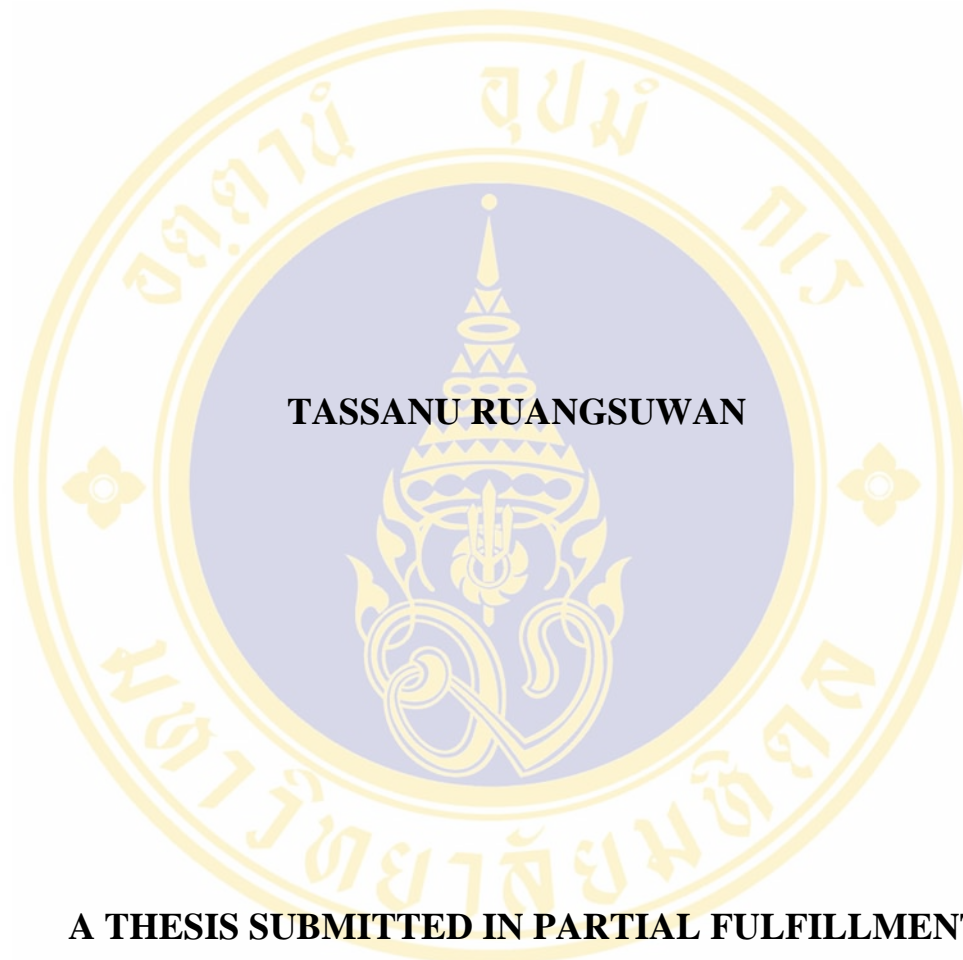


**A STUDY ON DESIGN AND TEST PERFORMANCE
OF GLASS BOTTLE CYCLONES**



**A THESIS SUBMITTED IN PARTIAL FULFILLMENT
OF THE REQUIREMENTS FOR
THE DEGREE OF MASTER OF SCIENCE
(INDUSTRIAL HYGIENE AND SAFETY)
FACULTY OF GRADUATE STUDIES
MAHIDOL UNIVERSITY**

2006

ISBN 974-04-7398-9

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Thesis
Entitled

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OF GLASS BOTTLE CYCLONES**



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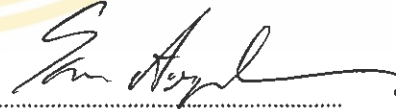
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OF GLASS BOTTLE CYCLONES**

Was submitted to the Faculty of Graduate Studies, Mahidol University
For the degree of Master of Science (Industrial Hygiene and Safety)

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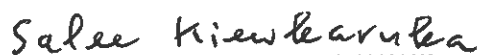
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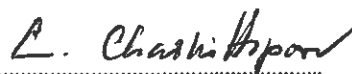
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ACKNOWLEDGEMENT

The achievement of this research was completed under guidance, reinforcement and kindness of many persons that have to be mentioned and received appreciation from the researcher.

I would like to express my deepest gratitude and sincere appreciation to my major advisor, Assoc. Prof. Vichai Pruktharathikul, for his guidance, valuable advises supervision, excellent encouragement, enthusiasm and patience throughout my study. My cordially gratitude is also expressed to all my co-advisor, Assoc. Prof. Dr. Chompusakdi Pulket, Assist. Prof. Dr. Sara Arphorn and Assist. Prof. Dr. Yongyut Pruksachat for their valuable suggestion and comment on this thesis.

I sincerely thank to Assoc. Prof. Jitrapun Pusapukdepob the external examiner, for her valuable suggestion and comment on this thesis.

I sincerely thank Mrs. Kanoknart Ngarmnetra and The Foundation for Labour and Employment Promotion for their financial support.

Sincere thanks to all person at Praditthorakarn community for their co-operation and facilities.

I am grateful to my family and my friends for their encouragement, entirely care and love. The usefulness of this thesis, I dedicate to my parents and my brothers along with the teachers who have taught me since my childhood.

Tassanu Ruangsuwan

A STUDY ON DESIGN AND TEST PERFORMANCE OF GLASS BOTTLE CYCLONES

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ABSTRACT

This study was an experimental study that designed and tested performance of axial entry glass bottle cyclones. The first experimental step was the selection of an appropriate shape of glass bottle for construction of glass bottle cyclones. The second experimental step was the study of the influences of outlet duct diameters and inlet vane angles on cyclone performances. All types of glass bottle cyclones were tested with grinding dust at airflow rate of 12 cfm and particle concentration between 330-400 mg/m³. The stack sampling method was used to measure the particle concentration at the inlet and outlet areas. The collected data were calculated according to the separation efficiencies of cyclones.

The results showed that the average separation efficiencies of glass bottle cyclones, which were constructed from Sauce, Beer and Nectar bottles, were 99.81%, 98.31% and 97.31% respectively. The Sauce bottle cyclones showed significant differences of separation efficiency between inlet vane angles 20°, 25° and 30° ($p < 0.001$). However, there were no significant differences of separation efficiency between $D_{e,0.42D}$ and $D_{e,0.5D}$ cyclones ($p > 0.067$). The results also indicated that the variations of outlet duct diameters and inlet vane angles influenced pressure drop. The study results revealed that the Sauce bottle cyclones could be used to control grinding dust.

KEY WORDS: CYCLONE / GLASS BOTTLE / GRINDING PROCESS

82 P. ISBN 974-04-7398-9

การออกแบบและทดสอบสมรรถนะของไซโคลนขวดแก้ว

(A STUDY ON DESIGN AND TEST PERFORMANCE OF GLASS BOTTLE CYCLONES)

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บทคัดย่อ

การศึกษานี้เป็นการศึกษาแบบทดลองโดยมีจุดมุ่งหมายเพื่อออกแบบและทดสอบสมรรถนะของไซโคลนขวดแก้วซึ่งมีทางเข้าอากาศในแนวแกน การทดลองในขั้นแรกเป็นการคัดเลือกรูปร่างของขวดแก้วที่เหมาะสมต่อการนำมาสร้างเป็นไซโคลน การทดลองขั้นที่สองเป็นการศึกษาอิทธิพลของขนาดเส้นผ่านศูนย์กลางท่อทางออกและขนาดมุมของใบพัดที่ส่งผลต่อสมรรถนะของไซโคลน ไซโคลนขวดแก้วทุกรูปแบบที่สร้างขึ้นจะได้รับการทดสอบที่อัตราการไหลของอากาศ 12 ลูกบาศก์ฟุต/นาที และช่วงความเข้มข้นฝุ่น 330-400 มิลลิกรัม/ลูกบาศก์เมตร การตรวจวัดความเข้มข้นฝุ่นบริเวณพื้นที่ทางเข้าและทางออกของไซโคลนจะใช้วิธีการเก็บตัวอย่างอนุภาคในท่อ (Stack sampling method) จากนั้นนำข้อมูลการตรวจวัดมาคำนวณหาประสิทธิภาพของการแยก

ผลการศึกษาพบว่าค่าเฉลี่ยประสิทธิภาพของการแยกของไซโคลนขวดแก้วที่สร้างจากขวดซอส ขวดเบียร์และขวดน้ำหวานมีค่าเท่ากับ 99.81%, 98.31% และ 97.31% ตามลำดับ จากการศึกษาไซโคลนขวดซอสได้พบความแตกต่างของประสิทธิภาพของการแยกระหว่างขนาดมุมของใบพัด 20°, 25° และ 30° อย่างมีนัยสำคัญทางสถิติ ($p < 0.001$) แต่ทั้งนี้จะไม่พบความแตกต่างของประสิทธิภาพของการแยกระหว่างขนาดเส้นผ่านศูนย์กลางท่อทางออก 0.5D และ 0.42D ($p > 0.067$) นอกจากนี้ผลการทดลองได้ชี้ให้เห็นว่าการเปลี่ยนแปลงของขนาดเส้นผ่านศูนย์กลางท่อทางออกและขนาดมุมของใบพัดจะส่งผลกระทบต่อความดันสูญเสียของไซโคลน ผลการศึกษาได้แสดงให้เห็นว่าไซโคลนที่สร้างจากขวดซอสสามารถนำมาใช้เป็นอุปกรณ์สำหรับควบคุมฝุ่นจากระบวนการขัด

82 หน้า ISBN 974-04-7398-9

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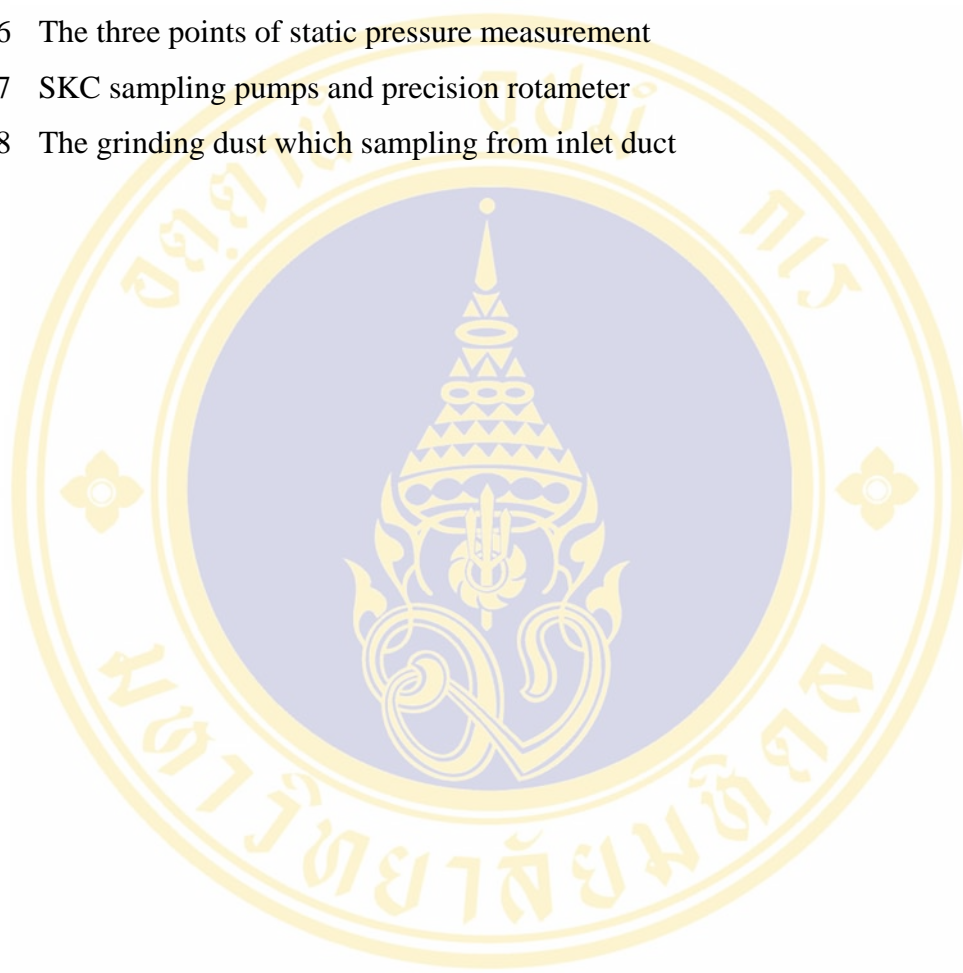
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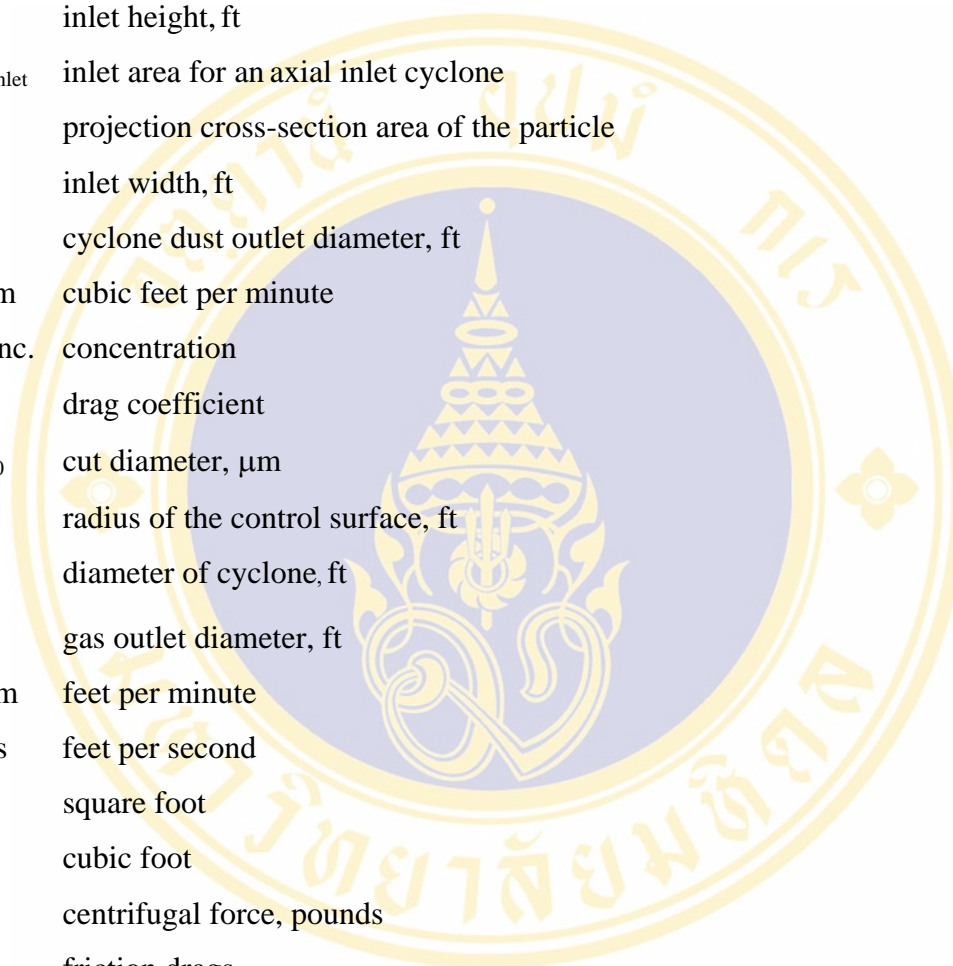
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LIST OF ABBRIVIATIONS



| | |
|--------------------|---|
| a | inlet height, ft |
| A_{inlet} | inlet area for an axial inlet cyclone |
| A_p | projection cross-section area of the particle |
| b | inlet width, ft |
| B | cyclone dust outlet diameter, ft |
| cfm | cubic feet per minute |
| conc. | concentration |
| C_f | drag coefficient |
| d_{50} | cut diameter, μm |
| d_c | radius of the control surface, ft |
| D | diameter of cyclone, ft |
| D_e | gas outlet diameter, ft |
| fpm | feet per minute |
| ft/s | feet per second |
| ft^2 | square foot |
| ft^3 | cubic foot |
| F_c | centrifugal force, pounds |
| F_f | friction drags |
| F_g | force of gravity |
| g | gravitational force, 32.2 ft/s^2 |
| G | cyclone configuration factor |
| h | cylindrical height, ft |
| H | cyclone height, ft |
| in.wg | inches of water (gauge) |
| K | empirical constant |
| l | natural length |
| mg/m^3 | milligram per cubic meter |

LIST OF ABBRIVIATIONS (Continued)

| | |
|-------------|--|
| m_p | particulate mass, pounds |
| n | vortex exponent, dimensionless |
| N_e | number of vortex turns |
| N_H | number of gas inlet velocity heads |
| Q | gas flow rate, ft ³ /s |
| R_p | radius of cyclone body, ft |
| r_c | radius of the control surface, ft |
| S | gas outlet length, ft |
| T | gas temperature, °F |
| v_g | inlet velocity, ft/s |
| v_p | particle velocity, ft/s |
| v_p^2/R | centrifugal acceleration, ft/s |
| v_s | Saltation velocity, ft/s |
| v_T | tangential velocity at radius R, ft/s |
| v_{Tp} | tangential velocity at perimeter, ft/s |
| $v_{t,max}$ | gas tangential velocity on the control surface |
| V_A | inlet vane angle, ° |
| w_i | proportion of particle size range |
| Z_c | height of the control surface, ft |
| β | Slope parameter |
| ω | Omega, ft/s |
| ρ_p | particle density, lb/ft ³ |
| ρ_g | gas density, lb/ft ³ |
| μ_g | gas viscosity), lb/ft-s |
| μm | micrometer, micron |
| η_i | fractional efficiency, % |
| η_T | overall separation efficiency, % |
| τ | Relaxation time, sec |
| ΔP | pressure drop, in.wg. |

CHAPTER I

INTRODUCTION

1.1 Background and Rationale

The most problems of industrialization are pollutions from production process, which caused effects to life and health of the workers. Moreover they can produce environmental impact to community and circumstance environment. The production process involves cutting, sanding, impaction or explosion would cause aerosol in working environment. If workers working without effective protection manners, it would be harmful to health and could develop to occupational diseases such as: silicosis, bisinosis and asbestosis. Furthermore some types of dust could cause of irritation, allergy and infection to the respiratory tracts. The effectiveness manner for control dust is to install the local exhaust ventilation system. The control unit of the ventilation system will be design as setting chamber, cyclone, multi-cyclone, wet scrubber, fabric filter or electrostatic precipitator. The separation efficiencies depend on types of dust separators and costs for construction devices. The main problem of Small and Medium Enterprises (SMEs) was concerned with the limited budget for investment. In 1999 the amounts of Small and Medium Enterprises in Thailand, which have workers less than 100, were 349,489 enterprises [1]. This is about 96.36% of total enterprises. This number excludes the projects of “One Tambon One Product (OTOP)”. From this data revealed that they reflect on the large amounts of risks that would be exposed to pollution in working environments without effective criteria for prevention and control. This may due to the limited budget for investment and lacked of appropriate technology and application for these groups.

The grinding dust is the main harmful factor to health of workers at production parts in Praditthorakarn community. It consists of metal dust (copper and tin) and grinding wheel dust. In humans, copper and tin dusts are the respiratory irritant. Workers exposed to copper dust report a number of symptoms that are suggestive of respiratory irritation, including coughing, sneezing, thoracic pain, and runny nose.

Suciu et al. (1981) had study of 75-100 workers involved in grinding and sieving copper dust at concentration between 111-434 mg/m³, lung radiographs revealed linear pulmonary fibrosis, and in some cases, nodulation. Moreover other symptoms such as hepatomegaly, anorexia, nausea, and occasional diarrhea were reported [2,3]. At the present time, the manners for control bronzewares grinding dust in Praditthorakarn community are using settling chamber and water trapping, but these are low collection efficiency. For this reason, workers in this community still exposed to grinding dust during working in grinding process. The important reasons, which they had not installed effectiveness control system, were the limited in economic and lacked of development appropriate technology for this community.

The appropriate characteristics of dust separators, which proper for Small and Medium Enterprises, should be included: high separation efficiency, low cost of construction, using small area for installation, simply to use and maintenance [4]. The dust separator, which according with these characteristics, is the multi-cyclone. However, the cost for construction multi-cyclone was high because almost cyclone were made by casting or welding from stainless steel or carbon steel by experienced person.

An applied technology of particles separation by using multi-cyclone, which proper for Small and Medium Enterprises, is the using of substitution materials to reduce cost of construction. The substitution materials should be sample materials, which low costs and give similar effectiveness of control as the others. This research study aims to use glass bottles because they were excessive waste from households and could reused and developed to be cyclone. Moreover the shapes and proportions of glass bottles were suitable for construction an axial inlet cyclones. Although the glass bottles were suitable for construction cyclones, but its diameter was smaller than general cyclones that the influences of shortcut flow will be occurred. Furthermore, the design patterns of axial cyclone and the suggestions of angles for inlet guide vanes design were ambiguous [5,6,7]. Both factors are the problems for small cyclone design. Therefore, these factors were included in the design step of this study to determine on selection the best type of constructed glass bottle cyclones. This study, glass bottle cyclones were designed on three considerations that consist of: the suitability of glass bottles for construction cyclone, the effects of gas outlet diameters

and inlet vanes angles on cyclone performance. All types of constructed glass bottle cyclones would be tested the performances with the grinding dust from Pradiththorakarn community. Then the each type of glass bottle cyclones would be discussed on cyclone performance.

1.2 Objectives

- 1) To design and construct glass bottle cyclones.
- 2) To determine the separation efficiency and pressure drop each type of glass bottle cyclones.
- 3) To study the effects of glass bottle shapes, gas outlet diameters and inlet vanes angles on glass bottle cyclones performance.

1.3 Hypotheses

- 1) Three shapes of glass bottle cyclones, which construction from Sauce, Beer and Nectar bottles, had separation efficiency at least 80 percent by weight.
- 2) The difference of the gas outlet duct diameters will be affecting on glass bottle cyclones performance.
- 3) The difference of the inlet vane angles will be affecting on glass bottle cyclones performance.

1.4 Variables

1.4.1 Independent variables

- 1) Shapes of glass bottle
- 2) Diameters of gas outlet duct
- 3) Angles of inlet vane

1.4.2 Dependent variables

- 1) Separation efficiency of glass bottle cyclones
- 2) Pressure drop of glass bottle cyclones

1.4.3 Extraneous variables

- 1) Airflow rate
- 2) Characteristics of grinding dust
 - Particle size distribution

- Particle concentration
- 3) Characteristics of testing instruments
 - Amount of inlet guide vanes
 - Air feeding part
 - Duct system
 - Hopper
 - Dust generator
 - 4) Air temperature
 - 5) Atmospheric pressure

1.5 Scope and Limitation

- 1) This study aimed to determine the suitability of glass bottles for construction axial entry cyclones and to study the effects of gas outlet diameters and inlet vanes angles on cyclone performance.
- 2) The setting of whole experiments was done in laboratory room, 6th building, Occupational and Safety Department, Faculty of Public Health, Mahidol University.
- 3) The sample dust was the grinding dust from bronzewares grinding process of Praditthorakarn community.
- 4) The particle concentration in chamber should be between 330-400 mg/m³, these according to the particle concentration at grinding process.
- 5) The internal diameters of PVC ducts, which using for construction gas outlet ducts of glass bottle cyclones, were 3 and 3.6 cm.
- 6) The thickness of acrylic sheet, which using for construction inlet guide vanes, was 2 mm.
- 7) The air feeding parts were constructed in pattern of tangential inlet and used for diffusion airstreams before got into glass bottle cyclones.
- 8) The theories of Iozia & Lieth (1990), Shepherd and Lapple (1939) were used to estimate the separation efficiencies and pressure drop of glass bottle cyclones respectively

1.6 Expected Outcomes and Benefits

- 1) Achievement on glass bottle cyclones design and construction, which caused to high performance and low cost of construction.
- 2) Knowing the influences of glass bottle shapes, gas outlet duct diameters and inlet vane angles that affected on cyclone performance.
- 3) Knowing the accordance between experimental results and theoretical approached on cyclone performance.
- 4) The study results will be used as the basic knowledge of dust separator technology, which can apply to Small and Medium Enterprises.

1.7 Glossary of Terms and Definitions

Glass bottle cyclones: A dust separator device used to remove particles from air stream. It constructs from Sauce, Beer and Nectar bottles in pattern of an axial entry cyclone, which consists eight of inlet vanes.

Sauce bottle: A glass bottle, which has straight cone shape, is the packages of chili sauce (PEGASUS[®], GOLDEN SPOON[®] brands), oyster sauce (MAGGI[®], KNORR[®] brands) and soy bean paste (UFC[®], FIRST PRICE[®] brands) etc. Its shape and dimensions were according to Table 3-1 and Figure 3-1.

Beer bottle: A glass bottle, which has concave cone shape, is the beer's package of BEER CHANG[®] brand. Its shape and dimensions were according to Table 3-1 and Figure 3-1.

Nectar bottle: A glass bottle, which has short concave cone shape, is the concentrated juice's package of HALE'S BLUE BOY[®] brand. Its shape and dimensions were according to Table 3-1 and Figure 3-1.

Performance of glass bottle cyclone: The capability of glass bottle cyclone while operating, it indicated by the separation efficiency and pressure drop.

Separation efficiency: The percentage of dust removed and retained from air by glass bottle cyclones.

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

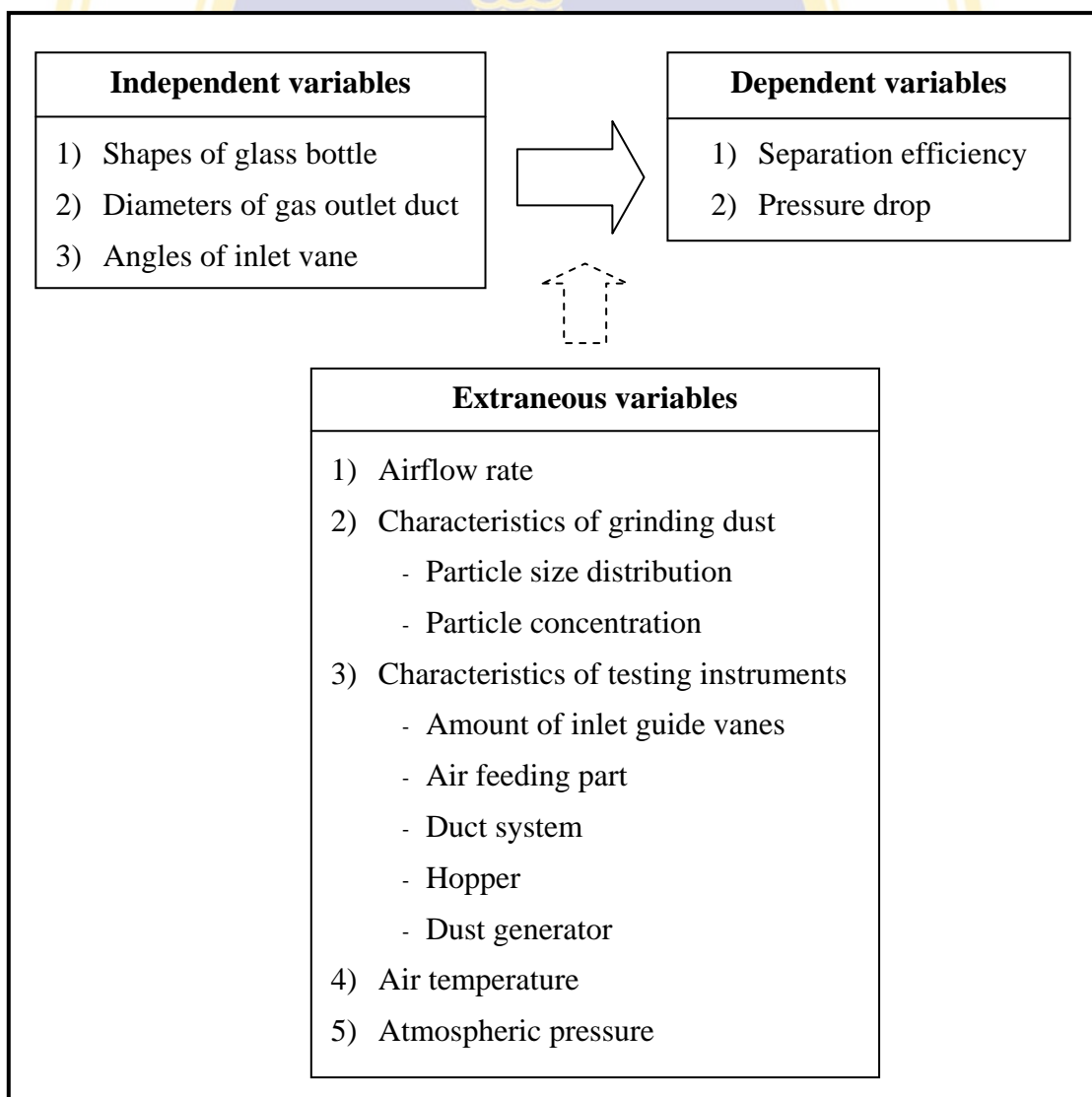
Grinding dust: Small solid particles created from bronzewares grinding process. It consists of metal dust (Copper and Tin) and grinder wheel dust.

Dust mixing chamber: An acrylic chamber, which its dimensions are 30 x 30 x 65 cm. Two of mixing blowers are installed at the side. The inlet hole for feeding dust is on the top and the outlet hole is on the lower side.

Dust generator: A device used to transport dust by drag chain, it propelled by motor. The grinding dust would be blowing down into mixing chamber by centrifugal forward blower.

Air feeding part: A device used to feed air stream into axial entry cyclones. It constructs from acrylic sheet in pattern of tangential inlet, which conforms to proportions of Stairmand's cyclone.

1.8 Conceptual Framework



CHAPTER II

LITERATURE REVIEW

2.1 Bronzeware Production Process [8]

Bronzeware is the main OTOP products of Praditthorakarn community. The bronzeware products in this community consist of spoons, forks, knife, bracelets and water dipper. The raw materials for produced bronzeware consist of copper (80%) and tin (20%). The production steps are classified as the following:

- a) Pour the tin into crucible and copper afterwards. This is because tin is the good heat conductor that can melt rapidly.
- b) Pour the ingredient into the mold, and then take to the pressed feather.
- c) Polishing the uneven parts by using coarse grinding wheel.
- d) Baking the pieces of bronzeware and then submerge into the water. This reaction will produce an effect to toughening materials.
- e) Decorating the configuration of bronzeware and then assembly with other materials such as wood handle.
- f) Polishing the particular parts by using sand grinding wheel.
- g) Burnishing bronzeware by using wax and fabric grinding wheel.
- h) Packaging the bronzeware.

The health harmful factor of workers at bronzeware production part is the grinding dust from polishing and burnishing steps. The small particles are spreading in working environment without installation an effective particle control system. Nowadays, the workers in this community still exposed to grinding dust during working in the bronzeware grinding process.

2.2 The grinding dust

The grinding dust is a small solid particles created from bronzeware grinding process. It consists of metal dust (copper and tin) and sand dust (grinder wheel). Long term exposure to sand dust would cause of silicosis. In humans, copper and tin dusts

are respiratory irritants [3]. Workers exposed to copper dust report a number of symptoms that are suggestive of respiratory irritation, including coughing, sneezing, thoracic pain, and runny nose (Askergren and Mellgren 1975; Suciu et al. 1981). In the Suciu et al. (1981) [2] study of 75–100 workers involved in grinding and sieving copper dust, lung radiographs revealed linear pulmonary fibrosis, and in some cases, nodulation. Furthermore other symptoms such as hepatomegaly, anorexia, nausea, and occasional diarrhea were reported. During the first year of operation, the workers were exposed to 434 mg/m^3 ; the exposure levels declined each year, and by year 3, the levels were 111 mg/m^3 . In sheet metal workers exposed to patina dust (copper-hydroxide-nitrate, copper-hydroxide-sulfate, copper silicate, copper oxide), 6 of the 11 examined workers had increased vascularity and superficial epistatic vessels in the nasal mucosa (Askergren and Mellgren 1975); no exposure levels were reported.

Copper is considered the etiologic agent in the occupational disease referred to as “vineyard sprayer’s lung”. This disease, which is observed in vineyard workers spraying an antimildew agent containing 1–2.5% copper sulfate neutralized with hydrated lime, was first described in humans by Cortez Pimentel and Marques (1969). In most cases, published information on this disease comes from case reports (Cortez Pimentel and Marques 1969; Cortez Pimentel and Menezes 1975; Stark 1981; Villar 1974; Villar and Nogueira 1980) with no concentration-response information.

2.3 The Importance Factors for Choosing Dust Separator [9]

There are several devices for used to reduce the particles concentration such as: gravity settling chamber, electrostatic precipitators, fabric filters, wet and dry centrifugal separators. Each type of dust separator will different on separation efficiency and condition of production process for installed. The consideration for using appropriate dust separator should consider as follows:

a) Environmental conditions such as: equipment location, available space, ambient conditions, available of adequate utilities, ancillary system facilities, maximum allowable emission, contribution of air pollution control system to wastewater and plant noise level.

b) Engineering conditions such as: contaminant characteristics (physical and chemical properties, concentration, toxicity, particulate sharp and size distribution,

etc.), gas stream characteristics (flow rate, temperature, pressure, humidity, reactivity, combustibility, corrosive, toxicity, etc.), design and performance characteristics of the particular control system (size, weight, fractional efficiency curve, power requirements, maintenance requirements, etc.)

c) **Economic conditions** such as: capital cost (equipment, installation, engineering, etc.), operating cost (utilities, maintenance, etc.), expected equipment lifetime and salvage value.

2.4 General Principles of Cyclone

A cyclone collector is a structure without moving parts in which the velocity of an inlet gas stream is transformed into a confine vortex from which centrifugal forces tend to drive the suspended particles to the wall of the cyclone body. The cyclone collector is wide widely used and cyclone theory is basis for many inertial separator designs. The cyclone is simple, inexpensive, have no moving parts, and can be built of any reasonable material of construction. The necessary elements of a cyclone consist of a gas inlet which produces the vortex, an axial outlet for clean gas and a dust discharge opening. The arrangements of the gas inlet lead to a classification cyclone in two types, there are tangential entry and axial entry cyclones.

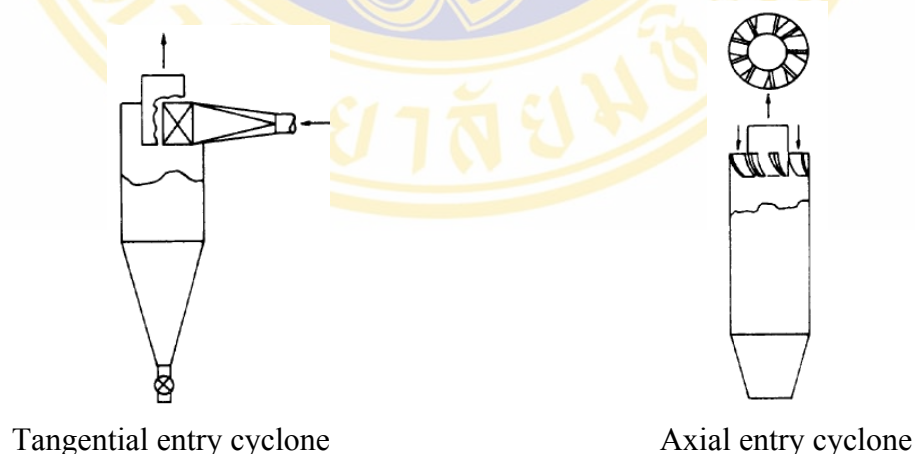


Figure 2-1 Types of cyclone

2.5 Standard Cyclone Configuration

Extensive work has been done to determine how the relative dimensions of cyclone affect their performance. Cyclones are designed with geometric similarity such that the ratio of the dimensions remains constant at difference diameters and

those dimensions can be expressed in terms of the body diameter. Table 2-1 presents standard dimension ratios along with the values of geometric configuration parameter, K , and a constant, N_H , relating the pressure drop through the cyclone to inlet velocity head. Figure 2-2 illustrates the various dimensions in table 2-2. [10]

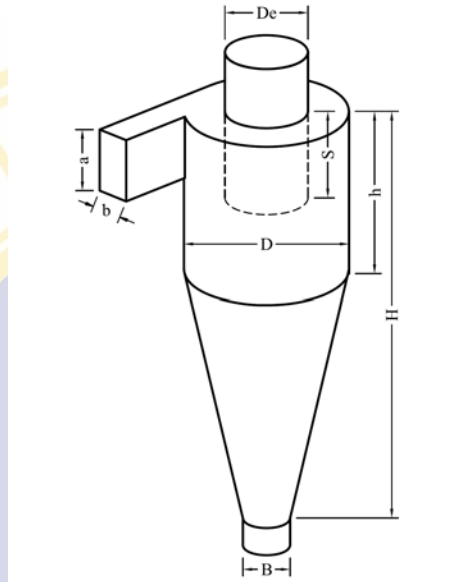


Figure 2-2 Geometric configuration parameters

Table 2-1 The cyclone design configuration

| Term | Description | | High efficiency | | Shepherd | Swift |
|--------------|----------------------|-------------------|-----------------|-------|----------|-------|
| | | | Stairmand | Swift | &Lapple | |
| D | Body diameter | | 1 | 1 | 1 | 1 |
| a | Inlet height | $K_a = a/D$ | 0.5 | 0.44 | 0.5 | 0.5 |
| b | Inlet width | $K_b = b/D$ | 0.2 | 0.21 | 0.25 | 0.25 |
| S | Outlet length | $K_S = S/D$ | 0.5 | 0.5 | 0.625 | 0.6 |
| D_e | Gas outlet diameter | $K_{D_e} = D_e/D$ | 0.5 | 0.4 | 0.5 | 0.5 |
| h | Cylinder height | $K_h = h/D$ | 1.5 | 1.4 | 2 | 1.75 |
| H | Overall height | $K_H = H/D$ | 4 | 3.9 | 4 | 3.75 |
| B | Dust Outlet diameter | $K_B = B/D$ | 0.375 | 0.4 | 0.25 | 0.4 |
| G | Configuration | | 551.3 | 699.2 | 402.9 | 381.8 |
| N_H | Inlet velocity head | | 6.4 | 9.24 | 8 | 8 |
| Surf | Surface parameter | | 3.67 | 3.57 | 3.78 | 3.65 |
| K/N_H Surf | | | 23.5 | 21.2 | 13.3 | 13.1 |

As show in Table 2-1, G is the efficiency parameter and N_H is the pressure drop parameter for the cyclone configuration. The ratio K/N_H is an optimization parameter. Table 2-1 shows that while the Swift design has the highest efficiency, the Stairmand design is optimum by these criteria.

2.6 Mechanisms of Cyclone Operation

The common cyclone will be used as the basis for describing the cyclone operation mechanism. There would be divided in three steps as follows:

2.6.1 Properties of gas flow patterns [11]

The gas entering the tangential inlet near the top of the cylindrical body creates a vortex or spiral flow downward between the wall of the gas discharge outlet and the body of the cyclone. This vortex, called the “main vortex”, continues downward even below the wall of the gas outlet, and at some region near the bottom of the cone, the vortex reverse its direction of axial flow but maintains its direction of rotation, so that a inner vortex core is formed traveling upward to the gas outlet. The tangential velocity of gas in the vortex (v_t) increase as the radius decreases from the radius of the cylindrical body (R_p) to a maximum at some intermediate radius; and from this intermediate point inward to the axis of the cylinder the tangential velocity decrease.

$$v_T = v_{Tp} \left(\frac{R_p}{R} \right)^n \quad (2.1)$$

where v_T = Tangential velocity at radius R, ft/s

v_{Tp} = Tangential velocity at perimeter, ft/s

R_p = Radius of cyclone body, ft

R = Radius, ft

n = Vortex exponent, dimensionless

2.6.2 Separation of dust particles in the vortex

The forces, which related to the separation mechanisms in cyclone, are the following:

1) Centrifugal force

Particle in gas stream being treated in a cyclone move in the circular path, with a tendency to be push out away from the center of motion. In other words, a

centrifugal force is exerted on the particles. This force is what causes the particles to be captured on the wall of the cyclone. This centrifugal force is expressed by the following equation:

$$F_c = \frac{m_p v_p^2}{R} = \frac{\rho_p d_p^3 v_p^2}{R} \quad (2.2)$$

where F_c = Centrifugal force, pounds

m_p = Particulate mass, pounds

v_p^2/R = Centrifugal acceleration, ft/second

v_p = Particle velocity, ft/s

R = Radius of motion or curvature, ft

2) Friction drag

It can be show that the Stokes's law force resisting the motion of a particle through the gas in the particle-size range 3 - 100 μm . The friction drag is expressed as:

$$F_f = \frac{C_f A_p \rho_p v_p^2}{2g} \quad (2.3)$$

where F_f = Friction drag

C_f = Drag coefficient

A_p = Projection cross-section area of the particle

ρ_p = Particle density

v_p = Particle velocity

3) Gravitational force is expressed as:

$$F_g = m_p \times g \quad (2.4)$$

where F_g = Force of gravity

m_p = Particulate mass

g = Acceleration caused by gravity, ft/second²

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size entering the cyclone. Barth's (1956) [12] separation theory is another representation of cut size theories. Barth calculated the terminal settling velocity for static particles, based on the exact balance between the centrifugal force and the drag force. The collection efficiency for any particle size is determined from the ratio of its settling velocity to the terminal settling velocity of the static particle. The fractional efficiency is expressed as:

$$\eta_i = \frac{1}{1 + \left(\frac{d_{50}}{d_i}\right)^\beta} \quad (2.6)$$

$$d_{50} = \sqrt{\frac{9\mu_g Q}{\pi\rho_p Z_c v_{t,\max}^2}} \quad (2.7)$$

$$v_{t,\max} = 6.1v_{inlet} \left(\frac{ab}{D^2}\right)^{0.61} \left(\frac{D_e}{D}\right)^{-0.74} \left(\frac{H}{D}\right)^{-0.33} \quad (2.8)$$

$$\ln \beta = 0.62 - 0.87 \ln d_{50} + 5.21 \ln \left(\frac{ab}{D^2}\right) + 1.05 \left[\ln \left(\frac{ab}{D^2}\right) \right]^2 \quad (2.9)$$

$$Z_c = (H - S) \quad \text{where } 2r_c < B \quad (2.10)$$

$$Z_c = (H - S) - \left(\frac{H-h}{(D/B)-1}\right) \left(\frac{2r_c}{B} - 1\right) \quad \text{where } 2r_c > B \quad (2.11)$$

$$r_c = 0.52 \left(\frac{D}{2}\right) \left(\frac{ab}{D^2}\right)^{-0.25} \left(\frac{D_e}{D}\right)^{1.53} \quad (2.12)$$

where η_i = Fractional efficiency, %

β = Slope parameter

d_{50} = Cut diameter, cm (for Eq.2.9)

Z_c = Height of the control surface, ft

r_c = Radius of the control surface, ft

Q = Total gas flow rate, ft³/s

$v_{t,\max}$ = Gas tangential velocity on the control surface, ft/s

Leith and Licht (1972) [13] developed another popular approach for cyclone design assuming that turbulence keeps the particle concentration at any height in the

cyclone well mixed. The theory allows a direct calculation of the collection efficiency for particles of any size and cyclones of arbitrary design. But unfortunately, there is experimental evidence to support the fact that there is, indeed, a concentration gradient in the radial direction of cyclones. Leith and Licht equation is expressed as:

$$\eta_i = 1 - \exp \left\{ -2 \left[\frac{G \tau_i Q}{D} (n + 1) \right]^{\frac{0.5}{n+1}} \right\} \quad (2.13)$$

where n = Vortex exponent

$$n = 1 - \left[1 - (12D / 2.5)^{0.14} \left[\frac{T + 460}{530} \right]^{0.3} \right] \quad (2.14)$$

G = Cyclone configuration factor

τ_i = Relaxation time, sec

T = Gas temperature, °F

Iozia & Lieth (1990) [14], based on the Lapple's and Barth's theory, proposed a logistic function to describe the fractional efficiency for cyclones with geometries which were variations of the Stairmand high-efficiency cyclone. This equation has an empirical parameter that allows adjustment of the sharpness of the cut of cyclone. Iozia & Lieth equation is expressed as:

$$\eta_i = \frac{1}{1 + \left(\frac{d_{50}}{d_i} \right)^\beta} \quad (2.15)$$

β , d_{50} and $v_{t,max}$ would be calculated from Barth (1956)

and $Z_c = (H - S)$ where $d_c < B$ (2.16)

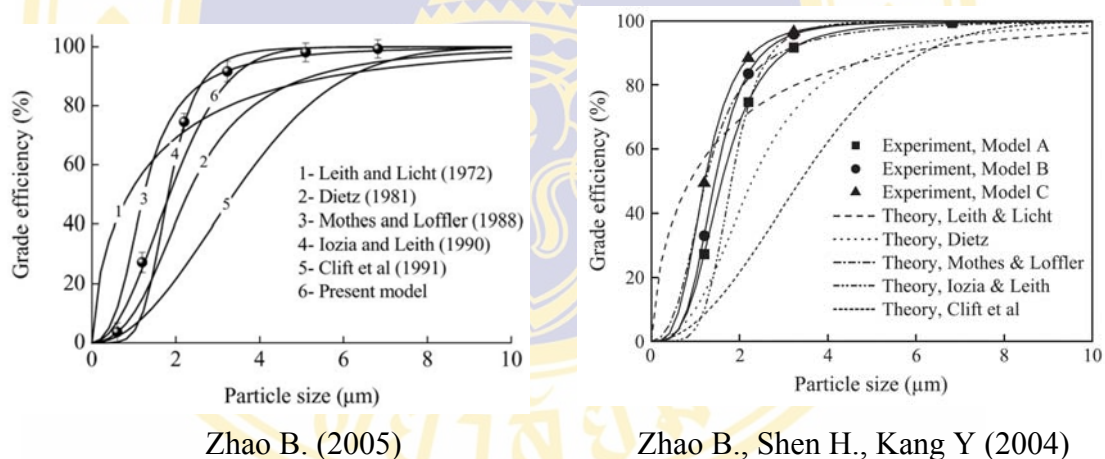
$$Z_c = (H - S) - \left(\frac{H - h}{(D/B) - 1} \right) \left(\frac{d_c}{B} - 1 \right) \text{ where } d_c > B \quad (2.17)$$

$$d_c = 0.47D \left(\frac{ab}{D^2} \right)^{-0.25} \left(\frac{D_e}{D} \right)^{1.4} \quad (2.28)$$

where d_c = Radius of the control surface, ft

In order to describe the cyclone performance, the theories of cyclone particle collection are developed by many contributors using different methods with simplifying assumptions. Representative researches mainly include: B. Zhao (2004) [15, 16], R. Xiang (2000) [17], J. Gimbut (2004) [18]. These studies showed accordant results that Barth (1956) and Iozia & Lieth (1990) models exhibited similar trends with experimental values than Lieth & Licht theory (1972). The shape of fractional efficiency curve from Lieth & Licht theory was flat, so it caused to over estimate for small particles and under estimate for large particles.

W.D. Giffiths & F. Boyson (1995) [18] found that Barth model exhibit similar trends with experimental values than other model for small cyclones. Iozia & Lieth model exhibit similar trends with experimental values than other model for large cyclones.



Zhao B. (2005)

Zhao B., Shen H., Kang Y (2004)

Figure 2-3 Various shapes of fractional efficiency curve

2.7.3 Pressure drop

The pressure drop across a cyclone is an important concern to the designer and purchaser of such equipment. Cyclone design usually consists of choosing an acceptable standard design that will meet gas clean-up requirements at a reasonable pressure drop. While forcing the gas through the cyclone at higher velocities results in improved removal efficiencies, to do so increases the pressure drop and operating cost. There is ultimately an economic tradeoff between efficiency and operating cost. The pressure drop is usually the limiting factor in cyclone design. For these reasons,

numerous efforts have been made to predict pressure drop from design variables. One of the simplest pressure drop equations which correlate reasonably well was developed by Shepherd and Lapple (1939).

$$\Delta P = 0.003 \rho_g v_g^2 N_H \quad (2.19)$$

where ΔP = Pressure drop, in.wg.

N_H = Number of gas inlet velocity heads

$$N_H = K_c \left(\frac{ab}{D_e^2} \right) \quad (2.20)$$

The term K is an empirical constant equal to 16 for standard tangential inlet cyclone and 7.5 for a cyclone with an inlet vane. See Figure 2-2 for definition of dimensional terms such as a, b and D_e .

J. Gimbut (2004) [17] had studied the influences of air temperature and inlet velocity on the pressure drop of gas cyclone. This study, the computational fluid dynamics (CFD) and the empirical models such as Shepherd and Lapple, Casal and Martinez, Dirgo, and Coker have been chosen to predict the pressure drop over a cyclone. The results showed that the CFD numerical calculations a very small pressure drop deviation was observed, with less than 3% of deviation at different inlet velocity. The empirical model used for the prediction of pressure drop is much depends on the cyclone operating condition. Both Shepherd and Lapple, and Dirgo models show a good prediction on cyclone pressure drop under different operational inlet velocity. However, Dirgo's model is unable to predict accurately the pressure drop under different operating temperature. For the various temperature conditions, Shepherd and Lapple's pressure drop model prediction is the best. He suggests that the Shepherd and Lapple model should be used for estimation of pressure drop in cyclone design.

2.8 Design Factors Affecting Efficiency and Pressure Drop

2.8.1 Body diameter and dimension ratio

An increasing the ratio of the body diameter to the gas outlet diameter does show an increase in efficiency, so that the optimum ratio would appear to be between 2 and 3 [19]. Theoretically, efficiency should continue to increase with a decrease in cyclone diameter, but this has not been proved in practice. In a very small cyclone, the

gas outlet is dimensionally very close to the region where the dust is concentrated along the cyclone wall. Therefore any bouncing of large particles or local eddies caused by turbulence are more likely to result in accidental loss of dust to the gas outlet merely because the dimensions are so small.

The length of the cyclone body is importance. The separation efficiency increases with increasing cyclone length up to certain value and starts to decrease after that (Zhu & Lee, 1999; Alexander, 1949). Furthermore, R.B.Xiang & K.W.Lee (2004) [20] had studied the distribution of tangential velocity in cyclone at different cylindrical height through CFD simulation. The results found that in a certain cyclone, the tangential velocity distribution does not vary significantly with axial stations. However, tangential velocity in cyclones of different height is quite different. Tangential velocity is sharply reduced when cyclone height is increased, and this should be responsible for the lower separation efficiency observed in long cyclones by Zhu and Lee (1999).

2.8.2 Cone design

The cone of cyclone is the importance part to serve the practical function of delivering the dust to the central point for ease in disposal, and forces the main vortex to transform to vortex core in a shorter total length than would occur in a straight cylinder. Theoretically, the diameter at the apex of the cone should be greater than one-fourth the gas outlet diameter to prevent the vortex core from touching the wall of the cone and reentraining collected dust.

R. Xiang (2000) [21] and J. Gimbut (2004) [22] had studied the influence of cone dimensions on performances of cyclone, the cone dimensions in these study were $0.65D$, $0.5D$ and $0.375D$. The results showed that a cyclone with a smaller cone diameter results in a higher collection efficiency and pressure drop compared to a cyclone with a bigger cone diameter. This is due to a higher velocity magnitude and Reynolds number inside the cyclone with a smaller cone size compared to a cyclone of a bigger cone size. Furthermore, Yoshida et al (2001) [23] had studied the performance of Inoya's type cyclone, which has double conical sections. The result showed that the pressure drop of the Inoya's type cyclone is about 10% smaller than that of the conventional cyclone.

2.8.3 Inlet design

The design of the cyclone inlet is of critical importance to both cyclone efficiency and pressure drop because it is the main part to accelerate the gas in the cyclone to attain the required tangential velocity (v_T). The gas coming from a duct through the inlet is change from laminar flow to a circular vortex pattern. B. Zhao (2004) [15] had studied to comparison performance of cyclone between conventional tangential single inlet and symmetrical spiral inlet. The results indicated that the symmetrical spiral inlet cyclone had higher efficiency and pressure drop than conventional tangential single inlet.

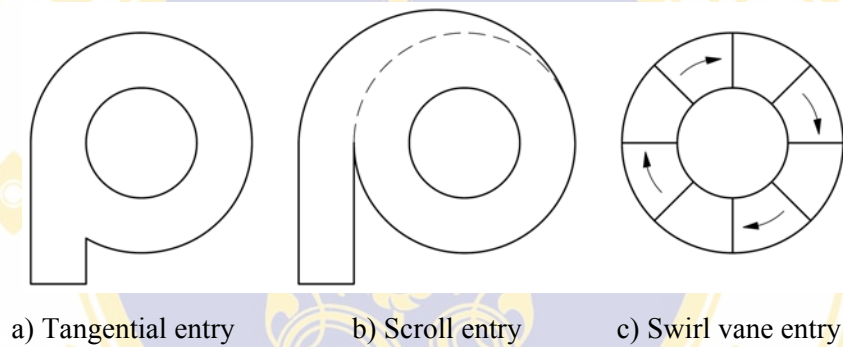


Figure 2-4 Types of cyclone inlet

The vane exit angle (β) is the main determining factor for axial entry cyclone design (see Figure 2-5). Yaodong W. (1991) [5] found that when decreasing β would increase the swirl intensity, the separation efficiency, and the pressure drop. If β is made too small separation and turbulence generation may occur. The recommended ranges for β were 20-29° or 15-30° [5]. Furthermore Lieblein S. (1950) [6] suggested ranges for β should be 12-40° for zero incidence angle, and should be 25-40° for other incidence angles. The recommended for spacing that expressed as the ratio u/t should be $\frac{1}{4}$ [5], where the possibility of separation at the leading edge of flat vanes is also indicated, while bent vanes, as shown here, are not subject to this.

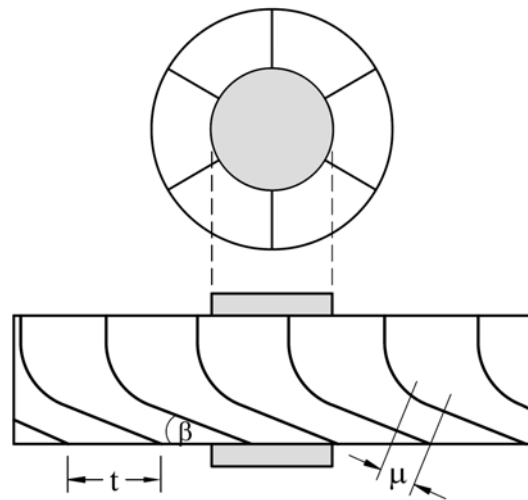


Figure 2-5 The variables for inlet guide vane design

2.8.4 Gas outlet design

The exit tube also is an important consideration in the design of any cyclone. The length of the tube must extend beyond the inlet so that eddies created in the annulus between the tube and the cyclone wall do not mix particulates up and into the exit tube. Lim K.S. (2003) [24] had studied the performance of a cyclone, with different vortex finders shape. The result showed that a decreasing diameter of the vortex finders would cause to increase cyclone efficiency and pressure drop.

R.B. Xiang & K.W. Lee (2004) [20] suggested that the necessities to avoid the shortcut flow in cyclone designs that, if the cyclone is extremely short so that the gas exit tube protrudes into the conical section, the efficiency of this cyclone will be lower, which is due to the considerable shortcut flow occurring at the entrance of the gas exit tube.

2.8.5 Effect of internal roughness

Roughness at the cyclone wall will cause local eddy currents to carry dust away from the wall and defeat any effort to concentrate it at the wall and separate it from gas stream. An increased roughness of the internal wall of the cyclone, probably increased local wall friction, reduces vortex intensity, with overall result that cyclone pressure drop and efficiency are reduced. Recently, an experimental study performed by Ozkoca (2001) showed that the vortex length increases with the decrease of surface resistance. A. Avci and I. Karagoz (2003) [25] had summarized that when decreasing

in surface resistance which eventually leads to decrease of velocity is an important way to high efficiency due to increasing in natural vortex length and residence time inside cyclone. Thus all seams on cyclone should be ground smooth on the inside or consist of carefully matched flanged joints.

2.9 Improving Cyclone Performance

A summary of changes in performance characteristics produced by changes in cyclone design and exhaust gas properties is given in Table 2-2

Table 2-2 Effects of cyclone and process change on cyclone performance

| Cyclone and process design change | Pressure drop | Efficiency | Cost |
|---------------------------------------|--------------------|------------|------------|
| Increase cyclone size (D_c) | Decreases | Decreases | Increases |
| Increase lengthen cylinder (h) | Decreases slightly | Increases | Increases |
| Increase lengthen cone | Decreases slightly | Increases | Increases |
| Increase exit tube diameter (D_e) | Decreases | Decreases | Increases |
| Increase area maintaining velocity | Increases | Decreases | Decreases |
| Increase velocity | Increases | Increases | Increases |
| Increase temperature | Decreases | Decreases | No. Change |
| Increase dust concentration | Decreases | Increases | No. Change |
| Increasing particle size or density | No. Change | Increases | No. Change |

2.10 Other Related Literatures

Klaus Willeke and Pal A. Tufto [26] had constructed the wind tunnel for study sampling efficiency. The sampling tube with internal diameter 0.565 cm, external diameter 0.635 cm, length 20 cm was using for sampling particle in tunnel. An experiment protocol consist of wind velocity at 2.5-10 m/s, sampling velocity at 1.25-10 m/s and sampling angle at 0° to $\pm 90^\circ$. The experimental results found that the sampling efficiency would be increased or decreased with significant, when inlet velocity differed from wind velocity. They concluded that the sampling efficiencies depend on particle size and sampling ratio ($R = \text{wind vel.} / \text{inlet vel.}$). The sampling

efficiency at sampling angle 0° will increased when increased wind velocity, but the sampling efficiency at sampling angle 30° , 60° and 90° will decreased when increased wind velocity. These results indicated that the sampling efficiencies at sampling angle 30° , 60° and 90° would be function of strokes number by using sampling ratio (R) for parameter, but at sampling angle 0° (isoaxial sampling condition) the sampling efficiency would not be function of strokes number. Furthermore the sampling efficiencies of particle smaller than 30 micron at sampling angle 0° will increase when increased sampling ratio (R) and the relative sampling efficiency would be equivalent to particle any size in this range when sampling particle at the sampling ratio = 1.

Vichai PruktharaThikul [4] has studied the efficiency of movable high efficiency cyclone. Cyclone diameter of 8 inches was used in this study for testing separation efficiencies with wood dust with the density of 1.0039 g/cm^3 . This study found that the size of dust has quite an effect on cyclone efficiency, i.e., at size 45 micron efficiency is about 95% whereas size above 106 micron efficiency is rather constant and reaches the value of about 99.7%. In addition, many factors that affecting to the cyclone efficiency is consisting of: airflow rate, size distribution and particle concentration.

Woraluk Kunathimapun [26] had studied performance of cyclone in foundry operation. The cyclone was designed according to the proportions of Stairmand high efficiency with diameter 17 inches. Then cyclone was tested separation efficiency at airflow rate 156-162 and 320-332 ft^3/min , with particle concentration 43-53, 109-114 and 217-230 mg/m^3 . This study found that the separation efficiencies were related to particle concentration, but no significant difference to the airflow rate.

Wanpen Songkham (2004) [28] had designed and constructed of multi-cyclone for dust removal in surfboard sanding process. The multi-cyclone consists nine of axial cyclones with a body diameter 6 inches, arranged in parallel. The system was tested for separation efficiency at airflow rate of 1,200-1,250, 1,400-1,450 and 1,600-1,650 cfm. This study found that the constructed multi-cyclone had the highest efficiency at airflow rate of 1,400-1,450 cfm (85.57%). Additionally, the results indicated that when increased the airflow rate, the pressure drop of multi-cyclone also increased.

Zhang Y. (2001) [7] had studied separation efficiency of Deduster at air flow rate 288 cfm. In prototype, the length of the separation chamber was 42 inches, the average radius of the annular tunnel was 3-1/3 inches, the gap of the annular tunnel was 1.5 inches and eight vane blades were evenly placed around the annular tunnel and angled at 60° with respect to the center axial line of the Deduster. This study found that the particle separation efficiency of the Deduster was 90% for particles larger than 10 µm and 77% for particles larger than 7 µm. In terms of mass concentration measured using mass samplers, the particle separation efficiency was 85%, because most of the dust mass is attributed to the larger particles.

Tsai C.J. (2004) [29] and **Maynard A.D.** (1999) [30] had developed model for estimated separation efficiency of an axial cyclone. These studies found that the characteristics of inlet guide vane could affect on cyclone performance. These characteristics consist of number of vanes, number of vane turns, radius of vane spindle, vane thickness, pitch and angle of vanes.

FL. Fassani (1999) [31] had studied the effect of high inlet solid loadings on cyclone pressure drop and separation efficiency. An extended range of concentrations was studied, up to 20 kg of solids/kg of gas, with average entrance velocities of 7, 18 and 27 m/s. The introduction of solid particles in the gas flow brought about a reduction in the cyclone pressure drop, compared to the dust free flow, along a extended loading range. The experiments also showed that the pressure drop essentially did not vary as a function of solid loading, and suggested that, as an approximation, the dust laden airflow cyclone pressure drop may be estimated as 47% of the clean air flow pressure drop. It was also observed that the higher the velocity, the higher the pressure drop, independently of solid loading. A trend of increasing separation efficiency with concentration was observed, up to 12 kg of solids/kg of gas, above which there was a tendency of reduction. At test conditions, the collection efficiency of the experiments with an entrance gas velocity of 18 m/s was higher than with 27 m/s.

CHAPTER III

MATERIALS AND METHODS

This study was an experimental study aimed to design and test performance of axial entry glass bottle cyclones. The experimental tests included: the testing of separation efficiency with grinding dust from Praditthorakarn community; the pressure drop measurement. The setting of the whole experiments was performed in laboratory room, 6th building, Occupational and Safety Department, Faculty of Public Health, Mahidol University.

3.1 Analyzing Methods and Instruments

3.1.1 Particle specific gravity

The measurement of particle specific gravity had performed according to the protocols of Specific gravity bottle method [28] (see Appendix A).

3.1.2 Particle size distribution

The Bronzeware grinding dust was analyzed the particle size distribution by using particle size analyzer; Mastersizer S Ver. 2.19, Serial Number: 32734-89, Malvern Instrument Ltd., UK (see Appendix C). An analyzing of the Mastersizer is base on the principle of Dynamic Light Scattering Technique. The range of scattering angles measured is tropically 0.01 - 135 degrees, these cause the size range covered 0.05 - 900 μm . At these sizes and angle ranges, the scattering properties are related to the internal optical properties of the sample material. The theories, which used to the model of scattering in this instrument, are the “Fraunhofer” and “Mie” scattering theory. These rely on the fact that, the diffraction angle is inversely proportional to the particle size. The detector array acquires light scattering data at the rate of 500 Hz (one measurement every 2 ms). The measurement range is between 0.05 - 900 μm and the accuracy is $\pm 2\%$ on Volume Median Diameter (VMD). The particle size distribution is

expressed in term of percentage by volume. This instrument composed of 4 units; small volume sample presentation unit, Mastersizer optical measurement unit, computer system and Malvern operating software.

3.1.3 Pressure drop

To measure pressure drop, incline manometer (Dwyer, Patent Nos 1917637, 2485437) was used to measure the static pressure at the inlet duct, pre-inlet guide vanes and outlet duct.

3.1.4 Air velocity

To measure duct velocity, standard Pitot tube (W.E. Anderson, 166-12, 108022-00, A 220) and incline manometer were used to measure the velocity pressure. After that the velocity pressure were calculated as air velocity.

3.1.5 Air temperature

To measure air temperature, standard thermometer was used to measure the temperature of air.

3.1.6 Atmospheric pressure

To measure atmospheric pressure, barometer was used to measure the atmospheric pressure.

3.1.7 Particle Concentration

The stack sampling method was used to measure the separation efficiencies of glass bottle cyclones by sampling the particle concentration at the inlet and outlet areas. The train sampling procedures included:

- a) PVC Filter, 37 mm, pore size 5 μm
- b) Filter Holders
- c) Glass sampling probes, the internal diameter of tip probe is 2.0 mm.
- d) SKC sampling pumps (Aircheck Sampler, model 224-PCXR8)
- e) Precision rotameter (LPM AIR, Cat. No. 320-2A05)
- f) Rubber tubes
- g) Weighing apparatus, which can read five figures.

3.2 Testing Instruments

3.2.1 Dust generator sets

The dust generator sets were used to generating particle concentration in chamber. The train of dust generator sets included: a) Acrylic chamber, which constructed from acrylic sheet and its dimensions are 30 x 30 x 65 centimeters. The inlet hole is on the top and outlet hole is on the lower side. b) Two centrifugal blowers were used to thoroughly mixing dust in chamber, there are installed at upon side of dust chamber. c) Drag chain conveyer was used to transport dust, and the sample dust was blowing down into dust chamber by centrifugal blower. The rate of dust transportation is 2 gram/min.

3.2.2 Exhaust ventilation system

1) Duct system

The duct system was constructed from acrylic ducts, its length and internal diameter are 45 and 3.00 cm respectively.

2) Air feeding part

A device used to feed air stream from duct into axial inlet cyclones. It was constructed in pattern of tangential entry and conforms to proportions of Stairmand's cyclone.

3) Glass bottle cyclones

A dust separator device used to remove particles from air stream by centrifugal force. It was constructed from glass bottles in pattern of axial entry cyclone that consists eight of inlet vanes. The air feeding part was constructed in pattern of tangential entry, which conforms to proportions of Stairmand's cyclone.

4) Damper

A device used to adjust airflow rate, it constructs from PVC duct and acrylic sheet.

5) Blower

Base on system pressure requirement, the centrifugal forward blower (SANYO DENKI, model T-N91-382-1); 250 watt supply motor; 2 pole type, 1/1.5Amp; 200 volt supply, was used in this study.

3.3 Data Collecting Procedures

3.3.1 The preparing phase

1) Analysis the physical properties of grinding dust

An analyzed physical properties of grinding dust were performed in laboratory room, 6th building, Occupational and Safety Department, Faculty of Public Health, Mahidol University and The National Metal and Materials Technology Center (MTEC). The analytical parameters are the following:

1.1) The particle density was analyzed by Specific gravity bottle method.

1.2) The particle size distribution was analyzed by using the particle size analyzer; Mastersizer S Ver. 2.19. The analyzing of Mastersizer is base on the principle of Dynamic Light Scattering Technique (see Appendix C).

2) The selection glass bottles for construction cyclone

2.1) The selection criterions

The purpose of this study was the construction of glass bottle cyclones by using glass bottles. Table 2-2 showed that the performance of Stairmand's cyclone was higher than other cyclones. Therefore, the proportions of glass bottles should be similar to the proportions of Stairmand's cyclone. The primary considered parameters for selection glass bottles consists of the body diameter (D), cylinder height (h), cone height, overall height (H) and dust outlet diameter (B)

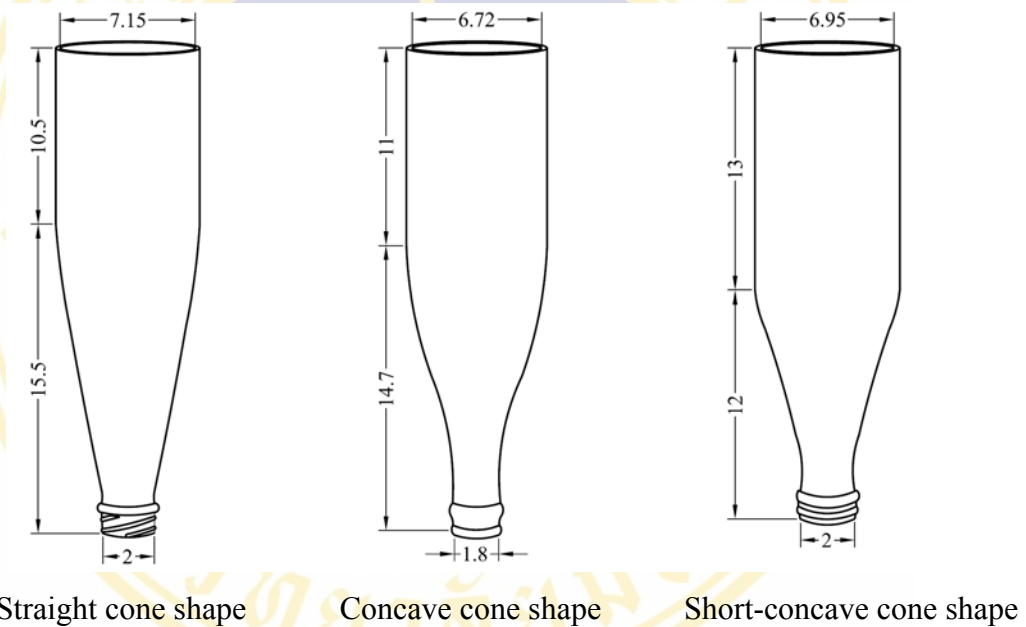
2.2) The shapes and proportions of glass bottles

The results of the primary surveyed to select an appropriate shape of glass bottles for construction cyclones found that there are three types of glass bottles, which its shapes and proportions are according to Stairmand's cyclone. The three types of glass bottles consist of Sauce, Beer and Nectar bottles. The dimensions and proportions of three bottles were showed in table 3-1 and 3-2.

Table 3-1 The dimensions of glass bottles

| No. | Type of bottle | Bottle diameter | Dust outlet diameter | Cylinder height | Cone height | Overall height |
|-----|----------------|-----------------|----------------------|-----------------|-------------|----------------|
| 1 | Source bottle | 7.15 | 2 | 10.5 | 15.5 | 26 |
| 2 | Beer bottle | 6.72 | 1.85 | 11 | 14.7 | 25.7 |
| 3 | Nectar bottle | 6.95 | 2 | 13 | 12 | 25 |

Note : unit = centimeter

**Figure 3-1** The shapes and dimensions of Sauce, Beer and Nectar bottles**Table 3-2** The proportions of glass bottles and standard cyclones

| Term | Description | Stairmand | Shepherd & Lapple | Source bottle | Beer bottle | Nectar bottle |
|------|----------------------|-----------|-------------------|---------------|-------------|---------------|
| D | Body diameter | 1 | 1 | 1 | 1 | 1 |
| h | Cylinder height | 1.5 | 2 | 1.47 | 1.64 | 1.87 |
| C | Cone height | 2.5 | 2 | 2.16 | 2.19 | 1.73 |
| H | Overall height | 4 | 4 | 3.64 | 3.82 | 3.60 |
| B | Dust outlet diameter | 0.375 | 0.25 | 0.28 | 0.27 | 0.29 |

3) Design and construction of glass bottle cyclones

3.1) Cutting the bottom of glass bottles

Steps for cutting bottom of glass bottles

- a) Determined point and marking with paper tape.
- b) Using portable grinder with glass cutter wheel to cutting the bottom of glass bottle. Turn on switch and then cutting glass bottom at marking point together with circulating glass bottle.
- c) When bottom of glass bottle was separated, and then used the side of grinder wheel to polish uneven parts.
- d) Using sand paper to polish the edge of glass bottle.

3.2) Criterion for glass bottle cyclones design.

After preparing cyclone body, this step is the design of additional parts for construction glass bottle cyclones. The additional parts consist of gas outlet diameter (D_e), gas outlet length (S), inlet height (h) and inlet width (b). The glass bottle cyclones should be designed to meet following criteria:

- a) $a < S$ to prevent short circulating of incoming dust to the outlet tube
- b) $b < (D - D_e)/2$ to avoid excessive pressure drop
- c) $H > 3D$ to keep the tip of vortex inside the cone
- d) Angle of cone between $7-8^\circ$ for ready slippage of dust
- e) $D_e/D = 0.4$ to 0.5 , $H/D_e = 8$ to 10 , $S/D_e = 1$ for maximum efficiency

3.3) Inlet guide vane design.

The characteristics of inlet guide vanes should be designed to meet following criterion: the inlet guide vane angles (β) should between $20^\circ - 30^\circ$ [5,6,7], the ratio of u/t should be $1/4$ [5] and amount of inlet guide vanes should be 8 blades [7]. The suggested rang of angles for inlet guide vane design was wide. Actually we will face some problems when design and construct the small cyclones, so this factor was included for consideration in designed step that it could assisting to select an appropriate type of glass bottle cyclones. This step, glass bottle cyclones were designed inlet vanes angle (V_A) at 20° , 25° and 30° to study the influences of inlet vane angles on performance of glass bottle cyclones.

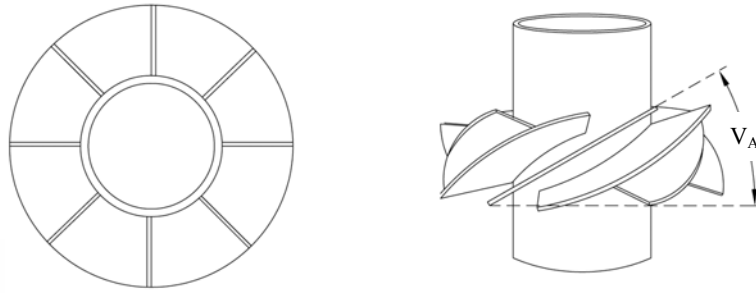


Figure 3-2 Characteristics of inlet guide vanes

4) Calculating the performances of glass bottle cyclones

4.1) Saltation velocity (v_s)

$$v_s = 2.055 \omega \left[\frac{(b/D)^{0.4}}{(1-b/D)^{1/3}} \right] D^{0.067} v_i^{2/3} \quad (3.1)$$

$$\text{and } \omega = \left[\frac{4g\mu_g(\rho_p - \rho_g)}{3\rho_g^2} \right]^{1/3} \quad (3.2)$$

where v_s = Saltation velocity, ft/s

ω = Omega, ft/s

b = Inlet width, ft

D = Diameter of cyclone, ft

v_g = Inlet velocity, ft/s

g = Gravitational force, 32.2 ft/s²

μ_g = Gas viscosity, lb/ft.s

ρ_p = Particle density, lb/ft³

ρ_g = Gas density, lb/ft³

The finding from the study of Kalen and Zenz:

If $v_i/v_s = 1.25$, cyclone will have maximum separation efficiency, and

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

4.2) Cut size diameter (d_{p50})

The cut size diameter could calculate by using Iozia & Lieth equation (1990) as follows:

$$d_{50} = \sqrt{\frac{9\mu_g Q}{\pi\rho_p Z_c v_{t,\max}^2}} \quad (3.3)$$

$$v_{t,\max} = 6.1v_{inlet} \left(\frac{ab}{D^2}\right)^{0.61} \left(\frac{D_e}{D}\right)^{-0.74} \left(\frac{H}{D}\right)^{-0.33} \quad (3.4)$$

$$d_c = 0.47D \left(\frac{ab}{D^2}\right)^{-0.25} \left(\frac{D_e}{D}\right)^{1.4} \quad (3.5)$$

$$Z_c = (H - S) \quad \text{where } d_c < B \quad (3.6)$$

$$Z_c = (H - S) - \left(\frac{H - h}{(D/B) - 1}\right) \left(\frac{d_c}{B} - 1\right) \quad \text{where } d_c > B \quad (3.7)$$

where d_{p50} = Cut size diameter, μ

a = Inlet height, ft

d_c = Radius of the control surface, ft

Z_c = Height of the control surface, ft

B = Cyclone dust outlet diameter, ft

H = Cyclone height, ft

h = Cylindrical height, ft

S = Gas outlet length, ft

4.3) Fractional efficiency (η_i)

The fractional efficiency could calculate by using Iozia & Lieth equation (1990) as follows:

$$\eta_i = \frac{1}{1 + \left(\frac{d_{50}}{d_i}\right)^\beta} \quad (3.8)$$

$$\ln \beta = 0.62 - 0.87 \ln d_{50} + 5.21 \ln \left(\frac{ab}{D^2}\right) + 1.05 \left[\ln \left(\frac{ab}{D^2}\right) \right]^2 \quad (3.9)$$

where η_i = Fractional efficiency, %

β = Slope parameter

d_{50} = Cut size diameter, cm

Q = Total gas flow rate, ft³/s

4.4) Overall separation efficiency (η_T)

$$\eta_T = \sum \eta_i w_i \quad (3.10)$$

where η_T = Overall separation efficiency, %

η_i = Grade or Fractional efficiency), %

w_i = Proportion of particle size range

4.5) Pressure drop (ΔP)

The pressure drop could calculate by using Shepherd and Lapple equations (1939) as follows:

$$\Delta P = 0.003 \rho_g v_g^2 N_H \quad (3.11)$$

$$N_H = K_c \left(\frac{ab}{D_e^2} \right) = K \left(\frac{A_{inlet}}{D_e^2} \right) \quad (3.12)$$

where ΔP = Pressure drop, in.w.g.

N_H = Number inlet velocity heads

A_{inlet} = Inlet area for an axial inlet cyclone

K = Empirical constant

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

($K = 16$ for a normal tangential inlet)

4.6) Separation efficiency for experimental data

$$S.E. = \left[\frac{\text{Dust conc. at inlet duct} - \text{Dust conc. at outlet duct}}{\text{Dust conc. at inlet duct}} \right] \times 100 \quad (3.13)$$

5) Connection the constructed glass bottle cyclones to the dust generator sets and the exhaust ventilation system.

6) Installation all component parts at laboratory room, 6th building, faculty of Public Health, Mahidol University.

3.3.2 The experimental phase

1) Steps of an experimental

The experimental phase included two important steps. The first experimental step was the selection an appropriate shape of glass bottles for construction glass bottle cyclones. The second experimental step was the study to the influences of outlet duct diameters and inlet vane angles on cyclone performance of glass bottle cyclones.

1.1) The selection an appropriate shape of glass bottles

Three types of glass bottles were assembling with the PVC duct, which its diameter was 3 cm, and the inlet vane angle was design at 20°. These caused to maximum separation efficiency. The proportions of glass bottle cyclones were showed in Table 3-3.

Table 3-3 The proportions of glass bottle cyclones.

| Term | Description | | Stairmand | Type of bottle cyclone | | |
|-------|----------------------|-------------------|-----------|------------------------|------|--------|
| | | | | Source | Beer | Nectar |
| D | Body diameter | | 1 | 1 | 1 | 1 |
| a | Inlet height | $K_a = a/D$ | 0.5 | 0.5 | 0.5 | 0.5 |
| b | Inlet width | $K_b = b/D$ | 0.2 | 0.2 | 0.2 | 0.2 |
| S | Outlet length | $K_S = S/D$ | 0.5 | 0.6 | 0.6 | 0.6 |
| D_e | Gas outlet diameter | $K_{D_e} = D_e/D$ | 0.5 | 0.42 | 0.44 | 0.43 |
| h | Cylinder height | $K_h = h/D$ | 1.5 | 1.47 | 1.64 | 1.87 |
| H | Overall height | $K_H = H/D$ | 4 | 3.64 | 3.82 | 3.60 |
| B | Dust outlet diameter | $K_B = B/D$ | 0.375 | 0.28 | 0.27 | 0.29 |

1.2) Study to the influences of outlet duct diameters and inlet vanes angles

The appropriate shape of glass bottle cyclones, which showed maximum separation efficiency in the first experimental step, was used to study in this step. The glass bottle cyclones were designed on two considerations. First, the gas outlet diameters of glass bottle cyclones were designed at 0.5D and 0.42D for study the influences of shortcut flow on cyclone performances. Then, these glass bottle cyclones were designed inlet vane angle (V_A) at 20°, 25° and 30° for study the influences of inlet vane angles on cyclone performances. The six patterns of glass bottle cyclones were

designed as $D_{e,0.5D}V_{A,20^\circ}$, $D_{e,0.5D}V_{A,25^\circ}$, $D_{e,0.5D}V_{A,30^\circ}$, $D_{e,0.42D}V_{A,20^\circ}$, $D_{e,0.42D}V_{A,25^\circ}$ and $D_{e,0.42D}V_{A,30^\circ}$ respectively. Then six patterns of glass bottle cyclones would take to testing performances with grinding dust at airflow rate of 12 ft³/min.

2) Steps of an experiment

2.1) Generating dust concentration in chamber

The dust generating is the importance step because the concentration of dust in chamber will affect to the separation efficiency of cyclones. Therefore, the dust generated should be consistency. The instruments for dust generating consist of; drag chain conveyer, propelling motor, an acrylic chamber, blowing down blower and mixing blowers. The rate of dust transportation should be 2 gram/min, these due to the results of particle sampling at bronzewares grinding process indicated that the particle concentration in chamber should between 330 - 400 mg/m³.

Steps for dust generating

- a) Weigh grinding dust for 70 g.
- b) Filling the grinding dust in the port.
- c) Turn on switch of propelling motor, blowing down blower and mixing blowers.
- d) Turn on switch of exhaust ventilation blower. Then adjust to properly flow rate.
- e) Observe the dispersion of dust in chamber. If concentration of dust is consistent, it would be ready to sampling.
- f) Filling grinding dust in the port when amount of dust was low.

2.2) The particle sampling

Particle sampling is the important step for evaluation the separation efficiencies of glass bottle cyclones. The stack sampling method was used in this study for sampling particles at the inlet and outlet areas at the same time by using glass sampling probes. The sampling flow rates were regulating to 1-2 l/min, these according to NIOSH Method 0500. Each type of glass bottle cyclones was performed to five repeated sampling.

Steps for particle sampling

- a) Weigh filters after kept in desiccator for 12 hours.
- b) Assembly filters with cassette filter holders, glass sampling probes and other component sets of particle sampling.
- c) Turn on switch of dust generator sets and exhaust ventilation blower.
- d) Using Pitot tube and incline manometer to measure the velocity pressure at the location 0.25D and 0.75D of horizontal and vertical axis (4 point). Then adjusted the airflow rate to 12 ft³/min.
- e) Observe the dispersion of dust in chamber, if the concentration of dust is consistent, then inserted the glass sampling probes into the inlet and outlet ducts at the same points of the measured velocity pressure.
- f) Turn on switch of sampling pumps, and adjust sampling velocity to be equal to the duct velocity at each point.
- g) The particle sampling time at the inlet duct was 2 min/point, and the outlet duct was 4 min/point. After turn off switch of sampling pumps, then must removed the glass sampling probe out from ducts.
- h) The sequences of particle sampling points were 1st, 2nd, 1st and 2nd of the horizontal axis, and then 3rd, 4th, 3rd and 4th of the vertical axis, overall 8 points.
- i) Note the environmental conditions such as air temperature and barometric pressure.
- j) After sampling, the glass sampling probes would be washing with 10 ml of acetone into the beakers. Then evaporated acetone in beakers at the room temperature.
- k) Keeping filters in desiccator for 12 hours.
- l) Weigh the filters and beakers.

2.3) The measurement of pressure drop

Each type of glass bottle cyclones would measure the pressure drop at the airflow rate 12 ft³/min. In this study incline manometer was used to measure static

pressure at three points included: the inlet duct, pre-inlet guide vane and the outlet duct of glass bottle cyclones.

3.4 Statistical Analysis

The data were analyzed by using statistic as follows:

3.4.1 Descriptive statistic

To express the separation efficiencies, the particle concentrations at the inlet and outlet ducts, the mean and standard deviation was applied.

3.4.2 Inferential statistic

3.4.2.1 The comparison mean of glass bottle cyclones separation efficiencies between an experimental results and the criterion level at 80% was determined by One Sample T-Test.

3.4.2.2 The comparison of glass bottle cyclones separation efficiencies at different outlet duct diameters was determined by Independent-sample T Test.

3.4.2.3 The comparison of glass bottle cyclones separation efficiencies at different inlet vanes angles was determined by analysis of variance (One-way ANOVA) and followed by multiple comparisons (Tukey HSD).

CHAPTER IV

RESULTS

This study started with dust characteristics and size distribution analysis. Then the glass bottle cyclones were designed and constructed in pattern of axial entry cyclone, which consists eight of inlet guide vanes. The experimental phases included two important steps. The first experimental step was the selection of an appropriate shape of glass bottles for construction of glass bottle cyclones. The second experimental step was the study of the influences of outlet duct diameters and inlet vanes angles on cyclone performances. The theories of Iozia & Lieth (1990) and Shepherd and Lapple (1939) were used to estimation cyclone separation efficiency and pressure drop respectively. Finally, all types of glass bottle cyclones were tested with the grinding dust at airflow rate of 12 cfm. The results of the study can describe into 4 parts as follows:

Part 1: Dust characteristics and size distribution

Part 2: Glass bottle cyclones performances (theoretical approach)

Part 3: The experimental results

Part 4: Comparison of performance against shapes of glass bottles, outlet duct diameters, and inlet vane angles

Part 1: Dust Characteristics and Size Distribution

The sample dust from bronzewares grinding process was analyzed to define density and specific gravity. By using specific gravity bottle method, the particle density and specific gravity was 2.12 g/cm^3 (132.64 lb/ft^3) and 2.135 respectively. The particle size distribution was analyzed by particle analyzer, Mastersizer S Ver. 2.19.

Table 4-1 The particle size distribution of grinding dust

| Particle size (µm) | Average size (µm) | Weight by volume (%) | Cumulative weight (%) |
|--------------------|-------------------|----------------------|-----------------------|
| 0.00 - 10.48 | 5.24 | 2.3 | 2.30 |
| 10.48 - 19.31 | 14.90 | 8.51 | 10.81 |
| 19.31 - 35.56 | 27.43 | 12.58 | 23.39 |
| 35.56 - 56.23 | 45.90 | 19.67 | 43.06 |
| 56.23 - 88.91 | 72.57 | 22.78 | 65.84 |
| 88.91 - 140.58 | 114.75 | 19.37 | 85.21 |
| 140.58 - 222.28 | 181.43 | 11.22 | 96.43 |
| 222.28 - 351.46 | 286.87 | 3.57 | 100.00 |

The analytical results showed that the particle size distribution of bronzewares grinding dust ranged from 1.68 to 351.46 micron with the average size was 80.91 micron. Afterwards, the percentage of cumulative weight and particle size average can be plotted graph, and then comparing with Stairmand particle size distribution standard curves (Figure 4-1). The results showed that the sample dust can be classified into coarse dust.

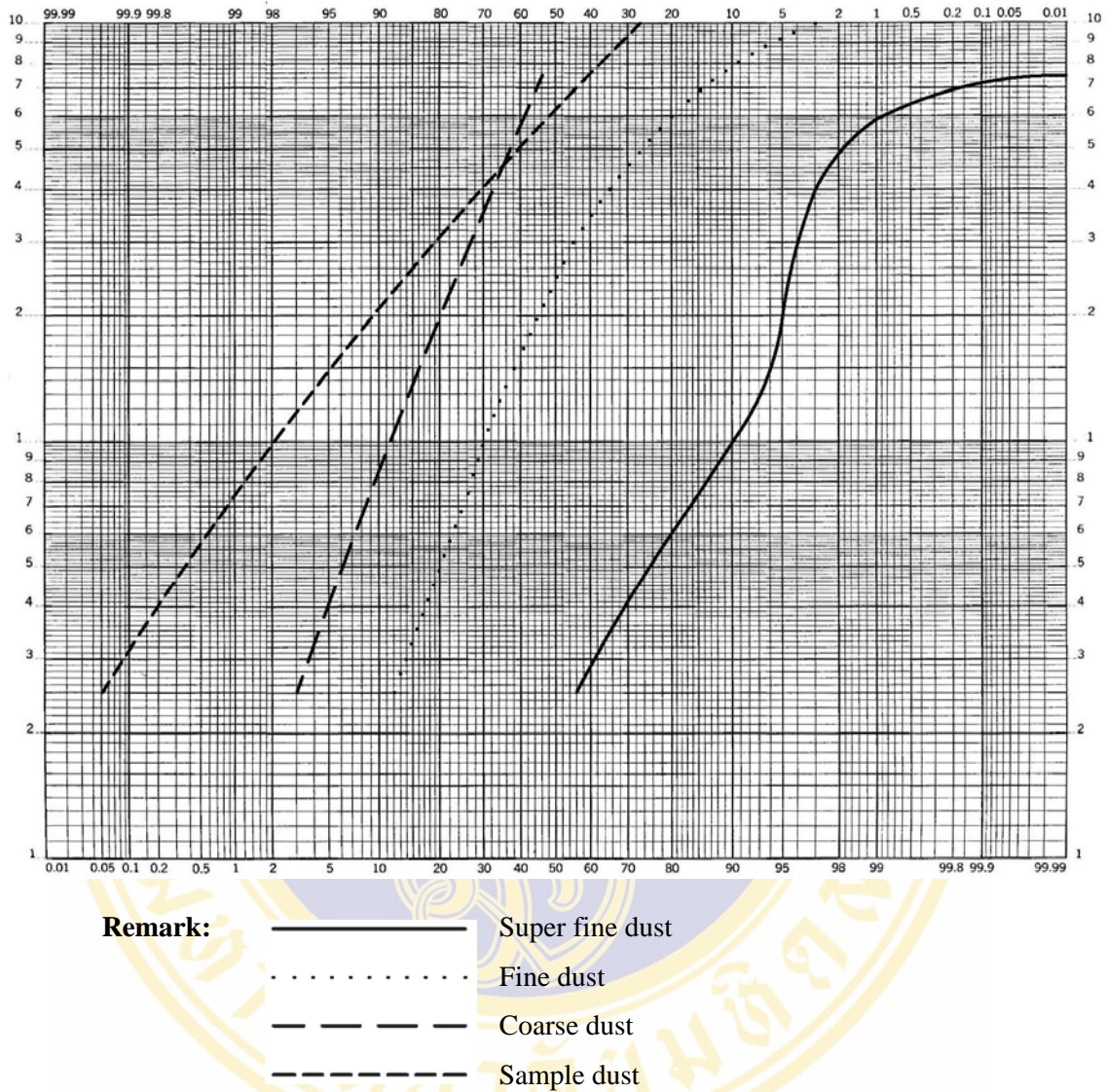


Figure 4-1 The particle size distribution of grinding dust compared with Stairmand standard curves

Part 2: The Glass Bottle Cyclones Performances (Theoretical Approach)

The separation efficiencies of glass bottle cyclones were estimated by theory of Iozia & Lieth (1990) and the pressure drop were estimated by theory of Shepherd and Lapple (1939). The glass bottle cyclones design configurations, which using as the variables for performance calculations, were showed in Table 4-2 and Table 4-3.

Table 4-2 Glass bottle cyclones design configurations for the first experimental step

| Type of glass bottle cyclone | Proportions for cyclone design (ft) | | | | | | | | I_A | A_{inlet} (ft ²) |
|------------------------------|-------------------------------------|-------|-------|-------|-------|-------|-------|-------|-------|--------------------------------|
| | D | a | b | S | D_e | h | H | B | | |
| Sauce bottle | 0.235 | 0.118 | 0.047 | 0.141 | 0.098 | 0.345 | 0.855 | 0.066 | 20° | 0.0082 |
| Beer bottle | 0.220 | 0.110 | 0.044 | 0.132 | 0.098 | 0.361 | 0.841 | 0.059 | 20° | 0.0074 |
| Nectar bottle | 0.228 | 0.114 | 0.046 | 0.137 | 0.098 | 0.426 | 0.821 | 0.066 | 20° | 0.0078 |

Table 4-3 Sauce bottle cyclones design configurations for the second experimental step

| Type of Sauce bottle cyclone | Proportions for cyclone design (ft) | | | | | | | | I_A | A_{inlet} (ft ²) |
|------------------------------|-------------------------------------|-------|-------|-------|-------|-------|-------|-------|-------|--------------------------------|
| | D | a | b | S | D_e | h | H | B | | |
| Pattern I | 0.235 | 0.118 | 0.047 | 0.141 | 0.118 | 0.345 | 0.855 | 0.066 | 20° | 0.0070 |
| Pattern II | 0.235 | 0.118 | 0.047 | 0.141 | 0.118 | 0.345 | 0.855 | 0.066 | 25° | 0.0092 |
| Pattern III | 0.235 | 0.118 | 0.047 | 0.141 | 0.118 | 0.345 | 0.855 | 0.066 | 30° | 0.0119 |
| Pattern IV | 0.235 | 0.118 | 0.047 | 0.141 | 0.098 | 0.345 | 0.855 | 0.066 | 20° | 0.0082 |
| Pattern V | 0.235 | 0.118 | 0.047 | 0.141 | 0.098 | 0.345 | 0.855 | 0.066 | 25° | 0.0105 |
| Pattern VI | 0.235 | 0.118 | 0.047 | 0.141 | 0.098 | 0.345 | 0.855 | 0.066 | 30° | 0.0134 |

Prediction of glass bottle cyclones performance

Testing condition variables:

$$\text{Air temperature} = 30.5 \text{ }^\circ\text{C}$$

$$\text{Air density } (\rho_g) = 0.0725 \text{ lb/ft}^3$$

$$\text{Air viscosity } (\mu_g) = 1.269 \times 10^{-5} \text{ lb/ft.s}$$

$$\text{Atmospheric pressure} = 758 \text{ mm.Hg.}$$

$$\text{Particle density } (\rho_p) = 132.64 \text{ lb/ft}^3$$

$$\text{Airflow rate} = 12 \text{ fi}^3/\text{min}$$

Calculation procedures of Sauce bottle cyclone

- 1) Calculating inlet velocity (v_i)

$$\begin{aligned} v_i &= \frac{Q}{A_{inlet}} \\ &= \frac{12}{0.0082} \\ &= 1,463 \text{ ft/min or } 24.39 \text{ ft/sec} \end{aligned}$$

- 2) Calculating Saltation velocity (v_s)

$$\begin{aligned} v_s &= 2.055 \omega \left[\frac{(b/D)^{0.4}}{(1-b/D)^{1/3}} \right] D^{0.067} v_i^{2/3} \\ \omega &= \left[\frac{4g\mu_g(\rho_p - \rho_g)}{3\rho_g^2} \right]^{1/3} \\ &= \left[\frac{4 \times 32.2 \times 1.269 \times 10^{-5} (132.64 - 0.0725)}{3 \times 0.0725^2} \right]^{1/3} \\ &= 2.395 \text{ ft/s} \\ v_s &= 2.055 \times 2.395 \left[\frac{(0.047/0.235)^{0.4}}{(1-0.047/0.235)^{1/3}} \right] 0.235^{0.067} \times 24.39^{2/3} \\ &= 21.26 \text{ ft/s} \\ v_i/v_s &= 24.39/21.26 = 1.15 \end{aligned}$$

- 3) Calculating cut size diameter (d_{p50})

$$d_{50} = \sqrt{\frac{9\mu_g Q}{\pi\rho_p Z_c v_{t,max}^2}}$$

- 3.1) Calculating $v_{t,max}$

$$\begin{aligned} v_{t,max} &= 6.1 v_{inlet} \left(\frac{ab}{D^2} \right)^{0.61} \left(\frac{D_e}{D} \right)^{-0.74} \left(\frac{H}{D} \right)^{-0.33} \\ &= 6.1 \times 24.39 \left(\frac{0.118 \times 0.047}{0.235^2} \right)^{0.61} \left(\frac{0.098}{0.235} \right)^{-0.74} \left(\frac{0.855}{0.235} \right)^{-0.33} \\ &= 45.67 \text{ ft/s} \end{aligned}$$

3.2) Calculating d_c

$$\begin{aligned}
 d_c &= 0.47D \left(\frac{ab}{D^2} \right)^{-0.25} \left(\frac{D_e}{D} \right)^{1.4} \\
 &= 0.47 \times 0.235 \left(\frac{0.118 \times 0.047}{0.235^2} \right)^{-0.25} \left(\frac{0.098}{0.235} \right)^{1.4} \\
 &= 0.058 \text{ ft}
 \end{aligned}$$

3.3) Calculating Z_c

where $d_c < B$ ($0.058 < 0.066$)

$$\begin{aligned}
 Z_c &= (H - S) \\
 &= (0.855 - 0.141) \\
 &= 0.714 \text{ ft}
 \end{aligned}$$

3.4 Calculating d_{p50}

$$\begin{aligned}
 d_{50} &= \sqrt{\frac{9\mu_g Q}{\pi \rho_p Z_c v_{t,\max}^2}} \\
 &= \sqrt{\frac{9 \times 1.269 \times 10^{-5} \times 0.2}{\pi \times 132.64 \times 0.714 \times 45.67^2}} \\
 &= 6.12 \times 10^{-6} \text{ ft} \\
 &= 1.86 \mu\text{m}
 \end{aligned}$$

4) Calculating Fractional efficiency

$$\eta_i = \frac{1}{1 + \left(\frac{d_{50}}{d_i} \right)^\beta}$$

$$\ln \beta = 0.62 - 0.87 \ln(1.86 \times 10^{-4}) + 5.21 \ln \left(\frac{0.118 \times 0.047}{0.235^2} \right) + 1.05 \left[\ln \left(\frac{0.118 \times 0.047}{0.235^2} \right) \right]^2$$

$$\beta = 5.29$$

Table 4-4 Fractional efficiency of each particle size average

| Particle size (µm) | Average size (d _i) (µm) | Weight by volume (w _i) (%) | η _i |
|--------------------|-------------------------------------|--|----------------|
| 0.00 - 10.48 | 5.24 | 2.3 | 0.995 |
| 10.48 - 19.31 | 14.90 | 8.51 | 1 |
| 19.31 - 35.56 | 27.43 | 12.58 | 1 |
| 35.56 - 56.23 | 45.90 | 19.67 | 1 |
| 56.23 - 88.91 | 72.57 | 22.78 | 1 |
| 88.91 - 140.58 | 114.75 | 19.37 | 1 |
| 140.58 - 222.28 | 181.43 | 11.22 | 1 |
| 222.28 - 351.46 | 286.87 | 3.57 | 1 |

Table 4-4 showed fractional efficiency of each particle size average that can be used to calculate the overall collection efficiency of Sauce bottle cyclones as follows:

5) Calculating overall separation efficiency (η_T)

$$\begin{aligned}
 \eta_T &= \sum \eta_i w_i \\
 &= (2.3 \times 0.995) + (8.51 \times 1) + (12.58 \times 1) + (19.67 \times 1) + \\
 &\quad (22.78 \times 1) + (19.37 \times 1) + (11.22 \times 1) + (3.57 \times 1) \\
 &= 99.99\%
 \end{aligned}$$

6) Calculating pressure drop (ΔP)

The pressure drop could calculate by using Shepherd and Lapple equation (1939) as follows:

$$\begin{aligned}
 \Delta P &= 0.003 \rho_g v_g^2 N_H \\
 N_H &= K \left(\frac{A_{inlet}}{D_e^2} \right) \\
 &= 7.5 \left(\frac{0.0082}{0.098^2} \right) \\
 &= 6.4 \\
 \Delta P &= 0.003 \times 0.0725 \times 24.39^2 \times 6.4 \\
 &= 0.828 \text{ in.wg}
 \end{aligned}$$

Then used the cyclone configuration parameters in Table 4-2 and Table 4-3 to calculation the performances of Beer, Nectar and Sauce bottle cyclones pattern I to pattern VI by following performance the calculation procedures of Sauce bottle cyclone form step 1 to step 6 respectively. All variables and performance parameters, which resulting from the calculation, were showed in Table 4-5.

Table 4-5 Variables and performance parameters from theoretical approached

| Type of glass bottle cyclone | Calculation variable | | | | | | | Performance parameter | | |
|------------------------------|----------------------|-----------|-----------------------|---------------|---------------|---------|-------|------------------------|-----------------|-----------------------|
| | v_i (ft/s) | v_i/v_s | $v_{t,max}$ (ft/s) | d_c (ft) | Z_c (ft) | β | N_H | d_{50} (μ m) | η_r (%) | ΔP (in.wg) |
| Sauce bottle | 24.39 | 1.15 | 45.67 | 0.058 | 0.714 | 5.29 | 6.40 | 1.86 | 99.99 | 0.83 |
| Beer bottle | 26.67 | 1.19 | 46.68 | 0.059 | 0.709 | 5.38 | 5.86 | 1.82 | 99.99 | 0.91 |
| Nectar bottle | 25.64 | 1.17 | 44.94 | 0.058 | 0.684 | 5.13 | 6.09 | 1.92 | 99.99 | 0.87 |
| Pattern I | 28.57 | 1.21 | 46.71 | 0.074 | 0.687 | 5.25 | 3.77 | 1.87 | 99.99 | 0.67 |
| Pattern II | 21.74 | 1.10 | 35.54 | 0.074 | 0.687 | 4.32 | 4.96 | 2.46 | 99.89 | 0.51 |
| Pattern III | 16.81 | 1.01 | 27.48 | 0.074 | 0.687 | 3.31 | 6.41 | 3.18 | 99.57 | 0.39 |
| Pattern IV | 24.39 | 1.15 | 45.67 | 0.058 | 0.714 | 5.29 | 6.40 | 1.86 | 99.99 | 0.83 |
| Pattern V | 19.05 | 1.06 | 35.67 | 0.058 | 0.714 | 4.24 | 8.19 | 2.39 | 99.92 | 0.65 |
| Pattern VI | 14.93 | 0.97 | 27.96 | 0.058 | 0.714 | 3.43 | 10.46 | 3.05 | 99.65 | 0.51 |

Table 4-5 showed the resemblance of performances between Sauce, Beer and Nectar bottle cyclones that resulting from theoretical approached. There showed accordant results that, when decreasing the inlet vane angles, the cut diameters also increased, while the inlet velocities, the overall efficiencies and the pressure drop were increased. Furthermore the performances of $D_{e,0.5D}$ and $D_{e,0.42D}$ Sauce bottle cyclones at the same inlet vane angles had slightly different on the cut diameters and overall efficiencies, but the pressure drop had extremely different.

Part 3: The Experimental Results

Step 1: The selection an appropriate shape of glass bottles for construct glass bottle cyclone

The separation efficiencies and pressure drop of glass bottle cyclones which constructed from Sauce, Beer and Nectar bottles were tested performances at the airflow rate of 12 cfm and the particle concentration between 330-400 mg/m³. The experimental results were showed in Table 4-6 and Figure 4-2

Table 4-6 The performances of glass bottle cyclones

| Type of glass bottle cyclone | No. | η (% by weight) | Pressure drop (in.wg.) |
|------------------------------|-------------|-----------------|------------------------|
| Sauce bottle | 1 | 99.75 | 0.77 |
| | 2 | 99.78 | |
| | 3 | 99.89 | |
| | 4 | 99.88 | |
| | 5 | 99.78 | |
| | <i>Mean</i> | <i>99.81</i> | - |
| | <i>S.D.</i> | <i>0.06</i> | - |
| Beer bottle | 1 | 98.11 | 0.85 |
| | 2 | 98.29 | |
| | 3 | 98.48 | |
| | 4 | 98.43 | |
| | 5 | 98.26 | |
| | <i>Mean</i> | <i>98.31</i> | - |
| | <i>S.D.</i> | <i>0.15</i> | - |
| Nectar bottle | 1 | 97.38 | 0.81 |
| | 2 | 97.41 | |
| | 3 | 97.31 | |
| | 4 | 97.38 | |
| | 5 | 97.09 | |
| | <i>Mean</i> | <i>97.31</i> | - |
| | <i>S.D.</i> | <i>0.13</i> | - |

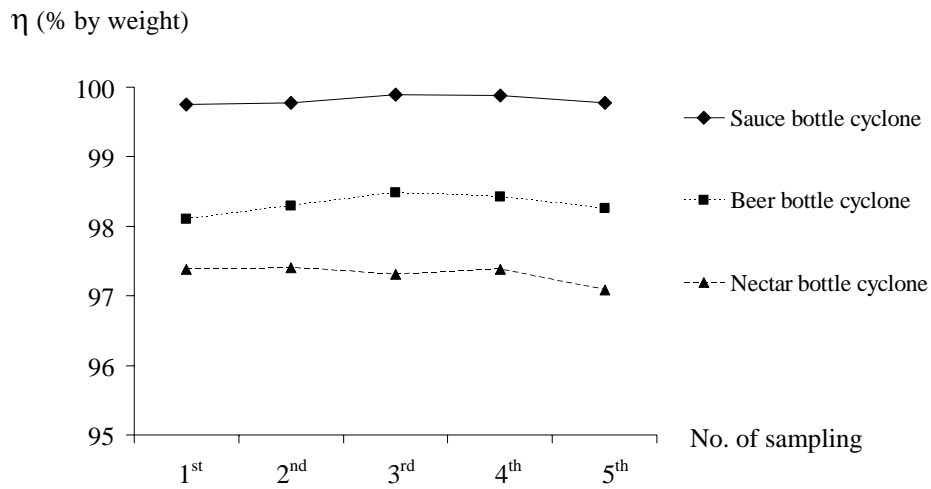


Figure 4-2 Comparison separation efficiencies of glass bottle cyclones which constructed from three types of glass bottle

Table 4-6 and Figure 4-2 showed that the average separation efficiency of glass bottle cyclones, which were constructed from Sauce, Beer and Nectar bottles, were 99.81%, 98.31% and 97.31% respectively. The separation efficiencies of Sauce bottle cyclone were higher than Beer and Nectar bottle cyclones. Furthermore the pressure drop of Sauce bottle cyclone was lower than Beer and Nectar bottle cyclones. These experimental data revealed that the Sauce bottle cyclone, which has straight cone shape, was the appropriate type for construction cyclone in experimental step 2.

Step 2: The experiment to study the influences of outlet duct diameters and inlet vanes angles on cyclone performance

This step the Sauce bottle cyclones were designed and constructed in six patterns. These six patterns were designed as $D_{e,0.5D}V_{A,20^\circ}$, $D_{e,0.5D}V_{A,25^\circ}$, $D_{e,0.5D}V_{A,30^\circ}$, $D_{e,0.42D}V_{A,20^\circ}$, $D_{e,0.42D}V_{A,25^\circ}$ and $D_{e,0.42D}V_{A,30^\circ}$ respectively. Then, all patterns of Sauce bottle cyclones were tested performances at the airflow rate of 12 cfm and the particle concentration between 330-400 mg/m³. The experimental results were showed in Table 4-7 and Table 4-8

Table 4-7 The performances of Sauce bottle cyclone pattern I, II and III

| Pattern of Sauce bottle cyclone | No. | η (% by weight) | Pressure drop (in.wg.) |
|---------------------------------|-------------|-------------------------|---------------------------|
| Cyclone pattern I | 1 | 99.72 | 0.66 |
| | 2 | 99.70 | |
| | 3 | 99.77 | |
| | 4 | 99.73 | |
| | 5 | 99.80 | |
| | <i>Mean</i> | 99.74 | - |
| | <i>S.D.</i> | 0.04 | - |
| Cyclone pattern II | 1 | 99.50 | 0.51 |
| | 2 | 99.56 | |
| | 3 | 99.36 | |
| | 4 | 99.42 | |
| | 5 | 99.63 | |
| | <i>Mean</i> | 99.49 | - |
| | <i>S.D.</i> | 0.11 | - |
| Cyclone pattern III | 1 | 99.34 | 0.45 |
| | 2 | 99.50 | |
| | 3 | 99.46 | |
| | 4 | 99.50 | |
| | 5 | 99.33 | |
| | <i>Mean</i> | 99.43 | - |
| | <i>S.D.</i> | 0.08 | - |

Table 4-8 The performances of Sauce bottle cyclone pattern IV, V and VI

| Pattern of Sauce bottle cyclone | No. | η (% by weight) | Pressure drop (in.wg.) |
|---------------------------------|-------------|-------------------------|---------------------------|
| Cyclone pattern IV | 1 | 99.75 | 0.77 |
| | 2 | 99.78 | |
| | 3 | 99.89 | |
| | 4 | 99.88 | |
| | 5 | 99.78 | |
| | <i>Mean</i> | <i>99.81</i> | - |
| | <i>S.D.</i> | <i>0.06</i> | - |
| Cyclone pattern V | 1 | 99.50 | 0.66 |
| | 2 | 99.64 | |
| | 3 | 99.69 | |
| | 4 | 99.55 | |
| | 5 | 99.63 | |
| | <i>Mean</i> | <i>99.60</i> | - |
| | <i>S.D.</i> | <i>0.08</i> | - |
| Cyclone pattern VI | 1 | 99.49 | 0.60 |
| | 2 | 99.55 | |
| | 3 | 99.56 | |
| | 4 | 99.51 | |
| | 5 | 99.34 | |
| | <i>Mean</i> | <i>99.49</i> | - |
| | <i>S.D.</i> | <i>0.09</i> | - |

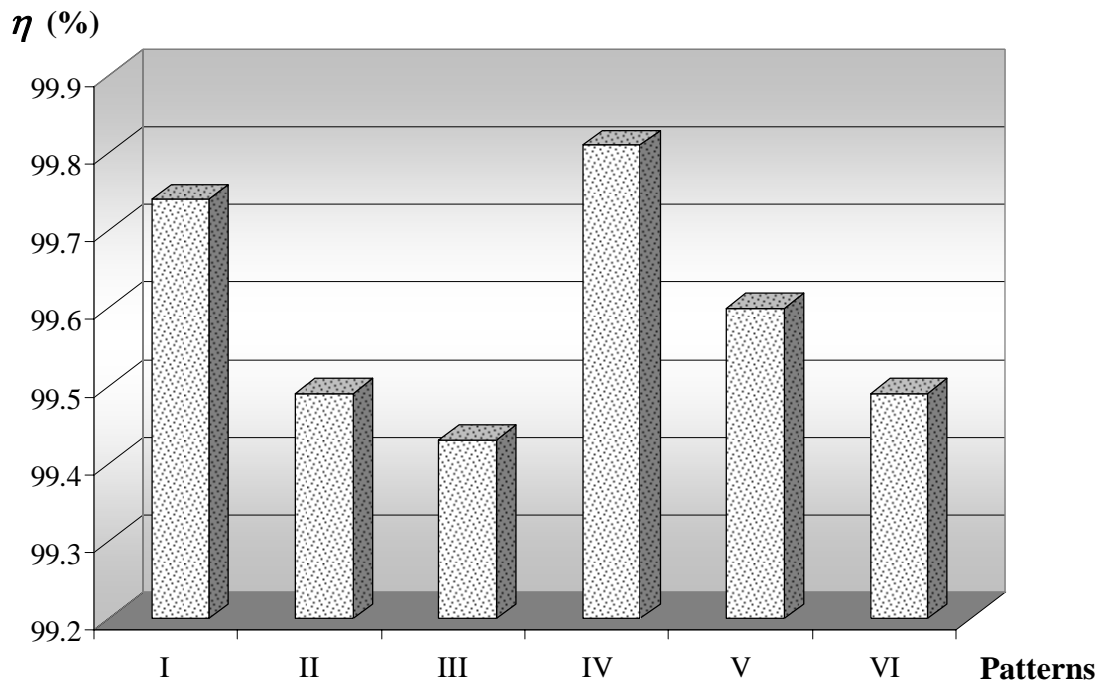


Figure 4-3 The separation efficiencies of Sauce bottle cyclones pattern I to pattern VI

Table 4-7, Table 4-8 and Figure 4-3 showed that the Sauce bottle cyclone pattern IV had the separation efficiency and pressure drop higher than other cyclones. These showed accordant results that when decreasing the inlet vane angles, the separation efficiencies and the pressure drop were increased. Furthermore the separation efficiencies between $D_{e,0.5D}$ and $D_{e,0.42D}$ Sauce bottle cyclone at the same inlet vane angles had slightly different, but the pressure drop had extremely different.

Part 4: Comparison Cyclone Performances against Outlet Duct Diameters, and Inlet Vane Angles

1) Comparison separation efficiencies of Sauce bottle cyclones with different outlet duct diameters

Table 4-9 Comparison separation efficiencies between $D_{e,0.5D}$ and $D_{e,0.42D}$ Sauce bottle cyclones at inlet vane angle 20° by using Independent-sample T Test

| | n | \bar{Y} | S | t | df | p |
|--------------------|----------|-----------|----------|----------|-----------|----------|
| Cyclone pattern I | 5 | 99.74 | 0.040 | 2.121 | 8 | 0.067 |
| Cyclone pattern IV | 5 | 99.81 | 0.064 | | | |

Table4-10 Comparison separation efficiencies between $D_{e,0.5D}$ and $D_{e,0.42D}$ Sauce bottle cyclones at inlet vane angle 25° by using Independent-sample T Test

| | n | \bar{Y} | S | t | df | p |
|--------------------|----------|-----------|----------|----------|-----------|----------|
| Cyclone pattern II | 5 | 99.49 | 0.108 | 1.833 | 8 | 0.104 |
| Cyclone pattern V | 5 | 99.60 | 0.076 | | | |

Table4-11 Comparison separation efficiencies between $D_{e,0.5D}$ and $D_{e,0.42D}$ Sauce bottle cyclones at inlet vane angle 30° by using Independent-sample T Test

| | n | \bar{Y} | S | t | df | p |
|---------------------|----------|-----------|----------|----------|-----------|----------|
| Cyclone pattern III | 5 | 99.43 | 0.085 | 1.167 | 8 | 0.277 |
| Cyclone pattern VI | 5 | 99.49 | 0.089 | | | |

Table 4-9, Table 4-10 and Table 4-11 showed accordant results that there were no significant differences of separation efficiencies between $D_{e,0.5D}$ and $D_{e,0.42D}$ Sauce bottle cyclones ($p > 0.067$).

2) Comparison separation efficiencies of Sauce bottle cyclones with different inlet vane angles

Table 4-12 Comparison separation efficiencies of Sauce bottle cyclones between inlet vane angles 20°, 25° and 30°, at $D_{e,0.5D}$ by using ANOVA

| | SS | df | MS | F | p |
|----------------|-------|----|-------|-------|-------|
| Between Groups | 0.280 | 2 | 0.140 | 20.63 | 0.001 |
| Within Groups | 0.082 | 12 | 0.007 | | |
| Total | 0.362 | 14 | | | |

Table 4-12 showed that there was significant difference on separation efficiencies of Sauce bottle cyclones between inlet vane angles 20°, 25° and 30° ($p < 0.001$).

Table 4-13 Comparison separation efficiencies of Sauce bottle cyclones between inlet vane angles 20°, 25° and 30°, at $D_{e,0.42D}$ by using ANOVA

| | SS | df | MS | F | p |
|----------------|-------|----|-------|-------|-------|
| Between Groups | 0.274 | 2 | 0.137 | 23.19 | 0.001 |
| Within Groups | 0.071 | 12 | 0.006 | | |
| Total | 0.345 | 14 | | | |

Table 4-13 showed that there was significant difference on separation efficiencies of Sauce bottle cyclones between inlet vane angles 20°, 25° and 30° ($p < 0.001$).

Table 4-14 Comparison the separation efficiencies between Sauce bottle cyclone pattern I, II and III (Multiple comparisons: Tukey HSD)

| Sauce bottle cyclones | Mean Difference | Std. Error | p |
|--------------------------|-----------------|------------|-------|
| Pattern I - Pattern II | 0.250* | 0.05214 | 0.001 |
| Pattern I - Pattern III | 0.318* | 0.05214 | 0.001 |
| Pattern II - Pattern III | 0.068 | 0.05214 | 0.420 |

* The mean difference is significant at the .05 level.

Table 4-15 Comparison the separation efficiencies between Sauce bottle cyclone pattern IV, V and VI (Multiple comparisons: Tukey HSD)

| Sauce bottle cyclones | Mean Difference | Std. Error | p |
|-------------------------|-----------------|------------|-------|
| Pattern IV - Pattern V | 0.214* | 0.04865 | 0.002 |
| Pattern IV - Pattern VI | 0.326* | 0.04865 | 0.001 |
| Pattern V - Pattern VI | 0.112 | 0.04865 | 0.094 |

* The mean difference is significant at the .05 level.

Table 4-14 and 4-15 showed the mean differences of Sauce bottle cyclones between inlet vane angles 20°, 25° and 30°. At the 95 % confidence interval, the mean separation efficiency of Sauce bottle cyclones at the inlet vane angle of 20° was higher than inlet vane angles of 25° and 30° ($p < 0.002$), but the mean separation efficiency of Sauce bottle cyclones between inlet vane angles of 25° and 30° was no significant difference ($p > 0.094$)

3) Comparison the pressure drop of Sauce bottle cyclones with different outlet duct diameters

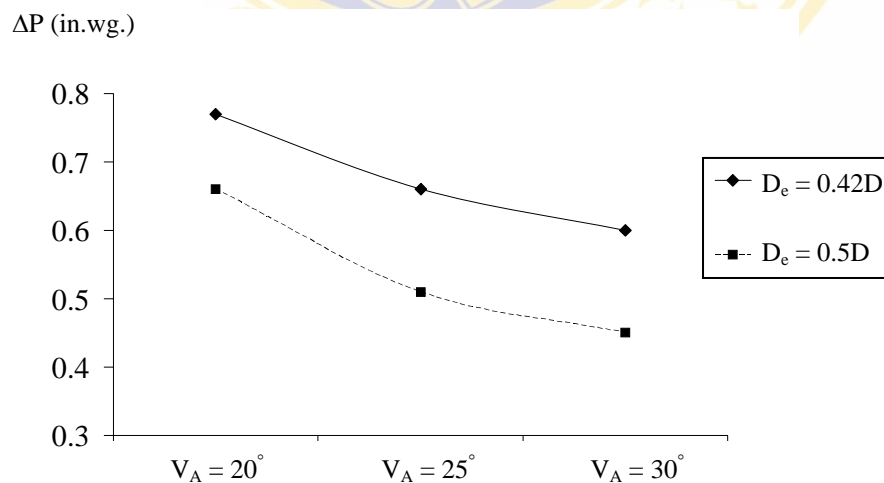


Figure 4-4 Comparison the pressure drop of Sauce bottle cyclones between inlet vane angles 20°, 25° and 30°

Figure 4-4 showed accordant results that, at the same outlet duct diameters when increasing the inlet vane angles from 20° to 30°, the pressure drop of Sauce bottle cyclones were decreased continuously.

4) Comparison the pressure drop of Sauce bottle cyclones with different inlet vanes angles

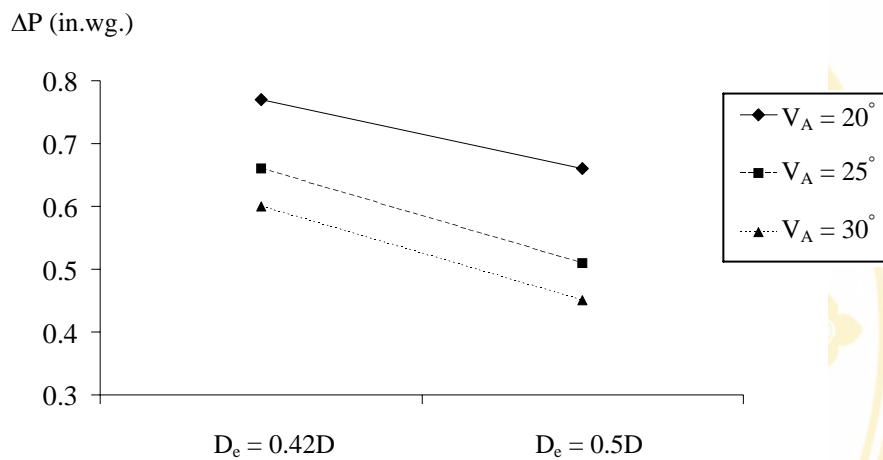


Figure 4-5 Comparison pressure drop of Sauce bottle cyclones between outlet duct diameters 0.5D and 0.42D

Figure 4-5 showed accordant results that, at the same inlet vane angles there were significant differences on pressure drop between $D_{e,0.5D}$ and $D_{e,0.42D}$ cyclones. These results revealed that the $D_{e,0.42D}$ cyclones had the pressure drop higher than $D_{e,0.5D}$ cyclones.

CHAPTER V

DISCUSSION

5.1 Discussion of Study Design

This study was an experimental research design, which was conducted in laboratory room, faculty of Public Health, Mahidol University.

5.1.1 Glass bottle cyclones design and construction

The important criterions for design and construction glass bottle cyclones in this study consist of the shapes of glass bottle, the outlet duct diameters and the inlet vane angles. All of these factors would affecting on cyclone performances [20,24,29,30]. The first experimental step, three shapes of glass bottles were assembling with the PVC duct, which its diameter was 3 cm, and the inlet vane angle was designed at 20°, these caused of maximum separation efficiency. The second experimental step, the six patterns of Sauce bottle cyclones were designed as $D_{e,0.5D}V_{A,20^\circ}$, $D_{e,0.5D}V_{A,25^\circ}$, $D_{e,0.5D}V_{A,30^\circ}$, $D_{e,0.42D}V_{A,20^\circ}$, $D_{e,0.42D}V_{A,25^\circ}$ and $D_{e,0.42D}V_{A,30^\circ}$ respectively. To reduce the erroneous inferences of this study, the researcher had been performed to control the instrumental error of testing instruments that will occur in the designing phase. The controlling factors consists of the amounts of inlet vane, number of vane turns, vane thickness, radius of vane spindle, wall thickness of outlet ducts and the characteristics of air feeding part.

5.1.2 Particles sampling

The stack sampling method was used to measure the particle concentration at the inlet and outlet areas. The sampling flow rates were regulated to 1-2 l/min, and the particles were sampling by glass sampling probes, which its internal diameter was 2 mm. The particle concentration in mixing chamber was regulated to 330-400 mg/m³, these according to the particle concentration at bronzewares grinding process in Praditthorakarn community.

To reduce the erroneous inferences of this study, the researcher had been performed to control the measurement error that will occur in the experimental phase and analysis phase. The controlling factors consist of: a) Choosing PVC filters to reduce the influences of the humidity on filters weight. b) Choosing SKC industrial sampling pumps for continuously and stable sampling flow rate. c) The sets of sampling instruments were identically used in every time of particle stack sampling. d) The filters and beakers weight measurement were performed at the same time and condition of each day. e) The weight of dust, which used to generating in chamber at each time, was 70 grams. f) To prevent unwanted particles got into sampling probes, therefore, when the sampling was accomplished, the sampling probes should be pulled away from duct rapidly. g) All of instruments had been calibrated before use and other component parts had been cleaned every time after used.

Moreover, to reduce the interpersonal error, the reading value of all instruments had performed by researcher alone. Furthermore, to reduce random error and sampling variation, the measurement of separation efficiency was performed by five repeated of particle sampling in each type of cyclones.

5.2 Discussion of Study Results

5.2.1 The selection an appropriate shape of glass bottles

The average separation efficiencies of glass bottle cyclones, which were constructed from Sauce, Beer and Nectar bottles, were 99.81%, 98.31% and 97.31% respectively. These results found that the separation efficiencies of glass bottle cyclone all shapes were according to the hypothesis of this study that higher than the criterion level (80%). The separation efficiencies of Sauce bottle cyclones were higher than Beer and Nectar bottle cyclones. These indicated that the cone characteristics of glass bottles gave effects on separation efficiency of glass bottle cyclones. These experimental results were according to the study of R. Xiang (2000) [21], J. Gim bun (2004) [22] and Yoshida et al (2001) [23]. An observation by researcher during experiment found that the application of centrifugal force easily to drove particles out of the gas stream toward the wall of cyclone separator, that result in a concentrated dust layer swirling slowly down the wall of the cyclone body into the dust hopper of the Sauce bottle cyclones. On the contrary, there was not easily to drive particles out

in Beer and Nectar bottle cyclones. The concentrated dust layer was swirling surround the concave cone shapes, these caused of particle accumulation and particle reentrainment at the concave cones. Finally, it could reduce the separation efficiency of Beer and Nectar bottle cyclones. Furthermore, the overlapped of internal splice in Nectar bottle caused the uneven swirling of the main vortex that result in particles reentrainment and reduced separation efficiency of Nectar bottle cyclone.

Additional, the pressure drop of glass bottle cyclones which were constructed from Sauce, Beer and Nectar bottles were 0.77, 0.85 and 0.81 in.wg respectively. The pressure drop of Beer bottle cyclone was higher than Sauce and Nectar bottle cyclones. These caused by the differences of cone shapes and cone dimensions, because of the cone dimension of Beer bottle was 1.85 cm that smaller than Sauce and Nectar bottles which the cone dimension were 2 cm. These results were according to the study of R. Xiang (2000) [21], J. Gimbut (2004) [22] and Yoshida et al (2001) [23].

5.2.2 The effects of outlet duct diameters on glass bottle cyclones performances

According to the results of this study, at the same inlet vane angles when decreasing the outlet duct diameters of Sauce bottle cyclones from 0.5D to 0.42D, the separation efficiencies have no significant differences ($p > 0.067$). These results was not related to the study of Lim K.S. (2003) [24], Zhu and Lee (1999) and Moore and McFarland (1993); they mentioned that the outlet duct diameters is an especially important dimension, which significantly affects the cyclone performance as its size plays a critical role in defining the flow field inside the cyclone, including the pattern of the outer and inner spiral flows. Nevertheless, Lim K.S. (2003), Zhu and Lee (1999), Moore and McFarland (1993) had studied in tangential entry cyclones which differs from axial entry cyclones in this study. An increasing the outlet duct diameters of axial entry cyclones caused reduce the inlet area, but it would not occurred in tangential entry cyclones. This study found that when increasing the outlet duct diameters of glass bottle cyclones from 0.42D to 0.5D, the inlet area was decreased 0.87 times and inlet velocities were increased 1.15 times. The decreasing of inlet area caused increasing the intensity of the vortex and the centrifugal force in cyclones.

Therefore the experimental results found that, although the decreasing of duct outlet diameters could reducing the influence of short cut flow in axial entry cyclone, but it would decreased the intensity of the vortex and the centrifugal force in cyclones. Furthermore, the experimental results showed that there were no significant differences on separation efficiencies between $D_{e,0.5D}$ and $D_{e,0.42D}$ cyclones. These due to the compensation between the influences of short cut flow and the centrifugal force that would occurring in axial entry cyclone.

Additional, the study found the significant difference of the pressure drop between outlet diameters 0.5D and 0.42D of Sauce bottle cyclones. At the same inlet vane angles, the pressure drop of $D_{e,0.42D}$ cyclones were higher than $D_{e,0.5D}$ cyclones. These caused by the differences of the gas outlet areas that concerned with the airflow resistance that result in differences of cyclones pressure drop.

5.2.3 The effects of inlet guide vane angles on glass bottle cyclones performances

The variation of inlet vane angles had marked effect on separation efficiency of Sauce bottle cyclones. There was significant differences of separation efficiency of Sauce bottle cyclones between the inlet vane angles 20°, 25° and 30° ($p < 0.001$). The results showed the accordance of separation efficiency between $D_{e,0.5D}$ and $D_{e,0.42D}$ cyclones that the separation efficiencies at the inlet vane angle of 20° was higher than the inlet vane angles 25° and 30° with significant differences ($p < 0.002$), but there were no significant differences between inlet vane angles 25° and 30° ($p > 0.094$). These results were according to the study of Yaodong W. (1991) [5] that the separation efficiencies of Sauce bottle cyclones related to the angles of inlet vane. An increasing of the separation efficiencies of Sauce bottle cyclones concerns with the decreasing of the inlet vane angles, these due to the decreasing of inlet vane angles caused reducing the inlet area of glass bottle cyclones. This study found that when decreasing 5° of inlet vane angles, the inlet area of Sauce bottle cyclones were decreased 0.78 times and the inlet velocities were increased 1.29 times. These result in an increasing the intensity of the vortex and the centrifugal force in Sauce bottle cyclones.

Additional, the study found that the pressure drop of Sauce bottle cyclone, which were designed inlet vanes angles as 20°, 25° and 30°, had significant differences.

At the same outlet duct diameters, the pressure drop of glass bottle cyclones will increase when decreased the inlet vane angle. These caused by the difference of inlet area that concerned with the airflow resistant at the inlet vanes, that result in difference of cyclones pressure drop.

5.2.4 Comparison cyclone performances between the experimental results and the theoretical prediction.

The first experimental step found the differences between the separation efficiencies from experimental results and the theoretical approach. The separation efficiencies of Sauce, Beer and Nectar bottle cyclones from theoretical approached were 99.99%, but the experimental results found there were 99.81%, 98.31% and 97.31% respectively. These caused by the differences of glass bottles cone shapes. Furthermore, the results found the resemblances of pressure drop between theoretical approached and the experimental results. The pressure drop of Sauce, Beer and Nectar bottle cyclones from theoretical approached were 0.83, 0.91 and 0.87 in.wg respectively, and from experimental results were 0.77, 0.85 and 0.81 in.wg respectively. These also indicated that the pressure drop from theoretical approached was higher than the experimental results, and pressure drop of Sauce bottle cyclone was lower than Nectar and Beer bottle cyclones.

The second experimental step found the accordance between the theoretical approached and the experimental results. There showed accordant results that when decreasing inlet vane angles, the separation efficiency and the pressure drop were increased. Moreover, the results found the slightly different on separation efficiencies between $D_{e,0.5D}$ and $D_{e,0.42D}$ cyclones, but the pressure drop had extremely different. These results indicated that the theory of Iozia & Lieth (1990) was over estimated on separation efficiency than the actual value about 0.25%. Furthermore, the theory of Shepherd and Lapple (1939), which using for estimated pressure drop, had a good prediction at the inlet vane angle of 25° , but it would over estimated about 12.23% for the inlet vane angle 20° and under estimated about 14.17% for the inlet vane angle 30° .

5.3 Discussion of an application

The experimental results of this study revealed that the six patterns of Sauce bottle cyclones showed satisfactory performance to control grinding dust. Therefore, the Sauce bottle cyclones could apply to construct dust separators such as multi-cyclone. The amounts of Sauce bottle cyclone for construction of multi-cyclone related to the quantity of airflow rate. This study using the moderate airflow rate for testing performances of Sauce bottle cyclones, but in the useful conditions, the airflow rate can increase to the maximum point, which it cause to increase the performances of Sauce bottle cyclones and reduce the size of multi-cyclone.

The maximum airflow rate is relating to the inlet velocity which can calculate from the ratio of v_i/v_s . The study of Kalen and Zenz found that, if the ratio of v_i/v_s equaled to 1.25, the separation efficiency of cyclone will maximum, but, if the ratio of v_i/v_s more than of 1.35, the particle reentrainment will be occurred. The values of v_i/v_s depend on the proportions of cyclone, the characteristics of dust and the properties of fluid. The inlet velocities of Sauce bottle cyclones, which calculated at the ratio of v_i/v_s equal to 1.25 and 1.35, were 31.50 and 39.73 ft/s respectively. Then use these inlet velocities for calculation to find the amounts of Sauce bottle cyclones, which use for construction multi-cyclone at the target airflow rate.

CHAPTER VI

CONCLUSION AND RECOMMENDATION

6.1 Conclusion

This study aimed to design and test performance of axial entry glass bottle cyclones. The first experimental step, three types of glass bottles were assembling with the PVC duct, which its diameter was 3 cm, and the inlet vane angle was designed as 20° , these caused of maximum separation efficiency. The second experimental step, the six patterns of Sauce bottle cyclones were designed as $D_{e,0.5D}V_{A,20^\circ}$, $D_{e,0.5D}V_{A,25^\circ}$, $D_{e,0.5D}V_{A,30^\circ}$, $D_{e,0.42D}V_{A,20^\circ}$, $D_{e,0.42D}V_{A,25^\circ}$ and $D_{e,0.42D}V_{A,30^\circ}$ respectively. All types of glass bottle cyclones were tested performances at airflow rate of 12 cfm and the particle concentration between 330-400 mg/m³. The stack sampling method was used to measure the particles concentration at the inlet and outlet areas. The collected data were calculated according to the separation efficiency of cyclones.

The results of this study were concluded as follows:

6.1.1 The characteristics of grinding dust

The particle size distribution of bronzewares grinding dust ranged from 1.68 to 351.46 micron with the average size was 80.91 micron. The percentage of cumulative weight and dust size average can be plotted graph, and the comparing with Stairmand particle size distribution standard curves. The result showed that sample dust could classify into coarse dust.

6.1.2 The selection an appropriate type of glass bottles

The mean separation efficiencies of Sauce, Beer and Nectar bottle cyclones were 99.81%, 98.31% and 97.31% respectively. These values were according to the hypothesis of this study, that these separation efficiencies were higher than the criterion level (80%). The Sauce bottle, which has straight cone shape, showed

maximum separation efficiency and low pressure drop than other cyclones. Therefore, Sauce bottle was appropriate type for construction glass bottle cyclone.

6.1.3 The effects of outlet duct diameters on Sauce bottle cyclones performance

The variation of outlet duct diameters at the same inlet vane angles had no significant differences on separation efficiency of the Sauce bottle cyclones ($p>0.067$). However, the variation of outlet duct diameters at the same inlet vane angles had significant differences on pressure drop that the $D_{e,0.42D}$ cyclones had pressure drop higher than $D_{e,0.5D}$ cyclones.

6.1.4 The effects of inlet guide vanes angles on Sauce bottle cyclones performance

The variation of inlet vane angles at the same outlet duct diameters had marked effects on separation efficiency of Sauce bottle cyclones. There was significant difference of cyclone separation efficiency between inlet vanes angles 20° , 25° and 30° ($p<0.001$). The results found that when decreasing the angles of inlet vanes, the separation efficiency and pressure drop of Sauce bottle cyclones were increased.

6.2 Recommendation

6.2.1 Recommendation for an application

The study results found that the Sauce bottle cyclones had satisfactory performance for control grinding dust with the mean separation efficiency was 99.60 % (± 0.162). This data revealed that Sauce bottle cyclones could apply to construction dust separator devices for control dusts in following industries:

- 1) The grinding process of Bronzeware production.
- 2) The shell and marble sanding process of jewelry industry
- 3) The small wood furniture industry and wood handicraft, which relating to wood polishing process.

6.2.2 The recommendations for further study

- 1) The maximum airflow rate of glass bottle cyclone that cause to maximum separation efficiency without particle reentrainment should be considered.
- 2) The relation between amounts of inlet vane and performance of glass bottle cyclones should be considered.
- 3) The performance of multi-cyclone which construction from glass bottle cyclones should be considered.
- 4) The glass bottle cyclones would be tested separation efficiency with other sample dust such as wood dust, sand dust, etc.
- 5) The difference of separation efficiency and pressure drop between glass and steel cyclones should be considered.

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APPENDIX A

Particle Density and Specific Gravity Analysis

Particle specific gravity can be calculated by following equation:

$$S = \frac{\rho_p}{\rho_{st}} \quad (\text{A-1})$$

where

- S = Particle specific gravity
- ρ_p = Particle density, g/cm³
- ρ_{st} = Density of reference substance, g/cm³

This study was using distill water as the reference substance, density of the water at 30 °C is 1 g/cm³, the particle density will calculate by equation as follows:

$$\rho_p = \frac{M_p}{V_p} \quad (\text{A-2})$$

where

- M_p = Particle mass, g
- V_p = Particle volume, cm³

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

$$V_p = V_{st} \quad (\text{A-3})$$

$$S = \frac{M_p}{M_{st}} \quad (\text{A-4})$$

We can mention that the specific gravity of the 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 know 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 and record the weight as M_1 .
- 2) Place sample particles about one-fourth into the bottle, weigh bottle with contain 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 the particle density

$$\text{Mass of particle} = M_2 - M_1$$

$$\text{Mass of particle + Mass of displaced water} = M_3 - M_1$$

$$\text{Mass of water} = M_4 - M_1$$

$$\text{Mass of displaced water} = M_3 - M_2$$

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

$$\rho_p = \frac{(M_2 - M_1)\rho_{st}}{(M_4 - M_1) - (M_3 - M_2)} \quad (\text{A-5})$$

Table A-1 The parameters for particle density calculation

| No. | Weight (g) | | | | | | |
|-----|------------|----------|----------|----------|-------------|-------------|-------------|
| | M_1 | M_2 | M_3 | M_4 | $M_2 - M_1$ | $M_4 - M_1$ | $M_3 - M_1$ |
| 1 | 14.05913 | 17.65092 | 27.63604 | 25.73659 | 3.59179 | 11.67746 | 9.98512 |
| 2 | 14.16117 | 17.48846 | 27.68488 | 25.90853 | 3.32729 | 11.74736 | 10.19642 |
| 3 | 14.06353 | 16.40156 | 27.01277 | 25.76828 | 2.33803 | 11.70475 | 10.61121 |
| 4 | 14.18160 | 17.23643 | 27.54225 | 25.92191 | 3.05483 | 11.74031 | 10.30582 |
| 5 | 13.06803 | 15.93385 | 26.95138 | 25.42579 | 2.86582 | 12.35776 | 11.01753 |

Calculation of Particle Density

$$\rho_1 = \frac{(3.59179) \times 1}{(11.67746) - (9.98512)} = 2.112 \text{ g/cm}^3$$

$$\rho_2 = \frac{(3.32729) \times 1}{(11.74736) - (10.19642)} = 2.135 \text{ g/cm}^3$$

$$\rho_3 = \frac{(2.33803) \times 1}{(11.70475) - (10.61121)} = 2.128 \text{ g/cm}^3$$

$$\rho_4 = \frac{(3.05483) \times 1}{(11.74031) - (10.30582)} = 2.119 \text{ g/cm}^3$$

$$\rho_5 = \frac{(2.86582) \times 1}{(12.35776) - (11.01753)} = 2.128 \text{ g/cm}^3$$

$$\rho_{p,avg} = \frac{2.112 + 2.135 + 2.128 + 2.119 + 2.128}{5} = 2.125 \text{ g/cm}^3$$

The average particle density of bronzewares grinding dust was 2.125 g/cm³ or 132.64 lb/ft³. These data will use to calculate cyclones performance.

APPENDIX B

Results of Particle Sampling and Pressure Drop Measurement

Table B-1 The Separation Efficiencies of Glass Bottle Cyclones which Constructed from Sauce, Beer and Nectar Bottles

| Type of glass bottle cyclone | No. | Concentration (mg/m ³) | | η (% by weight) |
|------------------------------|-------------|------------------------------------|-------------|-----------------|
| | | Inlet area | Outlet area | |
| Sauce bottle | 1 | 354.58 | 0.89 | 99.75 |
| | 2 | 365.00 | 0.79 | 99.78 |
| | 3 | 362.92 | 0.40 | 99.89 |
| | 4 | 397.08 | 0.50 | 99.88 |
| | 5 | 355.83 | 0.79 | 99.78 |
| | <i>Mean</i> | <i>367.08</i> | <i>0.67</i> | <i>99.81</i> |
| | <i>S.D.</i> | <i>17.35</i> | <i>0.21</i> | <i>0.06</i> |
| Beer bottle | 1 | 355.42 | 6.73 | 98.11 |
| | 2 | 356.67 | 6.11 | 98.29 |
| | 3 | 389.58 | 5.91 | 98.48 |
| | 4 | 350.00 | 5.50 | 98.43 |
| | 5 | 352.92 | 6.13 | 98.26 |
| | <i>Mean</i> | <i>360.92</i> | <i>6.08</i> | <i>98.31</i> |
| | <i>S.D.</i> | <i>16.22</i> | <i>0.44</i> | <i>0.15</i> |
| Nectar bottle | 1 | 341.88 | 8.94 | 97.38 |
| | 2 | 374.79 | 9.71 | 97.41 |
| | 3 | 390.21 | 10.48 | 97.31 |
| | 4 | 362.71 | 9.52 | 97.38 |
| | 5 | 351.88 | 10.24 | 97.09 |
| | <i>Mean</i> | <i>364.29</i> | <i>9.78</i> | <i>97.31</i> |
| | <i>S.D.</i> | <i>18.98</i> | <i>0.61</i> | <i>0.13</i> |

Table B-2 The Separation Efficiencies of Sauce Bottle Cyclones Pattern I, II and III

| Pattern of Sauce bottle cyclone | No. | Concentration (mg/m ³) | | η (% by weight) |
|------------------------------------|-------------|------------------------------------|-------------|--------------------|
| | | Inlet area | Outlet area | |
| Cyclone pattern I | 1 | 00 | 1.06 | 99.72 |
| | 2 | 347.08 | 1.06 | 99.70 |
| | 3 | 374.58 | 0.87 | 99.77 |
| | 4 | 385.00 | 1.06 | 99.73 |
| | 5 | 338.33 | 0.67 | 99.80 |
| | <i>Mean</i> | <i>365.67</i> | <i>0.94</i> | <i>99.74</i> |
| | <i>S.D.</i> | <i>21.55</i> | <i>0.17</i> | <i>0.04</i> |
| Cyclone pattern II | 1 | 388.12 | 1.95 | 99.50 |
| | 2 | 397.92 | 1.76 | 99.56 |
| | 3 | 336.67 | 2.15 | 99.36 |
| | 4 | 337.92 | 1.95 | 99.42 |
| | 5 | 371.67 | 1.37 | 99.63 |
| | <i>Mean</i> | <i>366.46</i> | <i>1.84</i> | <i>99.49</i> |
| | <i>S.D.</i> | <i>28.23</i> | <i>0.29</i> | <i>0.11</i> |
| Cyclone pattern III | 1 | 372.08 | 2.45 | 99.34 |
| | 2 | 377.50 | 1.90 | 99.50 |
| | 3 | 382.50 | 2.08 | 99.46 |
| | 4 | 381.25 | 1.90 | 99.50 |
| | 5 | 339.17 | 2.26 | 99.33 |
| | <i>Mean</i> | <i>370.50</i> | <i>2.12</i> | <i>99.43</i> |
| | <i>S.D.</i> | <i>17.97</i> | <i>0.24</i> | <i>0.08</i> |

Table B-3 The Separation Efficiencies of Sauce Bottle Cyclones Pattern IV, V and VI

| Pattern of Sauce bottle cyclone | No. | Concentration (mg/m ³) | | η (% by weight) |
|------------------------------------|-------------|------------------------------------|-------------|--------------------|
| | | Inlet area | Outlet area | |
| Cyclone pattern IV | 1 | 354.58 | 0.89 | 99.75 |
| | 2 | 365.00 | 0.79 | 99.78 |
| | 3 | 362.92 | 0.40 | 99.89 |
| | 4 | 397.08 | 0.50 | 99.88 |
| | 5 | 355.83 | 0.79 | 99.78 |
| | <i>Mean</i> | <i>367.08</i> | <i>0.67</i> | <i>99.81</i> |
| | <i>S.D.</i> | <i>17.35</i> | <i>0.21</i> | <i>0.06</i> |
| Cyclone pattern V | 1 | 336.25 | 1.67 | 99.50 |
| | 2 | 377.92 | 1.35 | 99.64 |
| | 3 | 352.92 | 1.09 | 99.69 |
| | 4 | 398.75 | 1.81 | 99.55 |
| | 5 | 375.42 | 1.39 | 99.63 |
| | <i>Mean</i> | <i>368.25</i> | <i>1.46</i> | <i>99.60</i> |
| | <i>S.D.</i> | <i>24.16</i> | <i>0.28</i> | <i>0.08</i> |
| Cyclone pattern VI | 1 | 372.08 | 1.89 | 99.49 |
| | 2 | 378.96 | 1.70 | 99.55 |
| | 3 | 389.38 | 1.70 | 99.56 |
| | 4 | 385.62 | 1.89 | 99.51 |
| | 5 | 343.54 | 2.27 | 99.34 |
| | <i>Mean</i> | <i>373.92</i> | <i>1.89</i> | <i>99.49</i> |
| | <i>S.D.</i> | <i>18.22</i> | <i>0.23</i> | <i>0.09</i> |

Table B-4 The Pressure Drop of Glass Bottle Cyclones

| Type of glass bottle cyclone | Static pressure (in.wg.) | | | Pressure drop (in.wg.) | | | Total |
|------------------------------|--------------------------|----------------|-------------|------------------------|---------------|--|-------|
| | Inlet duct | Pre-inlet vane | Outlet duct | Air feeding part | Axial cyclone | | |
| Sauce Bottle | 0.37 | 0.49 | 1.14 | 0.12 | 0.65 | | 0.77 |
| Beer Bottle | 0.30 | 0.44 | 1.15 | 0.14 | 0.71 | | 0.85 |
| Nectar bottle | 0.33 | 0.47 | 1.14 | 0.14 | 0.67 | | 0.81 |
| Cyclone pattern I | 0.37 | 0.50 | 1.03 | 0.13 | 0.53 | | 0.66 |
| Cyclone pattern II | 0.37 | 0.50 | 0.88 | 0.13 | 0.38 | | 0.51 |
| Cyclone pattern III | 0.37 | 0.50 | 0.82 | 0.13 | 0.32 | | 0.45 |
| Cyclone pattern IV | 0.37 | 0.49 | 1.14 | 0.12 | 0.65 | | 0.77 |
| Cyclone pattern V | 0.37 | 0.49 | 1.03 | 0.12 | 0.54 | | 0.66 |
| Cyclone pattern VI | 0.37 | 0.49 | 0.97 | 0.12 | 0.48 | | 0.60 |

APPENDIX C

The Particle Size Distribution Analyzer



Figure C-1 Particle size analyzer, Mastersizer S Ver. 2.19

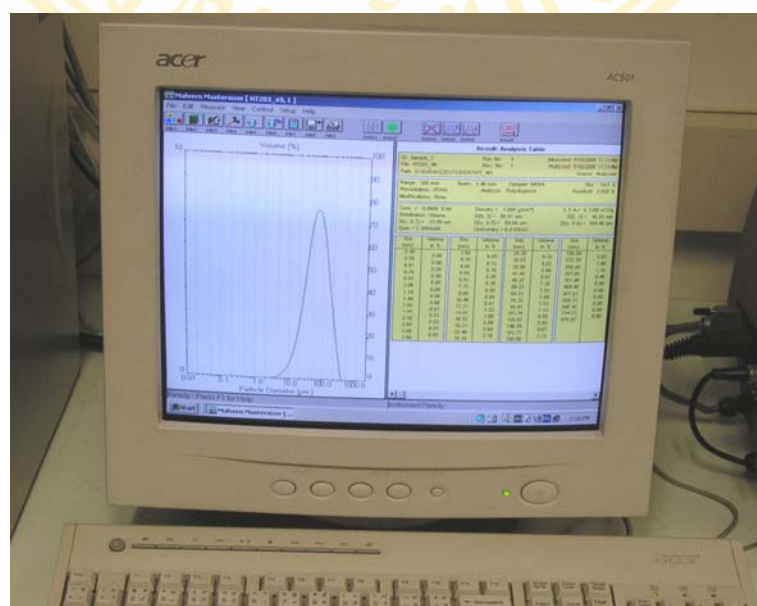
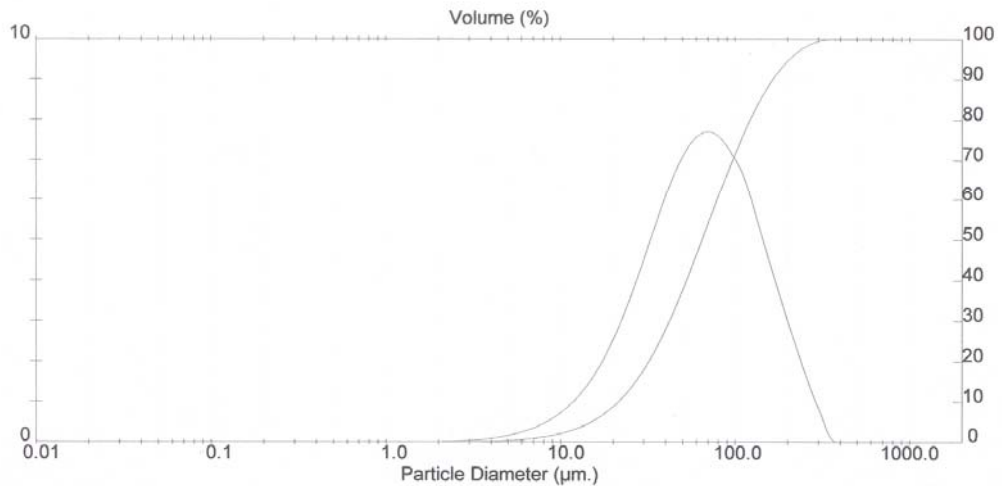
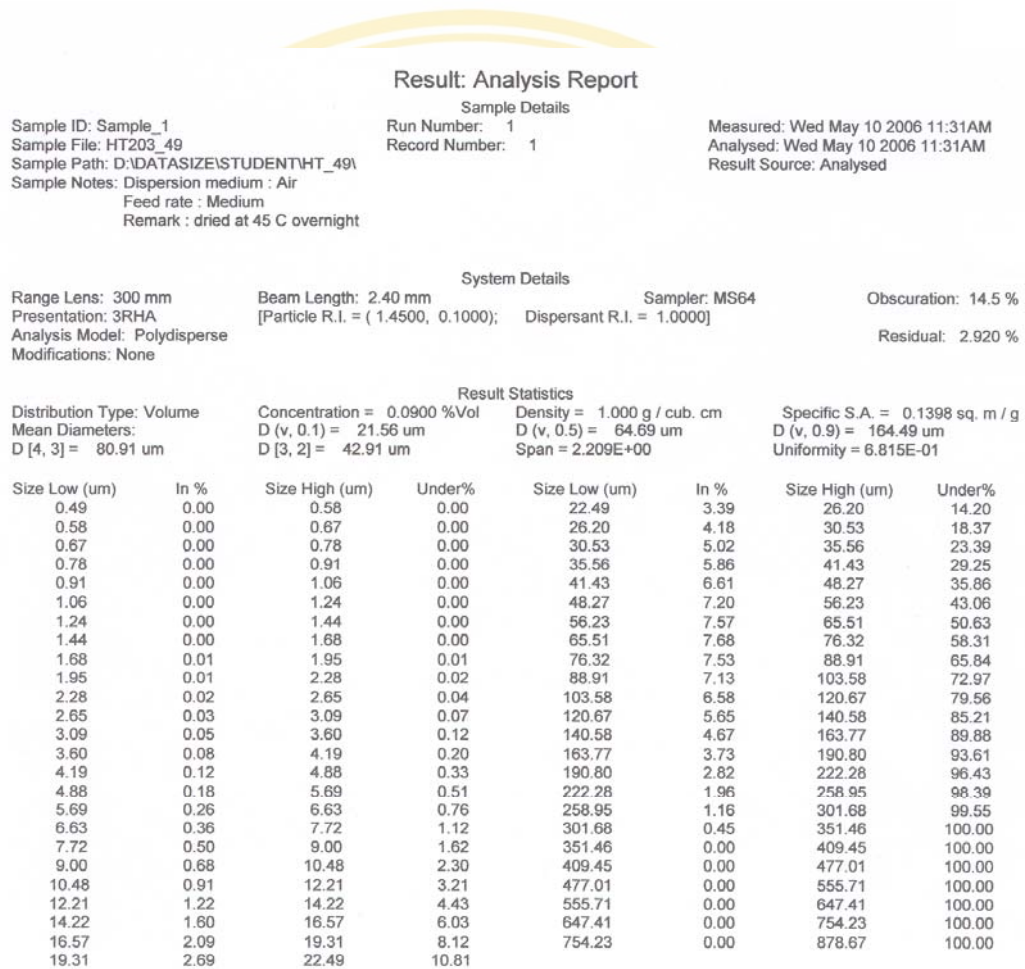


Figure C-2 Analysis report by Malvern operating software

APPENDIX D

Particle Size Distribution of Bronzeware's Grinding Dust



APPENDIX E

Glass Bottle Cyclones Design



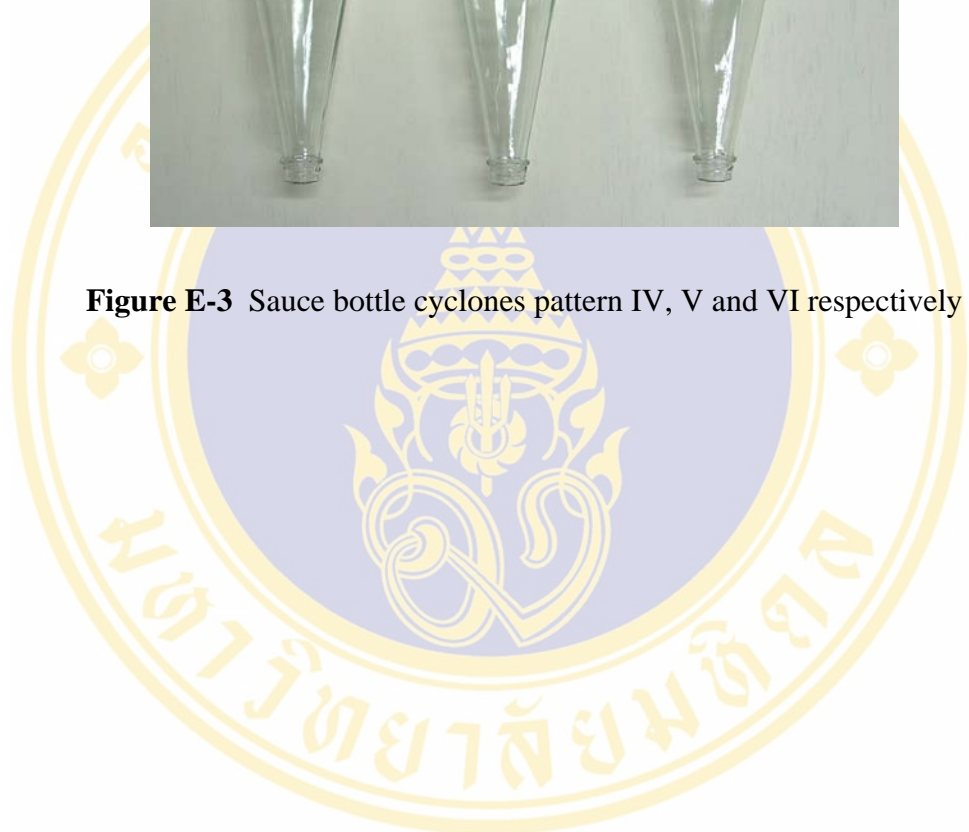
Figure E-1 Glass bottle cyclones which constructed from Sauce, Beer and Nectar bottles respectively



Figure E-2 Sauce bottle cyclones pattern I, II and III respectively



Figure E-3 Sauce bottle cyclones pattern IV, V and VI respectively



APPENDIX F

Ventilation System and Sampling Instruments



Figure F-1 Local exhaust ventilation system for testing cyclone performance

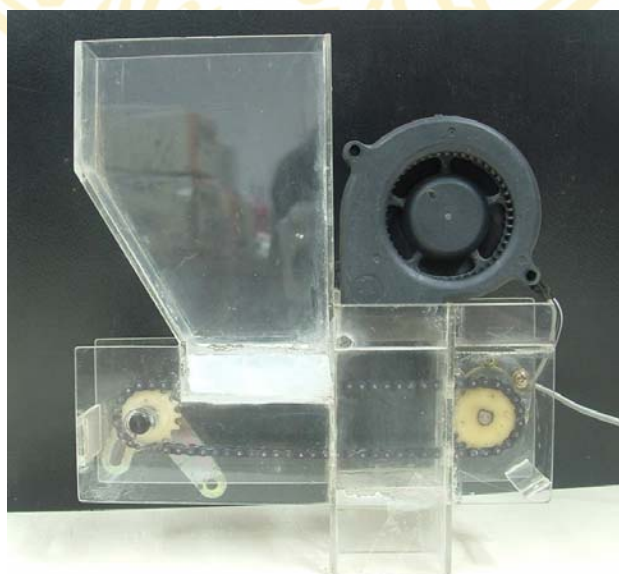


Figure F-2 The characteristics of dust generator



Figure F-3 The characteristics of glass sampling probes



Figure F-4 The particle sampling at the inlet and outlet areas

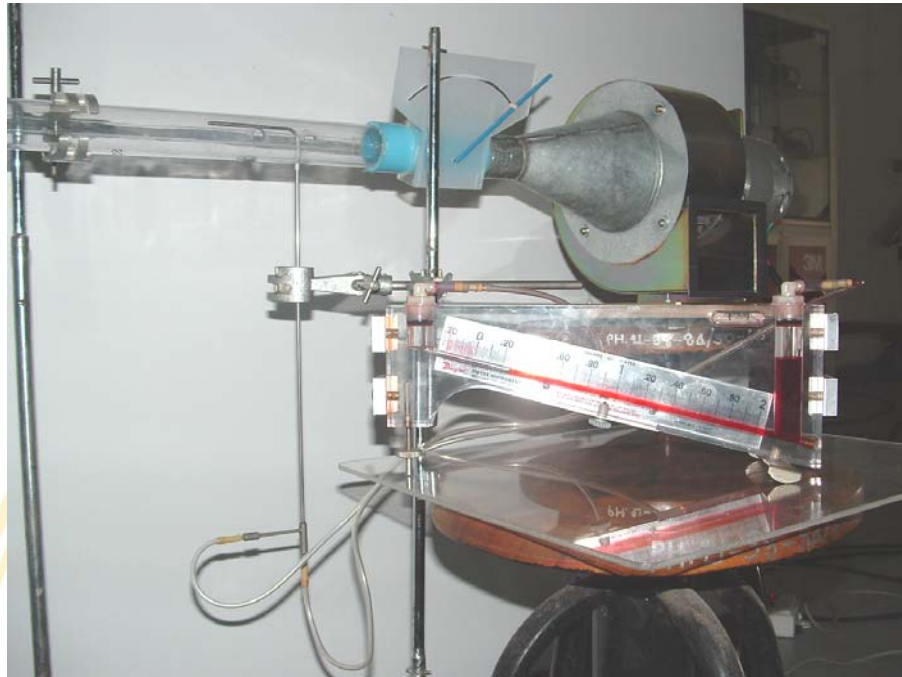


Figure F-5 The velocity pressure measurement



Figure F-6 The three points of static pressure measurement



Figure F-7 SKC sampling pumps and precision rotameter

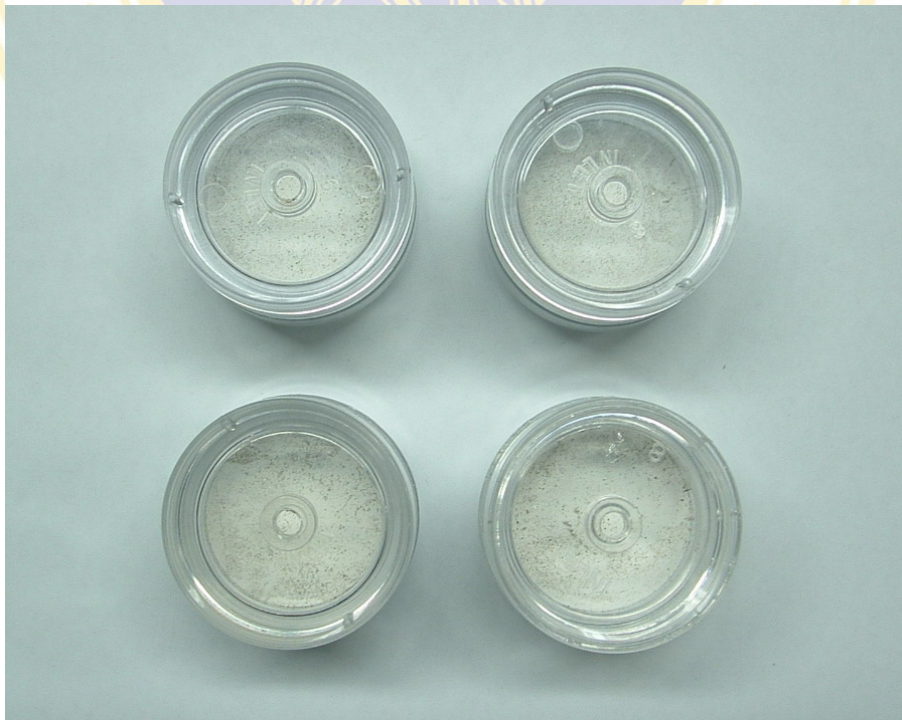
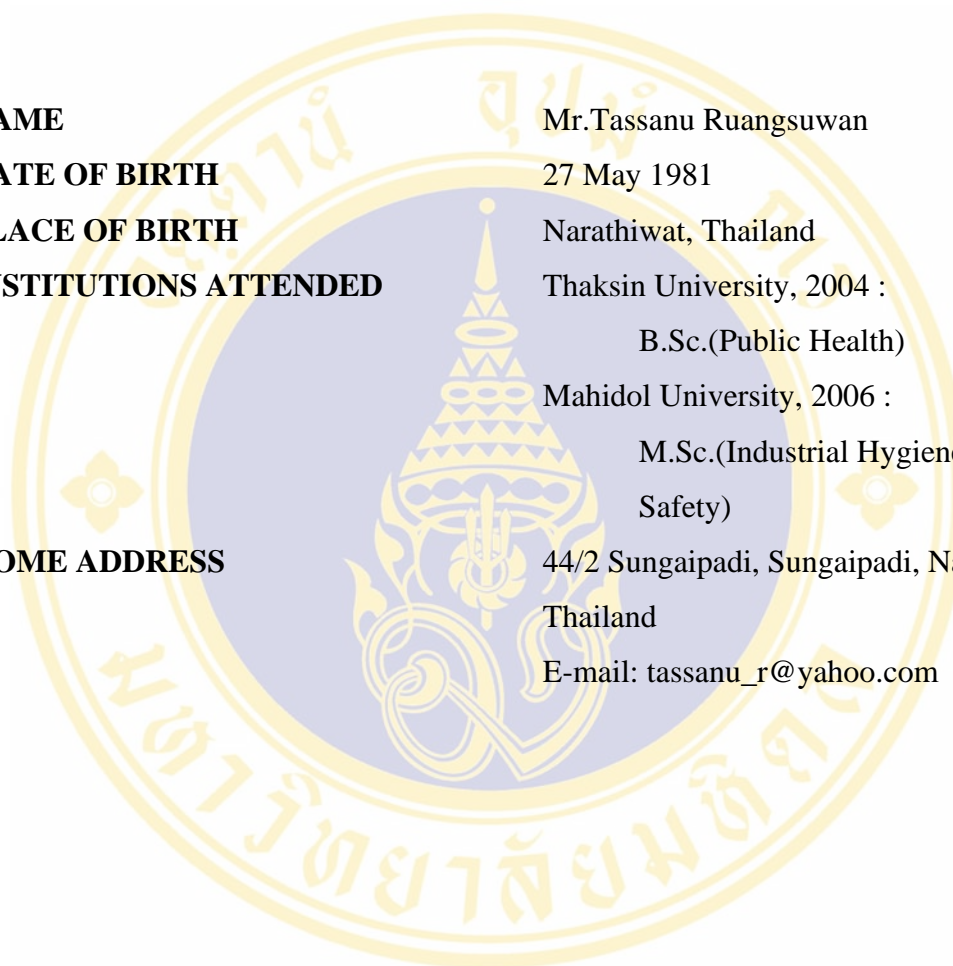


Figure F-8 The grinding dust which sampling from inlet area

BIOGRAPHY



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