DEVELOPMENT OF MULTI-CYCLONE FOR FINE DUST EMISSION CONTROL

NOREYLZA HUSSEIN

UNIVERSITI TEKNOLOGI MALAYSIA

DEVELOPMENT OF MULTI-CYCLONE FOR FINE DUST EMISSION CONTROL

NORELYZA HUSSEIN

A thesis submitted in fulfilment of the
requirements for the award of the degree of
Doctor of Philosophy

Malaysia-Japan International Institute of Technology
Universiti Teknologi Malaysia

JANUARY 2016

To my beloved family

ACKNOWLEDGEMENT

Alhamdullilah, all praise to ALLAH the Almighty for His blessing and guidance in helping and giving me the strength to complete this thesis. In particularly, I would like to take this opportunity to express my deepest gratitude and appreciations to my supervisor, Prof. Dr. Mohd Rashid Mohd Yusof for his kindness, encouragement and guidance.

My gratitude also goes to my family especially my beloved husband, Che Hafizan Che Hassan and my wonderful son, Che Muhammad Imran Che Hafizan for their endless love, moral support and encouragement in continuing my study and doing my research.

Thanks also to all my fellow friends who always give a moral support and critics in order to improve my research. Last but not least thanks to those people who is directly or indirectly involve in my research.

ABSTRACT

The aim of the study was to develop an optimized design multi-cyclone fine particulate emission control system named as MR-deDuster to fulfil the stringent environmental regulatory requirement of Malaysia Clean Air Regulation 2014. This is due to the existing multi-cyclones used do not effectively reduce the emissions level within the legislative limit at all times. The theoretical background of the unit was developed based on the modifications of established design equations available in the literature. The modified Lapple model with different definitions of maximum radial distance travelled by a particulate designated as *W*, as well as Leith and Licht model were used to predict the collection efficiency of the unit. Meanwhile, the modified Shepherd and Lapple model was used to predict the pressure drop across the unit. The predictions were later compared with the actual data obtained experimentally and the best method to represent the actual performance of the unit was identified. The computational fluid dynamics (CFD) model template in ANSYS-Fluent software was used to predict the flow pattern within the MR-deDuster unit to assist in understanding its fluid flow and the particulate collection mechanism. The actual pilot plant of the unit was fabricated based on the optimum design configurations and tested experimentally under various volumetric gas flow rates ranging from 0.13 to 0.21 m^3/s. To verify the theoretical findings, two different types of particulates samples, palm oil mill boiler fly ash (POFA) and PreKot^{TM} were tested. The result showed that the unit was able to attain high collection efficiency at a relatively low pressure drop based on the theoretical and experimental findings, which highlighted the ability of the unit as an efficient particulate emission separator. Both theoretical and experimental studies also demonstrate that the increase of volumetric gas flow rate results in a reduction of cut diameter with an increase of fractional and overall collection efficiency as well as pressure drop of the MR-deDuster. However, as observed in the experimental study, the collection efficiency reduced at a volumetric gas flow rate of 0.21 m^3/s due to saltation velocity phenomenon. The modified Lapple model of $W = D\text{-}D_e/2$ was identified as the closest model to represent the actual collection efficiency of MR-deDuster. Meanwhile, the modified Shepherd and Lapple model with constant K = 3.7 was accepted as the model to represent the actual pressure drop of the unit. In conclusion, the development of MR-deDuster unit is able to offer a better multi-cyclone unit in capturing the fine particulate for many industries as well as providing new theoretical analysis on multi-cyclone.

ABSTRAK

Tujuan kajian ini adalah untuk membangunkan satu rekabentuk berbilang siklon yang dioptimumkan sebagai sistem kawalan pelepasan zarah halus yang dinamakan sebagai MR-deDuster untuk memenuhi keperluan peraturan alam sekitar yang ketat iaitu Peraturan Udara Bersih Malaysia 2014. Ini adalah kerana berbilang siklon sedia ada yang digunakan tidak berkesan untuk mengurangkan pelepasan dalam had yang ditetapkan pada setiap masa. Latar belakang teori unit dibangunkan berdasarkan persamaan rekabentuk terubahsuai yang terdapat dalam rujukan. Model Lapple yang terubahsuai dengan takrifan berbeza jarak perjalanan jejarian maksimum oleh zarah yang dilabelkan sebagai *W*, serta Model Leith dan Licht telah digunakan untuk meramalkan kecekapan pengumpulan unit. Manakala, model Shepherd dan Lapple yang terubahsuai telah digunakan untuk meramalkan kejatuhan tekanan yang merentasi unit. Ramalan tersebut kemudiannya dibandingkan dengan data sebenar yang diperolehi secara ujkaji dan kaedah terbaik untuk mewakili prestasi sebenar unit dikenal pasti. Pengiraan dinamik bendalir (CFD) seperti dalam perisian ANSYS-Fluent telah digunakan bagi meramal corak aliran dalam unit MR-deDuster untuk membantu dalam memahami aliran bendalir dan mekanisme pengumpulan zarah. Loji pandu telah dibina berdasarkan rekabentuk tatarajah optimum dan diuji secara ujikaji menggunakan pelbagai kadar aliran isipadu gas dari 0.13 hingga 0.21 m^3/s. Untuk mengesahkan penemuan teori, dua jenis sampel zarah berbeza, abu terbang dandang kilang kelapa sawit (POFA) dan PreKot^{TM} telah diuji. Keputusan menunjukkan unit ini telah dapat mencapai kecekapan pengumpulan yang tinggi pada kejatuhan tekanan yang rendah berdasarkan penemuan teori dan ujikaji yang mengetengahkan keupayaan unit sebagai pemisah pelepasan zarah yang cekap. Kedua-dua teori dan kajian ujikaji juga menggambarkan bahawa peningkatan kadar aliran isipadu gas mengurangkan potongan garis pusat dengan meningkatkan pecahan dan keseluruhan kecekapan pengumpulan serta kejatuhan tekanan MR-deDuster. Walau bagaimanapun, seperti yang diperhatikan dalam kajian ujikaji, kecekapan pengumpulan berkurangan pada kadar aliran isipadu gas 0.21 m^3/s disebabkan fenomena halaju rayap-lompat. Model Lapple yang terubahsuai, $W = D\text{-}D_e/2$ telah dikenal pasti sebagai model yang paling tepat mewakili kecekapan pengumpulan sebenar MR-deDuster. Manakala, Model Shepherd dan Lapple yang terubahsuaisuai dengan nilai K = 3.7 telah diterima sebagai model mewakili kejatuhan tekanan sebenar unit. Secara kesimpulannya, pembangunan unit MR-deDuster mampu menawarkan unit berbilang siklon yang lebih baik dalam menangkap zarah halus untuk pelbagai industri serta menyediakan analisis teori baru untuk berbilang siklon.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

CFC	-	Circumfluent Cyclone
CFD	-	Computational Fluid Dynamics
COPD	-	Chronic Obstructive Pulmonary Disease
CV	-	Coefficient of Variation
DMC	-	Dense Medium Cyclone
DOE	-	Department of Environmental
DPM	-	Discrete Phase Model
EQR	-	Environmental Quality Report
ESP	-	Electrostatic Precipitator
GHG	-	Greenhouse Gas
ID	-	Induced Draft
NaHMP	-	Sodium Hexameta Phosphate
PAHs	-	Polycyclic Aromatic Hydrocarbons
PM	-	Particulate Matter
$PM_{0.1}$	-	Particulate below 0.1 µm in Aerodynamic Diameter
PM_{10}	-	Particulate below 10 µm in Aerodynamic Diameter
$PM_{2.5}$	-	Particulate below 2.5 µm in Aerodynamic Diameter
PoC	-	Post Cyclone
POFA	-	Palm Oil Mill Boiler Fly Ash
PRESTO	-	Pressure Staggering Option
RANS	-	Reynolds Averaged Navier Stokes
RNG	-	Renormalisation Group
RSTM	-	Reynold Stress Transport Model
SEM	-	Scanning Electron Microscope
TSP	-	Total Suspended Particulate Matter
US EPA	-	United States Environmental Protection Agency

LIST OF SYMBOLS

ΔP	-	Pressure drop [Pa]
Δt	-	Gas residence time [s]
A	-	Inlet entry area [m]
C_c	-	Cunningham correction factor [-]
D	-	Cyclone body diameter [m]
D_d	-	Cone tip diameter [m]
D_e	-	Vortex finder diameter [m]
d_p	-	Diameter of the particulate [m]
d_{pc}	-	Cut-diameter [m]
d_{pj}	-	Characteristic diameter of jth particulate size [μm]
F_c	-	Centrifugal force [N]
F_D	-	Drag force [N]
f	-	Frequency [Hz]
H	-	Height of tangential cyclone entry [m]
H_v	-	Pressure drop in number of inlet velocity head [m]
K	-	Constant configuration parameter of pressure drop [-]
k	-	Geometric configuration parameter of Leith & Licht [-]
K_H	-	Configuration ratio of H [-]
K_n	-	Knudsen number [-]
K_W	-	Configuration ratio of W [-]
L_b	-	Cyclone cylinder length [m]
L_c	-	Cyclone cone length [m]
L_v	-	Natural vortex length [m]
m_j	-	Mass fraction of particulate size range [-]
M_w	-	Gas molecular weight [kg/mol]

N	-	Number of cyclones install in the multi-cyclones [-]
N_e	-	Number of turn [-]
P	-	Gas pressure [Pa]
Q	-	Volumetric gas flow rate [m^3/s]
R	-	Cyclone body radius [m]
r	-	Radius of particulate [m]
S	-	Vortex finder length [m]
T	-	Gas temperature [K]
u_r	-	Radial velocity [m/s]
u_t	-	Tangential velocity [m/s]
v_i	-	Gas inlet velocity [m/s]
v_t	-	Terminal velocity [m/s]
W	-	Maximum particulate travel distance [m]
η_j	-	Collection efficiency for the *j*th particulate size [%]
η_o	-	Overall collection efficiency [%]
λ_g	-	Mean free path of the gas [m]
μ	-	Gas viscosity [kg/m.s]
ρ_g	-	Density of gas [kg/m^3]
ρ_p	-	Density of particulate [kg/m^3]
τ	-	Characteristic time associated with the motion [s]

LIST OF APPENDICES

CHAPTER 1

INTRODUCTION AND OVERVIEW

1.1 Introduction

Issues in connection with air pollution such as global warming, climate change, greenhouse gas (GHG) emissions and human health deterioration has become an international concern of the 21st century. Air pollution refers to the presence of any substance such as chemical, particulate matter (PM) and biological materials that is harmful or injurious to human health or welfare, animal or plant life, or property which has been acknowledged since industrial revolution. The famous incident such as London Smog Episode had changed the perspective of many countries towards the importance of air pollution. Such incident is less experienced in developed countries but unfortunately it is still occurring in developing countries especially in the Asia region (Autrup, 2010).

In Malaysia, there are three main sources of air pollution, these are mobile sources, stationary sources, and open burning sources (Afroz *et al.*, 2003). The emission of unburned hydrocarbons from motor vehicles is one of the most serious sources of air pollution in this country (Awang *et al.*, 2000; DOE, 2010). However, the main source of PM emission is from stationary sources including industries such as palm oil mill and power plant (DOE, 2010). The PM is likely to be prominent especially in urban environment. It is not only produced by mechanical processes due to construction activities and road dust resuspension but also from combustion sources (WHO, 2005). Combustion of biomass and agriculture materials may in fact contributes to the significant quantities of fine PM emission along with others gases such as carbon monoxide (CO), sulphur dioxide (SO_2) and nitrogen oxides (NO_x) (Lewtas, 2007).

PM is significant air pollutant which initially was not recognized as a hazard to public health and only acknowledged harmful to human health due to the increasing of mortality associated with acute (daily) and chronic (decades) exposures (Dockery, 2009). In both developed and developing countries, the evidence on airborne PM to cause adverse health effects upon exposures by urban population is consistently experienced throughout the world (WHO, 2005). Many studies have linked the PM exposure with the deterioration of human health especially the fine particulate size fraction. Numerous epidemiological studies reported that fine particulate is responsible as one of the causes contributes to respiratory and cardio-pulmonary disease (Fenger, 1999). In Malaysia, 2.4 per 10,000 population reported to be hospitalized each year associated to the PM exposure during haze days which representing an increase of 31% from normal days (Othman *et al.*, 2014).

Realising the negative impact of PM emission on human health and environment, the new Clean Air Regulation 2014 was promulgated early June of the same year. In order to meet the regulation limit, all industries generate PM are required to install particulates collector to restrict the emission of PM from deteriorating the atmosphere. As a result, air pollution control system such as fabric filter, scrubber, electrostatic precipitator (ESP) and multi-cyclones are installed in the industry as the particulates emission arrestor.

Multi-cyclones is the most widely used control technique especially in the palm oil mill industry due to its advantages such as simplicity of design, lower operating and maintenance cost as well as the ability to work in harsh operating conditions. However, the current multi-cyclones used are not effective enough to reduce the emission level within the legislative limit at all time. Thus, a study on the development a fine particulate emission control system was carried out seeking to provide a better performance multi-cyclones to meet more stringent emission limits. The study includes design and development of a prototype unit of the system to validate on its actual performance. A brief overview and significance of the study are presented in the following section.

1.2 Problem Statement

Combustion is one of the main sources of PM released into the atmosphere. Furthermore, combustion of biomass such as agriculture waste materials may actually be a main contributor to the outdoor air pollution especially in the fine particulate size fraction (WHO, 2005). For example; in Malaysia, palm fiber and shell are mainly used as fuel in the palm oil mill boiler to generate steam and energy for its daily operation. This generates a significant amount of particulates emission also known as palm oil mill boiler fly ash or POFA along with others pollutant gases like carbon monoxides (CO), sulphur dioxide (SO_2) and nitrogen oxides (NO_X). This activity contributes approximately 3.5 tons particulate emission per boiler per day, if it is not controlled (Chong *et al.*, 2011). The fluctuation of particulate emission from biomass burning especially in palm oil mill plant continued to become a big environmental issue in the industry as well.

Studies on the characteristics and control of particulate in the mills (Chong *et al.*, 2011; Rashid *et al.*., 1993; Rashid *et al.*, 1998) showed the particulate emission concentration in stack gas of a palm oil mill industry varied from 2.0 to 13.0 g/Nm^3 @ 7% O_2 with relatively high coefficient of variation (CV) of 84%. Preliminary study indicates that the particulate emission concentration emitted from the boiler was 5 to 33 times higher than the limit imposed on the facility. Worst still, none of the sample collected was able to meet its emission limits. Based on the finding, approximately 1.4 ton per mill of particulates are released into the atmosphere on a daily basis. The high concentration of PM will obstruct the industry to comply with the stringent regulation of new Clean Air Regulation 2014.

Generally, it was found that the collection efficiency of the existing multi-cyclones stood at 68% only which indicate the inefficient of the existing unit in capturing particulates especially the fine size fraction (Chong *et al.*, 2011). Thus, there is a considerable room for improvement in the design of a newly proposed control unit for the industry. In addition, most of the multi-cyclones installed in the palm oil mills are treated as the main air cleaner instead as pre-cleaner where generally it is meant as a latter. However, miniaturized cyclones arranged in a compartment known as a multi-cyclones have the potential to be an excellent particulate arrestor itself which is in line with this study.

In addition, studies on multi-cyclones are very limited and lacking. On the contrary, studies on a single cyclone already evolved more than 50 years. The current studies on multi-cyclones mainly discussed on the performance as well as flow pattern, and none of them discussed on the design configurations (Liu *et al.*, 2014; Masnadi *et al.*, 2010; Peng *et al*., 2007). The design configurations of a multi-cyclones is hardly available in literature merely due its confidentiality and commercial reason. Thus, this study is an attempt to offer a new improved multi-cyclone particulate emission control system with original first-hand dimensions and better performance even for fine particulate size fraction for all industries generate PM especially palm oil mill industry. In addition, the study will provide a better understanding of the design parameters affecting its performance and operation.

1.3 Objective of the Study

In general, the purpose of the study is to develop a new particulate control system which help to reduce fine particulate emission from industrial sources. Thus, in order to accomplish the purpose of the study, the following specific objectives have been identified:

i. To configure a design for a new multi-cyclone fine particulates emission control unit known as MR-deDuster.
ii. To theoretically evaluate and predict the performance of the proposed MR-deDuster.
iii. To experimentally validate the performance of the MR-deDuster in a pilot plant scale by comparison to the theoretical findings.

Each of the study objectives is addressed accordingly in a separate chapter (4 5 and 6) of this thesis.

1.4 Scope of the Study

The scope of work involved in this study are divided into three different phases which are; i) configuration and designing of the MR-deDuster unit, ii) theoretical evaluation and prediction of MR-deDuster performance and iii) comparison on the performance of the unit of theoretically and experimentally. The configurations and design of the proposed multi-cyclone unit was based on established cyclone dimensions by Stairmand (1951), Swift (1969) and Lapple (1951) which mathematically modified to obtain six new sets of dimensions. The performance of six new set dimensions were later predicted based on modified

Lapple (1951) model for collection efficiency prediction as well as modified Shepherd and Lapple (1940) model for pressure drop prediction. The dimension selection of the unit was based on the most suitable criteria of high predicted collection efficiency and low pressure drop. The selection of MR-deDuster design is also based on axial dimension, whereas the optimum axial dimensions with excellent prediction performance was selected as the design of MR-deDuster unit.

The performance (which include collection efficiency and pressure drop) of MR-deDuster unit that adopted the dimensions selected previously was predicted using the Leith and Licht (1972) model and modified Lapple (1951) model with different definitions of maximum radial distance travel by the particulate, *W* as well as modified Shepherd and Lapple (1940) model. The collection efficiency and pressure drop was predicted using various volumetric gas flow rate ranging from 0.13 to 0.21 m^3/s. In addition, a CFD modelling software was also used to predict fluid flow of the unit which used to understand the flow characteristic, as an essential step to understand the collection efficiency and pressure drop of a cyclone.

The study also tested the actual performance of MR-deDuster which the output was later compared to the theoretical performance prediction. The actual data collection was obtained to verify and validate predicted performance of the unit. The comparison of MR-deDuster performance experimentally and theoretically also aids in identifying the most suitable theoretical approach to represent the actual performance of the unit and to develop the new semi-empirical model of MR-deDuster performance. The actual performance of MR-deDuster was evaluated via developing the pilot plant scale of MR-deDuster prototype. The pilot plant of MR-deDuster was composed of four prototype cyclones with each cyclone adopted the selected dimensions and assemble in parallel arrangement. The operating conditions of the prototype MR-deDuster in a pilot plant scale set up was also evaluated in term of volumetric gas flow rate and flow velocity. The pilot plant was tested to obtain the actual collection efficiency and pressure drop of the unit at various volumetric gas flow rate range from 0.13 to 0.21 m^3/s for two types of different particulates, POFA and PreKot^{TM}.

1.5 Significance of Study

The development of a new fine particulate emission control device as the air pollution system, which is developed to decrease the particulate emission from industry. The study offers a new construct multi-cyclones with original first-hand dimensions and improved performance. In turn, this will provide an alternative solution for industry to overcome particulate emission problem. In addition, the MR-deDuster designed with easy maintenance features. Therefore, the developed multi-cyclones has a positive potential for commercialization due to its new added values as well as the demand of multi-cyclones usage in Malaysian industry in controlling particulate emission.

The study predicted the performance of MR-deDuster using several approaches and later the performance was validate via comparing with the actual data obtain from pilot plant testing. This provides a better understand of the performance and operation of multi-cyclones in general. The comparison of theoretical and experimental data also provide the theoretical background (semi-empirical equation) for newly developed MR-deDuster specifically and multi-cyclones in general. The theoretical background also can be used as design consideration for developing other multi-cyclones in the future.

The development of MR-deDuster as high efficient multi-cyclones (with more than 95% collection efficiency of PM_{10}) also improved the ability of multi-cyclones as main air cleaner device instead of only being air pre-cleaner device. The industry prefer to choose cyclone as air cleaner because of its low cost compared to other particulate collector technologies. Therefore, the development of MR-deDuster offers a new particulate collector that low in cost but high efficiency for industry.

Lastly, the study serves as an important basis for future research work on air pollution control system in Malaysia especially in dry centrifugal collector technology.

1.6 Outline of the Thesis

The thesis consists of seven chapters with Chapter 4 to 6 arranged as independent journal papers suitable for publication submission. In fact, some of results of the study have been published in *Sains Malaysiana, Jurnal Teknologi, Journal of Environmental Research and Development* as well as in *Advance Material Research.* Each of the respective objective is addressed in Chapter 4 to 6 of the thesis.

Chapter 1 presents an overview of the study. It describes the background and the basis of the research. The problem statement as well as the significance of the study also present in this chapter. More importantly, the objectives of the study are stated along with the scope of study to give the reader the clear view of the main aim of the study.

Chapter 2 consist of literature review related to the study. It briefly describes particulate emission issue in general including its adverse effect towards human health. This chapter also describes the particulate emission control device available such as electrostatic precipitators (ESP), fabric collectors, wet collectors and dry centrifugal collectors. However, literatures on dry centrifugal cyclone collectors are emphasised in this chapter which include its operating principles, types as well as its performance. In addition, studies on the modification cyclone to improve the unit performance are also present in this chapter.

Chapter 3 presents the methodology of the whole study activity involved in the configuration and designing of the MR-deDuster unit, as well as evaluation, prediction and validation of its performance. Description of the development of MR-deDuster, theoretically and experimentally is described in detail in this chapter.

Chapter 4 reports on the selection of the configurations of the MR-deDuster. In this chapter a new cyclone dimensions and its design consideration on developing the unit is discussed where the final selected configurations are presented at the end of the chapter.

Chapter 5 presents the theoretical prediction performance of MR-deDuster and its fluid flow prediction using CFD modelling software. The predicted performance which consist of cut-diameter, fractional and overall collection efficiency as well as pressure drop of several theoretical approaches were evaluated and are reported in the chapter.

The actual performance of MR-deDuster is presented and discussed in Chapter 6. The observed cut-diameter, fractional and overall collection efficiency along with its pressure drop across the unit obtained from the pilot plant scale of the system is presented in the chapter. The comparison of theoretical and experimental performance of the unit also discussed in this chapter. The best theoretical method to represent the actual performance of the unit is also identified. Lastly, the new semi-empirical equation to represent the performance of MR-deDuster is introduced.

Finally, Chapter 7 gives the overall conclusion of the study and recommendations for possible research work in the future.

REFERENCES

Abrahamson, J., Martin, C. G., & Wong, K. K. (1978). The physical mechanisms of dust collection in a cyclone. *TransIChemE*, 56, 168-177.

Afroz, R., Hassan, M. N., & Ibrahim, N. A. (2003). Review of air pollution and health impacts in Malaysia. *Environmental Research*, 92(2), 71-77.

Alexander, R. M. (1949). Fundamentals of cyclone design and operation. *Proc. Aus. Inst. Min. Met. NS*, 152(3), 152-153.

Autrup, H. (2010). Ambient air pollution and adverse health effects. *Procedia-Social and Behavioral Sciences*, 2(5), 7333-7338.

Avci, A., & Karagoz, I. (2003). Effects of flow and geometrical parameters on the collection efficiency in cyclone separators. *Journal of Aerosol Science*, 34(7), 937-955.

Awang, M. B., Jaafar, A. B., Abdullah, A. M., Ismail, M. B., Hassan, M. N., Abdullah, R., & Noor, H. (2000). Air quality in Malaysia: impacts, management issues and future challenges. *Respirology*, 5(2), 183-196.

Azadi, M., & Azadi, M. (2012). An analytical study of the effect of inlet velocity on the cyclone performance using mathematical models. *Powder Technology*, 217, 121-127.

Barnes, P. J., Drazen, J. M., Rennard, S. I., & Thomson, N. C. (Eds.). (2009). *Asthma and COPD: basic mechanisms and clinical management*. Elsevier.

Bates, D. V. (1995). The effects of air pollution on children. *Environmental Health Perspectives*, 103(6), 49-53.

Benitez, J. (1993). *Process engineering and design for air pollution control*. Prentice Hall.

Bethea, R. M. (1978). *Air pollution control technology: an engineering analysis point of view*. Van Nostrand Reinhold.

Bohnet, I. M., & Lorenz, D. I. T. (1993). Separation efficiency and pressure drop of cyclones at high temperatures. *In Gas Cleaning at High Temperatures* (pp. 17-31). Springer Netherlands.

Brook, R. D., Franklin, B., Cascio, W., Hong, Y., Howard, G., Lipsett, M., & Tager, I. (2004). Air pollution and cardiovascular disease : A statement for healthcare professionals from the expert panel on population and prevention science of the American Heart Association. *Circulation*, 109(21), 2655-2671.

Bryant, H. S., Silverman, R. W., & Zenz, F. A. (1983). How dust in gas affects cyclone pressure drop. *Hydrocarbon Process. (United States)*, 62(6).

Buttner, H. (1988). Size separation of particles from aerosol samples using impactors and cyclones. *Particle & Particle Systems Characterization*, 5(2), 87-93.

Caplan, K. J. (1962). *Source control by centrifugal force and gravity*. AC Stern, Academic Press, New York, 11, 247.

Chen, J., & Shi, M. (2007). A universal model to calculate cyclone pressure drop. *Powder Technology*, 171(3), 184-191.

Chen, J., Lu, X., Liu, H., & Yang, C. (2007). Effect of the bottom-contracted and edge-sloped vent-pipe on the cyclone separator performance. *Chemical Engineering Journal*, 129(1), 85-90.

Cheremisinoff, P. N. (1993). *Air pollution control and design for industry*. CRC Press.

Chong, W. C., Rashid, M., Ramli, M., Zainura, Z. N., Norruwaida, J. (2011). Exhaust Gas Stream Recirculation on Particulate Control: A Case Study of a Palm Oil Mill Boiler. *Proceeding Regional Symposium on Engineering and Technology. 2011*. Kuching, Sarawak, Malaysia.

Chu, K. W., Wang, B., Yu, A. B., & Vince, A. (2009). CFD-DEM modelling of multiphase flow in dense medium cyclones. *Powder Technology*, 193(3), 235-247.

Chu, K. W., Wang, B., Yu, A. B., Vince, A., Barnett, G. D., & Barnett, P. J. (2012). CFD–DEM study of the effect of particle density distribution on the multiphase flow and performance of dense medium cyclone. *Minerals Engineering*, 22(11), 893-909.

Chuah, T. G., Gimbun, J., & Choong, T. S. (2006). A CFD study of the effect of cone dimensions on sampling aerocyclones performance and hydrodynamics. *Powder Technology*, 162(2), 126-132.

Cooper, C. D., & Alley, F. C. (2011). *Air pollution control: A design approach*. Waveland Press.

Cortes, C., & Gil, A. (2007). Modeling the gas and particle flow inside cyclone separators. *Progress in Energy and Combustion Science*, 33(5), 409-452.

Crawford, M. (1976). *Air pollution control theory*. New York: McGraw-Hill.

Danielson, J.A. (1973). *Air pollution engineering manual* (Vol 4). Environmental Protection Agency.

Department of Environment, Malaysia. (2010). DOE Malaysia Environmental Quality Report, Department of Environment. Ministry of Natural Resources and Environment Malaysia.

Dewika, N. (2002). The Effect of an External Suction at the Dust Hopper of a Cyclone. Master Thesis, Universiti Teknologi Malaysia.

Dietz, P. W. (1981). Collection efficiency of cyclone separators. *AIChE Journal*, 27(6), 888-892.

Dirgo, J., & Leith, D. (1985). Cyclone collection efficiency: comparison of experimental results with theoretical predictions. *Aerosol Science and Technology*, 4(4), 401-415.

Dockery, D. W. (2009). Health effects of particulate air pollution. *Annals of Epidemiology*, 19(4), 257-263.

Elsayed, K., & Lacor, C. (2011). The effect of cyclone inlet dimensions on the flow pattern and performance. *Applied Mathematical Modelling*, 35(4), 1952-1968.

Englert, N. (2004). Fine particles and human health—a review of epidemiological studies. *Toxicology Letters*, 149(1), 235-242.

Farzanegan, A., Gholami, M., Rahimyan, M. H. (2013). Multiphase flow and tromp curve simulation of dense medium cyclones using Computational Fluid Dynamics. *Journal of Mining & Environment*, 4(1), 67-76.

Fenger, J. (1999). Urban air quality. *Atmospheric Environment*, 33(29), 4877-4900.

Fenger, J. (2009). Air pollution in the last 50 years–From local to global. *Atmospheric Environment*, 43(1), 13-22.

Funk, P. A., Hughs, S. E., & Holt, G. A. (2013). Dust Cyclone Technology – A Literature Review. *Journal of Cotton Science*, 17, 40-51.

Gimbun, J., Chuah, T. G., Fakhru'l-Razi, A. and Choong, Thomas S. Y. (2005). The Influence of Temperature and Velocity on Cyclone Pressure Drop: A CFD study. *Chemical Engineering and Processing*, 44, 7-12.

Hoffmann, A. C., Berrino, A., Ray, M. B., & Arastoopour, H. (1999). On the shape of grade efficiency curves computed for centrifugal dedusters by CFD with Lagrangian particle tracking. *AIChE Symp.*1999.

Hsu, C. W., Huang, S. H., Lin, C. W., Hsiao, T. C., Lin, W. Y., & Chen, C. C. (2014). An Experimental Study on Performance Improvement of the Stairmand Cyclone Design. *Aerosol and Air Quality Research*, 14(3), 1003-1016.

Huggins, F. E., Huffman, G. P., Linak, W. P., & Miller, C. A. (2004). Quantifying hazardous species in particulate matter derived from fossil-fuel combustion. *Environmental Science & Technology*, 38(6), 1836-1842.

Iozia, D. L., & Leith, D. (1990). The logistic function and cyclone fractional efficiency. *Aerosol Science and Technology*, 12(3), 598-606.

Ji, Z., Wu, X., & Shi, M. (1993). Experimental research on the natural turning length in the cyclone. *Acta Petrolei Sinica Petroleum Processing Section*, 9, 86-86.

Jo, Y., Tien, C., & Ray, M. B. (2000). Development of a post cyclone to improve the efficiency of reverse flow cyclones. *Powder Technology*, 113(1), 97-108.

Kalen, B., & Zenz, F. A. (1974). Theoretical-empirical approach to saltation velocity in cyclone design. In AIChE Symposium Series (Vol. 70, No. 137, pp. 388-396).

Kampa, M., & Castanas, E. (2008). Human health effects of air pollution. *Environmental Pollution*, 151(2), 362-367.

Karagoz, I., & Avci, A. (2005). Modelling of the pressure drop in tangential inlet cyclone separators. *Aerosol Science and Technology*, 39(9), 857-865.

Karagoz, I., Avci, A., Surmen, A., & Sendogan, O. (2013). Design and performance evaluation of a new cyclone separator. *Journal of Aerosol Science*, 59, 57-64.

Kim, G. N., Choi, W. K., & Jung, C. H. (2007). The development and performance evaluation of a cyclone train for the removal of contaminated hot particulate in a hot cell. *Separation and Purification Technology*, 55(3), 313-320.

Kim, J. C., & Lee, K. W. (1990). Experimental study of particle collection by small cyclones. *Aerosol Science and Technology*, 12(4), 1003-1015.

Kim, K. H., Kabir, E., & Kabir, S. (2015). A review on the human health impact of airborne particulate matter. *Environment international*, 74, 136-143.

Koch, W. H., & Licht, W. (1977). New design approach boosts cyclone efficiency. *Chemical Engineering*, 84(24), 80-88.

Kulkarni, N., & Grigg, J. (2008). Effect of air pollution on children. *Paediatrics and Child Health*, 18(5), 238-243.

Lapple, C. E. (1951). Processes use many collector types. *Chemical Engineering*, 58(5), 144-151.

Leith, D., & Licht, W. (1972). The collection efficiency of cyclone type particle collectors: a new theoretical approach. *AIChE Symp. Ser*. 68(126), 196-206.

Lewtas, J. (2007). Air pollution combustion emissions: characterization of causative agents and mechanisms associated with cancer, reproductive, and cardiovascular effects. *Mutation Research/Reviews in Mutation Research*, 636(1), 95-133.

Licht, W. (1988). *Air pollution control engineering: Basic calculations for particulate collection (Vol. 10).* CRC Press.

Liu, Q., & Ray, M. B. (2001). Recycling the Flow of Post-Cyclone to Increase the Efficiency of Reverse Flow Cyclone. *Journal of Chemical Engineering of Japan*, 34(4), 540-544.

Marinos, C., Economopoulou, A. A., & Economopoulos, A. P. (2007). Comparative fractional efficiency predictions by selected cyclone simulation models. *Journal of Environmental Engineering*, 133(5), 556-567.

Masnadi, M. S., Grace, J. R., Elyasi, S., & Bi, X. (2010). Distribution of multi-phase gas–solid flow across identical parallel cyclones: modeling and experimental study. *Separation and Purification Technology*, 72(1), 48-55.

Mckenna, J. D., Mycock, J. C., & Theodore, L. (1995). *Handbook of air pollution control engineering and technology*. CRC Press.

Mothes, H., & Löffler, F. (1988). Prediction of particle removal in cyclone separators. *Int. Chem. Eng*, 28(2), 231-240.

Moya, J., Bearer, C. F., & Etzel, R. A. (2004). Children's behavior and physiology and how it affects exposure to environmental contaminants. *Pediatrics*, 113(3), 996-1006.

Norelyza, H., & Rashid, M. (2013). Performance of MR-Deduster on particulate emission control for a different area of axial entry. *Journal of Environmental Research Development*, 7(4), 1392-1398.

Othman, J., Sahani, M., Mahmud, M., & Ahmad, M. K. S. (2014). Transboundary smoke haze pollution in Malaysia: inpatient health impacts and economic valuation. *Environmental Pollution*, 189, 194-201.

Ozkoca, O. (2001). *Experimental investigation of the pressure losses and efficiencies in different type of cyclones* (Doctoral dissertation, Msc thesis, Uludag Univercity,(Bursa) Turkey).

Papp, M. (1998). Quality assurance handbook for air pollution measurement systems. Volume 3: Stationary Source Specific Methods Environmental Monitoring System Laboratory. Environmental Protection Agency, Office of Air Quality Planning and Standards, Research Triangle Park, NC (United States).

Peng, W., Hoffmann, A. C., Dries, H., Regelink, M., & Foo, K. K. (2007). Reverse-flow centrifugal separators in parallel: Performance and flow pattern. *AIChE journal*, 53(3), 589-597.

Perkins H. C. (1974). *Air Pollution.* McGraw Hill.

Pope III, C. A. (2007). Mortality effects of longer term exposures to fine particulate air pollution: review of recent epidemiological evidence. *Inhalation Toxicology*, 19(S1), 33-38.

Qian, F., & Wu, Y. (2009). Effects of the inlet section angle on the separation performance of a cyclone. *Chemical Engineering Research and Design*, 87(12), 1567-1572.

Ramachandran, G., Leith, D., Dirgo, J., & Feldman, H. (1991). Cyclone optimization based on a new empirical model for pressure drop. *Aerosol Science and Technology*, 15(2), 135-148.

Rashid, M., & Rozainee, M. (1993). Particulate emissions from a palm oil mill plant– a case study. *Jurnal. Teknologi*, 22, 19-24.

Rashid, M., Ramli, M., & Rozainee, M. (1998). A field evaluation of particulate emission concentrations in palm oil mill boilers. *Jurnal Teknologi*, 29(1), 1-6.

Ray, M. B., Luning, P. E., Hoffmann, A. C., Plomp, A., & Beumer, M. I. (1998). Improving the removal efficiency of industrial-scale cyclones for particles smaller than five micrometre. *International Journal of Mineral Processing*, 53(1), 39-47.

Raysoni, A. U., & Li, W. W. (2009). Health impacts of traffic related air pollution. *Journal of Environmental Research and Development*, 4(2), 421-429

Research and Education Association (REA). (1973*). Pollution control technology*. New York.

Riediker, M., Cascio, W. E., Griggs, T. R., Herbst, M. C., Bromberg, P. A., Neas, L., & Devlin, R. B. (2004). Particulate matter exposure in cars is associated with cardiovascular effects in healthy young men. *American Journal of Respiratory and Critical Care Medicine*, 169(8), 934-940.

Sacks, J. D., Stanek, L. W., Luben, T. J., Johns, D. O., Buckley, B. J., Brown, J. S., & Ross, M. (2010). Particulate matter-induced health effects: who is susceptible?. *Environmental Health Perspectives*, 119(4), 446-454.

Sahani, M., Zainon, N. A., Mahiyuddin, W. R. W., Latif, M. T., Hod, R., Khan, M. F., Tahir, N. M., & Chan, C. C. (2014). A case-crossover analysis of forest fire haze events and mortality in Malaysia. Atmospheric Environment, 96, 257-265.

Salcedo, R. L. R., Chibante, V. G., Fonseca, A. M., & Cândido, G. (2007). Fine particle capture in biomass boilers with recirculating gas cyclones: Theory and practice. *Powder Technology*, 172(2), 89-98.

Salcedo, R. L., & Pinho, M. J. (2003). Pilot-and industrial-scale experimental investigation of numerically optimized cyclones. *Industrial & Engineering Chemistry Research*, 42(1), 145-154.

Shaughnessy, W. J., Venigalla, M. M., & Trump, D. (2015). Health effects of ambient levels of respirable particulate matter (PM) on healthy, young-adult population. *Atmospheric Environment*, 123, 102-111.

Shepherd, C. B., & Lapple, C. E. (1940). Flow pattern and pressure drop in cyclone dust collectors cyclone without intel vane. *Industrial & Engineering Chemistry*, 32(9), 1246-1248.

Stairmand, C. J. (1951). The design and performance of cyclone separators. *Trans. Inst. Chem. Eng*, 29, 356-383.

Surmen, A., Avci, A., & Karamangil, M. I. (2011). Prediction of the maximum-efficiency cyclone length for a cyclone with a tangential entry. *Powder Technology*, 207(1), 1-8.

Swift, P. (1969). Dust control in industry. *Dust Control Equipment Limited*. 38.

Theodore, L. (2008). *Air pollution control equipment calculations*. John Wiley & Sons.

Theodore, L., & Buonicore, A. J. (1976). *Air Pollution Control Equipment, Vol. 1: Particulates*. CRC Press.

Theodore, L., & Paola, V. D. (1980). Predicting cyclone efficiency. *Journal of the Air Pollution Control Association*, 30(10), 1132-1133.

Varma, H. B. (1981). *Air pollution control equipment*. New Youk Berlin Heidiberg.

Vermylen, J., Nemmar, A., Nemery, B., & Hoylaerts, M. F. (2005). Ambient air pollution and acute myocardial infarction. *Journal of Thrombosis and Haemostasis*, 3(9), 1955-1961.

Wang, W., Zhang, P., Wang, L., Chen, G., Li, J., & Li, X. (2010). Structure and performance of the circumfluent cyclone. *Powder Technology*, 200(3), 158-163.

Weichenthal, S., Dufresne, A., & Infante-Rivard, C. (2007). Indoor ultrafine particles and childhood asthma: exploring a potential public health concern. *Indoor Air*, 17(2), 81-91.

Wood, C. J. (1990). *A performance model for coal-washing dense medium cyclones*. Ph.D thesis, University of Queensland, Australia

World Health Organization. (2005). WHO Air Quality Guidelines Global Update 2005: Report on a Working Group Meeting, Bonn, Germany, 18-20 October 2005. WHO Regional Office for Europe.

Xiang, R. B., & Lee, K. W. (2001). Exploratory study on cyclones of modified designs. *Particulate Science and Technology*, 19(4), 327-338.

Xiong, Z., Ji, Z., & Wu, X. (2014). Development of a cyclone separator with high efficiency and low pressure drop in axial inlet cyclones. *Powder Technology*, 253, 644-649.

Young, R. A., & Cross, F.L. (1982). *Specifying air pollution control equipment*. M. Dekker.

Zhu, Y., & Lee, K. W. (1999). Experimental study on small cyclones operating at high flowrates. *Journal of Aerosol Science*, 30(10), 1303-1315.