

**A STUDY ON DESIGNED AND CONSTRUCTED  
OF MULTI-CYCLONE FOR DUST REMOVAL  
IN SURFBOARD SANDING PROCESS**



**A THESIS SUBMITTED IN PARTIAL FULFILLMENT  
OF THE REQUIREMENTS FOR  
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Thesis  
entitled

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OF MULTI-CYCLONE FOR DUST REMOVAL  
IN SURFBOARD SANDING PROCESS**



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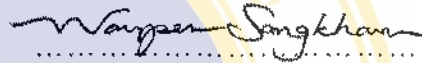
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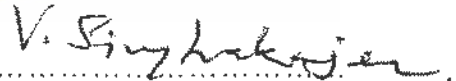
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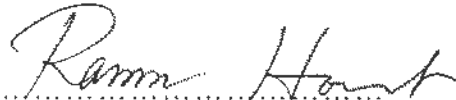
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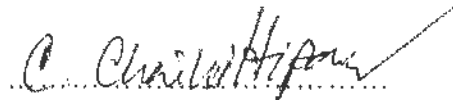
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**A STUDY ON DESIGNED AND CONSTRUCTED OF MULTI-CYCLONE FOR DUST REMOVAL IN SURFBOARD SANDING PROCESS**

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**ABSTRACT**

The purpose of this study was to design and construct a multi-cyclone for removing dust that was released by sanding fiberglass surfboards. The multi-cyclone included nine high-efficiency cyclones with axial inlets with a body diameter of 6 inches, arranged in parallel. Dimensions and shapes were calculated based on the Stairman hypothesis. Collection efficiency was estimated using the theory of Leith and Licht. The multi-cyclone was set up with a local exhaust ventilation system in which table hood and duct were designed according to the recommendation of the American Conference of Governmental Industrial Hygienists (ACGIH) Industrial Ventilation Manual. The system was tested for dust collection efficiency at three airflow rates: 1,200-1,250, 1,400-1,450, and 1,600-1,650 cfm.

The results of the study showed that variations in airflow rates had marked effects on dust collection efficiency. The constructed multi-cyclone had the highest efficiency at an airflow rate of 1,400 - 1,450 cfm. At this rate, the dust collection efficiency of the multi-cyclone was 85.57 percent which was in accordance with the hypothesis of this study. Additionally, the results indicated that when the airflow rate was increased, the pressure drop of the multi-cyclone also increased. However, the experimentally determined dust collection efficiency of the multi-cyclone was lower than that predicted by the theory of Leith and Licht with an error ranging from 3.16 - 6.69 percent.

**KEY WORDS: MULTI-CYCLONE/ DUST REMOVAL/  
SURFBOARD SANDING PROCESS**

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การออกแบบและสร้างมัลติไซโคลนเพื่อขจัดฝุ่นที่เกิดจากกระบวนการขัดกระดานโต้คลื่น  
(A STUDY ON DESIGNED AND CONSTRUCTED OF MULTI-CYCLONE FOR DUST REMOVAL  
IN SURFBOARD SANDING PROCESS)

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บทคัดย่อ

การศึกษานี้มีวัตถุประสงค์เพื่อออกแบบและสร้างมัลติไซโคลนเพื่อขจัดฝุ่นที่เกิดจากการขัดกระดานโต้คลื่นที่ทำจากไฟเบอร์กลาส มัลติไซโคลนที่จัดสร้างขึ้นประกอบด้วยไซโคลนชนิดประสิทธิภาพสูง ทางเข้าของก๊าซอยู่ในแนวแกน ขนาดเส้นผ่าศูนย์กลางของไซโคลนเท่ากับ 6 นิ้ว จำนวน 9 ตัว จัดเรียงกันแบบขนาน การคำนวณสัดส่วนและรูปร่างของตัวไซโคลนเป็นไปตามสมมติฐานของ Stairmand การประมาณประสิทธิภาพในการขจัดฝุ่นใช้ทฤษฎีของ Leith และ Licht เมื่อสร้างเสร็จแล้วจะติดตั้งเข้ากับระบบระบายอากาศเฉพาะที่ โดยออกแบบระบบโต๊ะขัด (table hood) และทำตามข้อเสนอแนะของกลุ่มการระบายอากาศในอุตสาหกรรมของ ACGIH และนำมาทดสอบหาประสิทธิภาพของการขจัดที่ช่วงอัตราการไหลของอากาศ 3 ระดับ ได้แก่ 1,200 – 1,250, 1,400 – 1,450 และ 1,600 – 1,650 ลูกบาศก์ฟุตต่อนาที ตามลำดับ

ผลการศึกษาพบว่า อัตราการไหลของอากาศที่เปลี่ยนแปลงไปมีผลต่อประสิทธิภาพในการขจัดฝุ่น โดยมัลติไซโคลนที่สร้างขึ้นจะมีประสิทธิภาพดีที่สุดเมื่ออัตราการไหลของอากาศที่เข้ามัลติไซโคลนอยู่ในช่วง 1,400 – 1,450 ลูกบาศก์ฟุตต่อนาที และประสิทธิภาพในการขจัดฝุ่นของมัลติไซโคลนในช่วงดังกล่าวเท่ากับ 85.57% ซึ่งเป็นไปตามสมมติฐานที่ตั้งไว้ นอกจากนี้ยังพบว่า เมื่อเพิ่มอัตราการไหลของอากาศก่อนเข้ามัลติไซโคลนมากขึ้นความดันสูญเสียของมัลติไซโคลนจะเพิ่มสูงขึ้น และเมื่อเปรียบเทียบประสิทธิภาพในการขจัดฝุ่นของมัลติไซโคลนระหว่างการทำนายโดยใช้ทฤษฎีของ Leith และ Licht กับผลการทดลอง พบว่าค่าที่ได้จากการทดลองจะต่ำกว่าค่าที่ทำนายโดยใช้ทฤษฎี โดยความผิดพลาดที่เกิดขึ้นจะอยู่ในช่วง 3.16 - 6.69%

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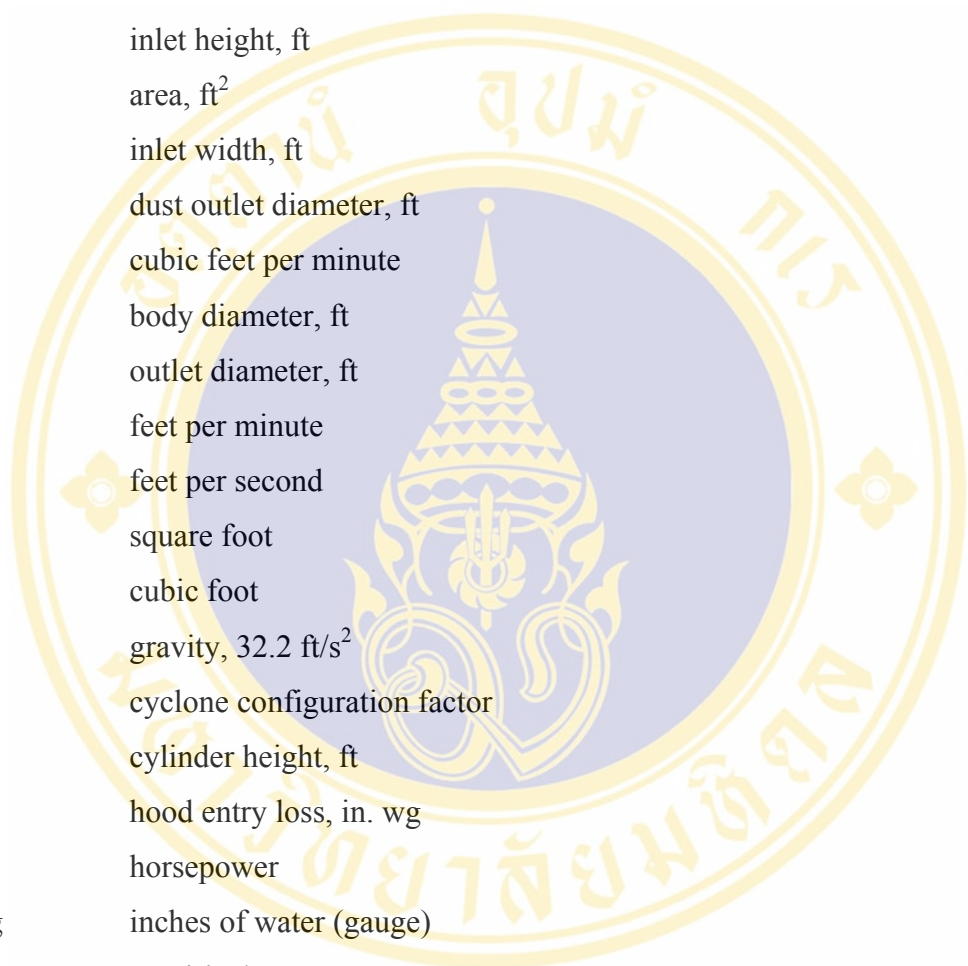
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## ABBREVIATIONS



|                   |                                 |
|-------------------|---------------------------------|
| a                 | inlet height, ft                |
| A                 | area, ft <sup>2</sup>           |
| b                 | inlet width, ft                 |
| B                 | dust outlet diameter, ft        |
| cfm               | cubic feet per minute           |
| D, Dc             | body diameter, ft               |
| De                | outlet diameter, ft             |
| fpm               | feet per minute                 |
| ft/s              | feet per second                 |
| ft <sup>2</sup>   | square foot                     |
| ft <sup>3</sup>   | cubic foot                      |
| g                 | gravity, 32.2 ft/s <sup>2</sup> |
| G                 | cyclone configuration factor    |
| h                 | cylinder height, ft             |
| he                | hood entry loss, in. wg         |
| HP                | horsepower                      |
| in. wg            | inches of water (gauge)         |
| K                 | empirical constant              |
| kPa               | kilopascal                      |
| l                 | natural length                  |
| mg/m <sup>3</sup> | milligram per cubic meter       |
| ME                | Mechanical Efficiency           |
| n                 | vertex exponent                 |
| N <sub>H</sub>    | number inlet velocity head      |
| ΔP                | pressure drop, Pa               |
| Pa                | pascal                          |

## ABBREVIATIONS (Continued)

|                |   |
|----------------|---|
| Q              | gas flow rate, cfm or ft <sup>3</sup> /s                  |
| rpm            | revolutions per minute                                    |
| s              | second  |
| S              | outlet length, ft   |
| SP             | static pressure, in. wg                                   |
| SPf            | fan static pressure, in wg                                |
| SPi            | inlet static pressure, in. wg                             |
| SPo            | outlet static pressure, in. wg                            |
| μm             | micrometer, micron  |
| η <sub>i</sub> | grade efficiency, %                                       |
| η <sub>T</sub> | overall collection efficiency, %                          |
| v <sub>i</sub> | inlet velocity, ft/s                                      |
| v <sub>s</sub> | saltation velocity, ft/s                                  |
| V              | Velocity, ft/s  |
| VP             | velocity pressure, in. wg                                 |
| VPd            | duct velocity pressure, in. wg                            |
| ω              | omega, ft/s   |
| ρ              | density, lb/ft <sup>3</sup>                               |
| μ              | viscosity, lb/ft.s  |
| τ              | relaxation time, s  |
| ACGIH          | American Conference of Governmental Industrial Hygienists |
| NIOSH          | National Institute for Occupational Safety and Health     |
| OSHA           | Occupational Safety and Health Administration             |
| PEL            | Permissible Exposure Limit                                |
| REL            | Recommended Exposure Limit                                |
| TLV            | Threshold Limit Value                                     |
| TLV-TWA        | Threshold Limit Value-Time Weighted Averages              |

## CHAPTER I

### INTRODUCTION

#### 1.1 Background and Rationale

At present, Industries in Thailand are growing rapidly lead to increasing constructed of many industrial areas. As a result, most people have more income from industrial investment. However, this situation not only gain the economic but also increase problems which are created from production process that might be affected to environment and workers health. Especially the process emitted dust or particulate to the atmosphere such as sanding process in reinforced plastic industry.

Reinforced plastic industry was growing up in Thailand for 20 years. Due to the benefits of reinforced plastic or fiberglass in terms of low cost and high efficiency so in the early period fiberglass can be used to reinforce cement and automotive boat. After that, it can be used to reinforce automobile materials, chair, windsurf and surfboard (1). In order to make reinforced plastic product, all of products have to be decorated shape by sand paper called sanding process which is released many fiber glass and polyester resin dust into the atmosphere.

Possick and Gellin (2) evaluated fiberglass manufacturing operation and found skin irritation among the workers and reported that more than 5 % of 4,000 workers leave job for 2 weeks because of skin irritation. Related to the study of Stam-Werkentin & et al (3) and Pertersen & Sabore (4) found that exposure to fiber glass can be induced skin, upper respiratory tract, and eyes irritation. Moreover, the cross sectional study of Weill & et al indicated the relationship between fiberglass and respiratory tract disorder. For polyester resin dust, the safety data sheet from the supplier suggested that skin irritation may occur and prolonged exposure possibly developing dermatitis (5). If eczematous develops, this most often occurs on the back of hands, wrists and forearms. Individuals with chronic respiratory conditions (i.e., asthma, chronic bronchitis, emphysema, etc.) may be adversely affected by any fume or airborne particulate matter exposure (6).

Ministry of Interior, Thailand, has the declaration of occupational standard for airborne fiber glass in air by classified it as nuisance dust. The recommended Threshold Limit Values-Time-Weighted Averages (TLV-TWA) are  $5 \text{ mg/m}^3$  of air for respirable dust and  $15 \text{ mg/m}^3$  of air for total dust (7). The Occupational Safety and Health Administration of the United State has the same recommendation and has no special method for control (8). In addition, The National Institute for Occupational Safety and Health (9) and American Conference of Governmental Industrial Hygienists (10) also have the strictly recommended TLV-TWA of total dust for fiber glass which is  $10 \text{ mg/m}^3$  in air.

Antousson & Runmark (11) found that reinforced plastic workers were exposed respirable dust of fiberglass 90-300% of TLV. Related to the researcher's survey found that the workers who work in surfboard sanding process were exposed respirable dust of fiber glass and polyester resin more than  $5 \text{ mg/m}^3$  that means their exposure are exceed the allowable standard of Ministry of Interior.

The researcher, the industrial hygienist, recognized this problem and would like to find the solution for reduce or remove dust that can be affected worker health and work environment. For this study, designed and constructed of suitable dust collector is needed. Due to the variety type of dust collector, for examples, cyclone, bag filter, electrostatic precipitator and scrubber, are different in advantages and disadvantages (12,13,14). Therefore, dust characteristics, collection efficiency, initial and operating cost will be considered. Dust sampling from surfboard industry indicated that the surfboard sanding process generates dust in wide size range. The previous studies suggested that bag filter was widely used because it can treat fine dust, however, easily obstruction from big size dust and that leads to pay high operating cost. Whereas the single high-efficiency cyclone can only handle coarse dust (15,16).

Considering of dust characteristics which generated from fiberglass surfboard sanding process and the cost-effective of dust collector, the researcher would like to study the collection efficiency of designed and constructed multi-cyclone for dust removal in surfboard sanding process. Then, finding the relationship between its collection efficiency and airflow rate.

## 1.2 Objectives

1. To study dust characteristics from fiberglass surfboard sanding process.
2. To design and construct multi-cyclone for dust removal in surfboard sanding process.
3. To determine collection efficiency of the constructed multi-cyclone.
4. To compare collection efficiency of the constructed multi-cyclone against different airflow rate.

## 1.3 Hypotheses

1. The constructed multi-cyclone has collection efficiency at least 85 percent for dust removal in surfboard sanding process.
2. The collection efficiency of the constructed multi-cyclone is related to airflow rate.

## 1.4 Variables

### 1.4.1 Independent variable

- Airflow rate

### 1.4.2 Dependent variable

- Collection efficiency of multi-cyclone

### 1.4.3 Extraneous variables

- Dust properties
- Dust size distribution
- Material of multi-cyclone construction

### 1.4.4 Environmental variables

- Temperature
- Air velocity

(In working area)

## 1.5 Scope and Limitation of study

The purpose of the research was to studies the collection efficiency of constructed multi-cyclone for dust removal in fiberglass surfboard sanding process. The multi-cyclone was composed of nine high-efficiency cyclones with axial inlet airflow which

body diameter was 6 inches and arranged in parallel. Dimensions and shapes were calculated based on the hypothesis of Stairmand. The collection efficiency estimation was used theory of Leith and Licht. Then, it was setting up with local exhaust ventilation system that table hood and duct were designed by the recommended of the American Conference of Governmental Industrial Hygienists (ACGIH) Industrial Ventilation Manual. After that, they were tested for dust collection efficiency at 3 levels of airflow rate as follows 1,200-1,250, 1,400-1,450, and 1,600-1,650 cfm respectively. For experimental procedure, surfboard was polished by the electrical disc sander (rational speed was 3,800 rpm with sandpaper No. 100).

### 1.6 Glossary of terms and definitions

**Dust:** Small solid particles created by the breaking up of larger particles by surfboard sanding process.

**Surfboard sanding process:** A surfboard making process used the electric sander to decorate surfboard, which released fiberglass and polyester resin dust into the workplace environment.

**Multi-cyclone:** A dust collector device to remove dust from exhaust system before discharge to outdoors. It consists of nine tubes of high-efficiency cyclone installed in parallel.

**Dust collector:** An air-cleaning device to remove heavy particulate loading from exhaust systems before discharge to outdoors.

**Pressure drop:** The difference in static pressure measured at two locations across the multi-cyclone or in a ventilation system; caused by friction or turbulence.

**Collection efficiency:** The percentage of dust removed and retained from air by a dust collector device, multi-cyclone.

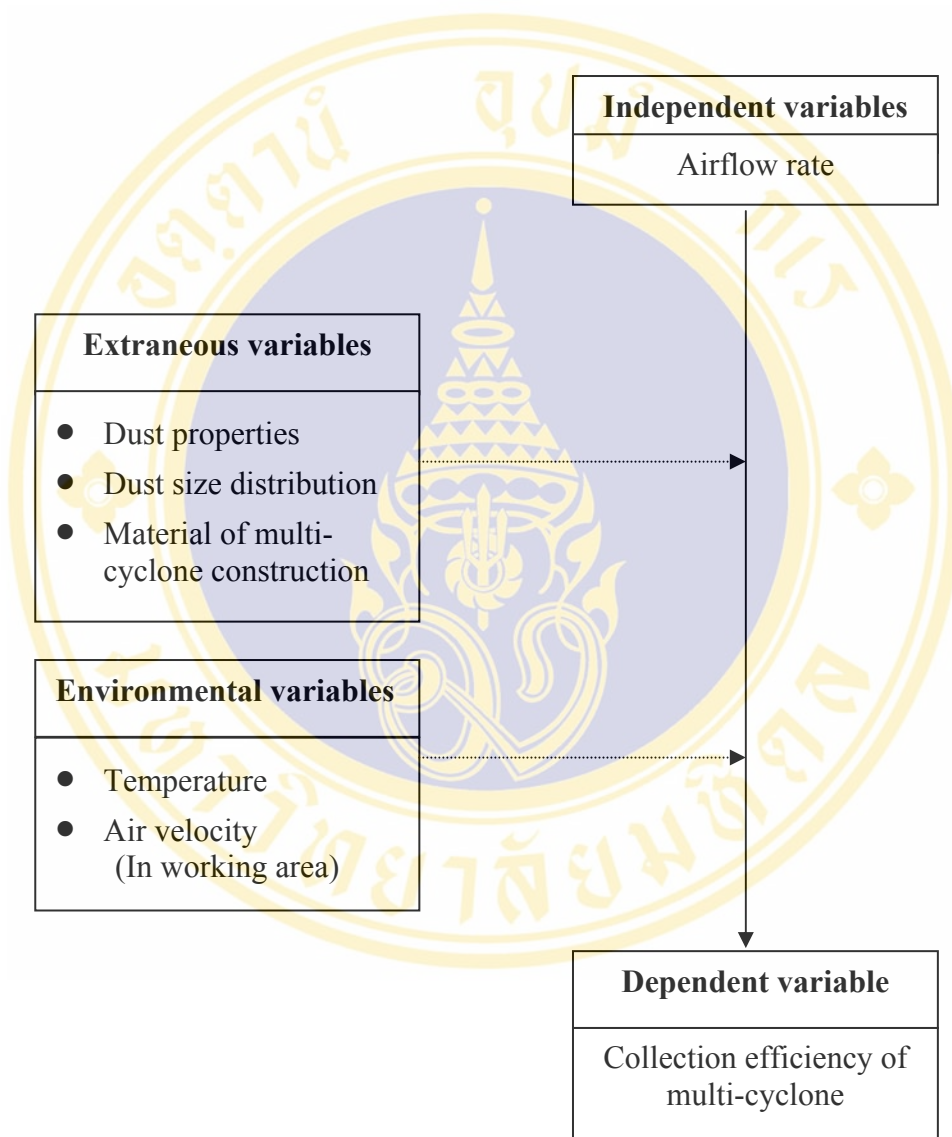
**Local exhaust ventilation system:** A system is designed to capture and remove process emissions prior their escape into the workplace environment. The system composes of hood, duct system, air-cleaning device, and fan.

**Hood:** A shaped inlet designed to capture contaminated air and conduct it into the exhaust duct system.

**Duct system:** A passageway made of sheet metal or other suitable material, not necessarily leak tight, used for conveying air or other gas at low pressures.

**Fan:** An air-moving device in the exhaust ventilation system, energy is required to overcome the system losses.

### 1.7 Conceptual framework



## CHAPTER II

### LITERATURE REVIEW

#### 2.1 Surfboard manufacturing

Surfboard manufacturing by using polyurethane foam and fiberglass or reinforced plastic began before World War II (18). Due to surfing is the famous water sport in Europe, most of surfboard manufacturing was established in Europe and Australia. For country in Southeast Asia, Thailand is the only country having this industry and exporting product more than 50% of all products in the world (19).

To produce surfboard, many processes can be affected worker health and environment. For example, sanding process that is releasing fiberglass and polyester resin dust to the atmosphere. These hazardous dusts can cause worker respiratory irritation, eye irritation and skin dermatitis (3,5,6). Moreover, it also lead to air pollution when releasing in high concentration.

#### 2.2 Fiberglass

Fiberglass is a man-made vitreous fibers (MMVF) made from hot and liquid (molten) glass or sand. Other names for fiberglass are fibrous glass and glass fibers. Silicon dioxide ( $\text{SiO}_2$ ) is the principal constituent (comprising 40 to 70%) of most MMVF. Lesser amounts of "intermediate oxides", such as  $\text{Al}_2\text{O}_3$ ,  $\text{TiO}_2$ , and  $\text{ZrO}_2$  and "modifiers" such as  $\text{MgO}$ ,  $\text{Li}_2\text{O}$ ,  $\text{BaO}$  and  $\text{CaO}$  are also present. Compositions can vary considerably, depending in part upon the characteristics requires in the final product (4).

There are two general types of fiberglass: continuous filament glass and glass wool. Continuous filament glass fibers are made by pulling molten glass through small holes. Continuous filament glass fibers can be twisted together to form yarn that is used to weave fiberglass fabric. Fiberglass fabric reinforces plastics, foams, and other materials used in the manufacture of boats, automobile bodies, and other products. Most types of continuous filament glass fibers have large diameters (6-15  $\mu\text{m}$ ). Glass wool fibers are made by blowing or spinning molten glass through small holes. Glass wool fibers are

widely used for thermal and sound insulation in commercial and residential buildings and typically have smaller diameter (1-10  $\mu\text{m}$ ) than continuous filament glass fibers (3).

The primary routes of potential human exposure to fiberglass are inhalation and dermal contact. Large-diameter (greater than 3.5  $\mu\text{m}$ ) glass fibers have been found to cause skin, eye, and upper respiratory tract irritation. Smaller-diameter fibers have the ability to penetrate the alveoli. This potential is cause for concern and is the primary reason that the fibers are subject to special controls. (20)

In 1995, The Research and Consulting Company (RCC) of Geneva, Switzerland studied in the rat found that no significant adverse effects in hamsters exposed to a very high concentration of the insulation glass wool fiber. However, early in the study, some of the hamsters exposed to a very high concentration of the special application fiber developed pulmonary fibrosis, and one of the animals shown signs of a cancer of the lining of the lung (21). Related to the study of International Agency Research Center (IARC) demonstrated carcinogenic effects in animals whose exposed with long (greater than 10  $\mu\text{m}$ ) and thin fibers (usually less than 1  $\mu\text{m}$  in diameter) (20). Moreover, previous study found that combination exposure of fiberglass and others chemical substance such as styrene and radon can caused higher toxicity (9).

During 1960-1962, 691 instances of occupational disease attributed to fiberglass exposure were reported in California, which annually receives over 30,000 case reports of occupational disease. Of the 691 cases, 38 were primarily respiratory tract irritation (9). In addition, the study of Possick et al in 1970 found that 5 % of the 4,000 workers who exposed fiberglass quit them job within 2 weeks due to skin irritation. The cross sectional study (1984) showed the relation between workers who exposed fiberglass and their respiratory system disorder. Related to the studies of Petersen and Sabroe (1991) and Stam-Werkentin et al (1994) found that exposed fiberglass can cause skin, eye, and upper respiratory irritation (9).

In 2001, an international review by International Agency for Research on Cancer (IARC) re-evaluated the 1988 IARC assessment of glass fibers. They removed glass fibers from its list of possible carcinogens by downgrading the classification of these fibers from Group 2B (possible carcinogen) to Group 3 (not classifiable as to carcinogenicity in humans). Since the conclusion reached by the U.S. National Academy of Sciences in 2000 found "no significant association between fiber exposure and lung

cancer or nonmalignant respiratory disease in the MMVF manufacturing environment (22).

The North American Insulation Manufacturers Association (NAIMA) exposure database currently includes data collected from a variety of sources, including manufacturers, contractors, academic institutions and third-party organizations suggested that Time-Weighted Average (TWA) exposure level in insulation industry range from 0.02 to 0.35 fibers/cc (21).

Jacob et al (23) have studied about airborne glass fiber concentrations during manufacturing operations involving glass wool insulation in 11 manufacturing operations found that the airborne concentrations of fibers range from 0.02 to 0.2 fibers/cc. Although this concentration was lower than OSHA recommendation, the researcher suggested that avoiding skin irritation, the recommended work practices of manufacturer should be followed. In addition, NIOSH recommends that workers subject to fiberglass exposure have comprehensive preplacement medical examinations with emphasis on skin susceptibility and prior exposure industry trades. Subsequent annual examinations should give attention to the skin and respiratory system with attention to pulmonary function (20).

Antonsson and Runmark (11) investigated the presence of respirable glass fibers in the dust from grinding, drilling and cutting of reinforced polyester plastics. The results showed that 10% of the Swedish Threshold Limit Value (TLV) for synthetic inorganic fibers seldom would be exceeded. All of the measurements of personal exposure to any kind of work involving reinforced plastics shown a mean concentration of dust from 97% to 300% of the TLV.

According to the provisions in the Health and Safety Partnership Program (HSPP) of NAIMA, any exposure to airborne respirable fibers in excess of the 1 fiber/cc permissible exposure limit averaged over an 8-hour workday will need controls to reduce exposures below the PEL. Engineering controls are preferred, but if these are not feasible or practical, then property used respiratory protection can be an effective control (21).

There have no directly recommended for airborne fiberglass in air in Thailand. However, Ministry of Interior has the declaration of occupational standard by classified it as nuisance dust. The recommended Threshold Limit Value-Time-Weighted Averages (TLV-TWA) are 5 mg/m<sup>3</sup> of air for respirable dust and 15 mg/m<sup>3</sup> of air for total dust (7).

The Occupational Safety and Health Administration (8) of the United State have the same recommended and which is 1 fiber/cc by using phase contrast microscopy. The National Institute for Occupational Safety and Health (9) and American Conference of Governmental Industrial Hygienists (10) also have the strictly recommended TLV-TWA of total dust for fiberglass which is 10 mg/m<sup>3</sup> in air.

### 2.3 Unsaturated polyester resin

Unsaturated polyester resin is a liquid plastic. It is widely used in fiberglass reinforced plastics product due to its low cost, high efficiency, durability and easy to mold. Generally, inactive form of unsaturated polyester resin looks alike engine oil and has strong flavor. When mixing with some chemical substance, it will change to active form, clear solid plastic, which has different color depend on its type. The five types of polyester resin are follow: 1) Ortho-phthalic acid, 2) Isophthalic acid, 3) Terephthalic acid, 4) Bisphenol-A, and 5) Vinylester. Unsaturated polyester resin is composed of monostyrene or styrene monomer extracted from benzene and ethylene. Monostyrene is used as an active solvent for polymerization reaction. Also it can be put in polyester resin and jell coat in order to easily spray and paint.

In surfboard manufacturing, polyester resin, Bisphenol-A type, are used in laminating process. After that, laminated surfboard will be take to sanding room for sanding decoration. In this process, it released mixed of polyester resin and fiberglass dusts having yellowish color and moderate flavor to the air (1).

Inhalation of polyester resin vapor may cause drowsiness, nausea, headache, fatigue, narcosis and dizziness. Moreover, severe exposure may cause a confused state. Irritation of the mucous membranes of the upper respiratory tract may occur. Irritation of skin may occur, with prolonged exposure possibly developing dermatitis. If eczematous develops, this most often occurs on the back of hands, wrists and forearms and may be absorbed through the skin. In addition, eye contact may cause an irritation of the mucous membranes, pain and redness. Individuals with chronic respiratory conditions (i.e., asthma, chronic bronchitis, emphysema, etc.) may be adversely affected by any fume or airborne particulate matter exposure (5,6).

ACGIH classified polyester resin dusts as nuisance dust, TLV-TWA is  $3 \text{ mg/m}^3$  for respirable dust and  $10 \text{ mg/m}^3$  for total dust (10). Nowadays, PEL of OSHA, REL of NIOSH and Thai law have not established for polyester resin dust.

## 2.4 Air cleaning devices (17)

Air cleaning devices remove contaminants from an air or gas stream. They are available in a wide range of designs to meet variations in air cleaning requirements. Degree of removal required, quantity and characteristics of the contaminant to be removed, and conditions of the air or gas stream will all have a bearing on the device selected for any given application. In addition, fire safety and explosion control must be considered in all selections.

For particulate contaminants, air cleaning devices are divided into two basic groups: air filters and dust collectors. Air filters are designed to remove low dust concentrations of the magnitude found in atmosphere air. They are typically used in ventilation, air-conditioning, and heating systems where dust concentration seldom exceed  $2 \text{ mg/m}^3$  of air and are usually well below  $0.2 \text{ mg/m}^3$ . Dust collectors are usually designed for the much heavier loads from industrial processes where the air or gas to be cleaned originates in local exhaust systems or process stack gas effluents. Contaminant concentrations will vary from less than 230 to  $230,000 \text{ mg/m}^3$  or more for each cubic meter of air or gas. Therefore, dust collectors are, and must be, capable of handling concentrations 100 to 20,000 times greater than those for which air filters are designed.

### 2.4.1 Selection of dust collection equipment

Dust collection equipment is available in numerous designs utilizing many different principles and featuring wide variation in effectiveness, first cost, operating and maintenance cost, space, arrangement, and materials of construction. Factors influencing equipment selection include the following:

**2.4.1.1 Contaminant concentration:** Contaminants in exhaust systems cover an extreme range in concentration and particle size. Concentrate can range from less than 230 to much more than 230 kg of dust per cubic meter of air. In low pressure conveying systems, the dust ranges from 0.5 to 100 or more micrometers in size.

Deviation from mean size (the range over and under the mean) will also vary with the material.

**2.4.1.2 Efficiency required:** Currently, there is no accepted standard for testing and/or expressing the "efficiency" of a dust collector. It is virtually impossible to accurately compare the performance of two collectors by comparing efficiency claims. The only true measure of performance is the actual mass emission rate, expressed in terms such as  $\text{mg}/\text{m}^3$ . Evaluation will consider the need for high efficiency-high cost equipment requiring minimum energy such as high voltage electrostatic precipitators, high efficiency-moderate cost equipment such as fabric or wet collectors, or the lower cost primary units such as the dry centrifugal group. If either of the first two groups is selected, the combination with primary collectors should be considered. When the cleaned air is to be discharged outdoors, the required degree of collection can depend on plant location; nature of contaminant (its salvage value and its potential as a health hazard, public nuisance, or ability to damage property); and the regulations of governmental agencies. Moreover, a safe recommendation in equipment selection is to choose the collector that will allow the least possible amount of contaminant to escape and is reasonable in first cost and maintenance while meeting all prevailing air pollution regulations. For some applications even the question of reasonable cost and maintenance must be sacrificed to meet established standards for air pollution control or to prevent damage to health or property.

**2.4.1.3 Gas stream characteristics:** The characteristics of the carrier gas stream can have a marked bearing on equipment selection. Temperature of the gas stream may limit the material choices in fabric collectors. Condensation of water vapor will cause packing and plugging of air or dust passages in dry collectors. Corrosive chemicals can attack fabric or metal in dry collectors and when mixed with water in wet collectors can cause extreme damage.

**2.4.1.4 Contaminant characteristics:** The contaminant characteristics will also affect equipment selection. Chemicals emitted may attack collector elements or corrode wet type collectors. Sticky materials, such as metallic buffing dust impregnated with buffing compounds, can adhere to collector elements, pluffign collector passages. Linty materials will adhere to certain types of collector surfaces or elements. Abrasive materials in moderate to heavy concentrations will cause rapid wear on dry metal

surfaces. Particle size, shape, and density will rule out certain designs. For example, the parachute shape of particles like the "bees wings" from grain will float through centrifugal collectors because their velocity of fall is less than the velocity of much smaller particles having the same specific gravity but a spherical shape. The combustible nature of many finely divided materials will require specific collector designs to assure safe operation.

**2.4.1.5 Energy consideration:** The cost and availability of energy makes essential the careful consideration of the total energy requirement for each collector type which can achieve the desired performance. An electrostatic precipitator, for example, might be a better selection at a significant initial cost penalty because of the energy savings through its inherently lower pressure drop.

**2.4.1.6 Dust Disposal:** Method of removal and disposal of collected materials will vary with the material, plant process, quantity involved, and collector design. Dry collections can be unloaded continuously or in batches through dump gates, trickle valves, and rotary locks to conveyors or containers. Dry materials can create a secondary dust problem if careful thought is not given to dust-free material disposal or to collector dust bin locations suited to convenient material removal.

## **2.4.2 Dust collector types (17)**

The four major types of dust collectors for particulate contaminants are electrostatic precipitators, fabric collectors, wet collectors, and dry centrifugal collectors.

**2.4.2.1 Electrostatic precipitators:** In electrostatic precipitation, a high potential electric field is established between discharge and collecting electrodes of opposite electrical charge. The discharge electrode is of small cross-sectional area, such as a wire or a piece of flat stock, and the collection electrode is large in surface area such as a plate. The gas to be cleaned passes through an electrical field that develops between the electrodes. At a critical voltage, the gas molecules are separated into positive and negative ions. This is called "ionization" and takes place at, or near, the surface of the discharge electrode. Ions having the same polarity as the discharge electrode attach themselves to neutral particles in the gas stream as they flow through the precipitator. These charged particles are then attracted to a collecting plate of dust particles lose their charge and then can be easily removed by washing, vibration, or gravity.

**2.4.2.2 Fabric collectors:** Fabric collectors remove particulate by straining, impingement, interception, diffusion, and electrostatic charge. The " fabric" may be constructed of any fibrous material, either natural or man-made, and may be spin into a yarn and woven or felted by needling, impacting, or bonding. Woven fabrics are identified by thread count and by thickness and weight of fabric per unit area. Non-woven (felts) are identified by thickness and weight per unit area. Regardless of construction, the fabric represents a porous mass through which the gas is passed unidirectionally such that dust particles are retained on the dirty side and the cleaned gas passes on through.

**2.4.2.3 Wet collectors:** Wet collectors, or scrubbers, are commercially available in many different designs, with pressure drop from 375 Pa to as much as 25 kPa. There is a corresponding variation in collector performance. It is generally accepted that, for well-designed equipment, efficiency depends on the energy utilized in air to water contact and is independent of operating principle. Efficiency is a function of total energy input per unit of volumetric flow rate whether the energy is supplied to the air or to the water. This means that well-designed collectors by different manufacturers will provide similar efficiency if equivalent power is utilized.

**2.4.2.4 Dry centrifugal collectors:** Dry centrifugal collector, or cyclone, separate entrained particulate from an air stream by the use or combination of centrifugal, inertial, and gravitational force. It is commonly used for the removal of coarse dust from an air stream, as a precleaner to more efficient dust collectors. Principal advantages are low cost, low maintenance, and relatively low pressure drops. However, it is not suitable for the collection of fine particles (24).

**Table 2-1 Advantages, Disadvantages, and Collection Efficiency of each Dust Collector Type (17,24,25)**

| Type                       | Particle Size ( $\mu\text{m}$ ) | Collection Efficiency (%) | Advantages   | Disadvantages  |
|----------------------------|---------------------------------|---------------------------|--|--|
| Dry centrifugal Cyclone    | 5-25                            | 50-90                     | <ul style="list-style-type: none"> <li>- simple structure</li> <li>- low initial cost</li> <li>- low maintenance cost</li> <li>- low to medium pressure drop</li> <li>- continuous releasing dust</li> <li>- can treat high dust load</li> <li>- not depend on temperature</li> <li>- small space requirement</li> <li>- suitable for coarse dust</li> </ul> | <ul style="list-style-type: none"> <li>- not suitable for coarse dust</li> <li>- sensitivity to dust load and gas flow rate</li> <li>- require many gas inlet chamber</li> </ul> |
| Fabric                     | < 1                             | > 99                      | <ul style="list-style-type: none"> <li>- simple to detect abnormal function</li> <li>- high collection efficiency</li> <li>- suitable for fine dust</li> </ul>   | <ul style="list-style-type: none"> <li>- not suitable for coarse dust</li> <li>- not suitable for high temperature and moisture gas</li> </ul>                                   |
| Electrostatic Precipitator | > 1                             | 95-99                     | <ul style="list-style-type: none"> <li>- using in both wet and dry systems</li> <li>- low pressure drop</li> <li>- medium maintenance cost</li> <li>- can treat high temperature gas</li> <li>- high collection efficiency</li> <li>- suitable for fine dust</li> </ul>  | <ul style="list-style-type: none"> <li>- high initial cost</li> <li>- sensitivity to dust load and gas flow rate</li> <li>- not suitable for explosive dust</li> </ul>           |
| Wet scrubber               | > 0.5                           | 80-99                     | <ul style="list-style-type: none"> <li>- minimizes a secondary dust</li> <li>- handle high-temperature and moisture-laden gas</li> <li>- suitable for corrosive gas</li> </ul>   | <ul style="list-style-type: none"> <li>- high operating cost</li> <li>- high maintenance cost</li> <li>- wastewater treatment cost</li> </ul>                                    |

The sampling data that the researcher collected from surfboard manufacturing found that surfboard sanding process is released high concentration dust to the air. The dust samples are analyzed by using the particle size distribution analyzer (Mastersizer S, Malvern Instruments Ltd., UK) which have laser light scattering technique. Size distribution of dust samples range from 1 to 594.3  $\mu\text{m}$  and 85 percent of this dust have

size more than 12  $\mu\text{m}$ . Therefore, dust collector will handle wide range size of dust before release to the atmosphere. The selected dust collector is multi-cyclone because it has many advantages such as simple structure easy to construct, low initial and maintenance cost, low energy lost, high collection efficiency, and suitable for dust characteristics which are emitted from surfboard sanding process.

## 2.5 Cyclone performance

### 2.5.1 Cyclone structure (12)

There are four major parts to a cyclone: inlet, cyclone body, dust discharge system, and outlet (Figure 2-1).

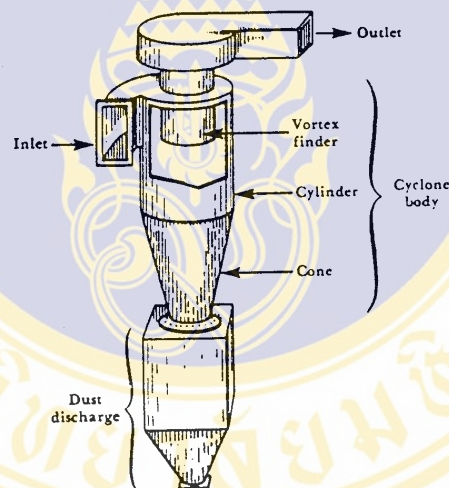
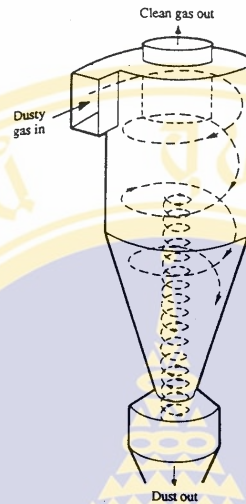


Figure 2-1 Cyclone Structure

### 2.5.2 Cyclone operating principles

Cyclones have no moving parts and come in many sizes and shapes. Regardless of this fact, the basic separation principle remains the same by the action of centrifugal force (12,26). The dust-laden gas enters the body tangentially and spirals downwards in a vortex motion (Figure 2-2). At the base of the unit the direction of axial flow reverses and the cleaned gas leaves the unit axial by spinning upwards in a tight, fast, central vortex.

Particles, which have moved to the wall, pass down to the hopper where they are removed (14).



**Figure 2-2 Cyclone Operating Principles**

The three forces acting on individual dust particles are gravitational, centrifugal, and frictional drag. The gravitational force is defined by Stokes law as applied to freely falling bodies. The frictional drag on a dust particle is caused by the relative motion of the particle and the gas and opposed the centrifugal forces acting on the particle. The major force causing separation of the dust particles from the gas stream is the centrifugal force induced by rotation of the dust-laden gas stream within the collector. The gravitational, centrifugal, and frictional forces combine to determine the particle path and performance ability (26).

The operating characteristics of the cyclonic separator can be determined by an examination of the formula for centrifugal force:

$$F = \frac{Mv^2}{r} \quad (2.1)$$

where  $F$  = centrifugal force exerted on particle  
 $M$  = particle mass  
 $v$  = particle velocity  
 $r$  = radius of dust particle path

In this expression the inertial force responsible for separation of the dust particle from the gas stream is proportional to the particle mass. Actually, both the particle specific gravity and its size and shape influence the mass value. The inertial force varies directly as the square of the velocity. Higher velocities are accompanied by increased pressure drops across the cyclone, as defined by the expression  $V = (2gh)^{1/2}$ , where  $h$  is the velocity pressure head and  $g$  is the gravity acceleration constant. Therefore, the initial force varies directly as the pressure drop across the collector. The developed inertial forces in a cyclone are inversely proportional to the cyclone radius, which confirms the fact that the large diameter cyclones yield very low collection efficiencies as compared to the smaller multiple-tube type.

The ratio of centrifugal force to the force of gravity can be expressed as

$$S = \frac{v^2}{rg} \quad (2.2)$$

where

$S$  = separation factor

$v$  = inlet velocity

$r$  = cyclone cylinder radius

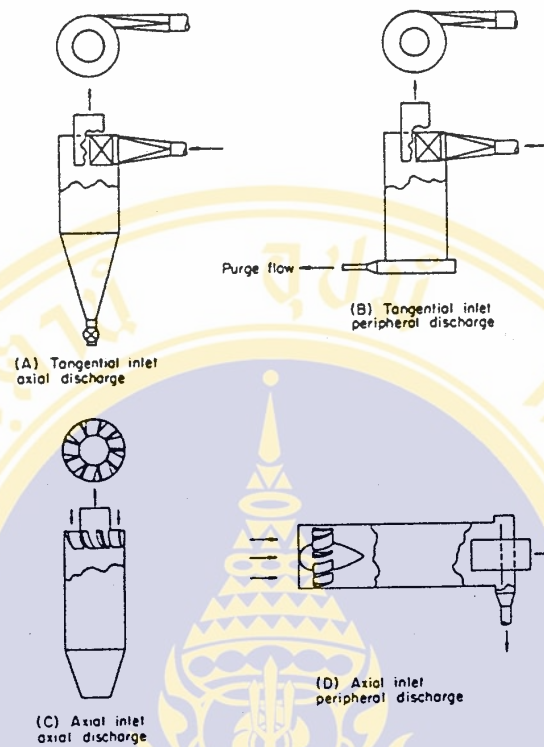
$g$  = gravitational constant

The separation factor, a dimensionless quantity, cannot be directly corrected to the collection efficiency. However, for cyclones of similar design and application, collection efficiency essentially varies directly as the separation factor. In practice, this factor varies from 5 for large diameter cyclones to 2500 for small multitube collectors (26).

### 2.5.3 Cyclone types

Cyclones are usually classified in four categories (Figure 2-3), depending on how the gas stream enters and leaves the unit (15):

- (1) tangential inlet with axial dust discharge
- (2) tangential inlet with peripheral dust discharge
- (3) axial inlet through swirl vanes with axial dust discharge
- (4) axial inlet through swirl vanes with peripheral dust discharge



**Figure 2-3 Cyclone Types**

When classified based on their collection efficiency, cyclones are divided into two types: high-efficiency cyclones and high-throughput cyclones (27).

For high-efficiency cyclone, the inlet gas velocity is higher thereby imparting a higher centrifugal force. They are generally less than 1 ft in diameter and have long cones. Heavy particles reach the wall of the cyclone with much smaller angular movement whereas lighter particles travel through a much greater angle to reach the wall, therefore requiring longer cones.

For high-throughput cyclone or conventional cyclone, diameters are generally larger, efficiencies moderate to lower, and they can handle larger flow rates. The ratio of gas volume to capital investment dollar is greater than for any other cleaning device. Applications of high-throughput cyclones include operations such as grinding, buffing, fiber processing, and wood chip separation. In high-throughput cyclones, particles greater than 50  $\mu\text{m}$  are collected with great efficiency.

As everybody knows, high-efficiency cyclone has collection efficiency more than conventional cyclone. However, no one can mention that how many different they are because many factors should be considered. In any case, we can compare their collection efficiency if we test by the same particle type, size range, and size distribution (Table 2-2) (28).

**Table 2-2 Collection Efficiency Ranges of Cyclones**

| Particle size range<br>(µm) | Collection efficiency (%) |                      |
|-----------------------------|---------------------------|----------------------|
|                             | High-efficiency cyclone   | Conventional cyclone |
| Less than 5                 | Less than 50              | 50 - 80 (L)          |
| 5 - 20                      | 50 - 80 (L)               | 80 - 95 (M)          |
| 20 - 40                     | 80 - 95 (M)               | 95 - 99 (H)          |
| Greater than 40             | 95 - 99 (H)               | 95 - 99 (H)          |
| Remarks:                    | 50 - 80 %                 | Low efficiency, L    |
|                             | 80 - 95 %                 | Medium efficiency, M |
|                             | 95 - 99 %                 | High efficiency, H   |

Cyclones can be built as either single units or in multiples. They can also be arranged in series or in parallel (27).

For series arrangement (Figure 2-4), used when separation with higher efficiency is requires, higher flow rates of carrier gas are encountered, or when it is required to protect a smaller high efficiency cyclone from larger abrasive particles. Larger particles are then initially collected in lower-efficiency or larger cyclones. The efficiency of two cyclones in series can be expressed by:

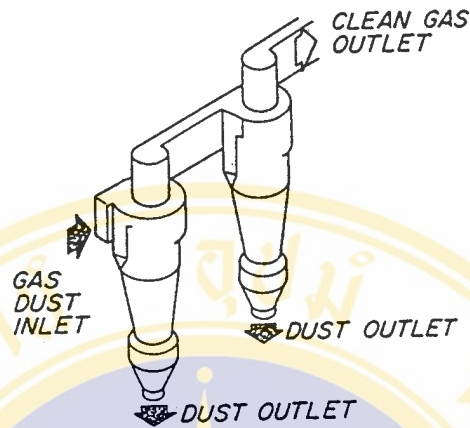
$$e = e_p + e_s (100 - e_p) \tag{2.3}$$

where

$e$  = overall efficiency

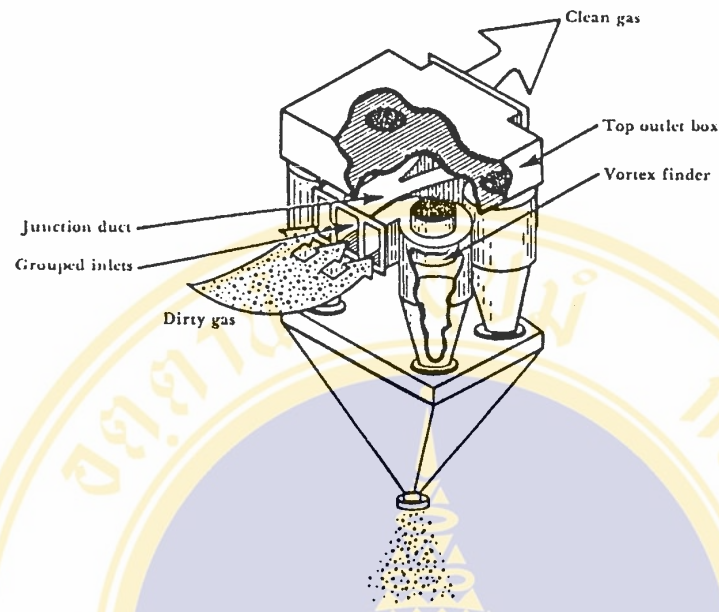
$e_p$  = efficiency of primary cyclone

$e_s$  = efficiency of secondary cyclone



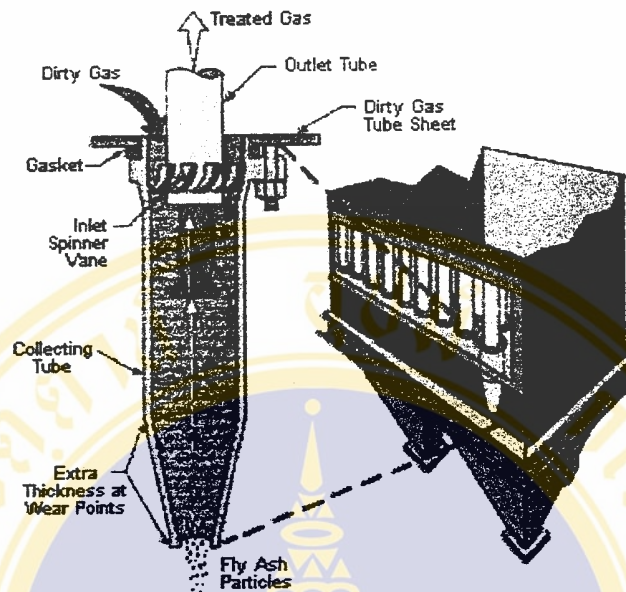
**Figure 2-4 Cyclones installed in Series**

For parallel arrangement (Figure 2-5), high volume of carrier gases, cyclones can be arranged in parallel by having a manifold to give uniform distribution of gas flow as well as particulate concentration. However, only one inlet and one outlet are used. Although parallel arrangements can handle larger gas flows than individual units, they can present difficulties. Care must be taken not to maintain excessive pressure differences between the various cyclone outlets feeding one hopper, because this can cause dust-entrained gas from the hopper to circulate between the cyclones and reduce overall efficiency, which will be less than that obtained from individual cyclones. This condition can be explained as follows: The cyclone which has lower pressure at the outlet will discharge more gas from the dust hopper than enters the cyclone. This means that gas in the ascending vortex will be greater; hence its velocity is increased but without any increase in radial velocity. This will reduce the efficiency of the cyclone. The problem can be solved by designing a manifold so that all cyclones are uniformly fed with an equal volume of carrier gas and with a uniform concentration of particulate. All cyclones feeding a common hopper should be identical in size and should operate under the same condition (27).



**Figure 2-5 Cyclones installed in Parallel**

When high efficiency (which requires small cyclone diameter) and large throughput are both desired, a number of cyclones can be operated in parallel. In a multi-cyclone separator, the housing contains a large number of tubes that have a common gas inlet and outlet in the chamber. The gas enters the tubes through axial inlet vanes that impart a circular motion. Due to the limited gas handling capacity of each tube, large numbers of tubes are mounted in parallel in a single collector (Figure 2-6) (24,29,30).



**Figure 2-6 Multi-cyclone**

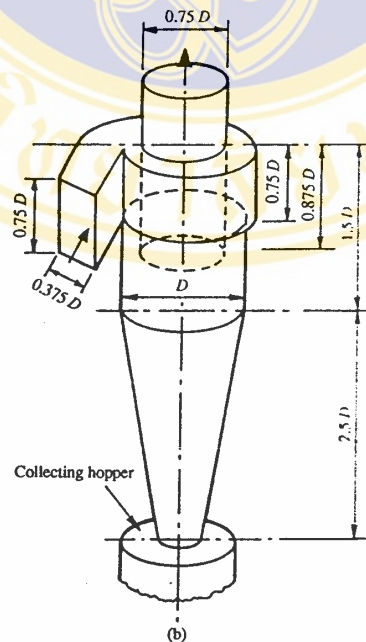
The arrangement of the tubes, as well as their diameter, affects the overall collection efficiency of a multi-cyclone. There is a small pressure drop in the incoming gas stream for each row of tubes it must pass; a decreasing length of outlet tube may be used to compensate for this, producing an organ-pipe arrangement. Alternatively, tubes can be arranged in groups, each with its own outlet plenum, and space in between the groups, which allows even and unimpeded gas flow to all tubes (29). The collection efficiencies for the small-diameter cyclones or collection tubes can be quite high with dusts that are  $5\ \mu\text{m}$  and larger (26).

#### 2.5.4 Cyclone Dimensions

The design of a cyclone separator represents a compromise among collection efficiency, pressure drop, and size. Higher efficiencies require higher pressure drops (i.e., inlet gas velocities) and larger sizes (i.e., body length) (31). In classical work that still serves as the basis for cyclone design, all dimensions were related to the body diameter ( $D_c$ ). There are several standard high efficiency cyclone dimensions which are shown in Table 2-3 (12,29,31). For example, standard high-efficiency cyclone designed by Stairmand is given on Figure 2-7 (12).

**Table 2-3 Dimensionless Design Ratios for High-Efficiency Cyclone**

|                          | Proportion (/D) |       |        |
|--------------------------|-----------------|-------|--------|
|                          | Stairman        | Swift | Lapple |
| D = body diameter        | 1.0             | 1.0   | 1.0    |
| a = inlet height         | 0.5             | 0.44  | 0.5    |
| b = inlet width          | 0.2             | 0.21  | 0.25   |
| S = outlet length        | 0.5             | 0.5   | 0.625  |
| De = outlet diameter     | 0.5             | 0.4   | 0.5    |
| h = Cylinder height      | 1.5             | 1.4   | 2.0    |
| H = Overall height       | 4.0             | 3.9   | 4.0    |
| B = dust outlet diameter | 0.375           | 0.4   | 0.25   |
| l = natural length       | 2.48            | 2.04  | 2.30   |
| G/N <sub>H</sub>         | 86.14           | 75.67 | 50.36  |



**Figure 2-7 High-efficiency Standard Cyclone Design**

### 2.5.5 Prediction of collection efficiency

Collection efficiency is a strong function of particle size and increases with increasing particle size. The collection efficiency of a single particle size can be determined by either a semi-empirical approach, developed by Lapple in 1951, or by one of several theoretical equations that have since been developed. For example, Leith and Licht developed an equation for collection efficiency from theoretical considerations that takes into account the back-mixing of uncollected particles and determines an appropriate average residence time for the gas in the cyclone (29).

Determination of the overall collection efficiency requires knowledge of the particle size distribution of the dust particles. Collection efficiencies for each size range are then weighted accordingly and the values summed (29).

#### 2.5.5.1 Theoretical approach

The basic of the simple theoretical derivation of efficiency is as follows: Particles enter with the gas stream, but tend to move outward under the influence of centrifugal force. This is resisted by the drag of the particles moving radially through the gas, and the resultant terminal or radial velocity of the particles is found by equating the centrifugal and drag forces. To be collected, particles must reach the outer wall before the gas leaves the outer vortex. The time and distance are both known: The time is the gas residence time, which depends on gas inlet velocity, radius of the cyclone, number of turns in the vortex, and the maximum value of the distance to be traveled is the length from the inner edge of the inlet to the outer wall. Assuming laminar flow, an expression is derived that relates the collection efficiency of the cyclone parameters and operating conditions:

$$\eta = \frac{\pi N_e \rho_p d_p^2 V_g}{9\mu W} \quad (2.4)$$

where

- $\eta$  = efficiency
- $N_e$  = effective number of turns
- $\rho_p$  = particle density
- $d_p$  = particle diameter
- $V_g$  = gas velocity
- $\mu$  = gas viscosity

This model indicates the strong dependence of efficiency on particle diameter (squared), the dependence on the number of vortex turns (related to the length of the cyclone) and inlet velocity, and the inverse dependence on cyclone inlet width, which is proportional to body diameter. However, the model predicts a finite value of particle diameter above which collection efficiency is 100% ("critical size"), whereas experimental evidence shows that efficiency approaches 100% asymptotically with increasing particle diameter (29).

There is a vast array of literature citing methods of predicting cyclone fractional efficiencies utilizing generalized equations. One of the best theoretical approaches is presented by Leith and Licht (13). For calculate fractional efficiencies, the equation is given by

$$\eta_i = 1 - \exp\{-2[(G\tau_i Q/Dc^3)(n+1)]^{0.5/(n+1)}\} \quad (2.5)$$

where  $\eta_i$  = Grade efficiency, %

$G$  = Cyclone configuration factor

$\tau$  = Relaxation time, sec

$n$  = Vortex exponent

$Q$  = Total gas flow rate, ft<sup>3</sup>/s

Moreover, they also give an expression for the cyclone vortex exponent:

$$n = 1 - [1 - (12Dc/2.5)^{0.14}][T + 460/530]^{0.3} \quad (2.6)$$

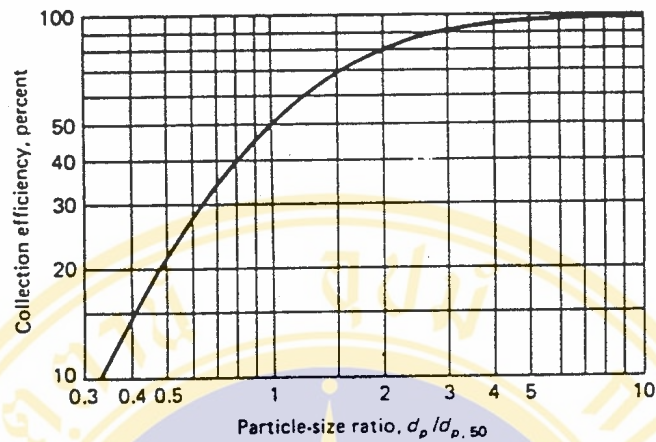
where  $n$  = Vortex exponent

$Dc$  = Cyclone diameter, ft

$T$  = Temperature, °F

### 2.5.5.2 Cut diameter approach

The semi-empirical approach developed by Lapple used this laminar flow treatment, but introduced the concept of a cut size,  $d_{p50}$ , defined as the size of particle that is collected with 50% efficiency. The value is a characteristic of the control device and operating conditions, not of the size range of the dust particles. Using experimental particle collection efficiency versus particle-size data, correlated for cyclones of standard proportions, he plotted a generalized curve, as shown in Figure 2-8.



**Figure 2-8 Cyclone Efficiency versus Particle-Size Ratio**

A particle whose collection efficiency is to be found is characterized by the ratio of its diameter,  $d_p$ , to the cut size,  $d_{p50}$ , which gives the value of the abscissa of the graph, and the collection efficiency is read from the ordinate. The value of the cut size is calculated from equation that mentioned before by setting efficiency equal to 0.5 and solving for  $d_p$ , which is now  $d_{p50}$  by definition:

$$d_{p50} = \left[ \frac{9\mu W}{2\pi N_e \rho_p V_g} \right]^{1/2} \quad (2.11)$$

Lapple's graph has been fitted to an algebraic equation by Theodore and De Paola, which makes it more convenient for computer applications:

$$\eta_j = 1/(1 + (d_{p50}/d_{pj})^2) \quad (2.12)$$

where  $d_{p50}$  = particle cut diameter

$d_{pj}$  = particle diameter in range  $j$

$\eta_j$  = fractional efficiency in range  $j$

Collection efficiency of cyclone is depending on many factors. In general, cyclone efficiency increases with an increase in the following (15,25,31,32):

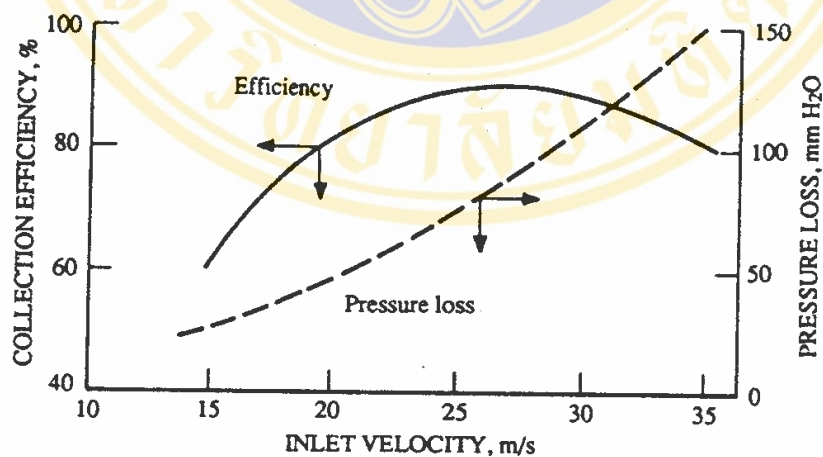
- 1) particle size
- 2) particle density
- 3) inlet gas velocity

- 4) cyclone body length
- 5) number of gas revolutions
- 6) smoothness of inner cyclone wall

An increase in the following will decrease the overall efficiency:

- 1) gas viscosity
- 2) cyclone diameter
- 3) gas outlet diameter
- 4) gas inlet area

The efficiency of dust removal increases with gas flow rate (due to the increase in Stokes Number) until a stage is reached where excessive turbulence is induced in the cyclone (Figure 2-9). The flat maximum in this curve defines the normal operating range of the cyclone. The fall in efficiency that occurs at inlet velocities in excess of 30 m/s is caused by turbulence which gives rise to bypassing and particle re-entrainment within the cyclone. Where a large reduction in gas flow rate is anticipated, the drop in efficiency that would result can be avoided by arranging a number of units in multiple groups. Moreover, the pressure drop through a cyclone is proportional to the square of the gas throughput (14).



**Figure 2-9 Collection Efficiency and Pressure Loss as a function of Inlet Velocity**

### 2.5.6 Prediction of pressure drop

Pressure drop is an important parameter because it relates directly to operating costs. As the pressure drop increases, so does the cost for power to move the gas through

the cyclone. However, as the pressure drop increases, the removal efficiency usually increases too. For these reasons, numerous efforts have been made to predict pressure drop from design variables. One of the simplest pressure drop equations which correlates reasonably well was developed by Shepherd and Lapple (12,29) that expressed as the number of inlet velocity heads:

$$N_H = K(ab/D_e^2) \quad (2.13)$$

Where  $N_H$  is the number of velocity heads,  $K$  is an empirical constant with a value of 16 for a tangential inlet cyclone and 7.5 for one with an inlet vane,  $a$  is the height of inlet,  $b$  is the width of inlet, and  $D_e$  is diameter of dust outlet. The pressure drop is as follows:

$$\Delta P = 0.003 \rho_f \cdot v_i^2 \cdot N_H \quad (2.14)$$

where

- $\Delta P$  = Pressure drop, in w.g.
- $\rho_f$  = Fluid density, lb/ft<sup>3</sup>
- $v_i$  = Inlet velocity, ft/s
- $N_H$  = Number inlet velocity head

Although other equations have been derived from theoretical considerations, they have generally not been found to be more accurate than the equation developed by Lapple, which stands as the most useful one for calculating pressure drop.

Pressure drop is a function of the square of inlet velocity, so too high a velocity will cause excessive pressure drop. On the other hand, too low a velocity would cause a low efficiency. A very high velocity would also actually decrease efficiency because of increased turbulence and saltation/reentrainment of particles.

In short, the following factors should be considered when designing of cyclones (27):

- 1) Dust size distribution, particulate density, shape, physical-chemical properties such as agglomeration, hygroscopic tendencies, stickiness, etc.
- 2) Contaminated gas stream--its temperature, pressure, humidity, condensable components, density, etc.
- 3) Process variables such as dust concentration, gas flow rate, allowable pressure drop, size to be separated.
- 4) Structural limitations, temperature and pressure rating, material of construction, space limitations, and etc.

## 2.6 Related literatures

**Vichai Pruktharathikul** (33) has studied the efficiency of moveable cyclone by using high-efficiency cyclone. This study found that size of dust has quite an effect on efficiency of the cyclone, i.e., at size 45 micron efficiency is about 95.0 percent whereas size above 106 micron efficiency is rather constant and reaches the value of about 99.7 percent. In addition, many factors that affect the efficiency are found, such as flow rate, distribution, and concentration of dust.

**Somboon Panlertchumnan** (34) has studied the performance of cyclone dust collector by using conventional cyclone. The cyclone shapes and dimensions were designed by following the hypothesis of Bhatia & Cheremisinoff whereas the cut diameter, pressure drop, and performance of the cyclone could be calculated by the hypothesis of Stairmand. This study found cyclone performance approach the expected value that predicted by using Stairmand's hypothesis. Moreover, the errors only involved range from 0.25 to 13 percent.

**Wirote Khomphatraporn** (35) has studied the optimization design for parallel cyclones having a tangential gas inlet, Leith and Licht's design equation, used for collection of particles in stack gas from fuel oil combustion of boiler. This study found cyclone performance, calculation of cyclone initial design, and operating cost can be simulated by the program. Measured pressure drop is usually higher than predicted pressure drop due to variation in cyclone during actual operating condition. Optimization and the evaluation of the costs indicated that predicted costs are usually lower than actual costs due to the exclusion of installation and transportation costs.

**Benjawan Chokpipatpol** (36) has studied and designed a cyclone for particulate reduction in flue gas and to compare the experimental results with the theoretical ones. The cyclone model is of the tangential inlet and axial discharge type; high-efficiency, medium throughput pattern. The shapes and dimensions were designed by following the hypothesis of Stairmand where the cyclone's performance could be evaluated by Leith and Licht. The results of this study found the efficiency of particle collection of cyclone were ranged from 91.22 to 94.27 percent for burning dried leaves and waste paper. Consequently, in performance analysis of cyclone with Leith and Licht's hypothesis the trend of the results appears to be the same as those predicted by theory. The error involved ranged from 1.43 to 10.21 percent.

**Panotson Sujayanont** (37) has written a computer program for cyclone design suitable for various inlet conditions of cyclone, and uses the outcome as engineering for cyclone design. The study is conducted by considering the concentration of particles emitted from cyclone to atmosphere which complying with air quality standard. The inlet contaminated gas velocity must not cause the solid particles settling down before entering the cyclone, and the inflow velocity must cause the solid particles settling down before leaving from the cyclone. Calculated results from the computer program will be compared with articles published in journals and results from the experiment of high efficiency, medium throughput cyclone. This study suggested that the result from the computer program and the articles by Koch W.H. and Licht W.L., Coker A.K. are closely but the results from the experiment are maximum difference from the computer program by 20.2 percent for pressure drop.

**Woraluk Kunathimapun** (38) has studied the design and performance analysis of cyclone dust collector (CDC) for foundry operation found that the performance of this designed was similar to that of Stairmand. The CDC performance in elimination of dust was related to dust concentrations; i.e. the performance increased in accordance with the dust concentrations. However, the CDC showed no significant differences in its performance when tested against two flow rate with in the range of CDC performance.

**Chalerm Sak Mahattanan and Thamsathit Muangthaworn** (39) have studied a design of air-cyclone particulate emission control device. The study showed that if the 3 factors increased; particle size, particle density, and gas inlet velocity, the performance of cyclone was increased. The results of experiment for all conditions considered appeared to be similar to those predicted by theory. The difference between experimental results and theoretical prediction were about 1 to 9 percents.

**Tran** (40) has studied experimental and theoretical studies on gas cyclone separators operating at high efficiency. It is shown that wall friction has negligible effect on particle motion, but dust particles on the wall move much more slowly than the surrounding gas, due to crowding. In the cylindrical section of a cyclone the dust traces out a stream line of the gas flow field near the wall. In the cone section, the centrifugal force has an upward component causing the dust to deviate slightly from gas stream lines. Measurements show that the residence time of dust particles is several times smaller than that of the gas. Moreover, it is found that re-entrainment of particles in the region near the

cone apex of a cyclone is a significant factor affecting collection efficiency of low and moderate efficiency cyclones (those which collect less than 80% of the incoming dust.) The use of an underflow which is recycled back to the cyclone is found to improve the collection efficiency of these cyclones by about 5%. For cyclones with efficiencies exceeding 90% the effect of re-entrainment is not important as most of the re-entrained particles will return to the cyclone wall.

**Iozia** (41) has studied the effect of dimensions on cyclone performance by using the static particle theory for particle collection in a cyclone, a particle of critical size remains suspended at the edge of an "inner core" where tangential velocity is at a maximum, and inertial and drag forces on the particle balance. In the first phase of this study the tangential velocity profile of the gas within a pilot-scale cyclone with adjustable inlet, outlet, length, and airflow was investigated. Equations were developed to predict the maximum tangential velocity and the length of the inner core from cyclone dimensions, and used with the static particle theory to predict cyclone cut diameter ( $d(50)$ ). The relationship between cyclone fractional efficiency and particle size  $d$  can be described using a logistic equation:  $\text{efficiency} = 1 / (1 + (d(50)/d)^{\text{sc b}})$ . To use this equation  $d(50)$  and the logistic slope parameter,  $\text{sc b}$ , must be known. Although  $d(50)$  can be predicted, no theory has been available to predict  $\text{sc b}$ . In the second phase of this study collection efficiency was measured for particles between 1.4 and 7.4 micrometers in diameter using pilot-scale apparatus to determine the dependence of the logistic slope parameter on cyclone dimensions and operating conditions. In the third and final phase of this study a cyclone optimization program (Dirgo and Leith, 1985) was used to investigate design changes that improve cyclone performance. The method of predicting  $d(50)$  developed in Phase I was used within the program; pressure drop was predicted using Stairmand (1949) or Barth (1956) pressure theories. Two designs, predicted to have lower cut diameters (for the same pressure drop) than a Stairmand (1951) high-efficiency cyclone, were fabricated and tested. These cyclones had measured cut diameters of 2.2 and 2.4  $\mu\text{m}$  compared to 3.5  $\mu\text{m}$  for the Stairmand cyclone at the same nominal pressure drop. This design method was generalized through curves to specify cyclone dimension ratios and  $d(50)$  for pressure drops ranging from 0.14 to 4.0 kPa. A technique to design optimum cyclones for any pressure drop, gas flow, and particle density was described.

**Schuster** (42) has studied the influence of powder properties on cyclone efficiency predictions (Agglomeration). Particle interactions were studied and accounted for in two phase gas solid flow in cyclone separation of dust from gas. A new cyclone model was developed that accounts for particle interactions in the form of agglomeration. Agglomeration was best described by the aerodynamic capture of the small (less than 10  $\mu\text{m}$ ) particles by the larger particles (60  $\mu\text{m}$ ) assuming that interception and inertial impaction were the dominant mechanisms. The new model was experimentally verified for the separation of cohesive powders of varying polydispersity at high dust loadings. Four powders of various cohesiveness (coal, calcium carbonate, Fluid Catalytic Cracking Catalyst, and aluminum hydroxide) were studied. The powders were separated into discrete size fractions and remixed to form polydisperse samples with controlled bimodal size distributions. The fractions ranged from 5 to 60  $\mu\text{m}$ . The powder systems were studied in cyclones under dust loading conditions ranging from 0.01 to 10.0 kg dust/m<sup>3</sup> of air at ambient conditions. Agglomeration of the small particles on the larger ones was determined to be a function of the cohesiveness of the powders, polydispersity, and concentration. It was also demonstrated that the removal efficiency of a powder system can be improved by altering its cohesive nature.

**Tongchai Jithan** (43) has studied designing the dust control system for cutting tile mixed with asbestos. Results of this study showed that the efficiency of the dust control system depends on the quantity of dust, distance and the speed, time and angle of the blade cutting the cement tile.

## CHAPTER III

### MATERIALS AND METHODS

This study was an experimental study aimed to design and construct multi-cyclone for dust removal in surfboard sanding process. The setting of this study was done in surfboard sanding room, C Building of Cobra International Co., Ltd.

#### 3.1 Analysis Methods and Instruments

##### 3.1.1 Particle Size Distribution

Size distribution of dust from surfboard sanding process was analyzed by using particle size analyzer, Mastersizer S Ver. 2.19 Serial Number: 33544-756, Malvern Instruments Ltd., UK (see Appendix B). The basic principle method of this instrument is laser diffraction called Low Angle Laser Light Scattering (LALLS). The method relies on the fact that diffraction angle is inversely proportional to particle size. Accuracy was  $\pm 2\%$  on Volume Median Diameter (VMD), the diameter which divides the spray volume such that half of the volume has droplets of diameters less than the VMD and half the spray volume has diameters greater than the VMD, (measured by an approved technique using a diffraction reference reticle). Particle size distribution is expressed in term of percentage by volume. It is composed of 4 units: small volume sample presentation unit, mastersizer optical measurement unit, computer system, and Malvern operating software.

##### 3.1.2 Dust or Particulate Concentration

Dust concentrations at inlet and outlet area of multi-cyclone were measured by using Microdust pro, Casella Cel Ltd., UK (see Appendix D), a portable, real time monitor for assessing the concentration of suspended particulate matter. It is probably the most versatile instrument available with the ability to measure from  $0 \mu\text{g}/\text{m}^3$  to  $2500 \text{ mg}/\text{m}^3$  by using a near forward angle light scattering technique. Infrared light of  $880\text{nm}$  wavelength is projected through the sensing volume where contact with particles causes

the light to scatter. The amount of scatter is proportional to the mass concentration and is measured by the photo detector. By using a narrow angle of scatter ( $12\text{-}20^\circ$ ) the majority of scattered light is in the diffracted and refracted components, which minimizes the uncertainty associated with particle color, shape and refraction index. Range of zero stability is  $\pm 0.002 \text{ mg/m}^3/^\circ\text{C}$  and resolution is  $0.001 \text{ mg/m}^3$ .

### **3.1.3 Pressure Drop**

To measure pressure drop, the different static pressure, Manometer, a U-tube partially filled with distilled water so constructed that the amount of displacement of the liquid indicates the pressure being exerted on the multi-cyclone.

### **3.1.4 Air Velocity**

Thermo-anemometer, hot-wire anemometer (Extech, model 407123, Extech Instrument Co., Ltd.) was used to measure the velocity of air.

### **3.1.5 Fan Speed Control**

To adjust fan speed and airflow rate, Frecon (model FOO1I-4x, A.P.Y. Engineering Co., Ltd., Thailand) 0.75 kW (1 HP) supply motor; 3 phase power supply was used in this study.

### **3.1.6 Polishing Equipment**

Sander polisher or electrical disc sander (model 9207SPB, Makita Co Anjo, Aichi, Japan) with diameter 180 mm (7 inches) and rotational speed was 3,800 rpm joined with sandpaper (KMCA, RSK) No. 100 was applied in surfboard sanding process.

## **3.2 Materials and Component Parts**

### **3.2.1 Sanding Bench**

According to ACGIH Industrial Ventilation: a manual of recommended practice, the suitable sanding bench was designed and constructed by the researcher. It was built from sheets of metal and bench area was  $1.08 \text{ m}^2$ .

### 3.2.2 Hood and Duct System

Similar to ACGIH recommended for constructing sanding bench, downdraft hood was chosen because it can draw contaminants away from the worker thus reducing exposures. Face and capture velocities were changed depending on adjusted flow rate. Duct system was flexible duct, the diameter chosen was 8 inches (see duct design and calculation in Appendix C).

### 3.2.3 Multi-cyclone

The multi-cyclone was composed of high-efficiency cyclones with axial inlet airflow and inlet fixed vane which body diameter was 6 inches, 9 of them arranged in parallel (3x3). All of the multi-cyclone component parts were made from sheet of stainless steel. The inlet plenum size was 1 ft-width and 2.56 ft-length and connected to the flexible duct which has 8 inches in diameter. Beneath multi-cyclone chamber was the cylinder hopper which has 1 ft-diameter.

### 3.2.4 Fan

Based on system pressure requirements, centrifugal fan (VENZ Super Power); 2.2 kW (3 HP) supply motor; 2 pole type, the impeller rotates at 2,950 rpm, 9.1-5.3 Amp; 220-380 V. power supply, was used in this study.

### 3.2.5 Stack

For disperses exhaust contaminants for dilution by the atmosphere, stack is needed. It made from sheets of metal 0.6 ft-width, 0.9 ft-length, and 4 ft-height.

The assembly of all component parts showed in appendix D.

## 3.3 Data collecting procedure

### 3.3.1 Preparing phase

- 1) Permission to conduct the study is obtained from the director of Cobra International Co., Ltd.
- 2) Data collecting from sanding room of surfboard industry including dust characteristics, temperature, and wind velocity in working area.

3) Sample dusts were determined density and specific gravity by specific gravity bottle method and determined dust size distribution by using Mastersizer S. The percentage of cumulative weight and dust size average can be plotted graph, and then comparing with Stairmand's particle size distribution standard curve.

4) Design the multi-cyclone dimensional proportion, shape and dimensions based on the hypothesis of Stairmand and predict its collection efficiency by using theory of Leith and Licht as follows:

#### 4.1 Calculating overall collection efficiency

$$\eta_T = \sum m_i \eta_i \quad (1)$$

where  $\eta_T$  = Overall collection efficiency (%)

$m_i$  = Proportion of particle size range

$\eta_i$  = Grade efficiency

#### 4.2 Finding saltation velocity (vs)

$$v_s = 2.055 \omega \left( \frac{(b/D_c)^{0.4}}{1 - (b/D_c)^{1/3}} \right) D_c^{0.067} \cdot v_i^{2/3} \quad (2)$$

$$\omega = [4g \cdot \mu (\rho_p - \rho_f) / 3\rho_f^2]^{1/3} \quad (3)$$

where  $v_s$  = Saltation velocity, ft/s

$\omega$  = Omega, ft/s

$b$  = Inlet width, ft

$D_c$  = Cyclone diameter, ft

$v_i$  = Inlet velocity, ft/s

$g$  = Gravity, 32.2 ft/s<sup>2</sup>

$\mu$  = Fluid viscosity, lb/ft.s

$\rho_p$  = Particle density, lb/ft<sup>3</sup>

$\rho_f$  = Fluid viscosity, lb/ft<sup>3</sup>

If  $v_i/v_s = 1.25$ , cyclone will be have maximum collection efficiency.

If  $v_i/v_s \geq 1.36$ , it will be caused the reentrainment.

#### 4.3 Calculating volumetric flow rate

$$Q = abv_i \quad (4)$$

where  $Q$  = Total gas flow rate, ft<sup>3</sup>/s

a = Inlet height, ft

b = Inlet width, ft

$v_i$  = Inlet velocity, ft/s

#### 4.4 Calculating Natural length, $l$

$$l = 2.3 D_e (D_c^2 / ab)^{1/3} \quad (5)$$

where  $l$  = Natural length, ft

$D_e$  = Cyclone gas outlet diameter, ft

$D_c$  = Cyclone diameter, ft

a = Inlet height, ft

b = Inlet width, ft

#### 4.5 Calculating vortex exponent (n), Cyclone configuration factor (G), and relaxation time ( $\tau$ )

$$n = 1 - [1 - (12D_c / 2.5)^{0.14}] [(T + 460) / 530]^{0.3} \quad (6)$$

where n = Vortex exponent

$D_c$  = Cyclone diameter, ft

T = Temperature, °F

$$G = 8K_c / K_a^2 \cdot K_b^2 \quad (7)$$

$$K_a = a / D_c \quad (7.1)$$

$$K_b = b / D_c \quad (7.2)$$

$$K_c = (2v_s + v_{nl, H}) / 2D_c^3 \quad (7.3)$$

$$v_s = \{ \pi [S - (a/2)] [D_c^2 - D_e^2] \} / 4 \quad (7.3.1)$$

If  $l > (H - S)$ ,  $v_H$  is chosen for calculate  $K_c$  (Eq. 7.3)

$$v_H = [(\pi D_c^2 / 4)(h - s) + (\pi D_c^2 / 4)[(H - h) / 3][1 + (B / D_c) - (B^2 / D_c^2)] - (\pi D_e^2 / 4)(H - S) \quad (7.3.2)$$

If  $l < (H - S)$ ,  $v_{nl}$  is chosen for calculate  $K_c$  (Eq. 7.3)

$$v_{nl} = [(\pi D_c^2 / 4)(h - s) + (\pi D_c^2 / 4)[(l + s - h) / 3][1 + (d / D_c) - (d^2 / D_c^2)] - (\pi D_e^2 / 4)l \quad (7.3.3)$$

$$d = D_c - (D_c - B)[(s + l - h) / (H - h)] \quad (7.3.3.1)$$

where G = Cyclone configuration factor

$K_c$  = Cyclone volume constant

$v_H$  = Volume below exit, ft<sup>3</sup>

$v_{nl}$  = Volume at natural length, ft<sup>3</sup>

$v_s$  = Annular volume above exit duct to middle or entrance duct,  $\text{ft}^3$

$B$  = Cyclone dust outlet diameter, ft

$H$  = Cyclone height, ft

$h$  = Cylindrical height of cyclone, ft

$s$  = Gas outlet length, ft

$d$  = Diameter of central core at point where vertex turns, ft

$$\tau = \rho_p(d_p i)^2 / (18\mu) \quad (8)$$

where  $\tau$  = Relaxation time, sec

$\rho_p$  = Particle density,  $\text{lb}/\text{ft}^3$

$d_p$  = Particle size, ft

$\mu$  = Fluid viscosity,  $\text{lb}/\text{ft}\cdot\text{s}$

$i$  = Subscript denoted interval in particle size range

#### 4.6 Calculating Grade or Fractional efficiency

$$\eta_i = 1 - \exp\{-2[(G\tau; Q/Dc^3)(n+1)]^{0.5/(n+1)}\} \quad (9)$$

where  $\eta_i$  = Grade efficiency, %

$G$  = Cyclone configuration factor

$\tau$  = Relaxation time, sec

$n$  = Vortex exponent

$Q$  = Total gas flow rate,  $\text{ft}^3/\text{s}$

4.7 Finding overall collection efficiency again by following Eq. (9) and then comparing with the result from Eq. (1). If the overall collection efficiency result of Eq. (9) is higher than that of Eq. (1), the dimensions of the designed cyclone should be accepted.

#### 4.8 Calculating pressure drop by using equation as follows:

$$\Delta P = 0.003 \rho_f \cdot v_i^2 \cdot N_H \quad (10)$$

$$N_H = K(ab/De) \quad (10.1)$$

where  $\Delta P$  = Pressure drop, in w.g.

$\rho_f$  = Fluid density,  $\text{lb}/\text{ft}^3$

$v_i$  = Inlet velocity,  $\text{ft}/\text{s}$

$N_H$  = Number inlet velocity head

$K$  = Empirical constant (K=7.5 for a cyclone with an inlet vane)

(K=16 for a normal tangential inlet)

$D_e$  = Cyclone gas outlet diameter, ft

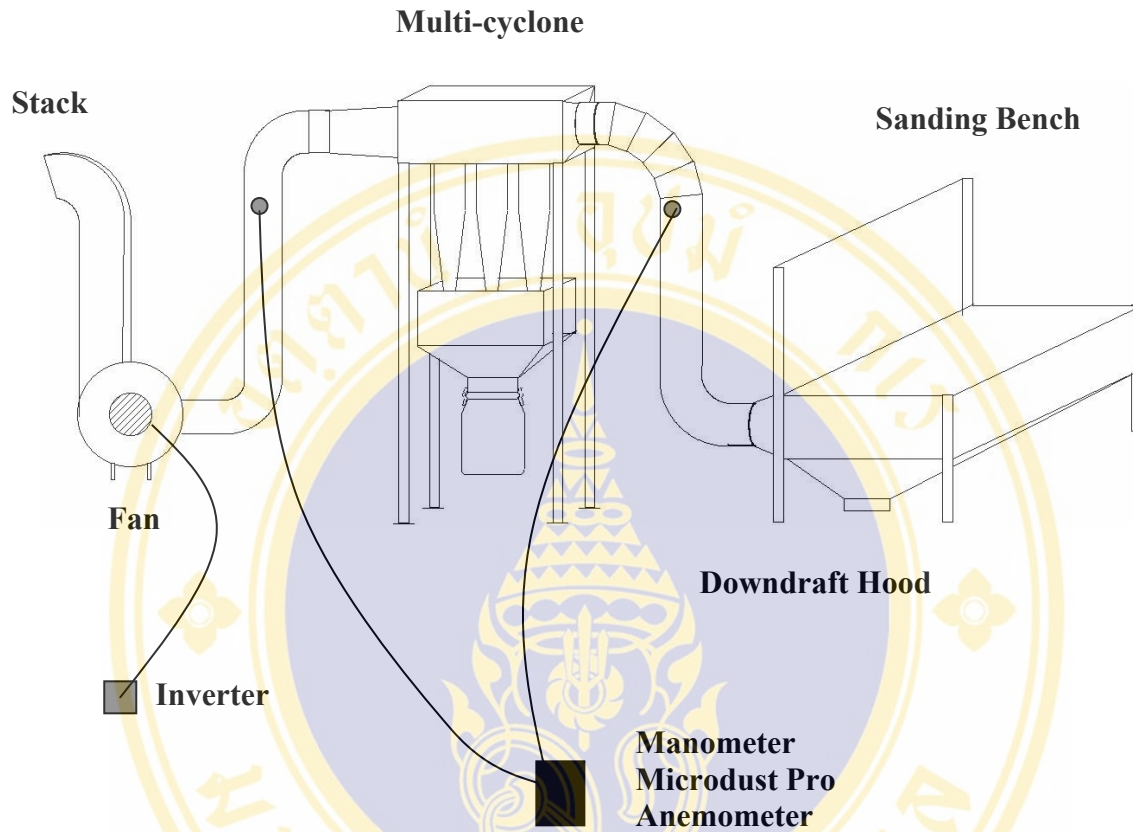
After designing, dimensional proportion of cyclone have to be under the criteria conditions:

- $a < s$
- $b < \frac{1}{2} (D_c - D_e)$
- $s + l \leq H$
- $s < h$
- $h < H$
- $\Delta P < 10$  in w.g.
- $v_i/v_s \leq 1.35$

5) Construct the multi-cyclone.

6) Connect the constructed multi-cyclone to hood and duct system by using ACGIH Industrial Ventilation Manual recommendation.

7) Install all component parts at sanding room, C Building, Cobra International Co., Ltd. as showed in Figure 3-1.



**Figure 3-1 Installation pattern**

### 3.2.2 Experimental phase

- 1) Prepare surfboard, sanding worker, electric disc sander, and sandpaper No. 100.
- 2) Record temperature, pressure, and air velocity at working area.
- 3) Turn on centrifugal fan and adjust inlet velocity upon required airflow rate (1,200-1,250, 1,400-1,450 and 1,600-1,650 cfm) by using inverter.
- 4) Sanding surfboard for 3 minutes.
- 5) Measure dust concentrations at inlet and outlet of the constructed multi-cyclone by using the Microdust Pro, set interval time record every 5 seconds.
- 6) Record pressure drop between inlet and outlet of the constructed multi-cyclone. (Stepwise testing from 2-6 for 5 times)
- 7) Adjust new required airflow rate (go back to 2 and follow step by step again).

8) Sampling dusts from inlet and outlet area of the multi-cyclone for comparing size distribution.

9) Data analysis

**Remark:** All testing used the same size of surfboard, sanding worker, and electric disc sander.

### 3.4 Data analysis

The data were analyzed by using statistics as follows:

#### 3.4.1 Descriptive statistics

To calculate the inlet and outlet dust concentrations of the constructed multi-cyclone and percentage of collection efficiency, mean and standard deviation was applied.

#### 3.4.2 Inferential statistics

3.4.2.1 The comparison mean of multi-cyclone collection efficiency between the theory prediction and the experimental results was determined by t-Test.

3.4.2.2 The comparison of multi-cyclone collection efficiency at 3 levels of airflow rate was determined by analysis of variance (One-way ANOVA) and followed by multiple comparisons (Least Significant Difference Method: LSD).

## CHAPTER IV

### RESULTS

This study started with dust characteristics and dust size distribution analysis. Then, the multi-cyclone was designed and constructed. It was composed of high-efficiency cyclones with axial inlet airflow which body diameter was 6 inches, 9 of them arranged in parallel. Dimensions and shapes were calculated based on the hypothesis of Stairmand. The collection efficiency estimation was used theory of Leith and Licht. Next, the multi-cyclone was setting up with local exhaust ventilation system that table hood and duct were designed by the recommended of American Conference of Governmental Industrial Hygienists (ACGIH) Industrial Ventilation Manual. Finally, it was tested for dust collection efficiency at 3 levels of airflow rate as follows 1,200-1,250, 1,400-1,450, and 1,600-1,650 cfm respectively. The results of the study can describe into 4 parts as follows:

Part 1: Dust characteristics and dust size distribution

Part 2: Multi-cyclone performance (theoretical approach)

Part 3: Experimental results

Part 4: Comparison of collection efficiency against different airflow rate

#### **Part 1: Dust Characteristics and Dust Size Distribution**

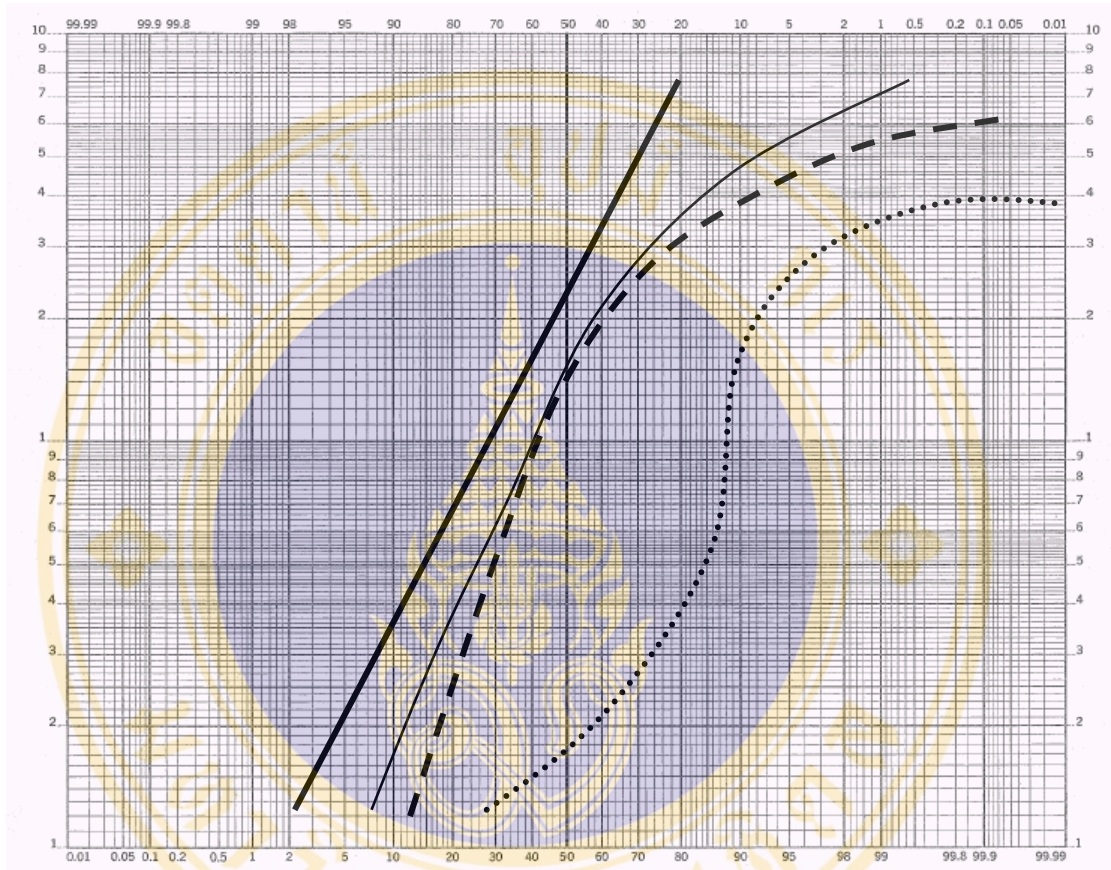
Sample dusts from fiberglass surfboard sanding process were analyzed to define density and specific gravity. By using specific gravity bottle method, dust density and specific gravity was 236 kg/m<sup>3</sup> (14.73 lb/ft<sup>3</sup>) and 0.236 respectively. Dusts size distribution was analyzed by the particle dust analyzer, Mastersizer S (Table 4-1).

**Table 4-1 Dust Size Distribution**

| Dust size<br>( $\mu\text{m}$ ) | Dust size average<br>( $\mu\text{m}$ ) | Weight by volume<br>(%) | Cum. wt.<br>(%) |
|--------------------------------|--|-------------------------|-----------------|
| 0-9.80                         | 4.90                                   | 6.97                    | 6.97            |
| 9.81-15.97                     | 12.89                                  | 7.45                    | 14.42           |
| 15.98-21.42                    | 18.70                                  | 7.78                    | 22.20           |
| 21.43-31.66                    | 26.55                                  | 10.90                   | 33.10           |
| 31.67-69.21                    | 50.44                                  | 37.16                   | 70.26           |
| 69.22-84.15                    | 76.68                                  | 10.51                   | 80.77           |
| 84.16-102.3                    | 93.23                                  | 4.92                    | 85.69           |
| 102.4-202.8                    | 152.60                                 | 8.37                    | 94.06           |
| 202.9-594.3                    | 398.60                                 | 5.94                    | 100.00          |

Table 4-1 showed that dust size distribution from surfboard sanding process ranged from 1 to 594.3 micron with an average size 40.31 micron. Therefore, percentage of cumulative weight and dust size average can be plotted graph, and then comparing with Stairmand particle size distribution standard curve (Figure 4-1). The result showed that sample dust can classified into fine dust.

**Figure 4-1 Sample Dust Size Distribution Compare with Stairmand Standard Curve**



Mass percent less than

- Remarks:
- ..... Super fine dust
  - - - - Fine dust
  - Coarse dust
  - Sample dust

**Part 2: Multi-cyclone performance (theoretical approach)****Table 4-2 Cyclone Design Configurations (Axial Entry)**

| Description             | Term | Size |      |
|-------------------------|------|------|------|
|                         |      | inch | ft   |
| Body diameter           | Dc   | 6    | 0.5  |
| Height of inlet         | a    | 3    | 0.25 |
| Width of inlet          | b    | 1.2  | 0.1  |
| Diameter of gas exit    | De   | 3    | 0.25 |
| Length of body          | H-h  | 9    | 0.75 |
| Overall length          | H    | 24   | 2    |
| Length of vertex finder | B    | 3    | 0.25 |
| Length of cone          | h    | 15   | 1.25 |
| Diameter of dust outlet | Dd   | 2.25 | 0.18 |

Table 4-2 showed the design configurations of high-efficiency cyclone. Its shapes and dimensions were calculated and designed based on Stairmand hypothesis.

The multi-cyclone was composed of high-efficiency cyclones with axial inlet airflow and inlet fixed vane which body diameter was 6 inches, 9 of them arranged in parallel (3x3). All of the multi-cyclone component parts were made from sheet of stainless steel. The inlet plenum size was 1 ft-width and 2.56 ft-length and connected to the flexible duct which has 8 inches in diameter. Beneath multi-cyclone chamber was the cylinder hopper which has 1 ft-diameter.

**Estimating of Cut Diameter**

From dust characteristics of sample dust, we can estimate the cut diameter for a multi-cyclone with inlet width 0.1 ft, body diameter was 0.5 ft, by using Stokes' law express into Equation (2.11).

$$d_{p50\alpha} = \left( \frac{9\mu W}{2\pi N_e \rho_p V_g} \right)^{1/2}$$

where  $W = 0.1$  ft,  $\mu = 1.2766 \times 10^{-5}$  lb/ft.s,  $N = 5$ ,  $V_g = 69$  ft/s,  $\rho_p = 14.73$  lb/ft<sup>3</sup>,

$$d_{p50\tau} = \left( \frac{(9)1.2766 \times 10^{-5}(0.1)}{2\pi(5)(14.73)(69)} \right)^{1/2}$$

$$= 4.2432 \times 10^{-5} \text{ ft}$$

$$= 12.9 \text{ micron}$$

The result of cut diameter showed that the size of particle which will be collected at 50% efficiency in a given multi-cyclone was 12.9 micron.

### Prediction of Multi-cyclone Collection Efficiency

#### Calculation Procedures

Temperature,  $T = 100.4 \text{ }^\circ\text{F}$

Atmospheric pressure,  $P_{\text{atm}} = 1 \text{ atm}$

Inlet velocity,  $v_i = 9.43 \text{ ft/s}$

Fluid viscosity,  $\mu = 1.2766 \times 10^{-5} \text{ lb/ft.s}$

Fluid density,  $\rho_f = 0.075 \text{ lb/ft}^3$

Particle density,  $\rho_p = 14.73 \text{ lb/ft}^3$

#### 1) Overall collection efficiency

$$\eta_T = \sum m_i \eta_i$$

$$= m_1 \eta_1 + m_2 \eta_2 + \dots + m_6 \eta_6$$

$$= 7.24(0.825) + 67.30(0.875) + 16.71(0.975) + 7.11(1) + 1.20(1) + 0.44(1)$$

$$= 89.90 \%$$

#### 2) Saltation velocity (vs)

$$v_s = 2.055 \omega \left( \frac{(b/Dc)^{0.4}}{1 - (b/Dc)^{1/3}} \right) Dc^{0.067} \cdot v_i^{2/3}$$

$$\omega = [4g \cdot \mu (\rho_p - \rho_f) / 3\rho_f^2]^{1/3}$$

$$= [4 \times 32.2 \times 1.2766 \times 10^{-5} (14.73 - 0.075) / 3(0.075)^2]^{1/3}$$

$$= 2.41 \text{ ft/s}$$

$$v_s = 2.055 \times 2.41 \left( \frac{(0.1/0.5)^{0.4}}{[1 - (0.1/0.5)]^{1/3}} \right) (0.5)^{0.067} \times (9.43)^{2/3}$$

$$= 12 \text{ ft/s}$$

$$v_i/v_s = 9.43/12 = 0.78$$

3) Volumetric flow rate

$$\begin{aligned}
 Q &= abv_i \\
 &= (0.25)(0.1)(9.43) \\
 &= 0.23 \text{ ft}^3/\text{s} \\
 &= 14.14 \text{ ft}^3/\text{min}
 \end{aligned}$$

5) Natural length,  $l$

$$\begin{aligned}
 l &= 2.3 \text{ De}(\text{Dc}^2/ab)^{1/3} \\
 &= 2.3 \times 0.25 [0.5^2/(0.25)(0.1)]^{1/3} \\
 &= 1.23 \text{ ft}
 \end{aligned}$$

6) Vortex exponent (n), Cyclone configuration factor (G), and relaxation time ( $\tau$ )

$$\begin{aligned}
 n &= 1 - [1 - (12\text{Dc}/2.5)^{0.14}] [(T+460)/530]^{0.3} \\
 &= 1 - [1 - (12(0.5)/2.5)^{0.14}] [(100.4+460)/530]^{0.3} \\
 &= 0.48
 \end{aligned}$$

$$G = 8\text{Kc}/\text{Ka}^2 \cdot \text{Kb}^2$$

$$\text{Ka} = a/\text{Dc} = 0.1/0.5 = 0.2$$

$$\text{Kb} = b/\text{Dc} = 0.25/0.5 = 0.5$$

$$\text{Kc} = (2v_s + v_{nl, H})/2\text{Dc}^3$$

$$\begin{aligned}
 v_s &= \{ \pi [S - (a/2)] [\text{Dc}^2 - \text{De}^2] \} / 4 \\
 &= \{ \pi [0.5 - (0.1/2)] [0.5^2 - 0.25^2] \} / 4 \\
 &= 0.029 \text{ ft/s}
 \end{aligned}$$

Here,  $l > (H-s)$ ;  $1.23 > (1.25-0.25)$ ,  $v_H$  is chosen for calculate Kc.

$$v_H = [(\pi\text{Dc}^2/4)(h-s) + [(\pi\text{Dc}^2/4)][(H-h)/3][(1+(B/\text{Dc})+(B^2/\text{Dc}^2)) - [(\pi\text{De}^2/4)(H-S)]]$$

$$\begin{aligned}
 d &= \text{Dc} - (\text{Dc} - B)[(s+l-h)/(H-h)] \\
 &= 0.5 - (0.5 - 0.25)[(0.5 + 0.97 - 1.25)/(0.75)] \\
 &= 0.42 \text{ ft}
 \end{aligned}$$

$$\begin{aligned}
 \text{Therefore, } v_H &= \{ [\pi(0.5)^2/4] \} (1.25 - 0.5) + \{ [\pi(0.5)^2/4][(0.75)/3] \} \{ [1 + (0.25/0.5)] + \\
 &\quad [ (0.25)^2 / (0.5)^2 ] \} - [ \pi(0.25)^2 / 4 ] (0.75) \\
 &= [ (0.19)(0.75) ] + [ (0.19)(0.25)(1.75) ] - [ (0.19)(0.75) ] \\
 &= 0.08 \text{ ft}
 \end{aligned}$$

$$\begin{aligned}
 \text{Kc} &= (2v_s + v_{nl, H})/2\text{Dc}^3 \\
 &= [2(0.029) + (0.08)]/2(0.5)^3 \\
 &= 0.55
 \end{aligned}$$

$$\begin{aligned} \text{Here, } G &= 8Kc/Ka^2.Kb^2 \\ &= 8(0.55)/(0.2)^2(0.5)^2 \\ &= 440 \end{aligned}$$

From equation  $\tau = \rho_p(d_{pi})^2/(18\mu)$ , we can calculate  $\tau$  as showed in Table 4-3.

**Table 4-3 Relaxation Time of Particle**

| Particle size<br>(Micron) | Average particle size      |                         | $\tau_i$ (sec)          |
|---------------------------|----------------------------|-------------------------|-------------------------|
|                           | (x 10 <sup>-6</sup> meter) | (x 10 <sup>-4</sup> ft) |                         |
| < 10                      | 5                          | 0.1641                  | 1.72 x 10 <sup>-5</sup> |
| 10 - 75                   | 42.5                       | 1.394                   | 1.24 x 10 <sup>-3</sup> |
| 75 - 150                  | 112.5                      | 3.691                   | 8.73 x 10 <sup>-3</sup> |
| 150 - 300                 | 225                        | 7.382                   | 3.49 x 10 <sup>-2</sup> |
| 300 - 425                 | 362.5                      | 11.894                  | 9.06 x 10 <sup>-2</sup> |
| > 425                     | 425                        | 13.944                  | 1.24 x 10 <sup>-1</sup> |

Table 4-3 showed relaxation time of each particle size that can be used for calculation grade or fractional efficiency as follows:

6) Grade or Fractional efficiency

$$\eta_i = 1 - \exp\{-2[(G\tau_i Q/Dc^3)(n+1)^{0.5/(n+1)}]\}$$

where  $Q = 0.23 \text{ ft}^3/\text{s}$

$$Dc = 0.5 \text{ ft}$$

$$n = 0.48$$

$$G = 440$$

**Table 4-4 Grade Efficiency**

| Average particle size (Micron) | $\tau_i$ (sec)        | $\eta_i$ (%) |
|--------------------------------|-----------------------|--------------|
| 5                              | $1.72 \times 10^{-5}$ | 0.4139       |
| 42.5                           | $1.24 \times 10^{-3}$ | 0.8986       |
| 112.5                          | $8.73 \times 10^{-3}$ | 0.9882       |
| 225                            | $3.49 \times 10^{-2}$ | 0.9992       |
| 362.5                          | $9.06 \times 10^{-2}$ | 0.9999       |
| 425                            | $1.24 \times 10^{-1}$ | 0.9999       |

Table 4-4 showed grade or fractional efficiency of each particle size that can be used for calculation overall collection efficiency of multi-cyclone as follows:

7) Calculate new overall collection efficiency

$$\begin{aligned}
 \eta_T &= \sum m_i \eta_i \\
 &= m_1 \eta_1 + m_2 \eta_2 + \dots + m_6 \eta_6 \\
 &= 7.24(0.4139) + 67.30(0.8986) + 16.71(0.9882) + 7.11(0.9992) + \\
 &\quad 1.20(0.9999) + 0.44(0.9999) \\
 &= 88.73 \%
 \end{aligned}$$

8) Calculating pressure drop by using equation as follows:

$$\Delta P = 0.003 \rho_f \cdot v_i^2 \cdot N_H$$

$$N_H = K(ab/De^2)$$

where  $K=7.5$  for a cyclone with an inlet vane

$$a = 0.25 \text{ ft}$$

$$b = 0.1 \text{ ft}$$

$$De = 0.25 \text{ ft}$$

$$N_H = 7.5[(0.25 \times 0.1)/0.25^2] = 3$$

$$\Delta P = 0.003 \rho_f \cdot v_i^2 \cdot N_H$$

$$= 0.003(0.075)(9.43)^2(3)$$

$$= 0.06 \text{ in w.g./each of cyclone}$$

$$= 0.54 \text{ in w.g./set of multi-cyclone}$$

For airflow rate range from 1,200 - 1,250 and 1,600 - 1,650 cfm, the designed condition, inlet velocity ( $v_i$ ) will be changed. Therefore, the result of prediction collection efficiency and pressure drop of the multi-cyclone will be changed too.

At airflow rate range from 1,200 - 1,250 cfm, the over all collection efficiency and pressure drop of the multi-cyclone was 87.80% and 0.40 in w.g. respectively.

At airflow rate range from 1,600 - 1,650 cfm, the over all collection efficiency and pressure drop of the multi-cyclone was 89.71% and 0.72 in w.g. respectively.

From the results of the calculation procedures, dimensional proportions of cyclone are under the criteria conditions as shown in Table 4-6.

**Table 4-5 Dimensional Proportion Criteria**

| Criteria                      | Result                           |
|-------------------------------|----------------------------------|
| $a < s$                       | $0.25 < 0.5$                     |
| $b < \frac{1}{2} (D_c - D_e)$ | $0.1 < \frac{1}{2} (0.5 - 0.25)$ |
| $s + l \leq H$                | $0.5 + 1.23 \leq 2$              |
| $s < h$                       | $0.5 < 1.25$                     |
| $h < H$                       | $1.25 < 2$                       |
| $\Delta P < 10$ in w.g.       | $0.54 < 10$ in w.g.              |
| $v_i/v_s \leq 1.35$           | $0.78 \leq 1.35$                 |

Table 4-5 showed the comparison of the designed dimensional proportion of high-efficiency cyclone and the recommended dimensional proportion criteria. The results found that all of the designed parameters have met the recommended criteria. Therefore, we can assume that the collection efficiency of constructed multi-cyclone has no difference from predicted value. Moreover, the turbulence and saltation/reentrainment of particles might be decreased.

### Part 3: Experimental Results

The collection efficiency and pressure drop of multi-cyclone were measured. The results are showed in Table 4-7.

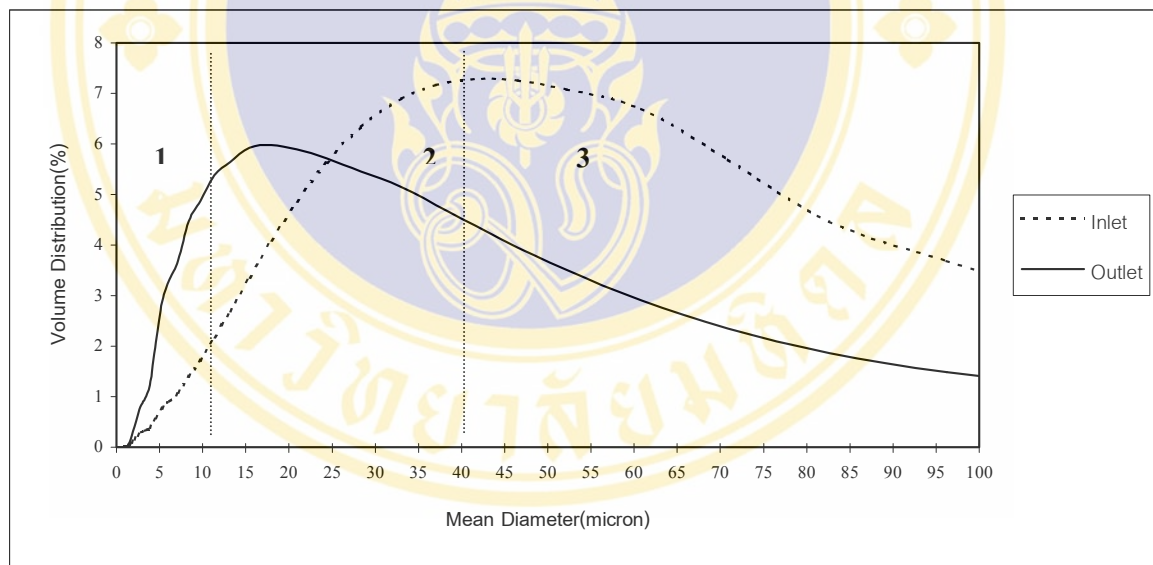
**Table 4-6 Collection Efficiency and Pressure drop of Multi-cyclone**

| Airflow Rate(cfm) | Collection Efficiency(%) | Pressure Drop (in. wg) |
|-------------------|--------------------------|------------------------|
| 1,200 - 1,250     | 81.58                    | 4.42                   |
|                   | 82.24                    |                        |
|                   | 81.04                    |                        |
|                   | 80.31                    |                        |
|                   | 81.19                    |                        |
| $\bar{x}$         | 81.27                    | -                      |
| S.D               | 0.71                     | -                      |
| 1,400 - 1,450     | 85.44                    | 4.82                   |
|                   | 85.01                    |                        |
|                   | 86.13                    |                        |
|                   | 86.00                    |                        |
|                   | 85.25                    |                        |
| $\bar{x}$         | 85.57                    | -                      |
| S.D               | 0.48                     | -                      |
| 1,600 - 1,650     | 83.57                    | 7.23                   |
|                   | 83.49                    |                        |
|                   | 82.61                    |                        |
|                   | 82.20                    |                        |
| 1,600 - 1,650     | 83.21                    | -                      |
|                   | $\bar{x}$                |                        |
| S.D               | 0.59                     | -                      |

Table 4-6 showed that average collection efficiency of multi-cyclone at airflow rate 1,200 - 1,250, 1,400 - 1,450, and 1,600 - 1,650 cfm are 81.27%, 85.57% and 83.02%, respectively. Adjusted airflow rate at 1,400 - 1,450 cfm, the collection efficiency of multi-cyclone is higher than airflow rate at 1,200 - 1,250 and 1,600 - 1,650 cfm. Additionally, the results indicated that when airflow rate was increased, the pressure drop of the multi-cyclone also increased.

The experimentally determined mean collection efficiency of the multi-cyclone was lower than that predicted by the theory of Leith and Lich with an error ranging from 3.16 - 6.69 percent.

**Figure 4-2 Comparison Mean Diameter of Volume Distribution at Inlet and Outlet Area**



In Figure 4-2 the mean diameter of volume distribution at inlet and outlet area of the multi-cyclone were analyzed by the particle size analyzer, Mastersizer S. Graph area will be plotted and divided into 3 parts. Part 1 represented superfine dust, dust diameter less than 10 micron, part 2 represented fine dust, dust diameter range from 10 to 40 microns, and part 3 represented coarse dust, dust diameter more than 40 micron. The result in part 1 showed that the percentage of dust volume distribution at outlet area is more than at inlet area; therefore, we can assumed that collection efficiency of multi-cyclone for superfine dust is quiet low. Whereas, the percentage of removal dust in part 2

is gradually increasing. At the mean diameter of dust is more than 25 micron, the percentage of dust volume at outlet area is less than at inlet area. Therefore, we can assume that the collection or removal efficiency of multi-cyclone was effectiveness when dust size is larger than 25 micron.

**Part 4: Comparison of Multi-cyclone Collection Efficiency**

**Table 4-7 Comparison Collection Efficiency of Multi-cyclone at 3 airflow rate ranges by using ANOVA**

|                | Sum of Squares | df | Mean Square | F      | Sig.    |
|----------------|----------------|----|-------------|--------|---------|
| Between Groups | 46.637         | 2  | 23.319      | 64.341 | < 0.001 |
| Within Groups  | 4.349          | 12 | 0.362       |        |         |
| Total          | 50.987         | 14 |             |        |         |

Table 4-7 showed that there was significant difference of collection efficiency between when testing with difference airflow rate levels ( $p < 0.001$ ).

**Table 4-8 Comparison Collection Efficiency of Multi-cyclone (Multiple comparisons: LSD)**

| Airflow Rate | Airflow Rate | Mean Difference (I-J) | Std. Error | Sig.   | 95% Confidence Interval |             |
|--------------|--------------|-----------------------|------------|--------|-------------------------|-------------|
| (I) Q        | (J) Q        |                       |            |        | Lower Bound             | Upper Bound |
| 1,200-1,250  | 1,400-1,450  | -4.2600               | 0.22524    | <0.001 | -4.9768                 | -3.5432     |
|              | 1,600-1,650  | -1.7300               | 0.22524    | 0.005  | -2.4468                 | -1.0132     |
| 1,400-1,450  | 1,200-1,250  | 4.2600                | 0.22524    | <0.001 | 3.5432                  | 4.9768      |
|              | 1,600-1,650  | 2.5300                | 0.22524    | 0.002  | 1.8132                  | 3.2468      |
| 1,600-1,650  | 1,200-1,250  | 1.7300                | 0.22524    | 0.005  | 1.0132                  | 2.4468      |
|              | 1,400-1,450  | -2.5300               | 0.22524    | 0.002  | -3.2468                 | -1.8132     |

The mean difference is significant at the .05 level.

Table 4-8 showed the mean difference of multi-cyclone collection efficiency. At 95% confidence interval, the mean of multi-cyclone collection efficiency at airflow rate

range 1,200 - 1,250 cfm was lower than at airflow rate range 1,400 - 1,450 and 1,600 - 1,650 cfm. The mean of multi-cyclone collection efficiency at airflow rate range 1,400 - 1,450 cfm was higher than at airflow rate range 1,200 - 1,250 and 1,600 - 1,650 cfm. Whereas the mean of multi-cyclone collection efficiency at airflow rate range 1,600 - 1,650 cfm was higher than at airflow rate range 1,200 - 1,250 and lower than at airflow rate range 1,600 - 1,650 cfm.



## CHAPTER V

### DISCUSSION

A designed and constructed multi-cyclone is one of an effective control method. However, the result in this study can be applied and some points have to be considered.

#### 5.1 Discussion of study design

This study was an experimental research design, which was conducted in surfboard manufacturing, a real working condition. For testing the collection efficiency of the multi-cyclone, this condition was different from previous studies which were done in laboratory (33,38,43). The advantage of the laboratory test is capable to control confounding factors and systemic error whereas testing in the real working condition is more difficult to control confounding factors than that one. The irregularity of data could be occurred due to the experiment as follows:

##### 5.1.1 Air Sampling

Dust concentration was measured by the Microdust Pro, the direct reading instrument. The raw concentration was recording every 5 seconds without integration. So the recording data was limited by time interval of recording. Moreover, assessing only the concentration of suspended particulate matter by light scattering method might be affected actual concentration. By using a narrow angle of scatter (12-20°) the majority of scattered light is in the diffracted and refracted components, which minimizes the uncertainty associated with particle color, shape and refraction index. However, before used this instrument, the researcher had been tested its validity with standard method (NIOSH Method No. 0500) and found that there have no difference between 2 methods (CI = 95%).

In addition, the error could be occurred when monitoring dust concentration at inlet and outlet area of multi-cyclone. Due to the location of measurement might be not proper, for example, if dust move nearby the inner layer of duct, not pass through the

sensor hole, the reading value might be detected less than the actual value. Due to this study had only one particle concentration analyzer, dust concentration monitoring at inlet and outlet area were taken in the different time so that reading value might be not refer to the real value. For solving this problem, controlling the dust concentration through the inlet plenum would be done as follows: 1) The worker had to continue sanding work through 3 minutes, using the same type and size of fiberglass surfboard, and sanding surfboard with the same electrical disc sander and sandpaper type. 2) The recording of dust concentration had to start after sanding surfboard for 1 minute. After recording for 3 minutes, the particle concentration analyzer would be still reading for 1 minute later for ensured that the dust concentration through the inlet plenum of the multi-cyclone had minimum changed. 3) Data analysis was chosen particularly raw data range from the beginning of the second minute to the end of the fourth minute.

For reduce interpersonal error, reading the values of all measurement has done by the researcher alone. All instruments have to be calibrated before use and all testing used the same size of surfboard, sanding worker, and electric disc sander.

### **5.1.2 Multi-cyclone Designing and constructing**

The multi-cyclone was composed of high-efficiency cyclones with axial inlet airflow and inlet fixed vane which body diameter was 6 inches, 9 of them arranged in parallel (3x3). Dimensions and shapes were calculated based on the hypothesis of Stairmand. The collection efficiency estimation was used theory of Leith and Licht. Due to the roughness of cyclone wall body is a significant factor affecting collection efficiency of the multi-cyclone. To minimize eddy currents, the body must be reasonably smooth internally so that all of the multi-cyclone component parts were made from sheet of stainless steel (surface roughness was 0.00015 per feet). The inlet plenum size was 1 ft-width and 2.56 ft-length and connected to the flexible duct which has 8 inches in diameter. Beneath multi-cyclone chamber was the cylinder hopper which has 1 ft-diameter. The advantage

To adjust fan speed and airflow rate, the inverter, Frecon (model FOO1I-4x, A.P.Y. Engineering Co., Ltd., Thailand) 0.75 kW (1 HP) supply motor; 3 phase power supply was used in this study. Adjusting airflow rate range 3 levels was setting up.

## 5.2 Discussion of study results

### 5.2.1 Sample dust

Sample dust size distribution from surfboard sanding process ranged from 1 to 594.3 microns with an average size was 40.31 micron. The percentage of cumulative weight and dust size average can be plotted graph, and then comparing with Stairmand particle size distribution standard curve. The result showed that sample dust can classified into fine dust.

Due to dust size distribution analysis was done by light scattering method, although it has many advantages such as easy to analyze and can express in minimum scale but it has some limitation. In process of analysis, the sample dusts have to mix with water substance. It may be formed to the large particle that different from the raw dust. Thus, sample dust that released from surfboard sanding process may be have size less than that analyzed by dust size distribution analyzer.

### 5.2.2 Comparison collection efficiency between the theoretical prediction and the experimental results

At airflow rate range from 1,200 – 1,250, 1,400 – 1,450 and 1,600 – 1,650 cfm, the mean collection efficiency of multi-cyclone was 81.27%, 85.57% and 83.02% respectively. These values were lower than that predicted by the theory of Leith and Leith with an error ranging from 3.16 - 6.69 percent. Similar to the study of Chalerm Sak Mahattanan and Thamsathit Muangthaworn (39) found that the difference of cyclone collection efficiency between experimental results and theoretical prediction were about 1 to 9 percent.

### 5.2.3 Relationship of collection efficiency and airflow rate

Variation in airflow rate has marked effect on collection efficiency of multi-cyclone. There was significant difference of collection efficiency when testing with difference airflow rate ranges ( $p < 0.01$ ). The result was similar to the study of Vichai Pruktharathikul (33) mentioned that flow rate is the one factor affecting to the efficiency of the cyclone. However, it was not related to the study of Woraluk Kunathimapun (38)

found that cyclone dust collector (CDC) have no significant differences in its performance when tested against two flow rate.

Considering with low airflow rate range (1,200 –1,250 cfm), the results showed that in this range has collection efficiency lower than airflow rate 1,400 – 1,450 and 1,600 – 1,650 cfm. This is related to the results of prior studied (26,33), the more increases airflow rate, the higher collection efficiency increases. Although an increase in airflow rate through the cyclone provides an increase in the collection efficiency, the collection efficiency of the multi-cyclone was reduced when increasing airflow rate range up to 1,600 – 1,650 cfm. This situation can be explained by the mechanism of cyclonic separator. Whenever airflow rate was increase, the inlet velocity was increase too. Thus, the fall in efficiency is caused by turbulence from excess inlet velocity which given rise to bypassing and particle re-entrainment within the cyclone. It is related to the result of previous study that this was occurs at inlet velocities in excess of 30 m/s (13). In summary, the proper airflow rate need to be considered due to it is a significant factor affecting collection efficiency of multi-cyclone.

The constructed multi-cyclone was worked highest efficiency based on under a control airflow rate range from 1,400 to 1,450 cfm. In this airflow rate range, the collection efficiency of multi-cyclone was 85.57 percent which was accordanced with the hypothesis of the study (85%). Whereas in airflow rate range from 1,200 - 1,250 and 1,600 - 1,650 cfm cannot reached the collection efficiency up to 85%. There are many reasons to explain this phenomena. First, dust characteristics might be affected the collection efficiency. Due to the sample dust is classified into fine dust that might be easy to causes re-entrainment. Second, the roughness of cyclone wall body is a significant factor affecting collection efficiency of multi-cyclone. It might be occurred from improper process of multi-cyclone welding. Finally, an air leakage at the base of either multi-cyclone upsets its operation and seriously affects performance. Thus, without the dust valve at the dust hopper may reduce its collection efficiency.

Dust size distribution analysis at inlet and outlet area of multi-cyclone showed that the percentage of dust volume at outlet area which dust size is more than 25 micron is gradually less than at inlet area. Therefore, we can assume that the collection or removal efficiency of multi-cyclone was effectiveness when dust size is larger than 25 micron.

#### 5.2.4 Pressure drop

According to the result of the study, pressure drop is a function of the square of inlet velocity, so too high a velocity will cause excessive pressure drop. On the other hand, too low a velocity would cause a low efficiency. Thus, the results indicated that when airflow rate was increased, the pressure drop of the multi-cyclone also increased.



## CHAPTER VI

### CONCLUSION AND RECOMMENDATION

#### 6.1 Conclusion

This study aimed to design and construction a multi-cyclone for removing dust that was released during fiberglass surfboard sanding process. The multi-cyclone was composed of nine high-efficiency cyclones with axial inlet airflow and body diameter of 6 inches, arranged in parallel. Dimensions and shapes were calculated based on the Stairman hypothesis. Collection efficiency was estimated using the theory of Leith and Licht. It was set up with a local exhaust ventilation system in which table hood and duct were designed according to the recommendation of the American Conference of Governmental Industrial Hygienists (ACGIH) Industrial Ventilation Manual. The system was tested for dust collection efficiency at three airflow rates: 1,200-1,250, 1,400-1,450, and 1,600-1,650 cfm.

In summary, the results of this study found as follows.

1. Sample dust size distribution from surfboard sanding process ranged from 1 to 594.3 microns with an average size was 40.31 micron. The percentage of cumulative weight and dust size average can be plotted graph, and then comparing with Stairmand particle size distribution standard curve. The result showed that sample dust can classified into fine dust.

2. Variation in airflow rate has marked effect on collection efficiency of multi-cyclone. There was significant difference of collection efficiency when testing with difference airflow rate ranges ( $p < 0.001$ ). At airflow rate range from 1,200 – 1,250, 1,400 – 1,450 and 1,600 – 1,650 cfm, the mean collection efficiency of multi-cyclone was 81.27%, 85.57% and 83.02% respectively. These values were lower than those prediction values by theoretical approach of Leith and Licht. The error involved ranged from 3.16 - 6.69%.

3. The constructed multi-cyclone was worked highest efficiency based on under a control airflow rate range from 1,400 to 1,450 cfm. At this airflow rate range, the

collection efficiency of multi-cyclone was 85.57% that is related to hypothesis of this study.

4. Dust size distribution analysis at inlet and outlet area of multi-cyclone showed that the percentage of dust volume at outlet area which dust size is more than 25 micron is gradually less than at inlet area. Therefore, we can assume that the collection or removal efficiency of multi-cyclone was effectiveness when dust size is larger than 25 micron.

5. For pressure drop, the results indicated that when airflow rate was increased, the pressure drop of the multi-cyclone also increased.

## 6.2 Recommendation

The results of this study will be used as a model of dust collector for the surfboard industry and this effective outcome could be applied in field practice. Moreover, its design could be used as a guideline to improve the similar multi-cyclone model for other industries. For higher dust collection efficiency, the multi-cyclone should be used as the pre-cleaner device and combined with the bag filter. In addition, the proper design of hood and duct system to capture contaminated air for reduction dust exposure of sanding worker would be considered.

Although the emitted dust concentration at the outlet area of the constructed multi-cyclone does not exceed the allowable standard, the sanding workers who exposed fiberglass dust should wear the proper respiratory-protective devices for their health protection and should have comprehensive pre-placement medical examinations with emphasis on skin susceptibility.

For the further study,

1. The relationship between collection efficiency of multi-cyclone and dust concentration should be considered.
2. The model of multi-cyclone should have been developed and tested for higher collection efficiency.
3. The measurements of personal exposure to respirable fiberglass dust in any kind of work involving surfboard sanding should be considered.

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## APPENDIX A

### Particle Density and Specific Gravity Analysis

Particle specific gravity can calculate by following equation:

$$S = \rho/\rho_{st} \quad (A.1)$$

where  $S$  = specific gravity of particle

$\rho$  = density of particle

$\rho_{st}$  = density of reference substance

When using distilled water as reference substance, density of water at 30 °C is 1,000 kg/m<sup>3</sup>, particle density will calculate by equation as follows:

$$\rho = M/V \quad (A.2)$$

where  $M$  = particle mass

$V$  = particle volume

If any substance have volume as equal as reference substance, that is mean

$$V = V_{st} \quad (A.3)$$

$$S = M/M_{st} \quad (A.4)$$

We can mention that "specific gravity of particle is ratio of the weight of a given volume of a substance to the weight of an equal volume of some reference substance, or, equivalently, the ratio of the masses of equal volumes of the two substances.

The particle density is determined by finding the mass of water displaced by a known mass of particle. In this case, a specific gravity bottle (pycometer) or a volumetric flask was used.

#### Procedure:

1. Weigh the clean, dry specific gravity bottle with cap and record the weight as  $M_1$ .
2. Place sample particle about one-third into the bottle, weigh bottle with contains and record the weight as  $M_2$ .
3. Add distilled water to fill the bottle, weigh and record the weight as  $M_3$ .

4. Empty the bottle, clean and dry it, full fill with distilled water, weigh and record the weight as  $M_4$ .
5. Calculate particle density.

$$\begin{aligned} \text{Mass of particle} &= M_2 - M_1 \\ \text{Mass of particle + Mass of displaced water} &= M_3 - M_1 \\ \text{Mass of water} &= M_4 - M_1 \\ \text{Mass of displaced water} &= M_3 - M_2 \end{aligned}$$

Here,  $M_{st} = (M_4 - M_1) - (M_3 - M_2)$ , following equation (A.1) and (A.4) so that we can mentioned that

$$\begin{aligned} S_{\text{particle}} = \rho_{\text{particle}} / \rho_{st} &= M_{\text{particle}} / M_{st} \\ \rho_{\text{particle}} &= \frac{(M_2 - M_1) \rho_{st}}{(M_4 - M_1) - (M_3 - M_2)} \end{aligned} \tag{A.5}$$

For example, sample dust from surfboard sanding process.

where

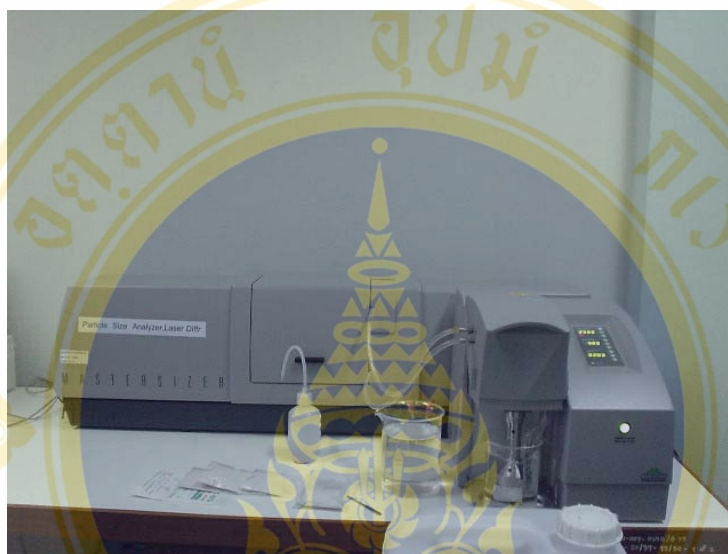
$$\begin{aligned} M_1 &= 40.505 \text{ g} \\ M_2 &= 42.549 \text{ g} \\ M_3 &= 87.551 \text{ g} \\ M_4 &= 94.051 \text{ g} \end{aligned}$$

$$\begin{aligned} \rho_{\text{dust}} &= \frac{(42.549 - 40.505)(1,000)}{(94.051 - 40.505) - (87.551 - 42.549)} \\ &= 239.63 \text{ kg/m}^3 \end{aligned}$$

When tested three times, dust density was 239.63, 231.41, and 235.60  $\text{kg/m}^3$  respectively, average dust density was 236  $\text{kg/m}^3$  and dust specific gravity was 0.236. These data will use to design multi-cyclone performance.

## APPENDIX B

### Particle Size Distribution Analysis



**Figure B-1 Particle Size Analyzer, Mastersizer S**



**Figure B-2 Analysis Report by Malvern Operating Software**

## APPENDIX C

### Local Exhaust Ventilation System Calculation

According to criteria of ACGIH Industrial Ventilation Manual (23 ed.), The duct system that connects the hood, air cleaning device (multi-cyclone), and fan must be properly designed. Moreover, hand grinding bench (VS-80-18) was designed for this study.

This bench required flow rate range from 0.75 to 1.25 m<sup>3</sup>/s/m<sup>2</sup> of bench area, minimum duct velocity was 18 m/s, and hood entry loss (he) was 0.25 VPd. When selected downdraft hood (bench area = 1.08 m<sup>2</sup>) and adjusted all parameters to SI system, design flow rate of system was range from 1,716 to 2,860 ft<sup>3</sup>/min.

This study aims to test 3 levels of flow rate; 1,200-1,250, 1,400-1,450, and 1,600-1,650 cfm, therefore, the highest flow rate was selected. At a duct velocity was 4,724 fpm, the calculating procedure of this system follows.

#### 1. Hood

$$V = 4,724 \text{ fpm}$$

$$Q = 1,650 \text{ cfm}$$

$$he = 0.25 \text{ VPd}$$

#### 2. Duct

Selected duct diameter

$$Q = AV$$

$$A = 1,650/4,724 = 0.3492 \text{ ft}^2$$

$$\text{Duct area} = \pi d^2/4$$

$$\text{Selected proper duct diameter} = 8 \text{ inches } (A = 0.3491\text{ft}^2)$$

$$Q = 0.349 \times 4,724$$

$$= 1,648 \text{ cfm}$$

#### 3. Calculating losses

##### 3.1 Acceleration loss

$$V = 4,005 \sqrt{VP}$$

$$\begin{aligned} VP &= (4,724/4,005)^2 \\ &= 1.39 \text{ in wg.} \end{aligned}$$

$$\begin{aligned} \text{where } SP &= -VP \\ &= -1.39 \text{ in wg.} \end{aligned}$$

### 3.2 Hood entry loss

$$\begin{aligned} \text{where } h_e &= 0.25 VP_d \\ &= 0.25 \times (-1.39 \text{ in wg.}) \\ &= -0.34 \text{ in wg.} \end{aligned}$$

### 3.3 Straight duct loss

$$\begin{aligned} \text{Duct length} &= 12.4 \text{ ft} \\ \text{Friction loss of 8 inches duct} &= -0.025 \text{ in wg/ft} \\ &= 12.4 \times (-0.025 \text{ in wg.}) \\ &= -0.31 \text{ in wg.} \end{aligned}$$

### 3.4 Elbow loss (90° 4 points)

$$\begin{aligned} 1\text{-}90^\circ \text{ elbow} &= 8 \text{ equivalent feet} \\ &= 8 (4)(-0.025 \text{ in wg.}) \\ &= -0.80 \text{ in wg.} \end{aligned}$$

### 3.5 Total loss before fan inlet (SP<sub>i</sub>)

$$\begin{aligned} &= (-1.39) + (-0.34) + (-0.31) + (-0.80) \\ &= -2.84 \text{ in wg.} \end{aligned}$$

### 4. Total loss after fan outlet (SP<sub>o</sub>)

$$\begin{aligned} &= 4 \text{ ft} \times (0.025 \text{ in wg.}) \\ &= 0.10 \text{ in wg.} \end{aligned}$$

### 5. Multi-cyclone loss

$$= -0.54 \text{ in wg.}$$

### 6. Overall losses (SP<sub>f</sub>)

$$\begin{aligned} &= SP_o - SP_i - VP_i \\ &= (1.39) - (-2.84) - (-0.54) - (0.10) \\ &= 4.67 \text{ in w.g.} \end{aligned}$$

### 7. Calculating horsepower

$$\begin{aligned} HP &= (Q \times SP_f) / 6,356 \text{ ME} \\ \text{where } Q &= 1,650 \text{ cfm} \end{aligned}$$

$$\begin{aligned} SP_f &= 4.67 \text{ in wg.} \\ ME &= 0.6 \\ \text{HP of Fan} &= (2,147 \times 4.67) / (6,356 \times 0.6) \\ &= 2.63 \text{ HP} \end{aligned}$$

According to the result of horsepower calculating, 3 HP fan should be considered.



### APPENDIX D

#### Figures of Multi-cyclone and Equipment

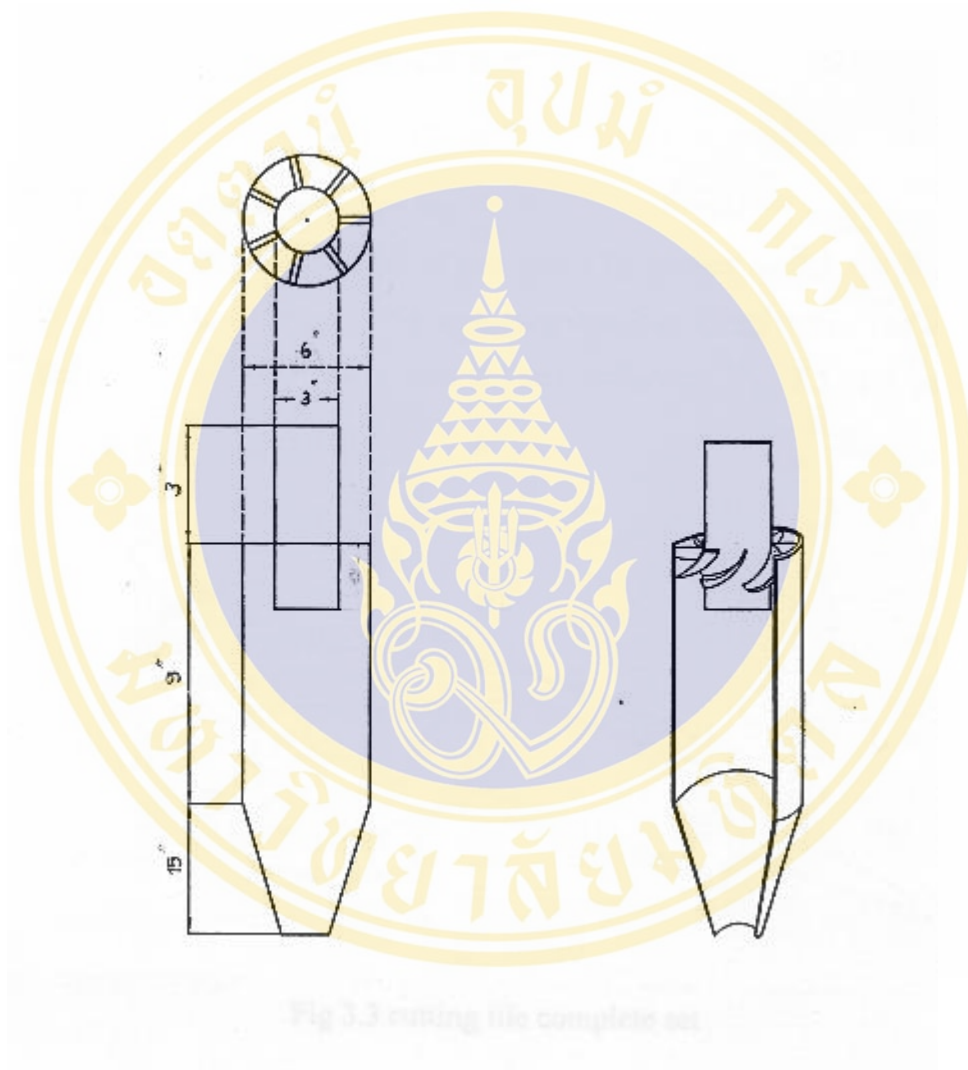
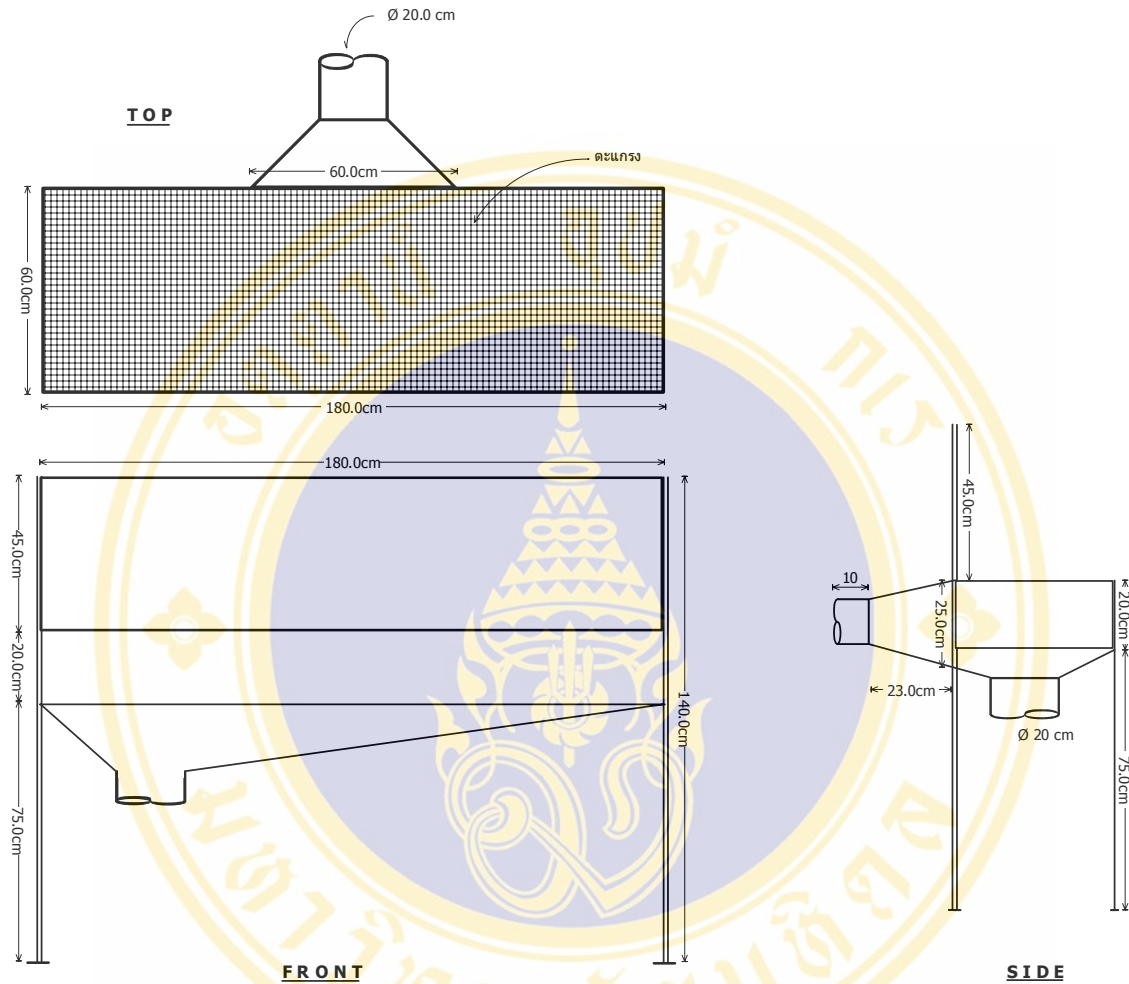
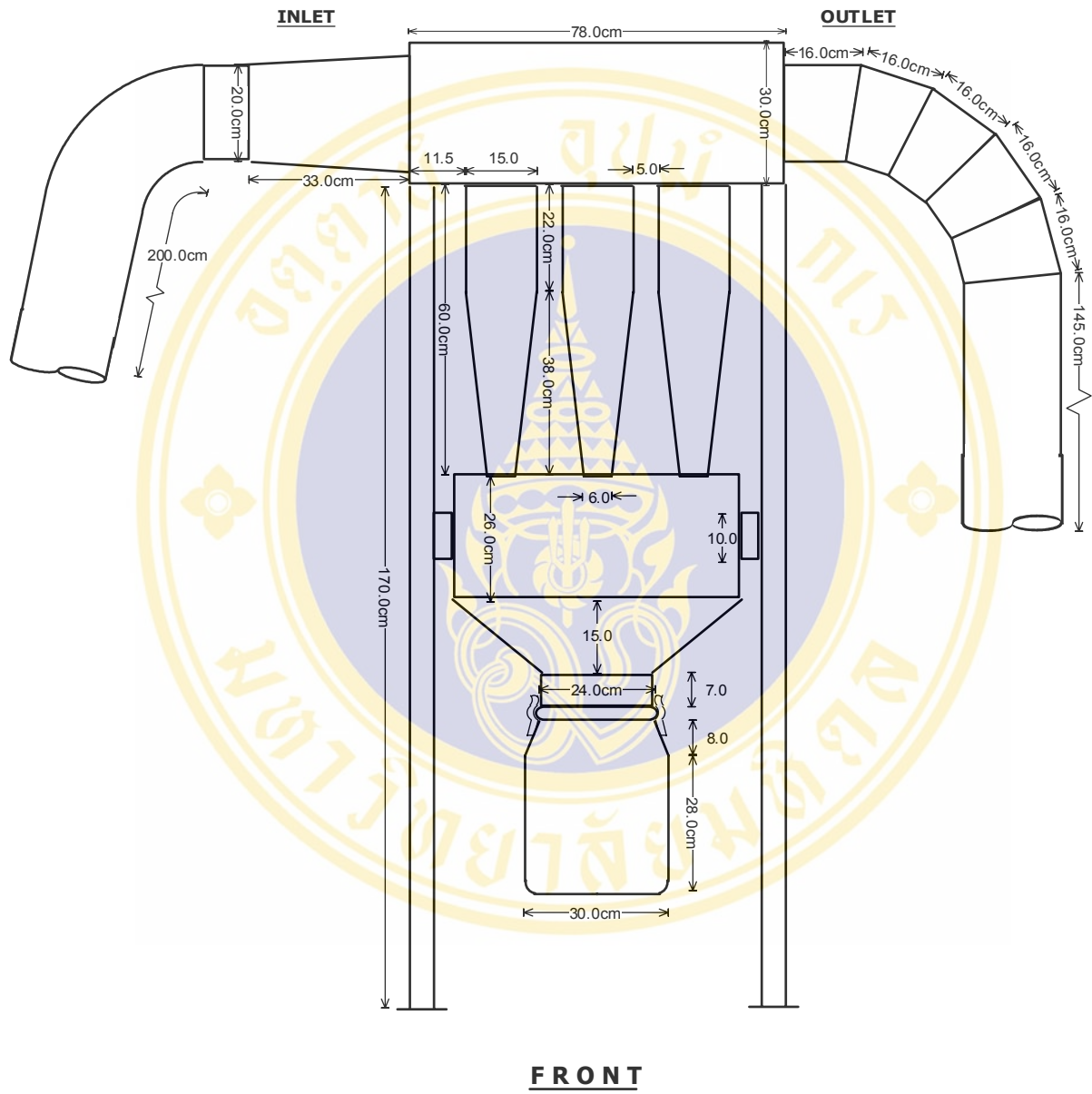


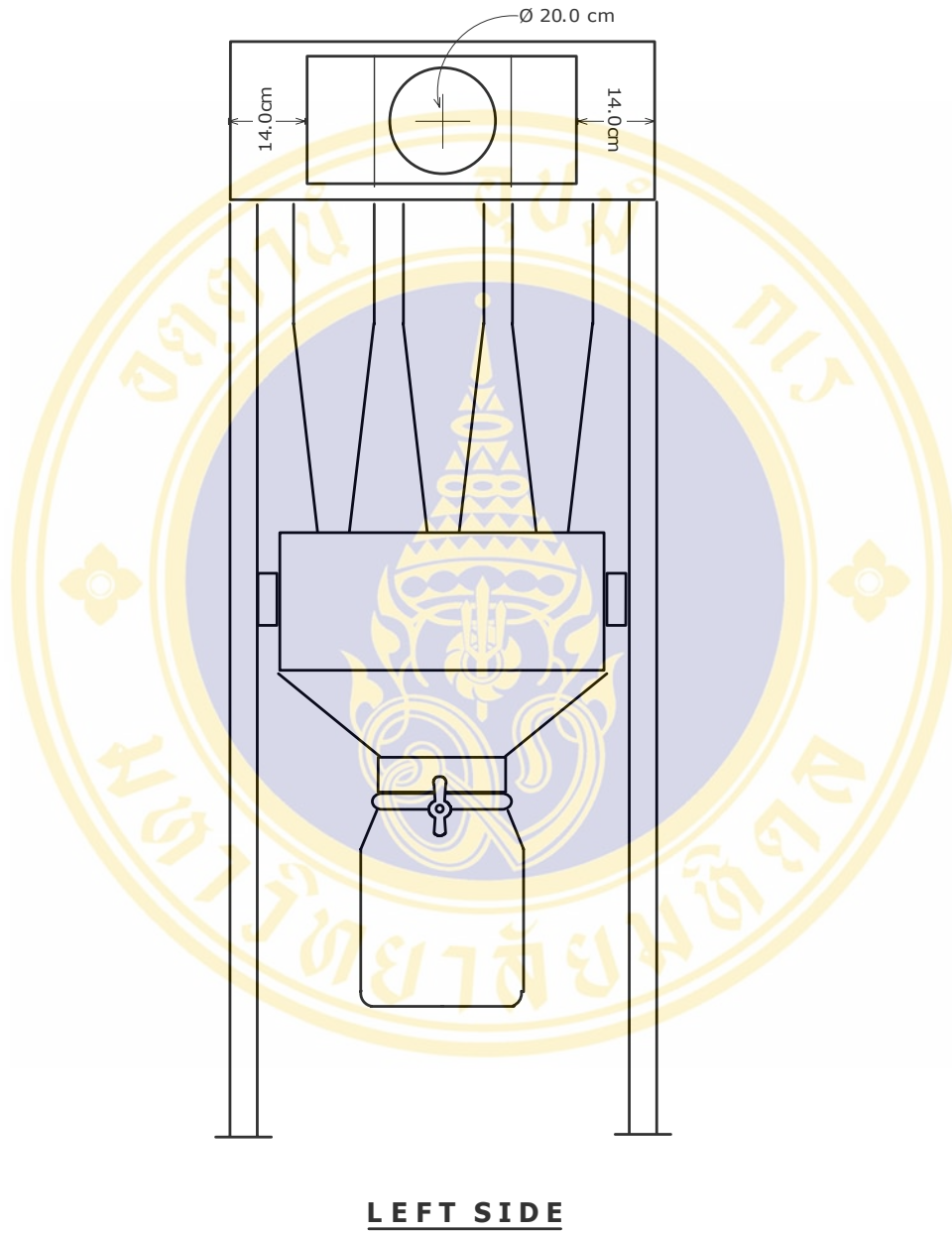
Figure D-1 Axial inlet cyclone



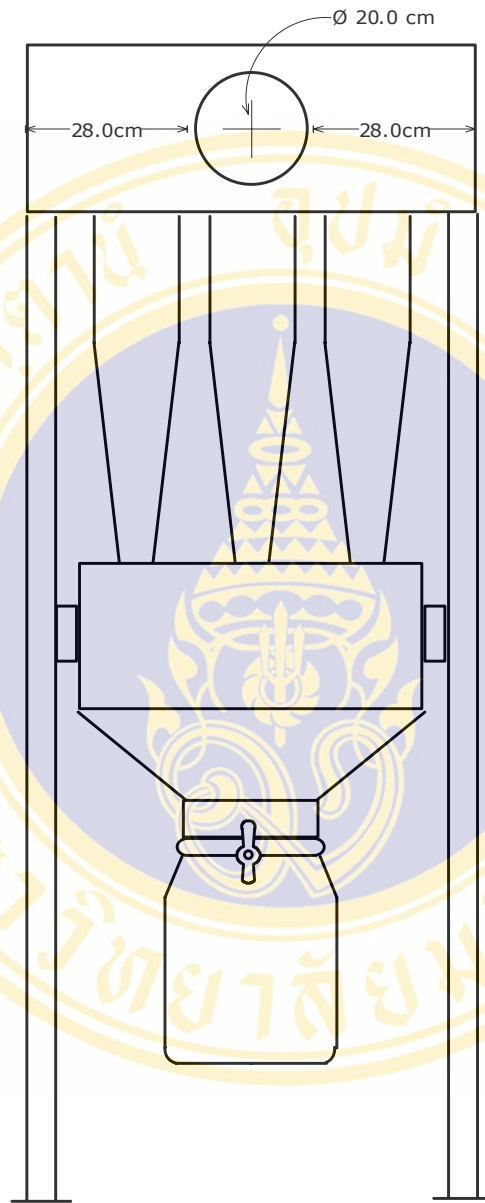
**Figure D-2 Sanding Bench and Downdraft Hood**



**Figure D-3 Multi-cyclone Structure (Front Side)**

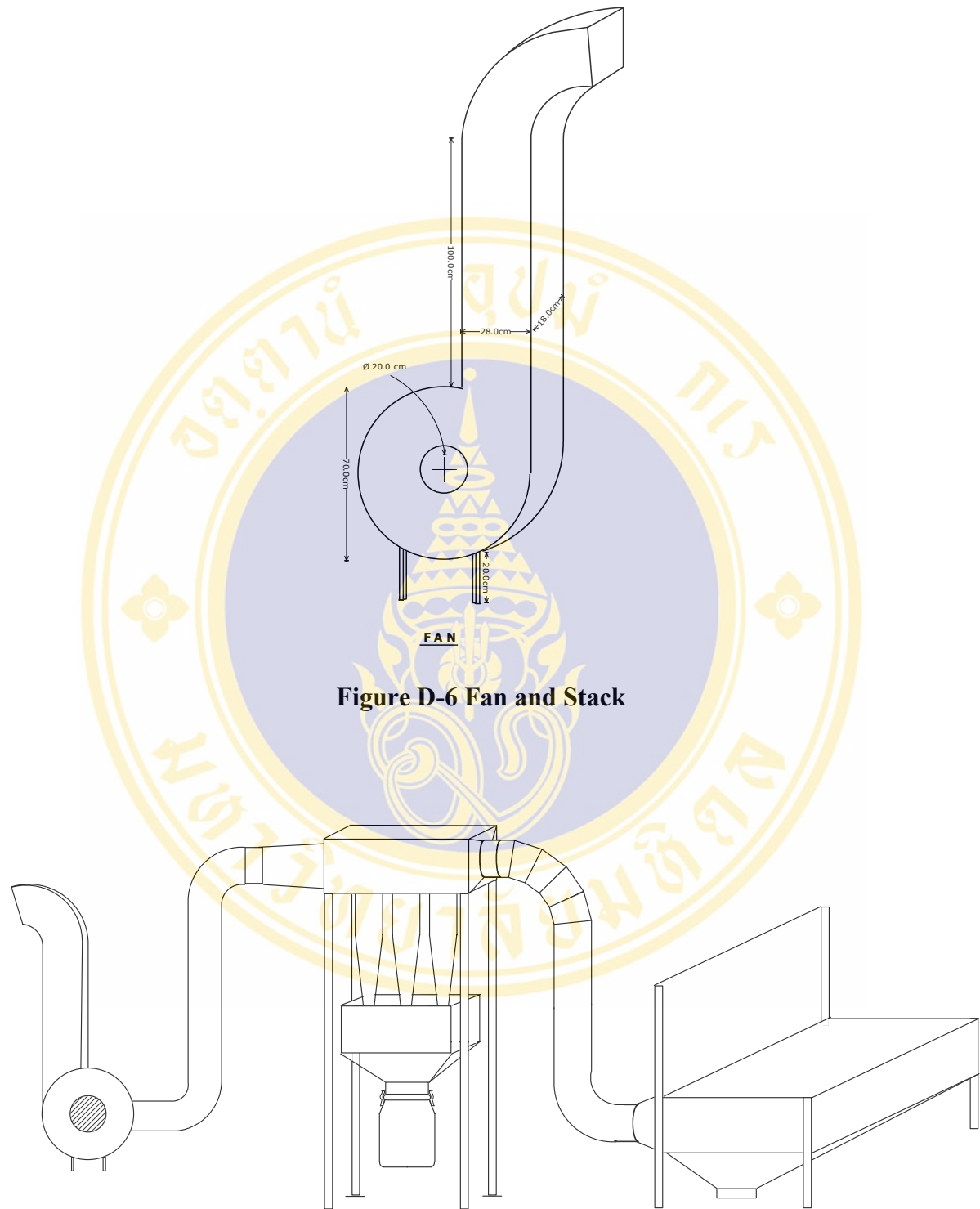


**Figure D-4 Multi-cyclone Structure (Left Side)**



**RIGHT SIDE**

**Figure D-5 Multi-cyclone Structure (Right Side)**



**Figure D-6 Fan and Stack**

**Figure D-7 Drawing of Local Exhaust Ventilation System**



**Figure D-8 Illustration of Local Exhaust Ventilation System**



**Figure D-9 Position of Work in Surfboard Sanding Process**



**Figure D-10 Particulate Detection (Microdust Pro)**



**Figure D-11 Anemometer (Thermo-Anemometer)**

## APPENDIX E

Table E-1 Collection Efficiency of Multi-cyclone (Airflow rate = 1,200-1,250 cfm)

| Time<br>(sec)     | Test 1                              |                                      | Test 2                              |                                      | Test 3                              |                                      | Test 4                              |                                      | Test 5                              |                                      |
|-------------------|-------------------------------------|--------------------------------------|-------------------------------------|--------------------------------------|-------------------------------------|--------------------------------------|-------------------------------------|--------------------------------------|-------------------------------------|--------------------------------------|
|                   | Inlet conc.<br>(mg/m <sup>3</sup> ) | Outlet conc.<br>(mg/m <sup>3</sup> ) | Inlet conc.<br>(mg/m <sup>3</sup> ) | Outlet conc.<br>(mg/m <sup>3</sup> ) | Inlet conc.<br>(mg/m <sup>3</sup> ) | Outlet conc.<br>(mg/m <sup>3</sup> ) | Inlet conc.<br>(mg/m <sup>3</sup> ) | Outlet conc.<br>(mg/m <sup>3</sup> ) | Inlet conc.<br>(mg/m <sup>3</sup> ) | Outlet conc.<br>(mg/m <sup>3</sup> ) |
| 0:05              | 16.818                              | 2.089                                | 15.357                              | 2.159                                | 16.945                              | 2.325                                | 11.427                              | 3.744                                | 16.745                              | 2.834                                |
| 0:10              | 15.351                              | 2.548                                | 17.986                              | 2.216                                | 13.562                              | 2.477                                | 13.285                              | 3.581                                | 12.558                              | 2.582                                |
| 0:15              | 14.729                              | 3.856                                | 15.922                              | 3.170                                | 14.964                              | 2.010                                | 14.999                              | 3.288                                | 14.540                              | 3.351                                |
| 0:20              | 17.012                              | 4.969                                | 17.070                              | 3.139                                | 12.404                              | 3.269                                | 12.488                              | 3.170                                | 14.609                              | 2.397                                |
| 0:25              | 18.554                              | 2.510                                | 16.865                              | 2.124                                | 13.183                              | 3.095                                | 14.098                              | 2.934                                | 15.243                              | 3.099                                |
| 0:30              | 14.942                              | 4.301                                | 15.660                              | 3.371                                | 13.537                              | 2.758                                | 12.717                              | 2.911                                | 13.289                              | 2.884                                |
| 0:35              | 15.962                              | 4.067                                | 17.754                              | 2.096                                | 15.487                              | 2.245                                | 14.019                              | 2.655                                | 12.040                              | 2.812                                |
| 0:40              | 15.792                              | 3.410                                | 15.150                              | 2.897                                | 13.531                              | 2.677                                | 12.970                              | 2.480                                | 14.005                              | 2.652                                |
| 0:45              | 14.206                              | 4.236                                | 15.556                              | 2.602                                | 17.490                              | 3.085                                | 15.664                              | 2.414                                | 15.211                              | 2.738                                |
| 0:50              | 16.030                              | 2.272                                | 15.873                              | 2.638                                | 13.789                              | 2.683                                | 10.655                              | 2.350                                | 13.254                              | 2.668                                |
| 0:55              | 16.854                              | 2.977                                | 14.956                              | 2.688                                | 16.245                              | 2.500                                | 11.180                              | 2.328                                | 15.024                              | 2.561                                |
| 1:00              | 15.853                              | 2.858                                | 16.751                              | 2.835                                | 15.956                              | 2.911                                | 12.265                              | 2.292                                | 13.346                              | 2.532                                |
| 1:05              | 16.540                              | 3.927                                | 14.251                              | 2.753                                | 17.754                              | 3.398                                | 13.490                              | 2.163                                | 15.395                              | 2.490                                |
| 1:10              | 16.438                              | 2.814                                | 15.236                              | 2.746                                | 16.114                              | 3.384                                | 14.746                              | 2.215                                | 13.150                              | 2.572                                |
| 1:15              | 15.177                              | 2.586                                | 16.200                              | 2.870                                | 15.758                              | 3.248                                | 15.903                              | 2.208                                | 12.215                              | 2.480                                |
| 1:20              | 17.132                              | 2.563                                | 16.630                              | 2.921                                | 16.814                              | 3.064                                | 12.446                              | 2.181                                | 14.188                              | 2.467                                |
| 1:25              | 16.723                              | 2.961                                | 17.207                              | 2.816                                | 14.352                              | 3.696                                | 12.306                              | 2.184                                | 12.146                              | 2.546                                |
| 1:30              | 14.840                              | 3.209                                | 15.090                              | 2.737                                | 16.890                              | 2.366                                | 13.101                              | 2.250                                | 14.168                              | 2.592                                |
| 1:35              | 16.822                              | 3.341                                | 15.968                              | 2.849                                | 14.808                              | 3.060                                | 15.293                              | 2.208                                | 14.448                              | 2.506                                |
| 1:40              | 18.027                              | 2.965                                | 16.387                              | 2.964                                | 13.907                              | 2.745                                | 11.325                              | 3.064                                | 12.160                              | 2.410                                |
| 1:45              | 17.211                              | 3.202                                | 14.512                              | 3.020                                | 14.611                              | 2.467                                | 15.053                              | 3.011                                | 13.372                              | 2.673                                |
| 1:50              | 16.971                              | 3.126                                | 15.421                              | 3.569                                | 16.247                              | 2.311                                | 13.272                              | 2.942                                | 15.534                              | 2.377                                |
| 1:55              | 18.362                              | 3.587                                | 15.316                              | 3.417                                | 14.943                              | 2.181                                | 14.026                              | 2.916                                | 14.014                              | 3.044                                |
| 2:00              | 17.888                              | 2.917                                | 17.174                              | 3.352                                | 13.205                              | 2.151                                | 14.122                              | 3.040                                | 13.083                              | 2.942                                |
| 2:05              | 18.453                              | 2.523                                | 16.750                              | 3.421                                | 15.922                              | 2.117                                | 16.337                              | 3.092                                | 12.972                              | 2.987                                |
| 2:10              | 18.143                              | 3.531                                | 15.472                              | 2.645                                | 14.320                              | 2.114                                | 18.340                              | 2.865                                | 13.444                              | 3.623                                |
| 2:15              | 21.113                              | 2.157                                | 14.573                              | 2.385                                | 14.669                              | 2.264                                | 14.026                              | 3.716                                | 12.494                              | 2.953                                |
| 2:20              | 15.961                              | 2.762                                | 18.528                              | 3.712                                | 16.327                              | 2.723                                | 15.131                              | 2.879                                | 12.297                              | 2.340                                |
| 2:25              | 16.914                              | 2.204                                | 16.928                              | 2.688                                | 14.097                              | 2.517                                | 14.144                              | 3.004                                | 16.408                              | 2.924                                |
| 2:30              | 15.659                              | 2.094                                | 15.089                              | 2.808                                | 14.013                              | 2.885                                | 12.298                              | 2.725                                | 13.744                              | 1.788                                |
| 2:35              | 14.926                              | 3.061                                | 17.194                              | 2.812                                | 15.517                              | 3.867                                | 13.489                              | 2.349                                | 14.242                              | 1.726                                |
| 2:40              | 15.334                              | 2.565                                | 14.439                              | 2.503                                | 13.280                              | 3.961                                | 16.093                              | 2.529                                | 12.956                              | 1.672                                |
| 2:45              | 14.214                              | 2.592                                | 15.834                              | 3.371                                | 14.821                              | 3.600                                | 14.987                              | 2.816                                | 12.969                              | 1.643                                |
| 2:50              | 16.515                              | 3.135                                | 14.150                              | 2.337                                | 14.061                              | 3.752                                | 15.580                              | 2.252                                | 14.190                              | 1.872                                |
| 2:55              | 17.192                              | 3.157                                | 14.421                              | 2.322                                | 15.756                              | 3.738                                | 12.879                              | 2.756                                | 12.002                              | 2.987                                |
| 3:00              | 13.530                              | 2.026                                | 16.543                              | 3.021                                | 17.441                              | 3.276                                | 12.982                              | 2.377                                | 13.054                              | 2.314                                |
| <b>Average</b>    | <b>16.450</b>                       | <b>3.031</b>                         | <b>15.950</b>                       | <b>2.833</b>                         | <b>15.076</b>                       | <b>2.859</b>                         | <b>13.809</b>                       | <b>2.719</b>                         | <b>13.736</b>                       | <b>2.584</b>                         |
| <b>S.D</b>        | <b>1.503</b>                        | <b>0.693</b>                         | <b>1.120</b>                        | <b>0.416</b>                         | <b>1.402</b>                        | <b>0.568</b>                         | <b>1.661</b>                        | <b>0.450</b>                         | <b>1.233</b>                        | <b>0.446</b>                         |
| <b>Efficiency</b> | <b>81.58</b>                        |                                      | <b>82.24</b>                        |                                      | <b>81.04</b>                        |                                      | <b>80.31</b>                        |                                      | <b>81.19</b>                        |                                      |

**Table E-2 Collection Efficiency of Multi-cyclone (Airflow rate = 1,400-1,450 cfm)**

| Time<br>(sec)     | Test 1                              |                                      | Test 2                              |                                      | Test 3                              |                                      | Test 4                              |                                      | Test 5                              |                                      |
|-------------------|-------------------------------------|--------------------------------------|-------------------------------------|--------------------------------------|-------------------------------------|--------------------------------------|-------------------------------------|--------------------------------------|-------------------------------------|--------------------------------------|
|                   | Inlet conc.<br>(mg/m <sup>3</sup> ) | Outlet conc.<br>(mg/m <sup>3</sup> ) | Inlet conc.<br>(mg/m <sup>3</sup> ) | Outlet conc.<br>(mg/m <sup>3</sup> ) | Inlet conc.<br>(mg/m <sup>3</sup> ) | Outlet conc.<br>(mg/m <sup>3</sup> ) | Inlet conc.<br>(mg/m <sup>3</sup> ) | Outlet conc.<br>(mg/m <sup>3</sup> ) | Inlet conc.<br>(mg/m <sup>3</sup> ) | Outlet conc.<br>(mg/m <sup>3</sup> ) |
| 0:05              | 16.818                              | 2.889                                | 15.461                              | 2.159                                | 16.816                              | 2.125                                | 16.427                              | 1.744                                | 15.745                              | 2.334                                |
| 0:10              | 15.351                              | 2.548                                | 18.986                              | 2.216                                | 17.562                              | 1.277                                | 15.235                              | 1.581                                | 16.558                              | 2.582                                |
| 0:15              | 14.729                              | 2.056                                | 15.922                              | 2.170                                | 14.964                              | 2.010                                | 16.999                              | 2.288                                | 14.540                              | 2.351                                |
| 0:20              | 17.012                              | 2.069                                | 17.070                              | 2.139                                | 14.050                              | 2.269                                | 15.488                              | 2.170                                | 14.609                              | 2.397                                |
| 0:25              | 18.554                              | 2.510                                | 16.865                              | 2.124                                | 15.183                              | 2.095                                | 14.098                              | 1.934                                | 15.243                              | 2.099                                |
| 0:30              | 14.942                              | 2.301                                | 15.660                              | 2.317                                | 17.537                              | 2.358                                | 16.717                              | 2.221                                | 13.289                              | 2.284                                |
| 0:35              | 15.962                              | 2.067                                | 17.754                              | 2.096                                | 15.487                              | 2.245                                | 14.019                              | 2.155                                | 17.040                              | 2.212                                |
| 0:40              | 15.792                              | 2.410                                | 15.150                              | 2.197                                | 16.531                              | 2.677                                | 17.970                              | 2.480                                | 14.005                              | 2.652                                |
| 0:45              | 14.206                              | 2.236                                | 15.556                              | 2.602                                | 17.490                              | 2.035                                | 15.664                              | 2.414                                | 15.211                              | 2.738                                |
| 0:50              | 16.030                              | 2.272                                | 15.873                              | 2.638                                | 17.789                              | 2.183                                | 16.655                              | 2.350                                | 16.254                              | 2.668                                |
| 0:55              | 16.854                              | 2.977                                | 14.956                              | 2.688                                | 16.245                              | 2.500                                | 15.180                              | 2.128                                | 15.024                              | 2.561                                |
| 1:00              | 15.853                              | 2.858                                | 16.751                              | 2.835                                | 15.956                              | 2.211                                | 17.265                              | 2.292                                | 13.346                              | 2.532                                |
| 1:05              | 16.540                              | 1.927                                | 14.251                              | 2.753                                | 17.754                              | 2.198                                | 16.490                              | 2.163                                | 15.395                              | 2.490                                |
| 1:10              | 16.438                              | 2.814                                | 15.236                              | 2.746                                | 16.114                              | 2.384                                | 14.746                              | 2.215                                | 13.150                              | 2.572                                |
| 1:15              | 15.177                              | 2.586                                | 16.200                              | 2.187                                | 15.758                              | 2.246                                | 15.903                              | 2.208                                | 16.215                              | 2.480                                |
| 1:20              | 17.132                              | 2.563                                | 16.630                              | 2.293                                | 16.814                              | 2.064                                | 15.446                              | 2.181                                | 14.188                              | 2.467                                |
| 1:25              | 16.723                              | 2.961                                | 17.207                              | 2.652                                | 14.352                              | 2.090                                | 15.241                              | 2.184                                | 15.146                              | 2.546                                |
| 1:30              | 14.840                              | 2.209                                | 15.090                              | 2.737                                | 16.890                              | 2.366                                | 17.010                              | 2.250                                | 14.168                              | 2.192                                |
| 1:35              | 16.822                              | 2.341                                | 15.968                              | 2.849                                | 15.408                              | 2.060                                | 15.293                              | 2.208                                | 14.448                              | 2.006                                |
| 1:40              | 18.027                              | 1.965                                | 16.387                              | 2.964                                | 15.907                              | 1.979                                | 14.325                              | 2.064                                | 17.160                              | 2.410                                |
| 1:45              | 17.211                              | 2.202                                | 14.512                              | 2.020                                | 14.611                              | 2.467                                | 15.053                              | 2.011                                | 13.372                              | 2.173                                |
| 1:50              | 16.971                              | 2.126                                | 15.421                              | 2.560                                | 16.247                              | 2.311                                | 16.272                              | 1.942                                | 15.534                              | 2.377                                |
| 1:55              | 18.362                              | 2.587                                | 15.316                              | 2.417                                | 14.943                              | 2.181                                | 14.026                              | 1.916                                | 14.014                              | 2.044                                |
| 2:00              | 17.888                              | 2.917                                | 17.174                              | 2.356                                | 15.205                              | 2.151                                | 14.122                              | 2.040                                | 17.083                              | 2.142                                |
| 2:05              | 18.453                              | 2.523                                | 16.750                              | 2.421                                | 15.922                              | 2.117                                | 16.337                              | 2.092                                | 17.972                              | 2.387                                |
| 2:10              | 18.143                              | 2.531                                | 15.472                              | 2.645                                | 14.320                              | 2.114                                | 18.340                              | 2.065                                | 16.444                              | 2.123                                |
| 2:15              | 21.113                              | 2.157                                | 14.573                              | 2.385                                | 14.669                              | 2.264                                | 14.026                              | 2.765                                | 16.494                              | 2.253                                |
| 2:20              | 15.961                              | 2.762                                | 18.528                              | 2.172                                | 16.327                              | 2.123                                | 15.131                              | 2.179                                | 14.297                              | 2.340                                |
| 2:25              | 16.914                              | 2.204                                | 16.928                              | 2.688                                | 16.097                              | 2.517                                | 14.144                              | 2.004                                | 16.408                              | 1.924                                |
| 2:30              | 15.659                              | 2.094                                | 15.089                              | 2.008                                | 14.013                              | 1.885                                | 16.298                              | 2.125                                | 16.744                              | 1.788                                |
| 2:35              | 14.926                              | 2.061                                | 17.194                              | 2.112                                | 15.517                              | 2.867                                | 17.849                              | 2.349                                | 14.242                              | 1.726                                |
| 2:40              | 15.334                              | 2.565                                | 14.439                              | 2.503                                | 16.280                              | 1.961                                | 16.093                              | 2.529                                | 15.956                              | 1.672                                |
| 2:45              | 14.214                              | 2.592                                | 15.834                              | 2.371                                | 14.821                              | 1.950                                | 14.987                              | 2.816                                | 16.546                              | 1.643                                |
| 2:50              | 16.515                              | 2.135                                | 16.250                              | 2.337                                | 14.061                              | 1.892                                | 15.580                              | 2.252                                | 14.190                              | 1.872                                |
| 2:55              | 17.192                              | 2.157                                | 15.421                              | 2.322                                | 15.756                              | 2.738                                | 16.879                              | 2.756                                | 17.002                              | 2.087                                |
| 3:00              | 13.530                              | 2.026                                | 16.543                              | 2.021                                | 17.441                              | 2.276                                | 15.982                              | 2.377                                | 15.054                              | 2.314                                |
| <b>Average</b>    | <b>16.450</b>                       | <b>2.394</b>                         | <b>16.067</b>                       | <b>2.408</b>                         | <b>15.857</b>                       | <b>2.200</b>                         | <b>15.758</b>                       | <b>2.207</b>                         | <b>15.336</b>                       | <b>2.262</b>                         |
| <b>S.D</b>        | <b>1.503</b>                        | <b>0.313</b>                         | <b>1.111</b>                        | <b>0.271</b>                         | <b>1.121</b>                        | <b>0.278</b>                         | <b>1.186</b>                        | <b>0.257</b>                         | <b>1.294</b>                        | <b>0.290</b>                         |
| <b>Efficiency</b> | <b>85.44</b>                        |                                      | <b>85.01</b>                        |                                      | <b>86.13</b>                        |                                      | <b>86.00</b>                        |                                      | <b>85.25</b>                        |                                      |

**Table E-3 Collection Efficiency of Multi-cyclone (Airflow rate = 1,600-1,650 cfm)**

| Time<br>(sec)     | Test 1                              |                                      | Test 2                              |                                      | Test 3                              |                                      | Test 4                              |                                      | Test 5                              |                                      |
|-------------------|-------------------------------------|--------------------------------------|-------------------------------------|--------------------------------------|-------------------------------------|--------------------------------------|-------------------------------------|--------------------------------------|-------------------------------------|--------------------------------------|
|                   | Inlet conc.<br>(mg/m <sup>3</sup> ) | Outlet conc.<br>(mg/m <sup>3</sup> ) | Inlet conc.<br>(mg/m <sup>3</sup> ) | Outlet conc.<br>(mg/m <sup>3</sup> ) | Inlet conc.<br>(mg/m <sup>3</sup> ) | Outlet conc.<br>(mg/m <sup>3</sup> ) | Inlet conc.<br>(mg/m <sup>3</sup> ) | Outlet conc.<br>(mg/m <sup>3</sup> ) | Inlet conc.<br>(mg/m <sup>3</sup> ) | Outlet conc.<br>(mg/m <sup>3</sup> ) |
| 0:05              | 16.812                              | 2.889                                | 15.461                              | 2.159                                | 16.816                              | 2.325                                | 10.427                              | 3.744                                | 15.745                              | 2.834                                |
| 0:10              | 15.450                              | 2.548                                | 18.986                              | 2.216                                | 13.562                              | 2.477                                | 13.285                              | 3.581                                | 16.558                              | 2.582                                |
| 0:15              | 14.729                              | 3.856                                | 15.922                              | 2.170                                | 14.964                              | 2.010                                | 14.999                              | 3.288                                | 14.540                              | 2.351                                |
| 0:20              | 17.012                              | 2.351                                | 17.070                              | 3.139                                | 11.404                              | 3.269                                | 13.488                              | 3.170                                | 14.609                              | 2.397                                |
| 0:25              | 18.554                              | 2.510                                | 16.865                              | 2.124                                | 13.183                              | 3.095                                | 14.098                              | 2.934                                | 15.243                              | 2.009                                |
| 0:30              | 14.942                              | 3.302                                | 15.660                              | 3.371                                | 15.537                              | 2.758                                | 12.717                              | 2.911                                | 13.289                              | 2.884                                |
| 0:35              | 15.962                              | 3.067                                | 17.754                              | 2.096                                | 15.487                              | 2.245                                | 14.019                              | 2.655                                | 14.040                              | 2.812                                |
| 0:40              | 15.792                              | 3.410                                | 15.150                              | 2.897                                | 13.531                              | 2.677                                | 12.970                              | 2.480                                | 14.005                              | 2.652                                |
| 0:45              | 14.206                              | 3.267                                | 15.556                              | 2.602                                | 17.490                              | 3.085                                | 15.664                              | 2.414                                | 15.211                              | 2.738                                |
| 0:50              | 16.030                              | 2.272                                | 15.873                              | 2.638                                | 13.789                              | 2.683                                | 13.655                              | 2.350                                | 13.254                              | 2.668                                |
| 0:55              | 16.854                              | 2.977                                | 14.956                              | 2.688                                | 16.245                              | 2.500                                | 14.382                              | 2.328                                | 15.024                              | 2.561                                |
| 1:00              | 15.853                              | 2.858                                | 16.751                              | 2.835                                | 15.956                              | 2.911                                | 15.373                              | 2.292                                | 14.364                              | 2.532                                |
| 1:05              | 16.540                              | 2.927                                | 14.251                              | 2.753                                | 17.754                              | 2.396                                | 13.490                              | 2.163                                | 15.395                              | 2.490                                |
| 1:10              | 16.438                              | 2.814                                | 15.236                              | 2.746                                | 16.114                              | 2.384                                | 14.746                              | 2.215                                | 13.150                              | 2.572                                |
| 1:15              | 15.177                              | 2.586                                | 16.200                              | 2.870                                | 15.758                              | 3.248                                | 15.903                              | 2.208                                | 16.215                              | 2.480                                |
| 1:20              | 17.132                              | 2.563                                | 16.630                              | 2.921                                | 16.814                              | 2.064                                | 14.446                              | 2.181                                | 14.188                              | 2.467                                |
| 1:25              | 16.723                              | 2.961                                | 17.207                              | 2.816                                | 14.352                              | 2.696                                | 16.306                              | 2.184                                | 15.146                              | 2.546                                |
| 1:30              | 14.840                              | 3.209                                | 15.090                              | 2.737                                | 16.890                              | 2.366                                | 13.101                              | 2.250                                | 14.168                              | 2.592                                |
| 1:35              | 16.822                              | 3.341                                | 15.968                              | 2.849                                | 14.808                              | 2.060                                | 15.293                              | 2.208                                | 14.448                              | 2.506                                |
| 1:40              | 18.027                              | 2.965                                | 16.387                              | 2.964                                | 16.093                              | 2.745                                | 14.325                              | 2.064                                | 15.160                              | 2.410                                |
| 1:45              | 17.211                              | 2.202                                | 14.512                              | 2.020                                | 14.611                              | 2.467                                | 15.053                              | 2.011                                | 13.372                              | 2.673                                |
| 1:50              | 16.971                              | 3.126                                | 15.421                              | 2.569                                | 16.247                              | 2.311                                | 16.227                              | 2.942                                | 15.534                              | 2.377                                |
| 1:55              | 18.362                              | 2.587                                | 15.316                              | 3.417                                | 14.943                              | 2.181                                | 14.026                              | 2.916                                | 14.014                              | 2.044                                |
| 2:00              | 17.888                              | 2.917                                | 17.174                              | 2.352                                | 13.205                              | 2.151                                | 14.122                              | 2.040                                | 13.083                              | 2.942                                |
| 2:05              | 18.453                              | 2.523                                | 16.750                              | 2.421                                | 15.922                              | 2.117                                | 16.337                              | 2.083                                | 16.972                              | 2.987                                |
| 2:10              | 18.143                              | 2.531                                | 15.472                              | 2.645                                | 14.320                              | 2.114                                | 18.340                              | 2.865                                | 15.444                              | 2.623                                |
| 2:15              | 21.113                              | 2.157                                | 14.573                              | 2.385                                | 14.669                              | 2.264                                | 14.026                              | 3.716                                | 14.494                              | 1.935                                |
| 2:20              | 15.961                              | 2.762                                | 18.528                              | 2.712                                | 16.327                              | 2.723                                | 15.131                              | 2.879                                | 15.297                              | 2.340                                |
| 2:25              | 16.914                              | 2.204                                | 16.928                              | 2.688                                | 14.097                              | 2.517                                | 14.144                              | 3.004                                | 16.408                              | 2.924                                |
| 2:30              | 15.659                              | 2.094                                | 15.089                              | 2.808                                | 14.013                              | 2.885                                | 16.298                              | 2.725                                | 15.744                              | 2.188                                |
| 2:35              | 14.926                              | 2.061                                | 17.194                              | 2.812                                | 15.517                              | 2.876                                | 15.489                              | 2.349                                | 14.242                              | 2.276                                |
| 2:40              | 15.334                              | 2.565                                | 14.439                              | 2.503                                | 13.280                              | 2.961                                | 16.093                              | 2.529                                | 14.953                              | 1.972                                |
| 2:45              | 14.214                              | 2.592                                | 15.834                              | 2.371                                | 14.821                              | 3.600                                | 14.987                              | 2.816                                | 15.969                              | 1.946                                |
| 2:50              | 16.515                              | 2.135                                | 14.150                              | 2.337                                | 14.061                              | 3.752                                | 15.580                              | 2.252                                | 14.190                              | 1.872                                |
| 2:55              | 17.192                              | 2.157                                | 14.421                              | 2.322                                | 15.756                              | 3.738                                | 14.879                              | 2.756                                | 14.002                              | 2.987                                |
| 3:00              | 13.530                              | 2.026                                | 16.543                              | 3.021                                | 17.441                              | 2.276                                | 13.982                              | 2.377                                | 15.403                              | 2.314                                |
| <b>Average</b>    | <b>16.452</b>                       | <b>2.703</b>                         | <b>15.981</b>                       | <b>2.638</b>                         | <b>15.160</b>                       | <b>2.637</b>                         | <b>14.650</b>                       | <b>2.608</b>                         | <b>14.802</b>                       | <b>2.486</b>                         |
| <b>S.D</b>        | <b>1.501</b>                        | <b>0.448</b>                         | <b>1.181</b>                        | <b>0.343</b>                         | <b>1.434</b>                        | <b>0.474</b>                         | <b>1.387</b>                        | <b>0.478</b>                         | <b>0.999</b>                        | <b>0.311</b>                         |
| <b>Efficiency</b> | <b>83.57</b>                        |                                      | <b>83.49</b>                        |                                      | <b>82.61</b>                        |                                      | <b>82.20</b>                        |                                      | <b>83.21</b>                        |                                      |

## BIOGRAPHY



|                                       |  |
|---------------------------------------|--|
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