	Boron	mg/l	1.0	4.0
(xix)	Iron (Fe)	mg/l	1.0	5.0
(xx)	Phenol	mg/l	0.001	1.0
(xxi)	Free Chlorine	mg/l	1.0	2.0
(xxii)	Sulphide	mg/l	0.50	0.50
(xxiii)	Oil and Grease	mg/l	Not Detectable	10.0

### **3.3 Basic Requirements of DOE**

Department of Environment (which is also known as Jabatan Alam Sekitar in Malay) Penang provides a series of requirements for the design of packed bed scrubber to ensure that every design has optimum operation besides complying with the emission standards. An approval of scrubber installation will be given by DOE before a new scrubber can be installed in a process plant. DOE officer also will perform on site checking of existing scrubbers to ensure that the scrubbers are operating within specifications.

For every new scrubber, an applicant should make a submission to DOE documenting the purpose of using the scrubber, its detailed design, its specification and so on. For instance, the applicant should specify the location of installing the scrubber, type of pollutant to be scrubbed, pollutant generation, associate components completing the scrubber systems, design of the scrubber, associated calculation and others.

DOE requires that the applicant specifies the type of pollutant, the pollutant concentration and the pollutant characteristics. The process flow chart for pollutant generation is required to be attached. The related process of generating the pollutant is also needed.

The applicant also needs to mention the flow of configuration of the designed packed bed scrubber (i.e. cross flow or counter current flow, etc). The flow of configuration is usually decided by engineers based on the process plant. The capacity of the scrubber is also required to be properly quoted. The quoted scrubber capacity is based on the rate of pollutant generation.

DOE insists that scrubber shell should be fabricated from material which has high strength and corrosion resistance to the gaseous pollutant. The final material for scrubber shell is chosen based on the nature of the pollutant.

DOE also requires that type of packing used in the scrubber is to be clearly stated. There is a variety of packing marketed with a range of material. The associated packing catalogue, packing specification and its operating curve are required to be submitted to DOE for reference.

Details of the associate equipment completing the scrubbing process such as fan and pump are required by DOE. The details include fan and pump catalogues, fan and pump operating curve and their specification. For fan, operating parameter such as capacity, static pressure, fan material and motor output are needed to be clearly stated. These parameters should efficiently optimize the scrubber operation. Similar requirements are needed for the pumps.

Apart from the above, detailed calculations of several operating conditions are needed by DOE. The calculations include dimension of scrubber, irrigation area, superficial gas velocity across the scrubber, *NTU* and *HTU*. Frictional losses or pressure drop through ducts, elbows and scrubber body are also needed. Gas loading rate (i.e. according to the pollutant generation rate), designed liquid flow rate, and desired fresh water make up rate have to be stated clearly. DOE also requires removal efficiency of the designed scrubber for a particular pollutant. The submission of these data is compulsory for DOE to verify the scrubber design.

DOE requires drawing and information concerning the process plant. These include premise key plan, location plan, building layout and elevation plan of the process plant. This is to ensure that DOE has the right information regarding the location of the scrubber that is to be installed. Beside the detailed drawings of the scrubber, ducting system has to be certified by a professional engineer to ensure that the scrubber is reliable.

DOE insists that height of chimney shall at least 3m from building roof top where a scrubber will be installed nearby. Chimney is a vertical smokestack which is connected to the gas outlet in order to channel the exhaust streams to the atmosphere. Apart from that, stair tread and platform is needed to be prepared for

chimney in order to do sampling works. Diameter of the sampling port shall have at least 100mm (4").

Besides, effluent sampling analysis report for every existing scrubber is required by DOE. This report shall be submitted to DOE once every two months to ensure that the effluent is harmless to people and environment. Similarly, emission report of gas and particles are required to be submitted once for every three months to DOE.

### **3.4 Factors Influencing Efficiency**

The following subsections show the factors influencing the scrubber efficiency as determined from the DOE requirements. These factors includes irrigation area, scrubbing liquid, bed depth, liquid flow rate, temperature, material of construction, packing, maintenance, liquid to gas ratio and heat effect.

#### **3.4.1 Irrigation Area**

Effective cross sectional area of a scrubber is a factor affecting the scrubber efficiency. The area should be properly designed so that the scrubber has sufficient area to accommodate the flow of gas and liquid. In addition, sufficient area of irrigation facilitates gas and particles removal.

Gas velocity increases with a decreased scrubber cross sectional area. For a scrubber which has a smaller cross sectional area, there is a higher potential for liquid to be held at packing void spaces. This situation increases scrubber pressure drop and decreases the mixing between the liquid and gas. Besides, variation of the liquid and gas flow rates is one of the causes that the gaseous pollutants lack the required residence time to be absorbed by the liquid. Consequently, gas velocity across the scrubber influences the retention time of the dirty gas which can affect the scrubber efficiency. Flooding occurs when packing void spaces is totally filled by the liquid. Flooding results in a layer of liquid at the top of packing and this forbid the liquid from flowing down through the packed bed. This significantly affects the absorption process and should be avoided.



The scrubber cross sectional area can be approximated by using the generalized pressure drop correlation (which is also known as Sherwood Hollaway Curve) as shown in Figure 3.1. Equation of the abscissa from Figure 3.1 is given in equation (3.1). Practically, the actual area of the scrubber is sized at a certain percent of the flooding velocity (the gas velocity at which flooding occurs).

$$\text{Abscissa} = \left( \frac{L}{G} \right) \sqrt{\frac{\rho_g}{\rho_l}} \quad (3.1)$$

Where

- $G$  = gas flow rate, kg/s  
 $L$  = liquid flow rate, kg/s  
 $\rho_g$  = density of the gas, kg/m<sup>3</sup>  
 $\rho_l$  = density of the liquid, kg/m<sup>3</sup>

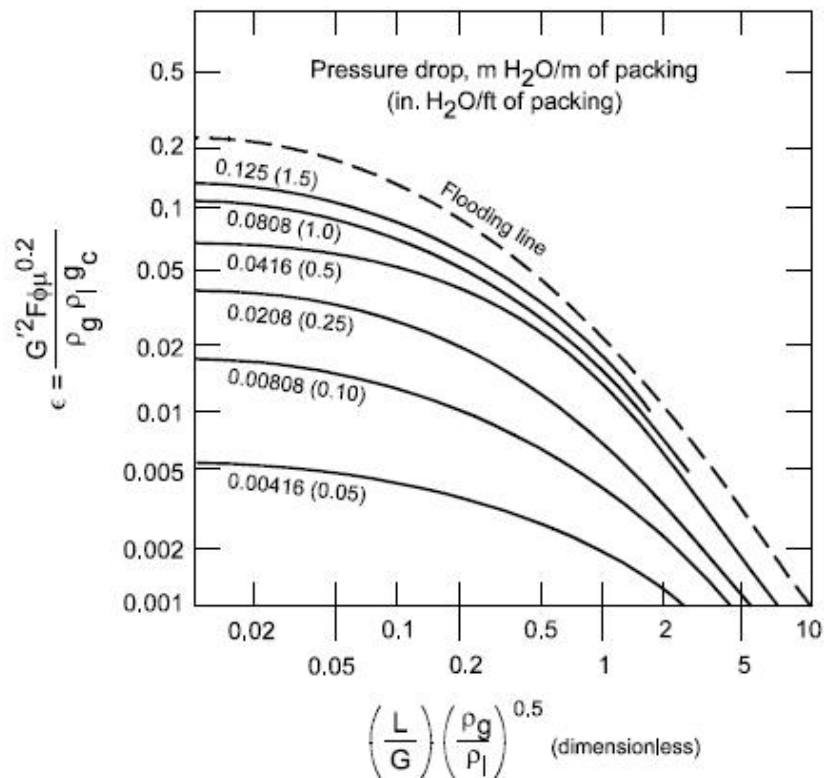


Figure 3.1 Generalized pressure drop correlation (Joseph et al. 1998)

From the value calculated in equation (3.1), proceed up the graph (Figure 3.1) to the flooding line and read across to obtain the corresponding ordinate. Equation of the ordinate is given in equation (3.2) where  $G_{flooding}$  is equivalent to  $G'$  in Figure 3.1. Equation (3.2) is rearranged to solve for  $G$  at flooding condition.

$$G_{flooding} = \sqrt{\frac{(\varepsilon)(\rho_g)(\rho_l)(g_c)}{F(\phi)(\mu)^{0.2}}} \quad (3.2)$$

Where

$G_{flooding}$	=	gas mass velocity per unit of cross sectional area, kg/s.m <sup>2</sup>
$\varepsilon$	=	ordinate value from Figure 3.1
$\rho_g$	=	density of the gas, kg/m <sup>3</sup>
$\rho_l$	=	density of the liquid, kg/m <sup>3</sup>
$g_c$	=	gravitational constant, 9.82m/s <sup>2</sup>
$F$	=	packing factor
$\phi$	=	ratio of water density to liquid density (dimensionless)
$\mu$	=	viscosity of liquid, kg/m.s or centipoise

Gas mass velocity in actual operating condition is a fraction of the gas mass velocity at the flooding condition. Equation (3.3) shows the formula for the actual operating gas mass velocity. The percentage of flooding is in the range of 50% to 75%.

$$G_{operating} = (f)(G_{flooding}) \quad (3.3)$$

Where

$G_{operating}$	=	gas mass velocity in actual operating condition, kg/s.m <sup>2</sup>
$G_{flooding}$	=	gas mass velocity at the flooding condition, kg/s.m <sup>2</sup>
$f$	=	the percent of flooding velocity (50% – 75%)

Finally, the cross sectional area of the scrubber is determined from equation (3.4)

$$A = \frac{G}{G_{operating}} \quad (3.4)$$

Where

$A$	=	cross sectional area of scrubber, $m^2$
$G_{operating}$	=	gas mass velocity in actual operating condition, $kg/s.m^2$
$G$	=	gas flow rate, $kg/s$

Scrubber cross sectional area obtained from equation (3.4) is used to determine the dimension of scrubber. For example, diameter for counter current flow packed bed scrubber (which is cylindrical in shape) can be obtained. Similarly, dimension of height and width can be approximated based on the area for cross flow packed bed scrubber (which is rectangular in cross section). In fact, a good determination of scrubber cross sectional area is important to ensure an efficient scrubber operation.

### 3.4.2 Scrubbing Liquid

Scrubbing liquid is a factor influencing the scrubber efficiency. Ideally, the selected scrubbing should have high solubility for the gas so that it enhances the rate of absorption. It should be economical such that a soluble gas requires minimum amount of scrubbing liquid to accomplish the scrubbing process. A chemical reagent can be added to the absorbing liquid to improve the gas solubility. This will improve the absorption performance of scrubber so that it can achieve the required removal efficiency for a particular pollutant.

Correctly using a scrubbing liquid for a pollutant removal is another factor that aids gas absorption. For inorganic gas control, sodium hydroxide, calcium hydroxide and sodium carbonate are the choices of scrubbing liquid in the absorption process. The acidic gas reacts with the alkaline to form salt and water. Apart from that, absorbing liquid such as water and mineral oils are usually applied to remove volatile organic compound from the process air stream.

The selected scrubbing liquid for pollutant removal should have low viscosity. Low viscosity liquid diminishes the flooding condition and pressure drop which in turn facilitates the absorption process. Additionally, the liquid should not be flammable and toxic. It should be reasonably inexpensive. In practice, the absorbed pollutant is kept in the integral sump. The absorbed pollutant is neutralized and reused again in the scrubber as a way to save for operating cost, since most scrubbing liquids are costly.

### **3.4.3 Bed Depth**

Packing provides large surface contact area for liquid and gas and greater gas residence time for contact. It also has feature of promoting uniform liquid distribution. These features ensure good mixing between the liquid and gas to encourage gas absorption. Depth of packing affects the absorption performance. Larger packed depth is preferred for a scrubber since it aids absorption and thus enhancing scrubber efficiency.

For a difficult gas separation, larger packing depth is necessary for the fume removal. Basically, the desired depth of packing is determined based on the required removal efficiency for the pollutant and the degree of mass transfer efficiency of the packing used in the scrubber. However, provision of large packing depth can increase the scrubber pressure drop.

Pressure drop results as gas flows through the packed bed. The pressure drop is actually caused by the resistance of packing and liquid that resists the gas flow. It is also caused by size and shape of packing. Thus, larger packed depth encounters higher pressure drop and consequently, a higher fan power will be required to drive the gas through the packed bed. This directly increases the operating cost of scrubber. By using a suitable packing, the pressure drop can be reduced. For instance, Tellerette packing has feature of reducing pressure drop in the scrubber. Hence, it helps to reduce the energy consumption and the operating cost.

From an economic point of view, bed depth should be designed sufficiently to optimize the scrubbing process based on the required removal efficiency for a

particular pollutant. Inadequate depth of packing is undesirable since it reduces gas residence time for contact and thus causing deficiency for the scrubber operation.

#### **3.4.4 Liquid Flow Rate**

The scrubbing liquid flow rate should be designed accurately to provide sufficient flow of liquid and prevent drying of packed bed. The sufficient flow of liquid ensures that the contaminated air streams are in continuously contact with the liquid. An adequate liquid distribution rate is also able to avoid flooding condition which may result from variation of gas and liquid flow rates.

The integral sump which keeps the absorbed pollutant serves as the liquid recirculation tank for the liquid recirculation system of packed bed scrubber. The neutralized liquid in the tank is pumped through piping into the scrubber and is reused again to scrub the dirty air stream. For a good scrubber performance, the recycled liquid must have an acceptable pH value to aid the absorption process. Fresh make up liquid is also continually supplied to the integral sump to dilute the pollutant concentration of the recycled liquid. These features help to ensure that the scrubbing process is efficient for scrubber.

Besides, regular checking should be provided to inspect the pumping process so that clogging can be avoided. It is because smooth flow of liquid ensures consistent liquid distribution rate. The pump is also having potential to be clogged by the sludge in the integral sump. This can affect uniform flow of recycled liquid into the scrubber. As a consequence of this, another pump is normally used to transport the sludge from the tank to the waste water treatment plant to reduce the potential of clogging.

#### **3.4.5 Temperature**

Inlet temperature of the exhaust gas is another parameter that affects the scrubber efficiency. Higher gas temperature can cause deficiency of the absorption process by evaporating the scrubbing liquid. Dry portion could result at the packed bed due to evaporation of liquid and this can cause severe absorption problem in which

absorption ceases if the packing is dried. Under this situation, it also provides adverse effect to the gas solubility and it directly decreases the absorption rate. Furthermore, high temperature of the air stream can damage the scrubber shell and the scrubber equipment due to rapid quenching between the hot gas and the liquid. Corrosion can occur.

Hence, temperature of the pollutant generation must be examined in a careful manner to avoid absorption deficiency. For a dirty air stream that has high temperature, the temperature of the air stream is usually reduced to an acceptable level of temperature before it enters the scrubber. For example, a spray chamber or a quencher is used to reduce the gas temperature before the gas is channeled to the scrubber.

Apart from that, viscosity, density, diffusivity and other properties of the air stream and liquid are temperature dependent. Generally, a lower temperature favors the process of physical absorption and protects unnecessary damage to the internal part of the scrubber.

#### **3.4.6 Material of Construction**

The selection of scrubber material is mainly dependent on the pollutant, the process operating condition and the absorbing liquid. Thus, the construction material of scrubber shell is another factor affecting the scrubber efficiency. The material selected should sustain against the corrosive gas. Otherwise, the scrubber body will rust. This will result in excessive emission and the efficiency of scrubber will be reduced accordingly. This is very dangerous.

For a scrubber to have a good operating condition, the scrubber material should be carefully reviewed so that a correct material can be chosen for the scrubber to operate efficiently. For instance, FRP is always a common choice of scrubber material. This material is considerably inexpensive as compared to other construction material. Furthermore, it has high corrosion resistance.

The internal surface of the scrubber is essential to have layers of plastic or corrosion resistant alloy due to presence of corrosive gas or liquid. For example, when highly corrosive liquid or gases is applied to a scrubber, layers of plastic material such as polypropylene are normally attached to the interior surface of the scrubber shell to protect the surface from rusting. Apart from that, the exterior surface of the scrubber body is usually lined with a coating such as epoxy resin or polyvinyl ester to protect the surface from environmental attack or atmospheric corrosion.

Hence, correct selection of scrubber construction material secures the scrubber operation from resulting excess emission through its body that caused by corrosion problem.

### **3.4.7 Packing**

Packing is the mass transfer media for the scrubber operation. To ensure an efficient mass transfer operation, the selected packing must have good characteristic in strength, good corrosion resistance and has high mass transfer efficiency. The chosen packing must also be able to handle the required flow rates of gas and liquid. Besides, it needs to be cost effective.

Corrosion is usually results at areas which have wet dry interface. Packing acts as the contact media for gas separation has high potential for corrosion. Consequently, packing material is normally chosen based on the degree of corrosiveness of the air stream. Packing which made from material such as ceramic has low strength and brittle. Material such as metal is inappropriate to be used for highly corrosive gas due to decomposition. Packing that made from plastic material such as polypropylene has greater resistance to corrosion and it is always used nowadays as the contact media for gases which are highly corrosive.

View ports and access doors are needed for every scrubber for inspection and maintenance of packing. The corrosion level of packing can be examined through the view ports. The access doors facilitate the scrubber cleaning process and replacement of new packing.

Therefore, suitable selection of packing material reduces the problem and cost of maintenance besides enhancing the scrubber operation. Packing is the critical media for pollutant removal in packed bed scrubber and therefore it needs to be selected based on properties of the system, pollutant, scrubbing liquid, etc.

### **3.4.8 Maintenance**

Packed bed wet scrubbers normally require a higher cost of maintenance as compared to other scrubber systems. This is because packing, entrainment separator, pump, fan require periodic maintenance so that they are operable within specification.

Plugging or solids build up can occur at the packed bed which can lead to non-uniform flow of liquid and gas. For example, scrubbing process that involves chemical reaction produces solid compound which can plug the packing. Additionally, packing is also possible to be plugged by dusts that come from the dirty air streams. These situations cause deficiency to the scrubber operation and therefore removal of these solids is necessary.

Periodic cleaning is necessary for packing to flush away the solid particles so that it is free from plugging. Prior to cleaning, scrubber is shut down and packing is removed. The cleaned packing will be reinstalled after cleaning. Apart from that, additional packing is required to be added to replace some portions of packing which are decomposed by the corrosive air streams.

Cleaning is also needed for the entrainment separator since it also has the potential to be plugged by the particulate matters. Excessive liquid carryover may result if the entrainment separator is not cleaned accordingly. Similarly, pump and packing support plate need periodic cleaning to remove clogging so that the flow of fluid is uniform.

Fan maintenance is also important. The fan belt drive and the fan impeller should be inspected and replaced from time to time. Improper operation of these parts can reduce the gas flow to scrubber that could reduce the scrubber performance.



Gas channeling is another operation problem of packed bed scrubber. Gas channeling results when gas moves through the packed bed by following the least resistance path. It is actually caused by lower gas flow rate and it happens at places which has greater void spaces. Consequently, gas is not uniformly distributed over the packing. To overcome this problem, gas and liquid flow rates have to be maintained at a proper level and therefore inspection is always needed.

#### **3.4.9 Liquid to Gas Ratio**

For a very high solubility gas, inappropriate supply of liquid can result dry portion at the packed bed and absorption will cease. This situation is undesirable since absorption is only occurs when packing is wetted. To overcome this problem, liquid to gas ratio which is another important factor affecting the scrubber efficiency needs to be properly considered. Furthermore, a correct liquid to gas ratio helps to prevent flooding condition and poor scrubber operation. Apart from that, a proper liquid to gas ratio must be maintained for a particular packing since there are many geometries of packing which required different liquid to gas ratio to optimize the scrubber performance

In practice, liquid to gas ratio for a scrubber operation should be greater than the minimum theoretical calculated value by 20 to 50 percents (i.e. without flooding). This guarantees that sufficient liquid is supplied so that packing remains wet. The actual supply of liquid can be optimized based on engineers' experience and their judgment for a particular scrubber operation.

#### **3.4.10 Heat Effects**

For packed bed scrubber, heat effects are usually omitted by assuming that isothermal condition exists in the scrubber and a safety factor is therefore needed. Heat generation in the scrubber comprised of heat from the exothermal chemical reaction between the liquid and gaseous pollutant, heat from vaporization, heat from condensation of gas and liquid, heat from mixing and so on. The heat generation leads to a rise in temperature which is able to reduce the absorption rate and cause damage to the associated equipment of the scrubber.

## 3.5 Theoretical Study

### 3.5.1 Removal Efficiency

In finding the theoretical efficiency of a packed bed scrubber, a vapor-liquid equilibrium data (i.e. equilibrium line or curve) for a specific pollutant-solvent system is needed. The equilibrium line is the relationship of gas absorption for liquid and gas. Each equilibrium line represents equilibrium condition between a pollutant and an associate liquid. For scrubber efficiency calculation in theory, parameters such as pollutant flow rate, pollutant concentration, gas composition, pollutant and liquid properties are required. Theoretically, prediction of efficiency both for cross flow and counter current flow packed bed scrubber is based on two parameters which are theoretical number of transfer units and absorption factor.

Several assumptions have been made in calculating the efficiency of the packed bed scrubber to simplify the procedure of calculation. For instance, the dirty air stream and the scrubbing liquid are assumed to behave ideally. Heat effects of the gas absorption is consider to be negligible therefore isothermal condition exist. The exhaust gas is also assumed to consist of a mixture of air and pollutant only. The velocities of the gas and liquid are assumed to be uniform across the packed bed. Furthermore, it is assumed that there is no evaporation of scrubbing liquid.

An equation that represents the efficiency of packed bed scrubber is given in equation (3.5). According to equation (3.5), removal efficiency of packed bed scrubber is determined based on inlet and outlet pollutant concentrations.

$$\eta = 1 - \left( \frac{y_{out}}{y_{in}} \right) \quad (3.5)$$

Where

$\eta$  = packed bed scrubber efficiency

$y_{in}$  = inlet pollutant concentration, ppm

$y_{out}$  = outlet pollutant concentration, ppm

In general, equation (3.5) is used to determine the required removal efficiency of a packed bed scrubber for a particular pollutant removal. The outlet pollutant concentration is fixed and it is taken from the emission standard. The inlet pollutant concentration is set by the process exhaust condition. Therefore, the required removal efficiency for the pollutant can be determined since the inlet and outlet pollutant concentrations are known. The efficiency found in equation (3.5) is used as a guideline so that a scrubber can be designed to achieve this value of efficiency. Thus, the discharge of the gas emission can be limited.

Equation (3.6) is an equation that represents the removal efficiency both for cross flow and counter current flow packed bed scrubbers according to Fthenakis (1996). It is a function of gas and liquid flow rate, absorption factor, slope of equilibrium line, number of transfer units, etc. Equation (3.6) is equivalent to equation (3.5). Efficiency calculation for cross flow differs from the one for counter current flow by using difference constant of  $c_2$  as shown in equation (3.12).

$$\eta = 1 - \left[ \frac{m(c_1 - c_1c_2) + c_2}{m(c_1 - c_1c_2) + 1} \right] \quad (3.6)$$

Where

- $\eta$  = packed bed scrubber efficiency
- $m$  = slope of equilibrium curve
- $c_1$  = a function shown in equation (3.7)
- $c_2$  = a function shown in equation (3.8) for counter current flow packed bed scrubber and for cross flow packed bed scrubber, it is shown in equation (3.12)

For counter current flow packed bed scrubber, the required parameters needed to calculate the efficiency are shown in equations (3.7), (3.8), (3.9), (3.10) and (3.11). These parameters will be substituted into equation (3.6) in order to determine the efficiency of counter current flow packed bed scrubber theoretically.

$$c_1 = \frac{G}{BL}(1-B) \quad (3.7)$$

Where

$G$  = gas flow rate, kg/s

$B$  = ratio of blow down flow to scrubber inlet liquid flow

$L$  = liquid flow rate, kg/s

$$c_2 = \frac{1 - \left(\frac{1}{AF}\right)}{e^\lambda - \left(\frac{1}{AF}\right)} \quad (3.8)$$

Where

$AF$  = absorption factor as shown in equation (3.9)

$\lambda$  = a function shown in equation (3.10)

$$AF = \frac{L}{mG} \quad (3.9)$$

Where

$L$  = liquid flow rate, kg/s

$m$  = slope of equilibrium curve

$G$  = gas flow rate, kg/s

$$\lambda = NTU \left(1 - \frac{1}{AF}\right) \quad (3.10)$$

Where

$NTU$  = number of transfer units as shown in equation (3.11)

$AF$  = absorption factor as shown in equation (3.9)

$$NTU = \frac{K_G a z}{G'} \quad (3.11)$$

Where

- $K_G$  = overall mass transfer coefficient in the gas phase, mol/m<sup>2</sup>.s  
 $a$  = total surface area of packing per unit volume of bed, m<sup>2</sup>/m<sup>3</sup>  
 $z$  = vertical dimension of scrubber, m  
 $G'$  = superficial gas mass flow rate, kg/m<sup>2</sup>.s

For cross flow packed bed scrubber, the parameters required for calculating the efficiency are the same with the one for counter current flow configuration. The same equation (3.6) is used, except that the function of  $c_2$  is difference as shown in equation (3.12).

$$c_2 = e^{-b-NTU} \sum_{i=0}^{\infty} \sum_{k=0}^{\infty} \frac{1+i}{(1+i+k)! k!} (b)^i (NTU b)^k \quad (3.12)$$

Where

- $b = \frac{NTU}{AF}$   
 $NTU$  = number of transfer unit as shown in equation (3.11)  
 $AF$  = absorption factor as shown in equation (3.9)

Equation (3.9) is an absorption factor ( $AF$ ) for a pollutant solvent system. The absorption factor is used to describe the relationship between the liquid to gas ratio and the equilibrium line. From equation (3.9), the slope of the equilibrium line  $m$  is obtained from a vapor-liquid equilibrium data for a specific pollutant solvent system. The following equation (3.13) can be used to calculate the  $m$  provided that the equilibrium line for a pollutant-solvent system is available.

$$m = \frac{y_o^* - y_i^*}{x_o - x_i} \quad (3.13)$$

Where

$y_o^*$  = mole fraction of pollutant in gas phase in equilibrium with mole fraction of the pollutant exiting in the liquid phase.

$y_i^*$  = mole fraction of pollutant in gas phase in equilibrium with mole fraction of the pollutant entering in the liquid phase.

$x_o$  = mole fraction of the pollutant exiting the scrubber in the liquid

$x_i$  = mole fraction of the pollutant entering the scrubber in the liquid

### 3.5.2 Bed Depth

Bed depth has a closed relationship in determining the removal efficiency of packed bed scrubber empirically, in which provision of larger bed depth increases the efficiency of packed bed scrubber. In a later section, bed depth is used to estimate the efficiency of packed bed scrubber empirically. Bed depth is determined based on *NTU* (number of transfer units) and *HTU* (height of transfer unit) where multiplication of the *NTU* and *HTU* gives rise to packing depth. The definition of *NTU* is a measure of the difficulty of the gas separation whereas *HTU* is a measure of the effectiveness of a particular packing for a gas separation.

*NTU* can be determined in a number of ways. The methods are discussed in the following sections. Normally, packing manufacturers or vendors provide *HTU* curves for engineers to design the packed bed scrubber system. The *HTU* curves were developed by the manufacturers of packing. Nowadays, many packing are designed and marketed for special application. Therefore, each packing has its *HTU* curve for a pollutant-solvent system. In a later section, a *HTU* curve is used to determine a bed depth for a scrubber empirically.

In theory, depth of packing is predicted based on diffusion principles. It is simply a product of *NTU* and *HTU*. A simple expression used to predict the depth of packing is shown in equation (3.14).

$$Z = HTU \times NTU \quad (3.14)$$

Where

- $Z$  = depth of packing, m  
 $HTU$  = overall height of transfer unit, m  
 $NTU$  = number of transfer units (dimensionless)

$HTU$  is defined as a function of gas flow rate, overall mass transfer coefficient, surface area of packing and pressure of the scrubbing system.  $NTU$  is a function of gas pollutant concentration that enters and exits the packed bed scrubber. Equations for  $HTU$  and  $NTU$  in terms of these parameters are given in equations (3.15) and (3.16) respectively according to Davis (1999).

$$HTU = \frac{G_m}{aAK_G} \quad (3.15)$$

Where

- $HTU$  = overall height of transfer unit, m  
 $G_m$  = gas molar flow rate, mol/s  
 $a$  = total surface area of packing per unit volume of bed,  $m^2/m^3$   
 $A$  = cross sectional area of scrubber,  $m^2$   
 $K_G$  = overall mass transfer coefficient in the gas phase,  $mol/s.m^2$

$$NTU = \int_{y_{out}}^{y_{in}} \frac{dy}{(y - y^*)} \quad (3.16)$$

Where

- $NTU$  = number of transfer units (dimensionless)  
 $y_{in}$  = inlet pollutant concentration, ppm  
 $y_{out}$  = outlet pollutant concentration, ppm  
 $y^*$  = pollutant concentration in gas in equilibrium, ppm

$$Z = \frac{G_m}{aAK_G} \int_{y_{out}}^{y_{in}} \frac{dy}{(y - y^*)} \quad (3.17)$$

Consequently, equation (3.17) as shown above is equivalent to equation (3.14), the determination of packing depth for packed bed scrubber in theory.

### 3.5.2.1 Number of Transfer Units

There are several ways used to determine the *NTU*: either graphically (Colburn diagram) or directly using an equation (Joseph et al. 1998). For low concentration pollutant, the *NTU* is determined based on gas phase as shown in equation (3.18).

$$NTU = \frac{\ln \left[ \left( \frac{y_i - mx_{en}}{y_o - mx_{en}} \right) \left( 1 - \frac{mG_m}{L_m} \right) + \frac{mG_m}{L_m} \right]}{1 - \frac{mG_m}{L_m}} \quad (3.18)$$

Where

- NTU* = number of transfer units based on an overall mass transfer coefficient in the gas phase,  $K_G$
- $y_i$  = mole fraction of pollutant in entering gas
- $y_o$  = mole fraction of pollutant in exiting gas
- $m$  = slope of equilibrium curve
- $x_{en}$  = mole fraction of pollutant in entering liquid
- $G_m$  = gas molar flow rate, mol/s
- $L_m$  = liquid molar flow rate, mol/s

Equation (3.18) is also can be solved graphically by using the Colburn diagram as shown in Figure 3.2. The Colburn diagram is plotted by using a number of absorption factors. The *NTU* can be obtained after an absorption factor and an abscissa (Figure 3.2) value are determined. By having a value of abscissa, the graph



is read up to a line corresponding to a absorption factor. The graph is then read across to obtain the corresponding  $NTU$ .

From Figure 3.2, the abscissa of the diagram is  $\frac{Y_1 - mX_2}{Y_2 - mX_2}$  where  $Y_1$  is the mole fraction of pollutant in the entrance gas,  $m$  is the slope of equilibrium line,  $X_2$  is the mole fraction of pollutant entering the scrubber in liquid and  $Y_2$  is the mole fraction of pollutant in the exiting gas (Joseph et al. 1998).

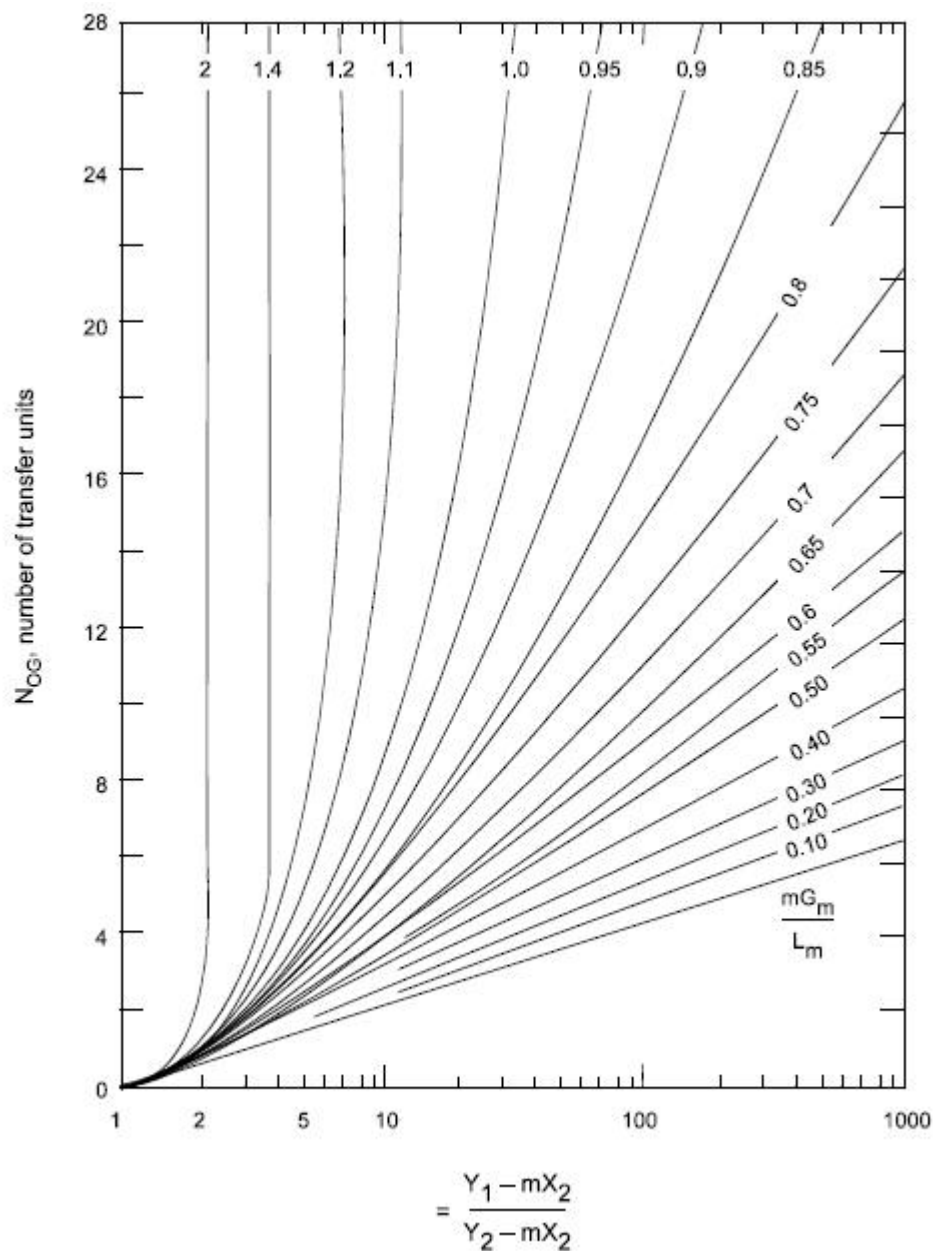


Figure 3.2 Colburn diagram (Joseph et al. 1998)

Equation (3.18) is further simplified to equation (3.19) so that equation (3.19) can be used to determine  $NTU$  for a pollutant which is very soluble in the liquid (Joseph et al. 1998). Equation (3.19) is also applied for a scrubbing process that involves a chemical reaction. For a pollutant solvent system with high liquid to gas ratio or a straight equilibrium line, equation (3.19) is also can be used to determine the  $NTU$ . As shown in equation (3.19), the  $NTU$  is dependent on inlet and outlet pollutant concentration.

$$NTU = \ln \frac{y_i}{y_o} \quad (3.19)$$

Where

- $NTU$  = number of transfer units based on an overall mass transfer coefficient in the gas phase,  $K_G$
- $y_i$  = mole fraction of pollutant in entering gas
- $y_o$  = mole fraction of pollutant in exiting gas

### 3.5.2.2 Overall Height of Transfer Unit

The overall height of transfer unit of the packed bed scrubber is actually comprised of height of liquid and gas transfer units as shown in equation (3.20) (Davis 1999). In particular, equations (3.22) and (3.23) represent the height of liquid and gas transfer units in details. The  $HTU$  is dependent on packing characteristic, physical properties of system, gas and liquid flow rate, height and cross section of scrubber.

$$HTU = HTU_G + \left( \frac{mG_m}{L_m} \right) HTU_L \quad (3.20)$$

Where

- $HTU$  = overall height of transfer unit, m
- $HTU_G$  = height of gas transfer unit, m
- $HTU_L$  = height of liquid transfer unit, m
- $m$  = slope of equilibrium line

$$G_m = \text{gas molar flow rate, mol/s}$$

$$L_m = \text{liquid molar flow rate, mol/s}$$

As shown in equation (3.21), the  $HTU_G$  from equation (3.20) is a function of gas molar flow rate, packing surface area, scrubber cross sectional area and mass transfer coefficient in gas phase. Likewise, the function of the  $HTU_L$  consists of liquid molar flow rate, packing surface area, scrubber cross sectional area and mass transfer coefficient in liquid phase.

$$HTU = \frac{G_m}{aAk_y} + \left( \frac{mG_m}{L_m} \right) \left( \frac{L_m}{aAk_x} \right) \quad (3.21)$$

Where

$$HTU = \text{overall height of transfer unit, m}$$

$$G_m = \text{gas molar flow rate, mol/s}$$

$$L_m = \text{liquid molar flow rate, mol/s}$$

$$a = \text{total surface area of packing per unit volume of bed, m}^2/\text{m}^3$$

$$A = \text{cross sectional area of scrubber, m}^2$$

$$k_y = \text{mass transfer coefficient in the gas phase, mol/s.m}^2$$

$$m = \text{slope of equilibrium curve}$$

$$k_x = \text{mass transfer coefficient in the liquid phase, mol/s.m}^2$$

Apart from the above, the  $HTU_L$  is also a function of packing constants, liquid Schmidt number, superficial liquid mass flow rate and the viscosity of liquid as shown in equation (3.22) according to Davis (1999). Equation (3.23) shows an equivalent function for  $HTU_G$  as well.  $HTU_G$  in equation (3.23) is a function of packing constants, gas Schmidt number, superficial liquid mass flow rate and superficial gas mass flow rate (Davis 1999).

$$HTU_L = \frac{L_m}{aAk_x} = \phi_p \sqrt{Sc_L} \left( \frac{L'}{\mu} \right)^\xi \quad (3.22)$$

Where

- $HTU_L$  = height of liquid transfer unit, m  
 $L_m$  = liquid molar flow rate, mol/s  
 $a$  = total surface area of packing per unit volume of bed,  $m^2$   
 $A$  = cross sectional area of scrubber,  $m^2$   
 $k_x$  = mass transfer coefficient in the liquid phase,  $mol/m^2.s$   
 $\phi_p$  = packing constant  
 $Sc_L$  = liquid Schmidt number  
 $L'$  = superficial liquid mass flow rate,  $kg/m^2.s$   
 $\mu$  = viscosity of liquid,  $kg/m.s$   
 $\xi$  = packing constant

$$HTU_G = \frac{G_m}{aAk_y} = \alpha \sqrt{Sc_G} \frac{(G')^\beta}{(L')^\gamma} \quad (3.23)$$

Where

- $HTU_G$  = height of gas transfer unit, m  
 $G_m$  = gas molar flow rate, mol/s  
 $a$  = total surface area of packing per unit volume of bed,  $m^2/m^3$   
 $A$  = cross sectional area of scrubber,  $m^2$   
 $k_y$  = mass transfer coefficient in the gas phase,  $mol/m^2.s$   
 $\alpha$  = packing constant  
 $Sc_G$  = gas Schmidt number  
 $G'$  = superficial gas mass flow rate,  $kg/m^2.s$   
 $\beta$  = packing constant  
 $L'$  = superficial liquid mass flow rate,  $kg/m^2.s$   
 $\gamma$  = packing constant

### 3.6 Empirical approach

In this project, efficiencies of cross flow and counter current flow packed bed scrubber are found based on an empirical approach since practical design of scrubber is empirical in nature. Most of the vapor liquid equilibrium data for the specific pollutant solvent systems are not readily available. These data are necessary for design of scrubbers and they are needed to determine scrubber efficiency theoretically. Thus, the empirical approach is considered to be practical to obtain the efficiency of packed bed scrubber. The empirical approach is acceptable by DOE Penang as a way to estimate the efficiency of packed bed scrubber.

Packing depth of scrubber is used to determine the scrubber efficiency in the empirical approach. Provision of larger packing depth enhances the absorption rate and it therefore increases the efficiency of scrubber. Consequently, packing depth is taken as the determinant of scrubber efficiency empirically.

Manufacturers of packing developed graph for estimating  $HTU$  after performing pilot plant studies. For this project, experimental data such as  $HTU$  curve of Tellerette packing is used to determine the packing depth of scrubber. The manufacturer of Tellerette packing is Ceilcote Air Pollution Control. In designing the packed bed scrubber system,  $HTU$  is obtained from the curve based on the gas and liquid loading rates of a pollutant-solvent system. When the  $HTU$  is obtained, it is used to determine the packing depth of the scrubber by multiplied it with the associated  $NTU$ .

In determining the scrubber efficiency, tables of contaminant of Ceilcote Air Pollution Control are used and the efficiency is found from the table based on the calculated packing depth. The data of Ceilcote Air Pollution Control are experimented and proven on the designed scrubbers which had been collected over the years. The tables of contaminant comprised of efficiencies for cross flow and counter current flow packed bed scrubber in particular and they are used in a later section for the determination of scrubber efficiency in empirical.

A procedure of determining the scrubber efficiency empirically is outlined as below.

- Determine the gas rate channeled to the packed bed scrubber.
- Determine a suitable liquid rate that is sufficient to scrub against the dirty air streams.
- Determine the *NTU* for the scrubber.
- Determine the *HTU* from a *HTU* curve of a packing for a pollutant-solvent system. The curve can be obtained from packing manufacturer.
- Determine the packing depth from *NTU* and *HTU*.
- The efficiency is obtained from the past experimented and proven efficiency data based on the calculated packing depth.

By using the empirical approach, a sample of determining the efficiencies of cross flow and counter current flow scrubbers are shown in the following sections.

### **3.6.1 Efficiency of Counter Current Flow Packed Bed Scrubber**

Assume that a new counter current flow packed bed scrubber is designed to have a capacity or air flow of 11,000 cfm. The scrubber design area is 20 ft<sup>2</sup>. The pollutant in the dirty streams is hydrochloric acid (HCL) which is generated from a plating operation. The inlet hydrochloric acid concentration is 1000 ppm (part per million). The temperature at the gas inlet is 100 °F (ambient). Scrubbing liquid of water is used and the contact media used for fume removal is #2 Type-R Tellerette packing.

Based on the assumption that the scrubbing process is isothermal, uniform flow of liquid and gas, no evaporation of scrubbing liquid and the hydrochloric acid is very soluble in water, the removal efficiency for the counter current flow packed bed scrubber is estimated by using the outlined procedure from section 3.6.

First of all, a *HTU* curve of #2 Type-R Tellerette packing (specifically for removal of gaseous hydrochloric acid by using water) is obtained from the manufacturer of packing. According to the *HTU* curve, parameters such as gas and liquid rates are required to determine the required *HTU* for the scrubber. The *HTU* curve is in

English unit and therefore conversion of unit is required. Consequently, the unit of gas rate for the scrubber is converted below based on dry air.

$$G = \frac{11,000 \text{ cfm} \times \frac{60 \text{ min}}{\text{hr}} \times \frac{29}{359 \text{ ft}^3 / \text{mole}} \times \frac{(460 + 32)^\circ R}{(460 + 100)^\circ R}}{20 \text{ ft}^2}$$

$$= 2,342 \frac{\text{lb}}{\text{hr} \cdot \text{ft}^2}$$

Where

29 = molecular mass of air

359 = specific volume of air under standard conditions,  $\text{ft}^3/\text{mole}$

The liquid rate is determined based on experiences of engineers. For example, the liquid rate is taken to be 6 USGPM per square feet of irrigated area and it is shown below with conversion of unit.

$$L = \frac{6 \text{ USGPM}}{\text{ft}^2}$$

$$= \frac{6 \text{ USGPM} \times \frac{3.785 \text{ L}}{\text{USG}} \times \frac{2.2 \text{ lb}}{\text{L}} \times \frac{60 \text{ min}}{\text{hr}}}{\text{ft}^2}$$

$$= 2,997 \frac{\text{lb}}{\text{hr} \cdot \text{ft}^2}$$

The *HTU* for the scrubber is then determined based on the calculated gas and liquid rates. The *HTU* curve for #2 Type-R Tellerette packing is shown in Figure 3.3. The *HTU* curve (Figure 3.3) is developed particularly for a scrubber system having liquid rate of 3,000  $\text{lb}/\text{hr} \cdot \text{ft}^2$ . Hence, the curve can be used since the parameter *L* (2,997  $\text{lb}/\text{hr} \cdot \text{ft}^2$ ) calculated above is closed to 3,000  $\text{lb}/\text{hr} \cdot \text{ft}^2$ .

**(HTU)<sub>og</sub> VS. GAS RATE**  
**TELLERETTE® TOWER PACKING**  
**GASEOUS HYDROCHLORIC ACID-AIR-WATER SYSTEM**  
**COUNTERCURRENT FLOW**

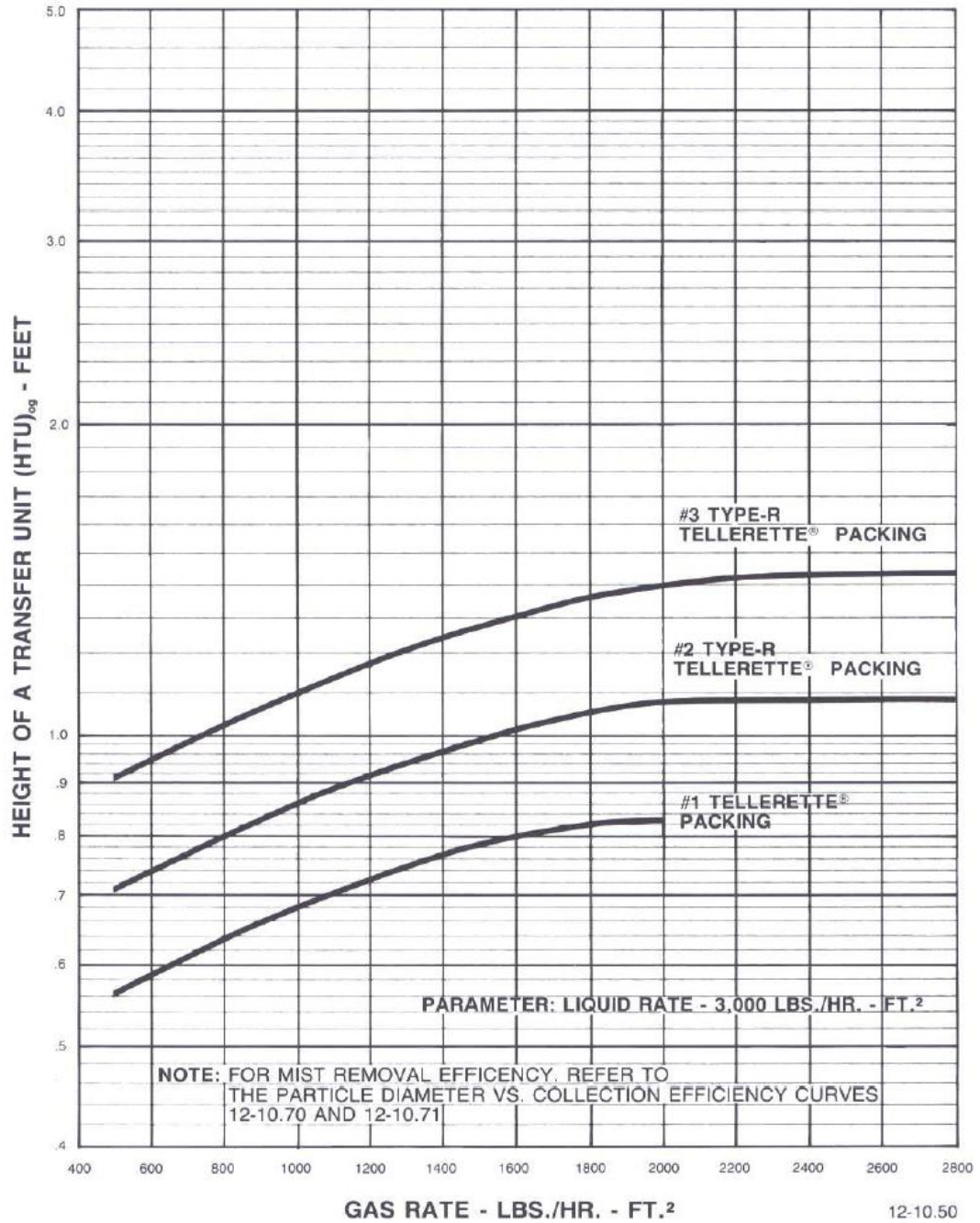


Figure 3.3 *HTU* of type-R Tellerette packing for counter current flow scrubber of gaseous hydrochloric acid-air-water system (Ceilcote Air Pollution Control 2005)



The abscissa of the curve (Figure 3.3) represents the gas rate of the scrubber operation. Consequently, the curve is read up from the calculated gas rate (2,342 lb/hr.ft) until it meets the curve of the #2 Type-R Tellerette packing. It is then read across to obtain the value of *HTU*. From the curve, the *HTU* is 329mm (1.08 ft) for the 11, 000 cfm counter current flow packed bed scrubber.

The *NTU* is determined from equation (3.19) since HCL is very soluble in water. Apart from that, the scrubber is designed to have outlet pollutant concentration of 50 ppm. The *NTU* is calculated by using equation (3.9) as shown below.

$$NTU = \ln \frac{1000}{50}$$

$$= 3.00$$

Packing depth is then determined from equation (3.14).

$$Z = 1.08 \text{ ft} \times 3.00$$

$$= 3.24 \text{ ft}$$

Therefore, it is recommended to use 1219.2mm (4 ft) of packing depth for the scrubber operation. From the table of contaminant for counter current flow packed bed scrubber as shown in Table 3.3, the efficiency of the scrubber based on 4 ft of packing depth is roughly in the range of 93% to 95%.

From Table 3.1, the emission of HCL for the 11, 000 cfm scrubber (new) is required to comply with standard C of hydrogen chloride which is 0.4g hydrogen chloride/ Nm<sup>3</sup>. The required outlet pollutant concentration is converted into ppm as shown in equation (3.25) below. Equation (3.25) is actually rearranged from equation (3.24) as an equation used for unit conversion.

Table 3.3 Table of contaminant for counter current flow packed bed scrubber in which the efficiency of scrubber is determined based on the designed packing depth (Ceilcote Air Pollution Control 2005) ( Refer Appendix C for additional description)

Contaminants	914.4mm (36")	1524mm (60")
	Packing Depth Removal Efficiency (%)	Packing Depth Removal Efficiency (%)
Acetic acid (CH <sub>3</sub> CO <sub>2</sub> H)	80-85	85-92
Acetone (CH <sub>3</sub> COCH <sub>3</sub> )	65	90
Aluminum Bright Dip	30-90	40-98
Amines (RNH <sub>2</sub> )	90-95	99+
Ammonia (NH <sub>3</sub> )	90-95	99+
Ammonium Hydroxide (NH <sub>4</sub> OH)	85-90	98-99
Ammonium Nitrate (NH <sub>4</sub> NO <sub>3</sub> )	85-90	98-99
Anodizing Solutions	85-90	98-99
Boric Acid (H <sub>3</sub> BO <sub>3</sub> )	80-90	95-98
Bromine (Br <sub>2</sub> )	90	97
Caustic (NaOH)	85-90	98-99
Chlorine (Cl <sub>2</sub> )	90	97
Chlorine Dioxide (ClO <sub>2</sub> )	50-60	70-85
Chromic Acid (H <sub>2</sub> CrO <sub>4</sub> )	85-95	99
Citric Acid	85-90	98-99
Cyanide Salts	85-90	98-99
Ethanol (CH <sub>3</sub> CH <sub>2</sub> OH)	80	93
Ethylene Oxide (ETO)	75	90
Formaldehyde (HCHO)	80-85	85-95
Formic Acid (HCO <sub>2</sub> H)	85-90	98-99
Hydrobromic Acid (HBr)	85-93	95-98
Hydrochloric Acid (HCL)	85-93	95-98
Hydrofluoric Acid (HF)	95	99

Table 3.3 Table of contaminant for counter current flow packed bed scrubber in which the efficiency of scrubber is determined based on the designed packing depth (Ceilcote Air Pollution Control 2005) (Refer Appendix C for additional description)

Contaminants	914.4mm (36")	1524mm (60")
	Packing Depth Removal Efficiency (%)	Packing Depth Removal Efficiency (%)
Hydrogen Cyanide (HCN)	90	97
Isopropanol	70	91-92
Mercaptans (RSH)	90	97
Methanol (CH <sub>3</sub> OH)	70	91-92
Methyl Sulfide	90	97
Nitric Acid (HNO <sub>3</sub> )	85-90	98-99
Nitrogen Oxides (NO <sub>x</sub> )	30-40	70
Oil Mists	85-90	95-98
Perchloric Acid	85-95	98-99
Phenol (C <sub>6</sub> H <sub>5</sub> OH)	80-90	90-95
Phosphate Salt Baths	85-90	98-99
Phosphoric Acid (H <sub>3</sub> PO <sub>4</sub> )	85-90	98-99
Silicon Tetrachloride (SiCl <sub>4</sub> )	85-93	95-98
Silicon Tetrafluoride (SiF <sub>4</sub> )	95	99
Sodium Chloride (NaCl)	85-90	98-99
Sodium Hydroxide (NaOH)	85-90	98-99
Sulfuric Acid (H <sub>2</sub> SO <sub>4</sub> )	85-90	98-99
Sulfur Dioxide (SO <sub>3</sub> )	85	95
Urea (H <sub>2</sub> NCONH <sub>2</sub> )	85-90	98-99
Hydrogen Sulfide (H <sub>2</sub> S)	90	97

$$\frac{mg}{Nm^3} = \frac{ppm \times MW}{22.4} \quad (3.24)$$

$$ppm = \frac{\left(\frac{mg}{Nm^3}\right) \times 22.4}{MW} \quad (3.25)$$

$$= \frac{\left(\frac{0.4 \times 10^3 mg}{Nm^3}\right) \times 22.4}{36.5g}$$

$$= 245 ppm$$

Where

MW = molecular weight of hydrochloric acid, 36.5g

Since the inlet and outlet pollutant concentrations are 1000 ppm and 245 ppm respectively, the required removal efficiency for hydrochloric acid according to the general emission standards can be calculated from question (3.5).

$$\eta = 1 - \left(\frac{245 ppm}{1000 ppm}\right)$$

$$= 0.755$$

$$= 75.5 \%$$

The required efficiency is 75.5%. As a result, the 11, 000 cfm of scrubber with 1219.2mm (4 ft) of packing depth is sufficient to fulfill the emission requirement by having removal efficiency in the range of 93% to 95% which is greater than the

required removal efficiency of 75.5 %. The designed packing depth is therefore satisfactory for the removal of hydrochloric acid.

### **3.6.2 Efficiency of Cross Flow Packed Bed Scrubber**

Assume a new cross flow packed bed scrubber which has similar specification with counter current flow packed bed scrubber as stated in section 3.6.1. Therefore, the cross flow packed bed scrubber is designed to have capacity of 11, 000cfm, a design cross sectional area of 20ft<sup>2</sup> in which the scrubber is used to scrub against hydrochloric acid. The inlet pollutant concentration is 1000ppm and the temperature at the gas inlet is 100°F. Water is used as the scrubbing liquid and the packing used is #2 type-R Tellerette packing.

For cross flow packed bed scrubber, the procedure of determining its efficiency is similar with the one for counter current flow packed bed scrubber by using the outlined procedure from section 3.6. In order to have a comparison in term of efficiency, the cross flow packed bed scrubber must have same constraints and assumptions as quoted for counter current packed bed scrubber. Thus, the cross flow packed bed scrubber has similar gas rate, liquid rate, *NTU*, *HTU* and definitely packing depth that designed for counter current flow packed bed scrubber in section 3.6.1.

Hence, the efficiency of the cross flow packed bed scrubber that designed with 1219.2mm (4 ft) of packing depth is determined from the table of contaminant for cross flow packed bed scrubber as shown in Table 3.4. From Table 3.4, the efficiency of the cross flow packed bed scrubber is in the range of 85% to 95% by having 4 ft of packing depth and it also greater than the required removal efficiency of 75.5 %. The designed packing depth is therefore adequate to fulfill the emission requirement.

Table 3.4 Table of contaminant for cross flow packed bed scrubber in which the efficiency of scrubber is determined based on the designed packing depth (Ceilcote Air Pollution Control 2005) (Refer Appendix C for additional description)

Contaminants	1219.2mm (48")	1828.8mm (72")
	Packing Depth Removal Efficiency (%)	Packing Depth Removal Efficiency (%)
Acetic acid (CH <sub>3</sub> CO <sub>2</sub> H)	80-85	85-92
Acetone (CH <sub>3</sub> COCH <sub>3</sub> )	65	90
Aluminum Bright Dip	30-90	40-98
Amines (RNH <sub>2</sub> )	90-95	99+
Ammonia (NH <sub>3</sub> )	90-95	99+
Ammonium Hydroxide (NH <sub>4</sub> OH)	98-99	99+
Ammonium Nitrate (NH <sub>4</sub> NO <sub>3</sub> )	85-90	98-99
Anodizing Solutions	98-99	99+
Boric Acid (H <sub>3</sub> BO <sub>3</sub> )	80-90	95-98
Bromine (Br <sub>2</sub> )	95	97-99
Caustic (NaOH)	98-99	99+
Chlorine (Cl <sub>2</sub> )	95	97-99
Chromic Acid (H <sub>2</sub> CrO <sub>4</sub> )	98-99	99+
Citric Acid	98-99	99+
Cyanide Salts	98-99	99+
Formaldehyde (HCHO)	80-85	85-95
Formic Acid (HCO <sub>2</sub> H)	85-90	98-99
Hydrobromic Acid (HBr)	85-95	98-99
Hydrochloric Acid (HCL)	85-95	98-99
Hydrofluoric Acid (HF)	95	99
Hydrogen Cyanide (HCN)	90-95	97-99
Mercaptans (RSH)	95	98-99
Methyl Sulfide	90	97

Table 3.4 Table of contaminant for cross flow packed bed scrubber in which the efficiency of scrubber is determined based on the designed packing depth (Ceilcote Air Pollution Control 2005) (Refer Appendix C for additional description)

Contaminants	1219.2mm (48")	1828.8mm (72")
	Packing Depth Removal Efficiency (%)	Packing Depth Removal Efficiency (%)
Nitric Acid (HNO <sub>3</sub> )	85-90	98-99
Nitrogen Oxides (NO <sub>x</sub> )	30-40	70+
Oil Mists	85-90	98-99
Perchloric Acid	85-95	98-99
Phenol (C <sub>6</sub> H <sub>5</sub> OH)	80-90	90-95
Phosphate Salt Baths	98-99	99+
Phosphoric Acid (H <sub>3</sub> PO <sub>4</sub> )	98-99	99+
Silicon Tetrachloride (SiCl <sub>4</sub> )	90-95	98-99
Silicon Tetrafluoride (SiF <sub>4</sub> )	95	99
Sodium Chloride (NaCl)	98-99	99+
Sodium Hydroxide (NaOH)	98-99	99+
Sulfuric Acid (H <sub>2</sub> SO <sub>4</sub> )	98-99	99+
Sulfur Dioxide (SO <sub>3</sub> )	90	98
Urea (H <sub>2</sub> NCONH <sub>2</sub> )	85-90	98-99
Hydrogen Sulfide (H <sub>2</sub> S)	95	98-99

## Chapter 4

### Results and Discussion

#### 4.1 Introduction

A survey was also done for this project to gain information regarding cross flow and counter current flow packed bed scrubber from related field of local consultants and DOE officer in Penang. The survey concerned with practical information of the current operating packed bed scrubber systems in Penang which is useful for comparing the efficiency of cross flow and counter current flow packed bed scrubber in real situation. A questionnaire for the survey is attached at Appendix E.

In this chapter, the results obtained from the example of empirical approach and survey are discussed and compared in terms of scrubber design, DOE requirements, packing depth, scrubbing liquid, impaction of liquid to the gas streams, space constraint, etc. The results from the survey are also included. Furthermore, the appropriateness of each flow configuration in term of their applications and constraints are analyzed.

Generally, the estimation of scrubber efficiency is subjected to the available data and literature according to the survey. The empirical approach is considered to be easier and cheaper. It is commonly used in Penang and acceptable by DOE Penang. To ensure safety, a safety factor is usually included in the design of packed bed scrubber system. In addition, the design of packed bed scrubber system is also compared with past or current operating system to guarantee its practicability of operation.



## 4.2 Scrubber Design

As previously noted, counter current flow arrangement has a vertical profile as compared to the horizontal profile of cross flow arrangement. The dissimilarity of arrangement between them causes a potential difference in their efficiencies.

In term of scrubber design, cross flow arrangement is possible to give lower efficiency due to its horizontal profile. Cross flow arrangement has a limitation in which some portions of the gas streams that enter the packed bed tends to flow from the packed bed to the location of nozzles. These portions of gas streams are also having tendency to flow through the intermediate spaces between the bottom packed bed and the sump. Due to absence of packing at this location (as indicated in Figure 2.8), the gaseous pollutants in the gas streams have insufficient residence time to be absorbed by the liquid. It results improper scrubbing process at these locations. Consequently, these portions of the gas streams flow through the mist eliminator and then enter the exhaust stack. Excess emission is therefore resulted. It is believed that this kind of situation is causing a drop of efficiency for the cross flow arrangement.

Counter current flow arrangement shows ideal design in which the gas streams enter the scrubber are fully encountered by the liquid which is supplied from the top of the packed bed. With this arrangement, there is no opportunity for any portion of the gas streams to flow away from scrubbing. Thus, counter current flow arrangement encourages greater mixing between the gaseous pollutants and liquid. As a consequence of this, counter current flow arrangement is desirable to give higher efficiency than cross flow arrangement.

Additionally, counter current flow arrangement is able to allocate more concentration gradients for gas and liquid. As compared to cross flow design, counter current flow design provides better pollutant removal in term of concentration gradients. Since the liquid supply is at the top of packed bed where the gas streams exit and therefore freshest air is being supplied to the gas streams as the gas streams move upwards.

The opposite direction of flow between gas and liquid in counter current flow arrangement also provides impact of the scrubbing liquid and gas. Subsequently, the impaction allows the pollutant to be easily collected by the scrubbing liquid and thus enhancing the pollutant removal.

For a scrubber to have good performance, uniform distributions of gas and liquid are essential. For example, the gas and liquid must be evenly distributed across the packing area. Cross flow arrangement shows uneven flow of gas streams since some portions of the gas tend to flow to the location of nozzles and intermediate spaces between the sump and the bottom packed bed. From this phenomenon, the gas streams are considered to flow through the path of least resistance. As a consequence of this, the performance of the cross flow packed bed scrubber is also considered to be affected by the uneven flow of gas.

Hence, a packed bed scrubber which is designed in counter current flow arrangement is able to provide higher efficiency as compared to cross flow packed bed scrubber, in term of scrubber design.

### **4.3 DOE Requirements**

In Penang, cross flow packed bed scrubber applies the same design requirements that placed for counter current flow packed bed scrubber since both of these scrubber designs apply the same concept and principle during operation. According to the survey, they are designed with similar associated equipment such as fan, pump, mist eliminator, pH controller, flow meter, metering dosing, pressure gauge, level sensor and so on completing the scrubbing process. The significant difference between them is their profile (i.e. horizontal or vertical).

Practically, they are having similar factors affecting the scrubber efficiency. Attention needs to be drawn for several factors such as liquid to gas ratio, type of packing, operating temperature, packing depth and superficial gas velocity across the scrubber which are the important factors that affecting the scrubber efficiency.

Apart from that, the general emission standard (Table 3.1) is given within a small range of pollutants. DOE insists the threshold limit values for chemical substances in the work environment adopted by American Conference of Government Industrial Hygienists (ACGIH) should be referred for pollutants which are not included in Table 3.1.

According to DOE Penang, most of the existing packed bed scrubbers in Penang were designed in counter current flow arrangement because of its possibility to give higher efficiency as compared to cross flow design. Cross flow arrangement is desirable when space is restricted for installation of counter current flow arrangement. For example, limited ceiling height is a factor. The profile of scrubber is usually decided by engineers based on site installation, applicant requirements or decision as well as other miscellaneous factors affecting the scrubber design.

#### **4.4 Type of Packing**

In present, there is a variety of packing available which are designed to optimize the efficiency of packed bed scrubber by using lesser packing depth. Each type of packing is designed with different geometry, dissimilar preferential flow direction, different sizes and made from a range of material. Normally, packing is designed to provide contacting areas between liquid and gas, promote uniform of liquid distribution and gas flow, have low resistance to gas flow, etc.

In fact, the scrubber efficiency depends on the type of packing used. The efficiency of mass transfer is dependent on the ability of packing to provide more contacting surface areas for liquid and gas. Normally, a high interfacial area between the gas and liquid created by packing facilitates the absorption process for fume removal. Therefore, different geometry of packing provides different mass transfer efficiency for packed bed scrubber system.

In some circumstances, both cross flow and counter current flow packed bed scrubbers would have same efficiency by using similar types of packing. This would be most probably caused by some packing that would have preferential flow

direction in vertical or horizontal, and subsequently they would behave differently in either cross flow or counter current flow configurations.

Nowadays in Penang, the type of packing used are frequently made from plastic or polypropylene because of its characteristics of light weight and high corrosion resistance. Since it has light weight, it can be easily dumped into the scrubber to take up a random arrangement. The plastic packing has a disadvantage in which it is prohibited to be used under high operating temperature.

There are mass transfer efficiency data as shown at Appendix D for a few types of packing. The data include properties of the packing, packing material, packing performance comparison among Tri-pack, Lanpac and Tellerette, etc. From the data, the mass transfer efficiency is dependent on a parameter known as *HTU*. For a particular pollutant-solvent system, the *HTU* is plotted versus liquid rate or gas rate. There are *HTU* curves plotted for a range of packing in which their mass transfer efficiencies are comparable for a particular pollutant solvent system. Based on the curves, a packing which provides low *HTU* is interpreted to be more efficient than others for a pollutant-solvent system since lesser packing depth will be required to achieve the required efficiency. The intention of developing this comparable information regarding packing is to allow engineers to choose an appropriate type of packing for a packed bed scrubber system.

Hence, packing is necessary to be carefully selected for a pollutant solvent system to effectively achieve the required removal efficiency and save for operating cost. Packing is also normally selected for packed bed scrubber system based on engineers' experience, its cost, the nature of fluids and operating temperature of a system according to the survey.

In Penang, Tellerette packing, Lanpac packing, Tri-packs and pall ring are commonly filled into cross flow and counter current flow packed bed scrubber as the contact media for gas and liquid. From the survey, the type of packing used in the scrubber has significant effect on the scrubber efficiency.

#### 4.5 Packing Size

Packing size also influences mass transfer rate. As shown in Figure 3.3, there are *HTU* curves for #1, #2 and #3 type-R Tellerette packing. The #2 type-R Tellerette packing used in the example of empirical approach (sections 3.6.1 and 3.6.2) has maximum outer diameter of 69.85mm (2.75 inches). #1 and #3 Type-R Tellerette packing have maximum outer diameter of 45.97mm (1.81 inches) and 95.25mm (3.75 inches) respectively.

Normally, the selection of packing size is important to ensure an efficient absorption process in which the packing size should be selected based on the size of scrubber shell. For scrubbers which have smaller shell, it is inadvisable to use large size of packing since it will result non-uniform liquid distribution. Therefore, it is suggested to reasonably use small size of packing for small scrubber shell. For example, #1 type-R packing can be applied in small scrubber shell to facilitate liquid distribution and thus enhancing the gas absorption.

Based on same gas rate, #3 type-R Tellerette packing provides greater *HTU* as compared to #1 and #2 type-R Tellerette packing as shown in Figure 3.3. Hence, the #3 type-R packing will provide greater packing when same *NTU* is applied as compared to #1 and #2 for a scrubber system. The range of *HTU* for the #1 type-R packing is limited for maximum gas rate of 2000 lb/hr. ft as shown in Figure 3.3. Hence, #1 type-R packing is considered to be suitable to be applied in scrubber having small capacity (i.e. small shell). The choice of packing size is usually dependent on engineers' experiences.

#### 4.6 Packing Depth

From the example of empirical approach (sections 3.6.1 and 3.6.2), the maximum efficiency that can be achieved by counter current flow and cross flow arrangements is 95% by having 1210mm (4 ft) of Tellerette packing. For cross flow arrangement, the efficiency dropped within the range of 85 % to 95 % whereas the range of efficiency for counter current flow was roughly between 93% and 95% for the example. Averagely, counter current flow arrangement is able to achieve efficiency

of 94% whereas cross flow arrangement is able to have efficiency of about 90%. Therefore, it is comparable that counter current flow arrangement is capable of having higher efficiency than cross flow arrangement by using Tellerette packing for the example.

With reference to Table 3.3 and 3.4, comparison between tables of contaminant from Ceilcote Air Pollution Control shows that cross flow arrangement is significant to have lower efficiency than counter current flow arrangement for same pollutant removal by using similar depth of Tellerette packing. For example, a counter current flow packed bed scrubber which is designed to have 1524mm (60 inches) of packing depth is estimated to have removal efficiency in between 85% and 92% for removal of acetic acid. For cross flow configuration, it needs 1828.8mm (72 inches) of packing depth in order to achieve equivalent efficiency that achieved by the counter current flow arrangement.

Therefore, scrubber which is designed in cross flow arrangement needs greater Tellerette packing depth as compared to counter current flow arrangement to achieve the equivalent efficiency for pollutant removal. From the example concerning the acetic acid, the efficiency of cross flow arrangement is increased by providing additional packing depth of 304.8mm (12 inches). As a consequence of this, it is showing that efficiency increases as the packing depth is increased.

From the survey, cross flow and counter current flow designs are able to achieve equivalent efficiency by using similar depth of Lanpac packing. This shows that Lanpac packing is capable of allowing uniform distribution of gas in horizontal direction as compared to Tellerette packing for pollutant removal. As a consequence of this, cross flow arrangement has ability to achieve the equivalent efficiency that achieved by counter current flow arrangement, it depends on the type of packing used. According to the survey, cross flow arrangement is observed to be unable to achieve higher efficiency than counter current flow arrangement by using similar packing depth and type of packing. Cross flow arrangement has possibility to achieve equivalent efficiency that can be achieved by counter current flow arrangement only.

Usually for a packed bed that constituted by packing that has high mass transfer capability, a lesser packing depth is required to achieve the equivalent efficiency as compared to a packed bed that composed by packing which has lower mass transfer capability.

#### 4.7 Scrubbing Liquid

Water is the scrubbing liquid for the example of empirical approach (sections 3.6.1 and 3.6.2) to scrub against the hydrochloric acid. Chemical such as sodium hydroxide (caustic solution) is an alternative choice of scrubbing liquid to scrub against the hydrochloric acid. Since sodium hydroxide is an alkaline, it can react with hydrochloric acid to form salt and water. From the survey, the use of chemical can improve the scrubber efficiency as compared to water due to chemical reaction or neutralization. The time required for chemical absorption is usually rapid as compare to physical absorption since chemical reaction is immediate. Therefore, chemical can be used to further enhance the removal efficiency of packed bed scrubber.

For the example of empirical approach (sections 3.6.1 and 3.6.2), both of the cross flow and counter current flow configurations can use sodium hydroxide to further enhance the scrubbing process. From an economic point of view, water is ideal for the example since the efficiencies of these flow arrangements are sufficiently fulfilling the emission requirement. Therefore, sodium hydroxide is unlikely to be taken as the scrubbing liquid for the example of empirical approach in order to save for the operating cost of the scrubber system. Consequently, water is always the common choice of scrubbing liquid and chemical is usually needed for difficult gas separation. According to the survey, the choice of scrubbing liquid is dependent on the nature of the pollutant, the solubility of the pollutant and cost.

For the example of the empirical approach, sodium hydroxide can be used to scrub against the hydrochloric acid in cross flow arrangement to increase its efficiency since the neutralization process aids the pollutant removal of the packed bed wet scrubber. The survey also showed that chemicals such as caustic solution and

sulphuric acid are commonly used for packed bed scrubber in Penang both for cross flow and counter current flow arrangements in certain pollutant-solvent system.

#### 4.8 Space Constraint

Space constraint at site is a factor affecting the decision of selecting scrubber designs. Apart from that, the design can be a decision of a customer in which a counter current flow arrangement or cross flow arrangement could be inappropriate to be installed in a process plant which has further development in the future.

In practice, space constraints such as floor area, height limitation and others are usually determining the design of a packed bed scrubber. For instance, height limitation dictates use of a cross flow packed bed scrubber although counter current flow arrangement is found to be more efficient for a pollutant solvent system. When a cross flow packed bed scrubber is applied with a difficult gas separation under this situation, chemical can be utilized as the scrubbing liquid or greater packing depth can be provided for the cross flow packed bed scrubber. By doing this, the cross flow packed bed scrubber is capable of achieving the required efficiency or improves its scrubbing efficiency for the difficult gas separation. However, the cross flow scrubber will be involving high operating cost for the gas separation.

For a site which has small footprint, it is wise to use the design of counter current flow which is a more efficient design as compared to cross flow configuration. Furthermore, more floor area is required for cross flow arrangement. Therefore, counter current flow design is ideal for a site which has small footprint.

Hence, space constraint at site must be taken into consideration to obtain a practical design of scrubber.



#### 4.9 Application and Capacity

According to the survey, cross flow and counter current flow packed bed scrubber can be used in any industries, particularly for gaseous pollutant removal. In most circumstances, counter current flow packed bed scrubber is mostly used in industries and it is applicable for a wide range of gaseous pollutants. It is very useful to remove high concentration of gaseous pollutant but restricted to high loading of solid particles due to plugging problem. To reduce the plugging problem, proper packing such as Tellerette packing which has better removal for particulate matter can be used.

For cross flow packed bed scrubber, it is relevant to be applied for high soluble gases since it has short residence time and less efficient for fume removal, as compared to counter current flow arrangement. It is also appropriate to use cross flow arrangement for process air streams which has low concentration of pollutant. By doing this, it is capable for cross flow arrangement to achieve the required removal efficiency for a particular pollutant removal. From the survey, cross flow packed bed scrubber has greater solid particles handling capacity as compared to counter current flow packed bed scrubber. Hence, cross flow design is also ideal for process air streams which have greater but acceptable level content of solid particles or dust for scrubbing.

According to the survey, packed bed scrubber can be designed in any capacity and it depends on customer requirements. Commonly, both of the cross flow and counter current flow packed bed scrubber can have capacity in the range of 1000cfm to 100 000cfm.

#### 4.10 Orientation

The orientation of the counter current flow and cross flow scrubber in terms of packed bed, mist eliminator, integral sump, gas inlet and gas outlet as indicated in Figure 2.7 and 2.8 are ideal. Care must be taken to locate view ports, pump and piping for the liquid recirculation system.

A view port should be placed on the scrubber shell so that packing that located inside the scrubber can be clearly viewed from outside. This is to make sure that maintenance can be provided once the packing is notified to be under corrosion. The view port is also used to inspect the operating condition of the nozzles in order to make sure that they are unplugged by solid particles. Normally, a scrubber should have at least two view ports where one of them is placed to inspect the nozzles and another one is used to check the corrosion level undertaken by the packing. Sometimes, three view ports will be placed for a scrubber. The number of view port is actually decided based on the size or capacity of packed bed scrubber.

The locations of piping system and pump are dependent on each other in which they are placed near to the integral sump. It is important to prevent the location of the piping for the liquid recirculation system from blocking the view ports. Otherwise, the operating condition of the packing and the nozzles will be invisible in a good manner. This will affect the maintenance job.

For most of the packed bed scrubbers in Penang, fan is usually located after the scrubber to ventilate the gas streams. This negative fan is always subjected to corrosion problem and has tendency of solid build up. Therefore, fan which made from FRP material is usually used for packed bed scrubbers in Penang to overcome the problem of corrosion. Maintenance and inspection are also given to prevent solid build up which may damage the blades of the fan.

## Chapter 5

### Conclusion and Recommendation

#### 5.1 Conclusion

From the results and discussion, the objective of the project which aims to study and compare the efficiency of cross flow and counter current flow packed bed wet scrubber is achieved. It is concluded that cross flow packed bed scrubber is less efficient than counter current flow packed bed scrubber. Counter current flow arrangement is potential to give higher efficiency and it is ideally chosen to effectively limit the discharge of pollutants. Factors affecting the scrubber efficiency should be considered in the design stage to ensure an efficient scrubber operation. Beside that, maintenance has to be planned and provided consistently to the scrubber to ensure long lasting of the scrubber operation without deficiency.

It is also concluded that the design of packed bed wet scrubber system requires expertise and experience of professional bodies. For a detailed or specific design, consultation with the manufacturer of packed bed wet scrubber is an essential step. Furthermore, design information for cross flow arrangement is limited. In general, cross flow design depends on design information available for counter current flow design.

The survey is constraint by a few participants due to limited number of consultant of packed bed scrubber in Penang. Therefore, information surveyed for this project is sufficient for general reference or discussion towards the understanding of packed bed scrubber system for counter current flow and cross flow designs. It is also hoped that this project can be introduced as an idea for other researchers to work out comprehensive studies for the packed bed wet scrubber, especially for the cross flow design. Finally, recommendation of new design requirements concerning the packed bed scrubber for DOE is excluded in this project due to time constraint.

## 5.2 Recommendation for Improving Scrubber Performance

Scrubber performance could be improved by several ways. The suggestions include elimination of liquid recirculation system, provision of additional packing depth, provision of multiple packed beds and the use of structured packing.

A packed bed scrubber can have better performance by providing greater packing depth to the scrubber. From the results and discussion, scrubber efficiency increases as the packing depth is increased. Additional packing promotes absorption rate since it creates more gas liquid contacting surface. Normally, it is suffice to design a packing depth which has met the required removal efficiency for a particular pollutant. To ensure a scrubber capable of having higher efficiency, the scrubber is suggested to have greater depth of packing to effectively reduce the gas emission.

Most of the counter current flow packed bed scrubbers in Penang are designed to have single packed bed as shown in Figure 2.7. Thus, packed bed scrubber is suggested to be designed with multiple packed beds and assembled with liquid redistributors at the intermediate spaces between packed beds. For instance, a packed bed with 4 ft depth can be replaced by two packed beds each with 2 ft. A liquid redistributor is placed at the intermediate of the packed beds to distribute liquid that flow from the top packed bed. This will help to overcome the plugging problem and ensure that the packing is absolutely wetted by having uniform flow of liquid supply. This is able to improve the performance of the counter current flow packed bed scrubber.

Liquid with absorbed pollutants are kept in the integral sump for neutralization before it is supplied again to the scrubber. The recycled liquid is important to be maintained at proper pH for an efficient scrubbing process. As a consequence of this, the liquid recirculation system is suggested to be removed from the packed bed scrubber system when water is used as the scrubbing liquid. Water is inexpensive and readily available. Non-recycled scrubbing liquid is suggested to be continuously supplied to the scrubber. It is recommended that liquid with absorbed pollutant in the integral sump is channeled to a waste water treatment plant. By doing this, the recycled liquid with pollutants (which may result from improper neutralization) is

prevented from entering the scrubber. Thus, scrubber performance could be improved by supply scrubbing liquid which is completely free from pollutant.

Packing is usually dumped into the packed bed scrubber up to certain depth to take up a random arrangement. Structured packing is recommended to be applied in the packed bed scrubber instead of using random packing especially for difficult gas separation to improve the scrubber performance. Structured packing consists of packing which made up from wire mesh. The material is arranged with regular geometry and therefore results a high surface area for gas absorption. Hence, structured packing has potential to improve the performance of scrubber.

### **5.3 Recommendation for Future Work**

The associated design of packed bed wet scrubber has three flow arrangements, namely cross flow, counter current flow and concurrent flow. In general, most discussions are based on cross flow and counter current flow arrangements. Therefore, future study can be done on concurrent flow arrangement and compare it to cross flow and counter current flow arrangements theoretically and empirically.

Nowadays, there is software available to design the packed bed scrubber. For example, tower internal guide and selection software program and packed tower design program (Norton 1996). Thus, future study can also be done by using these programs which believed that more precise design information can be learned for the packed bed wet scrubber system.

Application for a project from local consultants of packed bed scrubber is also can be done in the future. Participation in a project concerning packed bed scrubber is able to learn about the technical paper work, costing, etc considered in the design stage, fabrication of scrubber, construction work and installation of packed bed scrubber in a process plant, and so on. Therefore, many aspects of packed bed scrubber system can be studied by involving this sort of project.

## References

- Alley, E. Robert and Associate, Inc. 1998, *Air Quality Control Handbook*, McGraw-Hill, Inc.
- Barbour, Wiley, Oommen, Roy, Shareef, Gunseli Sagun & Vatauvuk, William M. 1995, *Wet Scrubber for Acid Gas*, U.S. Environmental Protection Agency
- Bond, Richard G., M.S., M. P. H., Straub, Conrad P., Ph. D & Prober, Richard, Ph. D 1972, *Handbook of Environmental Control, Volume 1: Air Pollution*, CRC Press, Chemical Rubber Co.
- Brown, Charles A., Jr. & Schnelle, Karl B. 2002, *Air Pollution Technology Handbook*, CRC Press LLC
- Buonicore, Anthony J. & Theodore, Louis 1982, *Air Pollution Control Equipment Selection, Design, Operation and Maintenance*, Prentice Hall, Inc., Englewood Cliffs, New Jersey
- Ceilcote Air Pollution Control 2005, *Standard and Custom Designed Countercurrent Packed Scrubbers (SPT Series)*, Air Cure Dynamics, Inc, viewed 15 March 2005, <<http://www.ceilcoteapc.com/literature/12-2.pdf>>
- Ceilcote Air Pollution Control 2005, *Standard and Custom Designed Crossflow Packed Scrubbers (HRP Series)*, Air Cure Dynamics, Inc, viewed 15 March 2005, <<http://www.ceilcoteapc.com/literature/12-4.pdf>>
- Ceilcote Air Pollution Control 2005, *Tellerette Tower Packings A Significant Advance in Mass Transfer Technology*, Air Cure Dynamics, Inc, viewed 15 March 2005, <<http://www.ceilcoteapc.com/literature/12-20.pdf>>

Comnesso, Stephen A., n.d., *Odor Control Issue at Fertilizer Plant*, O'Brien & Gere Engineers, Inc, viewed 15 March 2005,  
<<http://www.obg.com/infocenter/articles/odor-paper.pdf>>

Committee on Industrial Ventilation 1995, *Industrial Ventilation A Manual of Recommended Practice*, 22<sup>nd</sup> Ed., American Conference of Governmental Industrial Hygienists, Inc.

Crawford, Martin 1976, *Air Pollution Control Theory*, McGraw-Hill, Inc.

Croll-Reynolds 1990, *Selecting Material for Wet Scrubbing Systems*, Croll-Reynolds Co. Inc, viewed 15 March 2005,  
<[http://www.croll.com/\\_website/ca/techlib2.asp](http://www.croll.com/_website/ca/techlib2.asp)>

Davis, Wayne T. 1999, *Air Pollution Engineering Manual*, 2<sup>nd</sup> Ed., John Wiley and Sons, Inc.

Duncan, Joseph & Noll, Kenneth 1973, *Industrial Air Pollution Control*, Ann Arbor Science Publisher Inc.

Fthenakis, Vasilis M. 1996, *Cross-Flow Versus Counter-Current Flow Packed-Bed Scrubbers: A Mathematical Analysis*, Brookhaven National Laboratory, viewed 1 April 2005,  
<<http://www.osti.gov/servlets/purl/244411NvrDUU/webviewable>>

Hankinson, Kenneth C. 1928, *PF Online Feature Article: Scrubber Technology: An Update*, Gardner Publication, Inc, viewed 15 March 2005,  
<<http://www.pfonline.com/articles/029706.html>>

Heumann, William L. 1997, *Industrial Air Pollution Control Systems*, McGraw-Hill, Inc.

ICAC members, n.d., *ICAC Control Technology Descriptions*, ICAC, viewed 15 March 2005, <<http://www.icac.com/controls.html>>

Jaeger Products 1996, *Scrubbing Pollutant from Vent Streams*, Jaeger Product, Inc, Houston, Texas, viewed 15 March 2005,

<<http://www.jaeger.com/Brochure/gas%20scrubbing.pdf>>

Joseph, Gerald T., P.E. & Beachler, David S. 1998, *Scrubber System Operation Review*, 2<sup>nd</sup> Ed., North Carolina State University.

Kinematics 2002, *Product Profile*, Kinematics, viewed 15 March 2005,

<[http://www.trikinematics.com/p\\_profile1.html](http://www.trikinematics.com/p_profile1.html)>

Lee, C.C., & Shun Dar Lin 1999, *Handbook of Environmental Engineering Calculations*, McGraw-Hill, Inc.

Legal Research Board 1996, *Environmental Quality Act 1974 (Act127) & Subsidiary Legislations*, Member of the Malaysian Book Publishers Association

Marchello, J. M. 1996, *Control of Air Pollution Sources*, Marcel Dekker, Inc., New York & Basel

Mckenna, John D., Mycock, John C. & Theodore, Louis 1995, *Handbook of Air Pollution Control Engineering and Technology*, CRC Press, Inc.

Monroe Environmental 2002, *Monroe Horizontal Packed Bed Air/Gas Scrubber*, Monroe Environmental Corporation, viewed 15 March 2005,

<[http://www.monroenvironmental.com/PDF/ME\\_Horizontal\\_Packed\\_Bed.pdf](http://www.monroenvironmental.com/PDF/ME_Horizontal_Packed_Bed.pdf)>

Monroe Environmental 2002, *Monroe Vertical Packed Bed Air/Gas Scrubber*, Monroe Environmental Corporation, viewed 15 March 2005,

<[http://www.monroenvironmental.com/PDF/ME\\_Vert\\_Pack\\_Bed.pdf](http://www.monroenvironmental.com/PDF/ME_Vert_Pack_Bed.pdf)>



- Norton Chemical Process Products Corporation 1996, *IMTP High-Performance Random Packing*, Norton Chemical Process Products Corporation, viewed 26 July 2005,  
<[http://www.venus.rdc.pucrio.br/jacquesn/opll/complementar/rech\\_rand\\_NO RTON.pdf](http://www.venus.rdc.pucrio.br/jacquesn/opll/complementar/rech_rand_NO RTON.pdf)>
- Parker, Albert 1977, *Industrial Air Pollution Handbook*, McGraw-Hill Book Company (UK) Limited
- Pedersen, George C. 2001, *The State of the Art in Gas Cleaning for the Fertilizer Industry*, Kimre, Inc, viewed 15 March 2005,  
<<http://kimre.com/publications/afa2001.pdf>>
- Perry, Robert H. & Green, Don W. 1984, *Perry's Chemical Engineers' Handbook*, 6<sup>th</sup> Ed., McGraw-Hill, Inc.
- Sincero, Arcadio P. & Sincero, Gregoria A. 1996, *Environmental Engineering (A Design Approach)*, Prentice Hall, Inc.
- Stone, J. Neil 1998, *Fume Control and Scrubbing on Hydrochloric Acid Pickle Lines*, Cheresources, viewed 15 March 2005,  
<<http://cheresources.com/hclpiklezz.shtml>>
- U.S. Environmental Protection Agency, n.d., *Air Pollution Control Technology Fact Sheet*, EPA-452/F-03-015, viewed 15 March 2005,  
<<http://www.epa.gov/ttn/catc/dir1/fthermal.pdf>>

## Appendix A

### Project Specification

University of Southern Queensland

FACULTY OF ENGINEERING AND SURVEYING

**ENG 4111/4112 Research Project**  
**PROJECT SPECIFICATION**

**FOR: YAP LEE JIUAN**

**TOPIC: DESIGN OF WET SCRUBBER SYSTEMS**

**SUPERVISORS: Dr. Fok Sai Cheong (USQ)  
Mr. Teh Chee Seng**

**ENROLMENT: ENG 4111 – S1, X, 2005  
ENG 4112 – S2, X, 2005**

**PROJECT AIM:** This project aims to study and compare the efficiencies between the cross flow packed bed scrubber and the counter current vertical packed bed scrubber used in Penang, Malaysia.

**PROGRAMME: Issue A, 7 March 2005**

1. Literatures review of the packed bed wet scrubber system as an air pollution control device, including a theoretically study on the cross flow and the counter current vertical packed bed wet scrubber systems, their working mechanisms and the working principles
2. Investigate the Department of Environment (Penang) design requirements for these industry scrubber systems
3. Determine the factors influencing scrubber efficiencies. Gather relevant data and charts needed for the efficiency calculation
4. Find and compare the efficiencies of the cross flow and the counter current vertical packed bed wet scrubber systems, based on similar capacities and constraints
5. Analyze the results and identify their appropriateness in term of applications, orientations, constraints, etc. Recommend suggestions to improve their performances.

As time permits:

6. Recommend new design requirements for the Department of Environment (Penang)

**AGREED:**

\_\_\_\_\_ (Student) \_\_\_\_\_, \_\_\_\_\_ (Supervisors)

\_\_ / \_\_ / \_\_

\_\_ / \_\_ / \_\_

\_\_ / \_\_ / \_\_

## Appendix B

### #2 Type-R Tellerette Packing Characteristic

## Appendix B

### Physical data, physical description and mechanical properties for type-R Tellerette Packing (Ceilcote Air Pollution Control 2005)

#### Physical data.

Tellerette packing is available in a wide range of thermoplastic materials to meet varying service conditions. Thermoplastics withstand operating temperatures up to 300°F (149°C) and provide excellent corrosion resistance.

Thermoplastic materials are also lightweight, which can further reduce structural costs. Smaller columns can be fabricated from lighter-weight, corrosion-resistant FRP. Lower cost "open" support plates replace complex cap-type plates. Together, the physical properties of Tellerette packing contribute to reduced operating costs.

#### Physical Description.

Size	Maximum Dimensions OD	"Loop" Height	Number Pieces/Ft. <sup>2</sup>	Free Volume (%)	Surface Ft. <sup>2</sup> /Ft. <sup>3</sup>
No. 1	1.81"	0.75"	1000	87	55
No. 2 Type-R	2.75"	1.00"	275	93	38
No. 3 Type-R	3.75"	1.50"	102	92	30
No. 2 Type-K	3.25"	1.25"	165	95	28

#### Mechanical Properties.

Property	P/P	PVC	CPVC	XYDAP*
Operating Temp.	200°F	140°F	200°F	400°F
Tellerette Size	No. 1	No. 1	No. 1	—
	No. 2R	No. 2R	No. 2R	No. 2R
	No. 3R	—	—	—
	No. 2K	No. 2K	No. 2K	No. 2K
Lbs./Ft. <sup>3</sup>	5.5	9.0	9.85	—
	3.8	6.2	6.8	7.2
	4.7	—	—	—
	2.8	4.6	5.0	5.3

Tellerette packing is also available in other engineered thermoplastics.

\*Registered trademark, Dart Industries Inc.

\*\*Registered trademark, Jaeger Tri-Packs, Inc.

## Appendix C

### Tables of Contaminant

- C.1 Table of contaminant of counter current flow packed bed scrubber in which the efficiency of scrubber is determined based on the designed packing depth (Ceilcote Air Pollution Control 2005)
  
- C.2 Table of contaminant of cross flow packed bed scrubber in which the efficiency of scrubber is determined based on the designed packing depth (Ceilcote Air Pollution Control 2005)

C.1 Table of contaminant of counter current flow packed bed scrubber in which the efficiency of scrubber is determined based on the designed packing depth (Ceilcote Air Pollution Control 2005)

Contaminants	Type (See Note A)	SPT 36" packing depth (Low Efficiency) % Removal	SPT 60" packing depth (Medium Efficiency) % Removal	SPT 120" packing depth (High Efficiency) % Removal
Acetic Acid (CH <sub>3</sub> CO <sub>2</sub> H)	G&L	80-85	85-92	98-99
<sup>5</sup> Acetone (CH <sub>3</sub> COCH <sub>3</sub> )	G	65	90	97
<sup>3</sup> Aluminum Bright Dip	G&L	30-90	40-98	40-99
<sup>2</sup> Amines (RNH <sub>2</sub> )	G	90-95	99+	99.9+
<sup>2</sup> Ammonia (NH <sub>3</sub> )	G	90-95	99+	99.9+
Ammonium Hydroxide (NH <sub>4</sub> OH)	L	85-90	98-99	99+
Ammonium Nitrate (NH <sub>4</sub> NO <sub>3</sub> )	S	85-90	98-99	99+
Anodizing Solutions	L	85-90	98-99	99+
Boric Acid (H <sub>3</sub> BO <sub>3</sub> )	L	80-90	95-98	99+
<sup>1</sup> Bromine (Br <sub>2</sub> )	G	90	97	99.95
Caustic (NaOH)	L	85-90	98-99	99+
<sup>1</sup> Chlorine (Cl <sub>2</sub> )	G	90	97	99.95
<sup>3</sup> Chlorine Dioxide (ClO <sub>2</sub> )	G	50-60	70-85	95
Chromic Acid (H <sub>2</sub> CrO <sub>4</sub> )	L	85-95	99	99+
Citric Acid	L	85-90	98-99	99+
Cyanide Salts	L	85-90	98-99	99+
<sup>6</sup> Ethanol (CH <sub>3</sub> CH <sub>2</sub> OH)	G & L	80	93	99.5
<sup>3</sup> Ethylene Oxide (ETO)	G	75	90	99
<sup>1</sup> Formaldehyde (HCHO)	G & L	80-85	85-95	98-99
<sup>1</sup> Formic Acid (HCO <sub>2</sub> H)	G	85-90	98-99	99+
Hydrobromic Acid (HBr)	G & L	85-93	95-98	99.9-99.99
Hydrochloric Acid (HCl)	G, L	85-93	95-98	99.9-99.99
<sup>1</sup> Hydrofluoric Acid (HF)	G	95	99	99+
<sup>1</sup> Hydrogen Cyanide (HCN)	G	90	97	99.9
<sup>5</sup> Isopropanol	G	70	91-92	98-99
<sup>3</sup> Mercaptans (RSH)	G & L	90	97	99.9
<sup>5</sup> Methanol (CH <sub>3</sub> OH)	G	70	91-92	98-99
<sup>1,3</sup> Methyl Sulfide	G	90	97	99.9
Nitric Acid (HNO <sub>3</sub> )	L	85-90	98-99	99+
<sup>3</sup> Nitrogen oxides (NO <sub>x</sub> )	G	30-40	70	90
Oil Mists	L	85-90	95-98	99
Perchloric Acid	G	85-95	98-99	99+
Phenol (C <sub>6</sub> H <sub>5</sub> OH)	G & L	80-90	90-95	98-99
Phosphate Salt Baths	L	85-90	98-99	99+
Phosphoric Acid (H <sub>3</sub> PO <sub>4</sub> )	L	85-90	98-99	99+
Silicon Tetrachloride (SiCl <sub>4</sub> )	G	85-93	95-98	99.9+
Silicon Tetrafluoride (SiF <sub>4</sub> )	G	95	99	99.9+
Sodium Chloride (NaCl)	S & L	85-90	98-99	99+
Sodium Hydroxide (NaOH)	L	85-90	98-99	99+
Sulfuric Acid (H <sub>2</sub> SO <sub>4</sub> )	L	85-90	98-99	99+
<sup>1</sup> Sulfur Dioxide (SO <sub>2</sub> )	G	85	95	99+
Urea (H <sub>2</sub> NCONH <sub>2</sub> )	S	85-90	98-99	99+
<sup>1,3</sup> Hydrogen Sulfide (H <sub>2</sub> S)	G	90	97	99.9

- NOTES:
- 1) NaOH scrubbing liquid required
  - 2) H<sub>2</sub>SO<sub>4</sub> scrubbing liquid may be required
  - 3) Special scrubbing liquid required. Consult Ceilcote APC for recommendation.
  - 4) Consult Ceilcote APC if efficiencies or contaminants other than those shown are required.
  - 5) Consult Ceilcote APC
  - 6) Performance as shown is based upon gas and/or liquid droplets or solid particulate greater than 5 microns. If mists or particulates below 5 microns are present, consult Ceilcote APC.

NOTE A: G = Gas, L = Liquid particulate above 5 microns, S = Solid particulate above 5 microns



C.2 Table of contaminant of cross flow packed bed scrubber in which the efficiency of scrubber is determined based on the designed packing depth (Ceilcote Air Pollution Control 2005)

Contaminants	Type (See Note A)	Model HRP w/48" packing (Medium Efficiency) % Removal	Model HRP w/72" packing (High Efficiency) % Removal
Acetic Acid (CH <sub>3</sub> CO <sub>2</sub> H)	G&L	80-85	85-92
<sup>5</sup> Acetone (CH <sub>3</sub> COCH <sub>3</sub> )	G	65	90
<sup>3</sup> Aluminum Bright Dip	G&L	30-90	40-98
<sup>2</sup> Amines (RNH <sub>2</sub> )	G	90-95	99+
<sup>2</sup> Ammonia (NH <sub>3</sub> )	G	90-95	99+
Ammonium Hydroxide (NH <sub>4</sub> OH)	L	98-99	99+
<sup>5</sup> Ammonium Nitrate (NH <sub>4</sub> NO <sub>3</sub> )	S	85-90	98-99
Anodizing Solutions	L	98-99	99+
Boric Acid (H <sub>3</sub> BO <sub>3</sub> )	L	80-90	95-98
<sup>1</sup> Bromine (Br <sub>2</sub> )	G	95	97-99
Caustic (NaOH)	L	98-99	99+
<sup>1</sup> Chlorine (Cl <sub>2</sub> )	G	95	97-99
Chromic Acid (H <sub>2</sub> CrO <sub>4</sub> )	L	98-99	99+
Citric Acid	L	98-99	99+
Cyanide Salts	L	98-99	99+
<sup>1</sup> Formaldehyde (HCHO)	G & L	80-85	85-95
<sup>1</sup> Formic Acid (HCO <sub>2</sub> H)	G	85-90	98-99
<sup>5</sup> Hydrobromic Acid (HBr)	G & L	85-95	98-99
<sup>5</sup> Hydrochloric Acid (HCl)	G & L	85-95	98-99
<sup>1</sup> Hydrofluoric Acid (HF)	G	95	99
<sup>1</sup> Hydrogen Cyanide (HCN)	G	90-95	97-99
<sup>3</sup> Mercaptans (RSH)	G & L	95	98-99
<sup>1,2</sup> Methyl Sulfide	G	90	97
Nitric Acid (HNO <sub>3</sub> )	L	85-90	98-99
<sup>3</sup> Nitrogen oxides (NO <sub>x</sub> )	G	30-40	70+
Oil Mists	L	85-90	95-98
Perchloric Acid	G	85-95	98-99
Phenol (C <sub>6</sub> H <sub>5</sub> OH)	G & L	80-90	90-95
Phosphate Salt Baths	L	98-99	99+
Phosphoric Acid (H <sub>3</sub> PO <sub>4</sub> )	L	98-99	99+
Silicon Tetrachloride (SiCl <sub>4</sub> )	G	90-95	98-99
Silicon Tetrafluoride (SiF <sub>4</sub> )	G	95	99
Sodium Chloride (NaCl)	-S & L	98-99	99+
Sodium Hydroxide (NaOH)	L	98-99	99+
Sulfuric Acid (H <sub>2</sub> SO <sub>4</sub> )	L	98-99	99+
<sup>1</sup> Sulfur Dioxide (SO <sub>2</sub> )	G	90	98
<sup>5</sup> Urea (H <sub>2</sub> NCONH <sub>2</sub> )	S	85-90	98-99
<sup>1,2</sup> Hydrogen Sulfide (H <sub>2</sub> S)	G	95	98-99

- NOTES:
- 1) NaOH scrubbing liquid required.
  - 2) H<sub>2</sub>SO<sub>4</sub> scrubbing liquid may be required.
  - 3) Special scrubbing liquid required. Consult Ceilcote Air Pollution Control for recommendation.
  - 4) Consult Ceilcote Air Pollution Control if efficiencies or contaminants other than those shown are required.
  - 5) Consult Ceilcote Air Pollution Control.
  - 6) Performance as shown is based upon gas and/or liquid droplets or solid particulate greater than 5 microns. If mists or particulate below 5 microns are present, consult Ceilcote Air Pollution Control.

NOTE A:

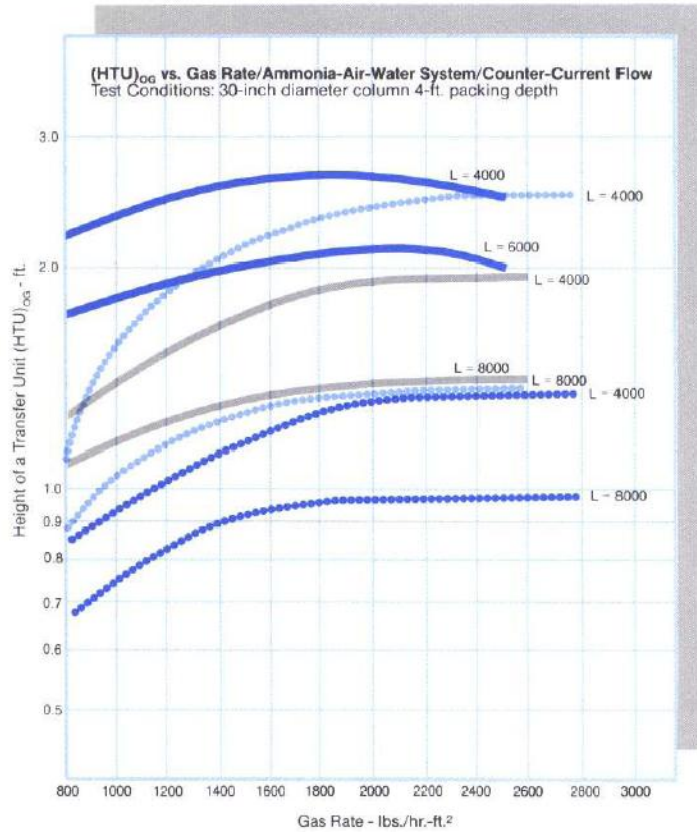
G = Gas  
L = Liquid particulate above 5 microns  
S = Solid particulate above 5 microns

## Appendix D

### Mass Transfer Efficiency Data

- D.1 Mass transfer efficiency data for several packing elements as compared to Tellerette packing (Ceilcote Air Pollution Control 2005)
- D.2 Pressure drop comparison for several packing elements as compared to Tellerette packing (Ceilcote Air Pollution Control 2005)
- D.3 Packing depth comparison for several packing elements as compared to Tellerette packing (Ceilcote Air Pollution Control 2005)
- D.4 Mass transfer efficiency data for several packing elements as compared to Jaeger Tri-Packs (Jaeger Products 1996)
- D.5 Mass transfer data and specification of Jaeger Tri-Packs (Jaeger Products 1996)

D.1 Mass transfer efficiency data for several packing elements as compared to Tellerette packing (Ceilcote Air Pollution Control 2005)



### Higher mass transfer efficiency.

The shape makes the difference.

By enhancing the agglomeration/dispersion cycle, Tellerette packing achieves dramatically higher mass transfer efficiency and dramatically improved collection efficiency.

Not all systems perform identically, but in all cases Tellerette packing has shown better performance than other commercial packings.

**Efficiency of No. 2 Type-K Tellerettes is 30% greater than No. 2 Tri-Packs and 50% greater than 2\" Plastic Saddles.**

*Tellerette packing has been tested in many systems including CO<sub>2</sub>-Air-NaOH, HCl-Air-H<sub>2</sub>O, Cl<sub>2</sub>-Air-NaOH, SO<sub>2</sub>-Air-NaOH, NH<sub>3</sub>-Air-H<sub>2</sub>SO<sub>4</sub>, H<sub>2</sub>S-Air-NaOH, H<sub>2</sub>S-Air-NaOCl, VOC Stripping and Heat Transfer.*

- No. 2 Tri-Packs\*\*
- 2\" Plastic Saddles
- No. 2 Tellerettes - Type-R
- No. 2 Tellerettes - Type-K

D.2 Pressure drop comparison for several packing elements as compared to Tellerette packing (Ceilcote Air Pollution Control 2005)

**Dramatic increases in operating benefits.**

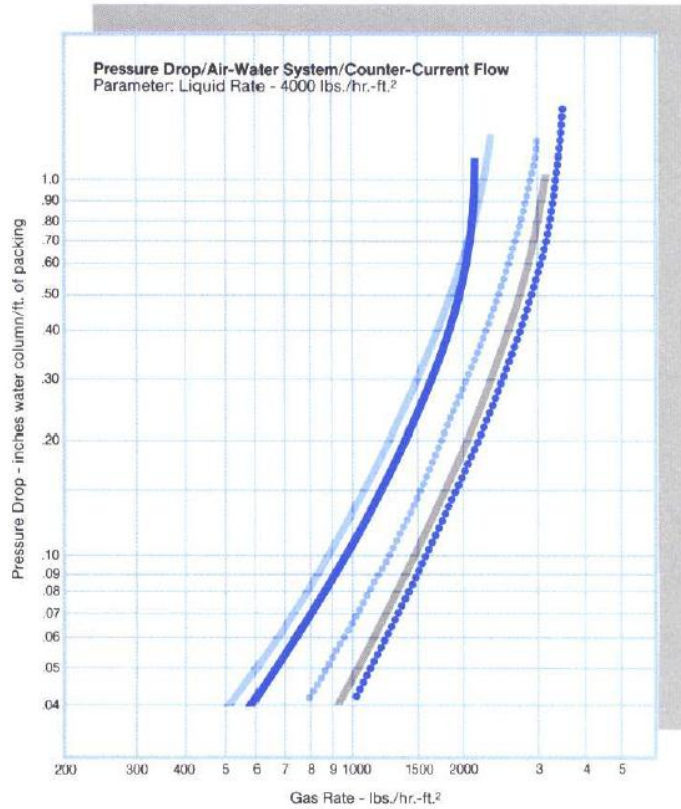
**Lower pressure drop.**

The shape makes the difference. Being a filamentous construction, Tellerette packing has no "dead volumes." This assures uniform orientation throughout the packed depth, with minimal resistance to gas flow. Thus, dramatically reduced pressure drop.

**Type-K Tellerettes 35% lower  $\Delta P$  at same capacity, or 20% increased capacity at same  $\Delta P$  than Type-R Tellerettes.**

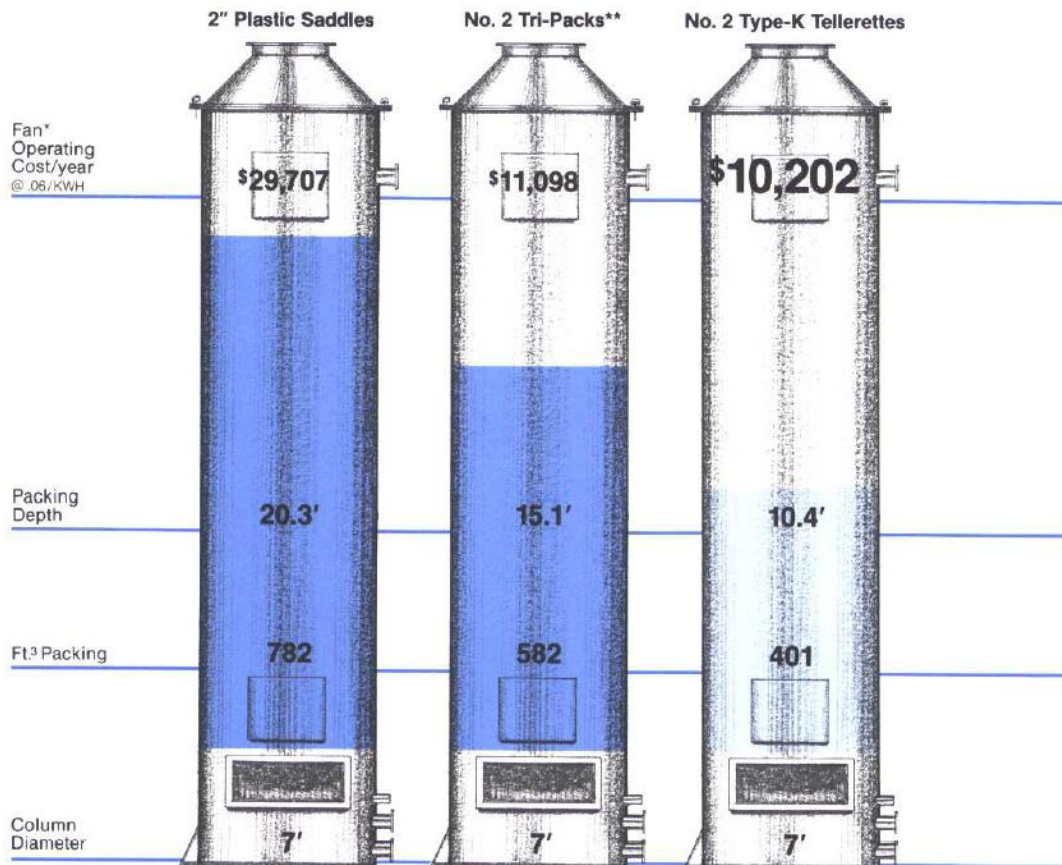
**Type-R 50% lower  $\Delta P$  at same capacity or 35% increased capacity at same  $\Delta P$  than 2" Plastic Saddles.**

- No. 2 Tri-Packs\*\*
- 2" Rings
- 2" Plastic Saddles
- No. 2 Tellerettes - Type-R
- No. 2 Tellerettes - Type-K



D.3 Packing depth comparison for several packing elements as compared to Tellerette packing (Ceilcote Air Pollution Control 2005)

## Replace packing: You win with Tellerettes.



**Comparative analysis.**

**System Requirements.**

1. Use once through H<sub>2</sub>O at 80°F
2. Use L = 4,000 lbs./hr.-ft.<sup>2</sup>
3. Removal Efficiency Required: 99%
4. Existing column diameter of 7'-0"

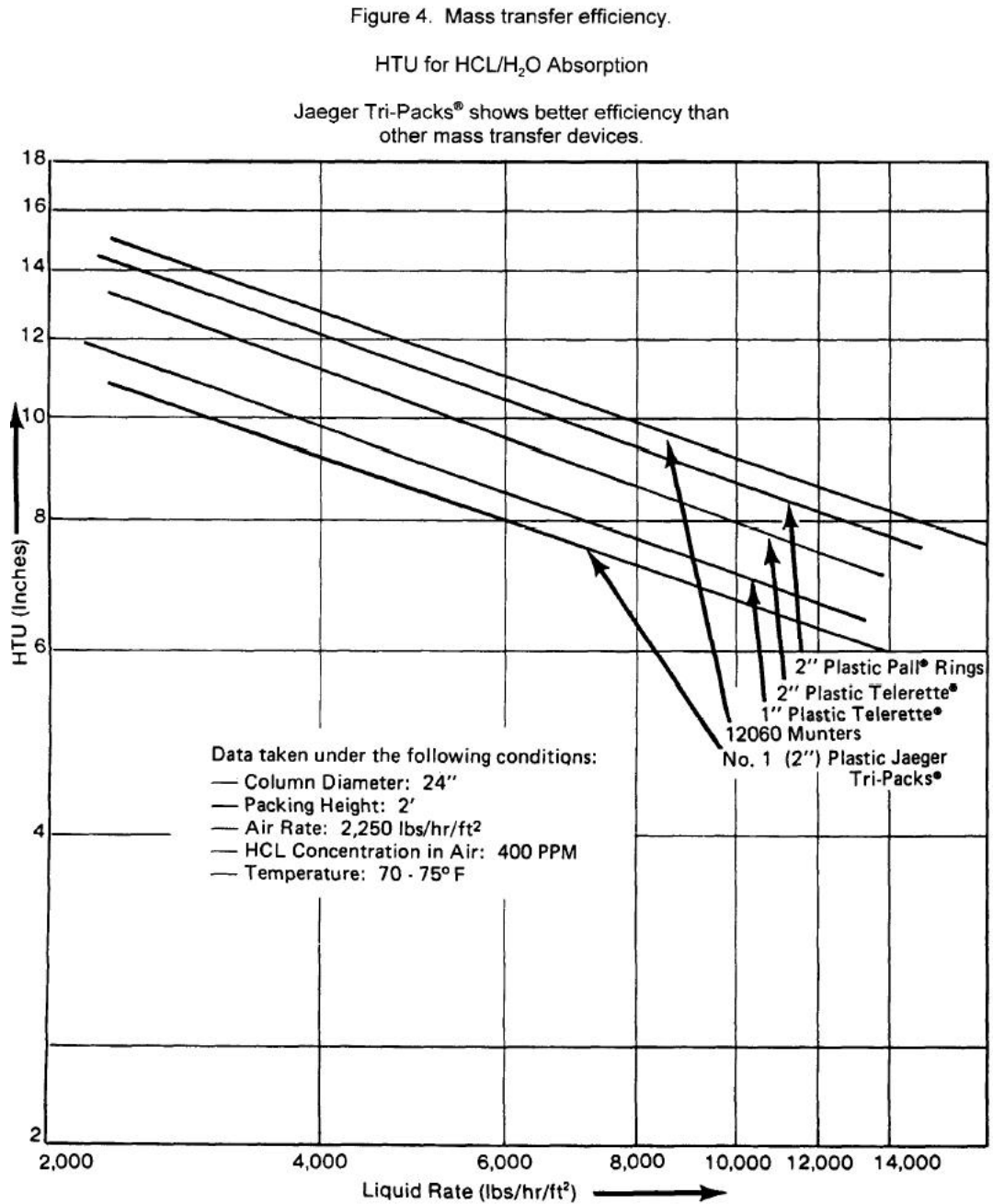
Compare No. 2 Type-K Tellerettes, No. 2 Tri-Packs and 2" Plastic Saddles for packing depth and pressure drop. The calculated G = 2,338 lbs./hr.-ft.<sup>2</sup> and Number of Transfer Units (N<sub>OG</sub>) = 7.81 for these requirements.

Result: The No. 2 Type-K Tellerettes provide the lowest pressure drop, packing height and operating costs.

Type of Packing	2" Plastic Saddles	No. 2 Tri-Packs	No. 2 Type-K Tellerettes
H <sub>OG</sub> Feet	2.66'	1.93'	1.33'
Pressure Drop inches WG/ft.	0.88"	0.33"	0.28"
Total ΔP across packing	17.86"	4.98"	2.91"
Fan BHP	83	31	22.5

\*Based on 8,000 hrs./year \*\*For Ceilcote Air Pollution Control Data on No. 2 Tri-Packs see Bulletin 12-10.80 and 12-10.81.

D.4 Mass transfer efficiency data for several packing elements as compared to Jaeger Tri-Packs (Jaeger Products 1996)



## D.5 Mass transfer data and specification of Jaeger Tri-Packs (Jaeger Products 1996)

### PLASTIC JAEGER TRI-PACKS®

#### SPECIFICATIONS

##### Materials

Twelve standard, injection moldable plastics are available:

Polypropylene (PP)	TopEx® (LCP)
Polyethylene (PE)	Kynar® (PVDF)
Polypropylene	Halar® (ECTFE)
Glass-Filled (PPG)	Teflon® (PFA)
Noryl® (PPO)	Tefzel® (ETFE)
Polyvinylchloride (PVC)	Tefzel® Glass-Filled (ETFE-G)
Corzan™ (CPVC)	

Other plastics are available on request.

Properties Table

Size (in.)	1	1 1/4"	2	3 1/2"
Geometric Surface Area (ft <sup>2</sup> /ft <sup>3</sup> )	85	70	48	38
Packing Factor (1/ft)	28	25	16	12
Void Space (%)	90	92	93.5	95
Bulk Density (lb/ft <sup>3</sup> ) (PP)	6.2	5.6	4.2	3.3

Sizes. Plastic Jaeger TriPacks® packings are made in four sizes:

1" Nominal  
1 1/4" Nominal  
2" Nominal  
3 1/2" Nominal

MASS TRANSFER DATA

Absorption System	G (lb/hr-ft)	L (lb/hr-ft)	Temp (°F)	HTU-Inches		
				1	2	3 1/2
HCl-H <sub>2</sub> O	1792	2048	77	7.0	10.6	12
HCl-NaOH	1567	2048	68	6.1	8.8	10
Cl <sub>2</sub> -NaOH	1229	2202	122	9.9	14.5	16
NO <sub>2</sub> -Na <sub>2</sub> S <sub>2</sub> O <sub>3</sub> -NaOH	717	1127	68	32.0	49.2	54
NH <sub>3</sub> -H <sub>2</sub> SO <sub>4</sub>	492	1024	68	4.1	6.0	7
NH <sub>3</sub> -H <sub>2</sub> O	512	1024	68	5.6	8.4	10
NH <sub>3</sub> -H <sub>2</sub> O	512	4096	68	3.6	5.4	6.2
SO <sub>2</sub> -NaOH	1946	4096	140	8.1	12.0	14
HF-H <sub>2</sub> O	1844	3072	77	4.6	6.9	8.1
H <sub>2</sub> S-NaOH	1229	1331	68	13.0	19.4	22
VOC Stripping	G (lb/hr-ft)	L (lb/hr-ft)	Temp (°F)	HTU-Inches		
				1	2	3 1/2
TCE(ppb)-H <sub>2</sub> O	479	12264	77	21.5	26.9	31.1
TCE(ppm/ppb)-H <sub>2</sub> O	600	12494	60	30.1	37.6	42.6
BTX(ppb)-H <sub>2</sub> O	722	12264	70	31.4	33.8	38.0

##### IMPORTANT NOTE:

Design data presented in this bulletin are for preliminary calculations only. Contact Jaeger before finalizing calculations.

JAEGER TRI-PACKS® is a Registered Trademark of JAEGER PRODUCTS, INC.

## Appendix E

### Questionnaire



Appendix E  
Questionnaire

University of Southern Queensland  
Faculty of Engineering and Surveying

## Evaluation of Wet Scrubber Systems

A questionnaire prepared by

Yap Lee Juan  
(0050027395)

Towards the degree of

Bachelor of Engineering (Mechanical)

**Purpose**

*This questionnaires aims to study and compare the efficiencies of cross flow and counter current flow packed bed wet scrubber. It is hoped that scrubber performance can be further improved to reduce the discharge of gas emission.*

**Date:** \_\_\_\_\_

**Section A: Contact Details**

1. Name: \_\_\_\_\_
2. Company Name/ Institution/ Authority: \_\_\_\_\_
3. Telephone No.: \_\_\_\_\_
4. Fax No.: \_\_\_\_\_

**Section B: Information about your position and company**

5. What is your position in company? (Please tick)

<input type="checkbox"/>	Manager
<input type="checkbox"/>	Engineer
<input type="checkbox"/>	Supervisor/ Technician
<input type="checkbox"/>	Others (Please specify): _____

6. How many employees in this company? (Please tick)

Manager	<input type="checkbox"/>	1-5	<input type="checkbox"/>	5-10	<input type="checkbox"/>	>10	
Engineer	<input type="checkbox"/>	1-5	<input type="checkbox"/>	5-10	<input type="checkbox"/>	>10	
Supervisor/ technician	<input type="checkbox"/>	1-5	<input type="checkbox"/>	5-10	<input type="checkbox"/>	>10	
Others. Please specify:	i)	<input type="checkbox"/>	1-5	<input type="checkbox"/>	5-10	<input type="checkbox"/>	>10
	ii)	<input type="checkbox"/>	1-5	<input type="checkbox"/>	5-10	<input type="checkbox"/>	>10

7. How long have you been involved in his company? (Please tick)

Less than 1 year	<input type="checkbox"/>
2-5 years	<input type="checkbox"/>
5-10 years	<input type="checkbox"/>
More than 10 years	<input type="checkbox"/>

**Section C: Design Requirements of DOE on Packed Bed Scrubber**

8. What are the design requirements of DOE both for counter current vertical flow and horizontal cross flow packed bed scrubbers?

Counter current vertical flow:

---

---

---

---

---

---

---

---

Horizontal cross flow:

---

---

---

---

---

---

---

---

**Section D: Factors Affecting Scrubber's Efficiency**

9. What are the factors that influencing these scrubbers' efficiency? (Please tick)

<input type="checkbox"/>	Scrubber sizing. Why?
<input type="checkbox"/>	Packing depth. Why?
<input type="checkbox"/>	Liquid distribution rate. Why?
<input type="checkbox"/>	Gas loading rate. Why?
<input type="checkbox"/>	Superficial gas velocity across the scrubber. Why?
<input type="checkbox"/>	Operating pressure. Why?
<input type="checkbox"/>	Pressure drop. Why?
<input type="checkbox"/>	Type of packing. Why?
<input type="checkbox"/>	Packing size. Why?
<input type="checkbox"/>	Material of construction. Why?
<input type="checkbox"/>	Operating temperature. Why?
<input type="checkbox"/>	Liquid to gas ratio. Why?
<input type="checkbox"/>	Others. Please comment. Why?

Comments for the above factors if they do:

Scrubber sizing: \_\_\_\_\_  
 \_\_\_\_\_  
 \_\_\_\_\_

Packing depth: \_\_\_\_\_  
 \_\_\_\_\_  
 \_\_\_\_\_

Liquid distribution rate: \_\_\_\_\_  
 \_\_\_\_\_  
 \_\_\_\_\_

Gas loading rate: \_\_\_\_\_  
 \_\_\_\_\_  
 \_\_\_\_\_

Superficial gas velocity across the scrubber: \_\_\_\_\_  
 \_\_\_\_\_  
 \_\_\_\_\_

Operating pressure: \_\_\_\_\_  
 \_\_\_\_\_  
 \_\_\_\_\_

Pressure drop: \_\_\_\_\_  
 \_\_\_\_\_  
 \_\_\_\_\_

Type of packing: \_\_\_\_\_

\_\_\_\_\_

Packing size: \_\_\_\_\_

\_\_\_\_\_

Material of construction: \_\_\_\_\_

\_\_\_\_\_

Operating temperature: \_\_\_\_\_

\_\_\_\_\_

Liquid to gas ratio: \_\_\_\_\_

\_\_\_\_\_

Others: \_\_\_\_\_

\_\_\_\_\_

\_\_\_\_\_

\_\_\_\_\_

**Section E: Scrubber's Efficiency Calculation**

10. What method is used to estimate the efficiency of a counter current vertical flow packed bed scrubber? (Please tick)

- |                          |  |
|--------------------------|--|
| <input type="checkbox"/> | Theoretical approach (i.e., based on an equation of scrubber's efficiency). What is the equation?                        |
| <input type="checkbox"/> | Empirical approach (i.e., based on chart, curve, past operating data, etc). What kinds of chart, curve or relating data? |
| <input type="checkbox"/> | Both of the above approaches. Please comment.  |
| <input type="checkbox"/> | Based on the designed packing height.  |
| <input type="checkbox"/> | Others. Please comment.  |

Comments:

\_\_\_\_\_

\_\_\_\_\_

\_\_\_\_\_

\_\_\_\_\_

11. Is the method used to calculate the efficiency of a horizontal cross flow packed bed scrubber is the same with counter current vertical flow packed bed scrubber? (Please tick)

- Yes, it is. (Please look question 12)
- No, they are different. (Please look question 13)

12. Are they going to have same efficiency if efficiency is calculated based on same constraints (i.e., same packing, pollutant, gas flow rate, liquid flow rate, sizing, application, etc) by using same method of calculation? (Please tick)

- Yes, they will be the same. (Please look question 14)
- No, they will be different. (Please look question 15)

13. What are the differences? (Please tick)

- Using different formula. What is the formula?
- Using different graph, chart, past operating data, etc. What are the data?
- Others. Please comment.

Comments:

---



---



---



---

14. Why theoretically counter current vertical design is said to have higher efficiency than horizontal cross flow design?

Comments:

---



---



---



---

15. Why they will be different? (Please tick)

- |                          |   |
|--------------------------|---|
| <input type="checkbox"/> | Because there is another efficiency equation for cross flow.<br>What is the equation?     |
| <input type="checkbox"/> | Because there are different chart, curve, operating data, etc used.<br>What are the data? |

Comments:

---



---



---



---

16. What kinds of data or factors are required for the efficiency calculation?  
(Please tick)

- |                          |                               |
|--------------------------|-------------------------------|
| <input type="checkbox"/> | HTU curve of the packing used |
| <input type="checkbox"/> | NTU                           |
| <input type="checkbox"/> | Henry's law constant          |
| <input type="checkbox"/> | Liquid loading rate           |
| <input type="checkbox"/> | Gas loading rate              |
| <input type="checkbox"/> | Packing height                |
| <input type="checkbox"/> | Others. Please comment.       |

Comments:

---



---



---



---



---

**Section F: Application**

17. What kinds of process that usually use counter current flow scrubber for scrubbing process? And how about cross flow? (Please tick)

Counter current flow:

<input type="checkbox"/>	Plating operations
<input type="checkbox"/>	Chemical processing
<input type="checkbox"/>	Pharmaceutical processing
<input type="checkbox"/>	Fertilizer processing
<input type="checkbox"/>	Food and beverages
<input type="checkbox"/>	Others. Please comment.

Cross flow:

<input type="checkbox"/>	Plating operations
<input type="checkbox"/>	Chemical processing
<input type="checkbox"/>	Pharmaceutical processing
<input type="checkbox"/>	Fertilizer processing
<input type="checkbox"/>	Food and beverages
<input type="checkbox"/>	Others. Please comment.

Comments:

---

---

---

---

---

---

---

---

Comments:

---

---

---

---

---

---

---

---

18. What kinds of process or operation are more suitable to use cross flow packed bed scrubber to scrub the pollutant than counter current flow scrubber? Please recommend and why.

Comments:

---

---

---

---

---

---

19. What kinds of process or operation are more suitable to use counter current flow packed bed scrubber to scrub the pollutant than cross flow scrubber? Please recommend and why.

Comments:

---

---

---

---

---

---



**Section G: Advantages and Limitations**

20. What are the advantages and limitations for counter current vertical flow?  
(Please tick)

Advantages:

Limitations:

<input type="checkbox"/>	High absorption rate	<input type="checkbox"/>	Particles tend to clog the packed bed
<input type="checkbox"/>	Ideal & compact design	<input type="checkbox"/>	High probability of flooding
<input type="checkbox"/>	Small footprint is required	<input type="checkbox"/>	Height limitation
<input type="checkbox"/>	Require minimum amount scrubbing liquid	<input type="checkbox"/>	High pressure drop
<input type="checkbox"/>	Others, please comment	<input type="checkbox"/>	Others, please comment

Comments:

---



---



---



---

21. What the advantages and limitations are for cross flow design scrubber?  
(Please tick)

Advantages:

Limitations:

<input type="checkbox"/>	Ideal when ceiling height is limited	<input type="checkbox"/>	Low absorption rate
<input type="checkbox"/>	Greater particle loading capacity	<input type="checkbox"/>	High maintenance
<input type="checkbox"/>	Can use multiple scrubbing liquid in series	<input type="checkbox"/>	High probability of flooding
<input type="checkbox"/>	Others, please comment	<input type="checkbox"/>	Others, please comment

Comments:

---



---



---



---

<b>Section H: Capacity</b>
----------------------------

22. What is the average range of capacity that usually designed for counter current flow scrubber? And cross flow scrubber? (Please tick)

Counter current flow:

	1,000 – 10, 000 cfm
	10, 000 – 30, 000 cfm
	30, 000 – 50, 000 cfm
	50, 000 – 100, 000 cfm
	Others. Please comment.

Cross flow:

	1,000 – 10, 000 cfm
	10, 000 – 30, 000 cfm
	30, 000 – 50, 000 cfm
	50, 000 – 100, 000 cfm
	Others. Please comment.

Comments:

---

---

---

---

---

Comments:

---

---

---

---

---

<b>Section I: Packing</b>
---------------------------

23. There are variety kinds of packing in market nowadays. Is each type of packing affecting the scrubber's efficiency by giving different efficiency? (Please tick).

	Yes, it is.
	No, it isn't.

24. What kind of packing that is usually filled into the cross flow and counter current flow packed bed scrubber? (Please tick).

Counter current flow:

	Tellerette packing
	Lanpac packing
	Tri-packs
	Pall ring
	Raschig ring
	Berl saddle
	Intalox saddle
	Others. Please comment.

Cross flow:

	Tellerette packing
	Lanpac packing
	Tri-packs
	Pall ring
	Raschig ring
	Berl saddle
	Intalox saddle
	Others. Please comment.

Comments:

---



---



---

25. What kind of packing material that usually filled into cross flow and counter current flow packed bed scrubber? (Please tick).

Counter current flow:

Cross flow:

<input type="checkbox"/>	Plastic/ Polypropylene
<input type="checkbox"/>	Metal
<input type="checkbox"/>	Ceramic
<input type="checkbox"/>	Carbon
<input type="checkbox"/>	Others. Please comment.

<input type="checkbox"/>	Plastic/ Polypropylene
<input type="checkbox"/>	Metal
<input type="checkbox"/>	Ceramic
<input type="checkbox"/>	Carbon
<input type="checkbox"/>	Others. Please comment.

Comments:

---



---



---

26. The choice of packing and its material depend on

<input type="checkbox"/>	the nature of the fluids.
<input type="checkbox"/>	the operating temperature.
<input type="checkbox"/>	packing size.
<input type="checkbox"/>	cost.
<input type="checkbox"/>	column size.
<input type="checkbox"/>	Others. Please comments.

Comments:

---



---



---

27. Will packing size influence the scrubber's efficiency?

<input type="checkbox"/>	Yes, it will.
<input type="checkbox"/>	No, it won't.

Comments:

---



---

<b>Section J: Scrubbing Liquid</b>
------------------------------------

28. What kind of scrubbing liquid that usually used in cross flow and counter current flow packed bed scrubber? (Please tick)

Counter current flow:

	Water
	Caustic solution
	Sulphuric acid
	Others. Please comment.

Cross flow:

	Water
	Caustic solution
	Sulphuric acid
	Others. Please comment.

Comments:

---



---



---



---

29. Is the selection of scrubbing liquid vital to ensure an efficient scrubbing process? Why?

	Yes, it is.
	No, it isn't.

Comments:

---



---



---

30. The choice of scrubbing liquid depends on

	nature of the pollutant.
	solubility of the pollutant.
	operating temperature.
	cost.
	Others. Please comment.

Comments:

---



---



---



---

31. Can the use of chemical such as caustic solution or sulphuric acid enhance the scrubbers' efficiency than using water? Why?

<input type="checkbox"/>	Yes, it can.
<input type="checkbox"/>	No, it cannot.

Comments:

---



---



---



---

**Section K: Improve Scrubber's Performance**

32. How to improve the scrubber performance of cross flow and counter current flow packed bed scrubber? (Please tick).

Counter current flow:

Cross flow:

<input type="checkbox"/>	Increase the packing depth	<input type="checkbox"/>	Increase the packing depth
<input type="checkbox"/>	Eliminate liquid recirculation system	<input type="checkbox"/>	Eliminate liquid recirculation system
<input type="checkbox"/>	Multistage of packed bed	<input type="checkbox"/>	Multistage of packed bed
<input type="checkbox"/>	Structured packing instead of random packing	<input type="checkbox"/>	Structured packing instead of random packing
<input type="checkbox"/>	Use smaller size of packing	<input type="checkbox"/>	Use smaller size of packing
<input type="checkbox"/>	Others. Please comment.	<input type="checkbox"/>	Others. Please comment.

Comments:

---



---



---



---



---

<b>Section L: Equipment Completing the Scrubber System</b>
--

33. What are the associated equipments completing the scrubbing process?

<input type="checkbox"/>	Pump
<input type="checkbox"/>	Mist eliminator
<input type="checkbox"/>	Fan
<input type="checkbox"/>	pH controller
<input type="checkbox"/>	Flow meter
<input type="checkbox"/>	Metering dosing
<input type="checkbox"/>	Pressure gauge
<input type="checkbox"/>	Level sensor
<input type="checkbox"/>	Actuated damper
<input type="checkbox"/>	Others, please comment

Comments:

---



---



---



---

34. Are cross flow and counter current flow scrubbers having the same associated equipments?

<input type="checkbox"/>	Yes, they are.
<input type="checkbox"/>	No, they aren't. What are the different equipments?

Comments:

---



---



---



---

35. Are regular maintenances and inspection needed for the equipments? What kinds of maintenances are necessary?

<input type="checkbox"/>	Yes, they are needed.
<input type="checkbox"/>	No, they are not necessary.

Comments:

---



---



---



---

<b>Section M: Maintenances</b>
--------------------------------

36. Is it true that cross flow and counter current flow scrubbers require high cost of maintenance? Why?

- |                          |               |
|--------------------------|---------------|
| <input type="checkbox"/> | Yes, it is.   |
| <input type="checkbox"/> | No, it isn't. |

Comments:

---



---



---



---

37. What kinds of maintenances are usually needed to ensure efficient scrubber operation?

- |                          |  |
|--------------------------|--|
| <input type="checkbox"/> | Do cleaning on the packing.                                    |
| <input type="checkbox"/> | Inspect the pump, fan, etc whether they are properly operated. |
| <input type="checkbox"/> | Check the pH of the liquid regarding the recirculation system. |
| <input type="checkbox"/> | Others. Please comment.  |

Comments:

---



---



---



---



---



---

38. How often these maintenances should be given?

- |                          |  |
|--------------------------|--|
| <input type="checkbox"/> | Everyday.                                    |
| <input type="checkbox"/> | Once a week.                                 |
| <input type="checkbox"/> | Once a month.                                |
| <input type="checkbox"/> | Depends on the scrubber operating condition. |
| <input type="checkbox"/> | Others. Please comment.                      |

Comments:

---



---



---



---



---



---

**Section N: Standard Guideline**

39. Is there a standard guideline that governs the scrubber's efficiency for a range of pollutant? What is the guideline?

- Yes, there is.  
 No, there isn't.

Comments:

---

---

---

40. Is the emission standard under Environmental Quality (Clean Air) Regulations Malaysia 1978 serves as the basic guidelines for the scrubber's efficiency?

- Yes, it is.  
 No, it isn't.

Comments:

---

---

---

---



## Appendix F

### Survey Endorsement & Verification

- F.1 Authorized Party Endorsement (DOE Penang)
- F.2 Survey Verification (Alloyplas Engineering Sdn. Bhd.)
- F.3 Survey Verification (Hexagon Tower Sdn. Bhd.)

F.1 Authorized Party Endorsement (DOE Penang)

*Design of Wet Scrubber Systems* \_\_\_\_\_ 1

**Purpose**

*This questionnaire aims to study and compare the efficiencies of cross flow and counter current flow packed bed wet scrubber. It is hoped that scrubber performance can be further improved to reduce the discharge of effluent gas.*

Date: 14/7/2005

**Section A: Contact Details**

1. Name: MOHAMAD FITRI SAID
2. Company Name/ Institution/ Authority: DOE PENANG
3. Telephone No.: 04-3334441
4. Fax No.: 04-3331667

MOHAMAD FITRI BIN SAID  
PEGAWAI KAWALAN ALAM SEKITAR  
NEGERI PULAU PINANG

**Section B: Information about your position and company**

5. What is your position in company? (Please tick)

- |                                     |   |
|-------------------------------------|---|
| <input type="checkbox"/>            | Manager                                 |
| <input type="checkbox"/>            | Engineer                                |
| <input type="checkbox"/>            | Supervisor/ Technician                  |
| <input checked="" type="checkbox"/> | Others (Please specify): <u>OFFICER</u> |

6. How many employees in this company? (Please tick)

- |                            |                          |     |                          |      |                                     |     |
|----------------------------|--------------------------|-----|--------------------------|------|-------------------------------------|-----|
| Manager                    | <input type="checkbox"/> | 1-5 | <input type="checkbox"/> | 5-10 | <input type="checkbox"/>            | >10 |
| Engineer                   | <input type="checkbox"/> | 1-5 | <input type="checkbox"/> | 5-10 | <input type="checkbox"/>            | >10 |
| Supervisor/ technician     | <input type="checkbox"/> | 1-5 | <input type="checkbox"/> | 5-10 | <input type="checkbox"/>            | >10 |
| Others. Please specify: i) | <input type="checkbox"/> | 1-5 | <input type="checkbox"/> | 5-10 | <input checked="" type="checkbox"/> | >10 |
| ii)                        | <input type="checkbox"/> | 1-5 | <input type="checkbox"/> | 5-10 | <input type="checkbox"/>            | >10 |

7. How long have you been involved in his company? (Please tick)

- |                    |                                     |
|--------------------|-------------------------------------|
| Less than 1 year   | <input checked="" type="checkbox"/> |
| 2-5 years          | <input type="checkbox"/>            |
| 5-10 years         | <input type="checkbox"/>            |
| More than 10 years | <input type="checkbox"/>            |

F.2 Survey Verification (Alloyplas Engineering Sdn. Bhd.)

*Design of Wet Scrubber Systems* \_\_\_\_\_ 1

**Purpose**  
 This questionnaires aims to study and compare the efficiencies of cross flow and counter current flow packed bed wet scrubber. It is hoped that scrubber performance can be further improved to reduce the discharge of effluent gas.

Date: 20/8/2005

**Section A: Contact Details**

1. Name: William Lee Wei Guan.
2. Company Name/ Institution/ Authority: Alloyplas Engr. Sdn. Bhd.
3. Telephone No.: +604-3903588
4. Fax No.: +604-3994471



**ALLOYPLAS ENGINEERING SDN. BHD.**  
(09152)  
 24, Lorong Nagasari 9, Taman Nagasari,  
 13600 Perai, Penang, Malaysia  
 Tel: 604-390 3588 Fax: 604-399 4471  
 E-mail: admin@alloypl.com.my  
 Home page: www.alloyplas.com

**Section B: Information about your position and company**

5. What is your position in company? (Please tick)

- |                                     |                                |
|-------------------------------------|--------------------------------|
| <input checked="" type="checkbox"/> | Manager                        |
| <input type="checkbox"/>            | Engineer                       |
| <input type="checkbox"/>            | Supervisor/ Technician         |
| <input type="checkbox"/>            | Others (Please specify): _____ |

6. How many employees in this company? (Please tick)

Manager	<input checked="" type="checkbox"/>	1-5	<input type="checkbox"/>	5-10	<input type="checkbox"/>	>10
Engineer	<input checked="" type="checkbox"/>	1-5	<input type="checkbox"/>	5-10	<input type="checkbox"/>	>10
Supervisor/ technician	<input type="checkbox"/>	1-5	<input type="checkbox"/>	5-10	<input checked="" type="checkbox"/>	>10
Others. Please specify:	<input type="checkbox"/>	1-5	<input type="checkbox"/>	5-10	<input type="checkbox"/>	>10
	<input type="checkbox"/>	1-5	<input type="checkbox"/>	5-10	<input type="checkbox"/>	>10

7. How long have you been involved in his company? (Please tick)

- |                    |                                     |
|--------------------|-------------------------------------|
| Less than 1 year   | <input type="checkbox"/>            |
| 2-5 years          | <input checked="" type="checkbox"/> |
| 5-10 years         | <input type="checkbox"/>            |
| More than 10 years | <input type="checkbox"/>            |

Questionnaire

F.3 Survey Verification (Hexagon Tower Sdn. Bhd.)

*Design of Wet Scrubber Systems* \_\_\_\_\_ 1

**Purpose**

*This questionnaires aims to study and compare the efficiencies of cross flow and counter current flow packed bed wet scrubber. It is hoped that scrubber performance can be further improved to reduce the discharge of effluent gas.*

Date: 30.7.05

**Section A: Contact Details**

- 1. Name: Theodoros Kabanis
- 2. Company Name/ Institution/ Authority: Hexagon Tower S/B
- 3. Telephone No.: 04-5081137
- 4. Fax No.: 04-5081140



**Section B: Information about your position and company**

5. What is your position in company? (Please tick)

- Manager
- Engineer
- Supervisor/ Technician
- Others (Please specify): \_\_\_\_\_

6. How many employees in this company? (Please tick)

Manager	<input checked="" type="checkbox"/>	1-5	<input type="checkbox"/>	5-10	<input type="checkbox"/>	>10
Engineer	<input type="checkbox"/>	1-5	<input checked="" type="checkbox"/>	5-10	<input type="checkbox"/>	>10
Supervisor/ technician	<input type="checkbox"/>	1-5	<input type="checkbox"/>	5-10	<input checked="" type="checkbox"/>	>10
Others. Please specify:						
i) <i>technicians</i>	<input type="checkbox"/>	1-5	<input type="checkbox"/>	5-10	<input checked="" type="checkbox"/>	>10
ii) <i>technicians</i>	<input type="checkbox"/>	1-5	<input type="checkbox"/>	5-10	<input checked="" type="checkbox"/>	>10

7. How long have you been involved in his company? (Please tick)


- Less than 1 year
- 2-5 years
- 5-10 years
- More than 10 years

Questionnaire

## Appendix G

### Authorized Letter

Appendix G  
Authorized Letter



**The University of Southern Queensland**

TOOWOOMBA QUEENSLAND 4350  
 AUSTRALIA  
 TELEPHONE (07) 4631 2100  
[www.usq.edu.au](http://www.usq.edu.au)

**FACULTY OF ENGINEERING AND SURVEYING**  
 Associate Professor Sai-Cheong Fok  
 Head of Mechanical and Mechatronic Engineering  
 PHONE (07) 4631 1345 FAX (07) 4631 2526  
 EMAIL [foksai@usq.edu.au](mailto:foksai@usq.edu.au)

3 February 2005 SCEJC/05/K

To whom it may concern

**Re: Research support request for Ms Yap Lee Juan**


Ms Yap Lee Juan (IC No 820220-07-5068) is a Bachelor of Engineering (Mechanical) student (Student No 0050027395) at the University of Southern Queensland, Australia. She is completing her studies through distance education and is currently working on her final year project concerning "The Design of Wet Scrubber System".

As scrubber systems may have significant impact on the air quality, Ms Yap would like to conduct some research concerning their impact on the environment in Malaysia. It would be appreciated if your department could assist her in this research by giving her access to relevant data for analysis.

Please do not hesitate to contact me if you need further clarification.

Thank you.

Yours sincerely




PERPUSTAKAAN  
UNIVERSITI SAINS MALAYSIA

Kemudahan Pinjaman Dituluskan dari  
11-4-05 hingga 11-4-05

*[Signature]* Tarikh: 9-4-05

T.T. Ketua Bahagian Pustaka dan  
Pembacaan dan Pengimbasan


**A/Prof Sai-Cheong Fok**  
 Head of Mechanical & Mechatronic Engineering



207/05/02

14/7/2005

GOOD UNIVERSITIES GUIDES  
**Australia's  
 University of the Year  
 2000 - 2001**  
 DEVELOPING THE E-UNIVERSITY



Joint Winner

