DESIGN AND DEVELOPMENT OF REAL-TIME PARTICULATE MATTER MEASURING INSTRUMENT APPLYING LASER SCATTERING TECHNIQUE FOR MICROENVIRONMENT MONITORING

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FACULTY OF SCIENCE AND NATURAL RESOURCES
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DECLARATION

I hereby declare that the material in this thesis is my own except for quotations, equations, summaries and references which have been duly acknowledged.

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ABSTRACT

Particulate Matter (PM) is one of the key indicators in determining Air Quality Index (AQI). While PM has been has identified as one of global health threat by the World Health Organization (WHO), and there is an urgent need for routine air monitoring data on components of the PM mass to identify the role of PM chemical components in causing adverse health effects for exposure control, assessment of particle exposure on a more personal level are not achievable by the conventional method due to their high cost and relatively large size. Therefore, it is crucial to have a better approach in monitoring particulate matter that can provide better spatial and temporal coverage which is made possible with the emergence of low-cost PM sensor. In this study a real time particulate matter measuring instrument applying laser scattering technique was developed and evaluated. Based on the evaluation, PMSA003 was selected as the best sensor to be applied in this PM monitoring instrument due to its high linearity response with reference instruments with $R^2>0.9$ and low intra-model variability of 17.71%. A humidity correction algorithm was developed based on the climate susceptibility test as it was observed there are strong correlation between the reported mass concentration and humidity at more than 65 %RH. To further improve the performance of the instrument, it was deployed in three ambient setting where the density factor for the conversion of particle distribution to mass concentration was obtained for the indoor, outdoor and factory setting. The finalized prototype was validated with the Thermo Scientific™ 1405 TEOM™ Continuous Ambient Particulate Monitor. TOEM is certified Federal Equivalent Method (FEM) instrument by US. Through the field deployment, the prototype showed high correlation with the reference instrument with $R^2 > 0.9332$ for $PM_{2.5}$ and $R^2 >0.7623$ for $PM_{10.0}$. In conclusion, an integrated real time particulate matter measuring instrument was designed, developed and evaluated where the term design is referring to the whole system design. The developed instrument shows excellent correlation with reference instruments thus validating its potential to be applied for real life application.

ABSTRAK

REKA BENTUK DAN PENGHASILAN INSTRUMEN PENGUKURAN JIRIM ZARAHAN MASA NYATA BERASASKAN SERAKAN LASER UNTUK PEMANTAUAN PERSEKITARAN MIKRO

Jirim Zarahan (PM) merupakan salah satu penentu Indeks Pencemaran Udara (IPU). Walaupun PM telah dikenal pasti sebagai salah satu ancaman kepada tahap kesihatan di dunia oleh Pertubuhan Kesihatan Sedunia (WHO) dan terdapat keperluan mendesak untuk pemantauan berterusan terhadap komponen PM dalam mengenal pasti kesannya terhadap tahap kesihatan manusia, namun taksiran terhadap kadar pendedahan PM pada skala individu tidak dapat dicapai oleh teknologi konvensional disebabkan oleh kos yang tinggi dan saiz yang agak besar. Oleh sebab itu, adanya keperluan mendesak untuk kaedah pemantuan PM yang boleh memberikan liputan ruangan dan temporal yang lebih mampan yang boleh dicapai menggunakan penderia PM kos rendah yang semakin berkembang pesat kini. Dalam kajian ini, sebuah instrumen pengukur PM masa nyata telah direka dibina dan dinilai. Melalui penilaian tersebut, penderia PMSA003 telah dipilih sebagai penderia terbaik untuk disepadukan dalam instrumen pengukur PM yang dibina kerana kelineran yang tinggi penderia tersebut dengan instrumen rujukan iaitu R^2>0.9 dan juga kebolehubahan intra-model yang rendah penderia tersebut iaitu sebanyak 17.71%. Algoritma pembetulan berasaskan kelembapan juga telah diolah melalui cerapan kajian kerentanan iklim yang menunjukkan tahap korelasi yang tinggi di antara kelembapan dan jirim PM pada tahap kelembapan melebihi 65 %RH. Bagi memperbaiki prestasi instrumen yang dibina, instrumen tersebut telah diuji di tiga lokasi ambien yang berbeza yang mana faktor ketumpatan telah diperoleh untuk pertukaran taburan zarah kepada kepekatan jisim untuk kawasan dalaman, luaran dan industri. Produk akhir instrumen telah diuji sisi dengan sisi berasama instrumen pengawasan kualiti udara automatik, Thermo Scientific™ 1405 TEOM™. TOEM merupakan instrumen kaedah setara persekutuan (FEM) yang diperakui oleh US. Melalui kajian ini, instrumen yang dibina menunjukkan korelasi yang tinggi dengan instrumen rujukan iaitu setinggi R^2>0.933 untuk $PM_{2.5}$ dan R^2>0.7623 untuk $PM_{10.0}$. Kesimpulannya, instrumen bersepadu bagi pengukuran PM masa nyata telah direka, dibina dan dinilai. Instrumen yang telah dibina menunjukkan tahap kolerasi yang tinggi dengan instrumen rujukan sekaligus mengesahkan kebolehupayaan instrumen tersebut untuk diaplikasikan dalam dunia nyata.

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LIST OF ABBREVIATIONS

AT	-	Standard Atmospheric Condition
AQI	-	Air Quality Index
BAM	-	Beta Attenuation Monitor
CF	-	Industrial Condition
CV	-	Coefficient of Variants
COTS	-	Commercial off The Shelf
CSV	-	Comma Separated Value
EPA	-	Environmental Protection Agency
FEM	-	Federal Equivalent Method
FRM	-	Federal Reference Method
GND	-	Ground
GSM	-	Global System for Mobile Communication
GUI	-	Graphical User Interface
H	-	Height
HEPA	-	High Efficiency Particulate Air
Hz	-	Hertz
IDE	-	Integrated Development Environment
IMV	-	Intra-Model Variability
L	-	Length
L/min	-	Liter per Minute
LB	-	Lower Boundary
LCD	-	Liquid Crystal Display
LED	-	Light Emitting Diode
LiPo	-	Lithium Polymer
LLS	-	Laser Light Scattering Technique
LOD	-	Limits if Detection
mAh	-	Milliampere Hour
min	-	Minimum
max	-	Maximum
nRMSE	-	Normalize Root Mean Square Error

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Pa	-	Pascal
PA	-	Purpleair
PCB	-	Printed Circuit Board
PTFE	-	Polytetrafluoroethylene
PM	-	Particulate Matter
RGB	-	Red Green Blue
RH	-	Relative Humidity
RTC	-	Real Time Clock
Rx	-	Receiver
SD	-	Serial Data
SDHC	-	Serial Data High Speed Card
SMPS	-	Scanning Mobility Particle Sizer
SPI	-	Serial Peripheral Interface
TEOM	-	Tapered Element Oscillating Microbalance
TFT	-	Thin Film Transistor
TSP	-	Total Suspended Solid
Tx	-	Transmitter
US	-	United States of America
VCC	-	Voltage Common Collector
W	-	Width
WHO	-	World Health Organization

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CHAPTER 1

INTRODUCTION

1.1 Research Background

Particulate Matter (PM) is a form of air pollution composing of a mixture of solid and liquid particles (World Health Organization, 2013). PM exist in various range of sizes and made up of hundreds of different chemicals originating from various sources which can either be classified as primary PM or secondary PM (Nagar *et al*., 2014). Primary PM originates from both human and natural activities such as agricultural and industrial activities as well as volcanic eruption, windblown dust and natural wildfires (Nagar *et al.,* 2014). Secondary PM originates from indirect formation of particles by the intermediate reactions of gases in the atmosphere.

PM is often used as one of the key indicator in Air Quality Index (AQI) due to their inhalable properties which may proposed health threat to living organisms (Brunekreef and Holgate, 2002). Various epidemiological studies had reported serious threat of PM to our cardiovascular system (Chuang *et al.,* 2011; World Health Organization, 2014) ranging from decreasing the lung function in children to increasing incidences of acute coronary events such as myocardial infarction and unstable angina (Gehring *et al*., 2013; Stafoggia *et al*., 2014).

Conventionally, PM exposure is controlled and measured by monitoring its mass concentration at different size fraction (Langner *et al.,* 2011). The most common practice is to monitor PM is by measuring particles with aerodynamic diameter of less than 10 µm or also known as $PM_{10.0}$ which is considered as the inhalable fraction. Lately, smaller particles with aerodynamic diameter of less than 2.5 µm or known as $PM_{2.5}$ are getting more attentions from regulatory body due to its ability to penetrate deeper into the cardiovascular system. Generally, the smaller the size of particle, the deeper it will penetrate the respiratory tract and the more adverse the effect (Brown *et al.,* 2013). Smaller particles have been reported to have caused decreased lung function in children as well as cardiovascular mortality (Brauer *et al.*, 2012; Brown *et al.*, 2013; Hadei *et al.*, 2017).

There are various methods to monitor PM mass concentration. The US Environmental Protection Agency (EPA) has introduced the gravimetric method as the Federal Reference Method (FRM) for PM monitoring (Noble *et al.*, 2010). Technically, the gravimetric method works by continuously sampling airborne particulate matter onto a polytetrafluoroethylene (PTFE) Teflon filter paper via a stream of steady air flow and later determining the mass of the deposited PM after 24-Hours (Peters *et al.*, 2001). Alternative to this method is the Beta Attenuation Monitor (BAM) which uses radioactive decay for determination of particulate matter concentrations and the tapered Element Oscillating Microbalance (TEOM). These alternative methods are also known as the Federal Equivalent Method (FEM).

While being preferred as the standard method for PM mass concentration monitoring, the FRM and FEM method proposed various spatial and temporal limitations (Castell *et al.*, 2017; Wilson *et al.*, 2002). The Gravimetric method for instance requires at least 24-hours of sampling thus limiting the temporal understanding on PM distribution (Amaral, de Carvalho, Costa, and Pinheiro, 2015). Besides that, the high cost of installation and maintenance for both FRM and FEM monitoring stations which can easily cost up to more than $10,000 has also resulted in relatively sparse monitoring (Schneider *et al.*, 2017) preventing robust spatial analysis on PM exposure to nearby residents (Wang *et al.,* 2015b). Due to this, there is an urgent need for cheaper and better yet reliable approach to PM monitoring.

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1.2 Problem Statement

Unlike gases, PM does not have any defined chemical structure or physical properties (Langner *et al.*, 2011) and their concentrations may vary depending on time, location and pollutant sources (Adams *et al.,* 2015; *Ambient Air Monitoring Protocol For PM2.5 and Ozone Canada-wide Standards for Particulate Matter and Ozone*, 2011; Balasubramanian *et al.,* 2000). While this is true, the Conventional approach to PM monitoring fail to capture spatial gradient in the areas they represent (Jovašević-Stojanović *et al.*, 2015). This is mainly due to the limited number of available stations which is caused by their high cost of deployment and complex operations (Cao, Chow, Lee, and Watson, 2013; Castell *et al.*, 2017).

While PM has been has identified as one of global health threat by the World Health Organization (WHO, 2005) and there is an urgent need for routine air monitoring data on components of the PM mass to identify the role of PM chemical components in causing adverse health effects for exposure control (Lippmann, 2012), assessment of particle exposure on a more personal level are not achievable by the conventional method due to their high cost and relatively large size (Castellani *et al.*, 2014).

Recent technological advancement has seen the emergence of optical based sensor for particulate matter monitoring. These sensors are not only affordable and compact in size, but they are also capable of reporting near real time reading of PM concentration making them highly potential to be integrated as portable device for personal exposure assessment. Furthermore, these low-cost PM sensors are also able to report mass concentration within the range that is compatible with the current PM exposure compliance thus making them the best candidate to supplement the existing monitoring approach.

While these low-cost PM sensors have the capability to report real-time reading of PM mass concentration, technically however, the mass concentration by these sensors is actually derived based on particle size distribution under assumptions that all particles is spherical and density is known (Liu *et al.,* 2017b). Hence, the accuracy of the reported mass concentration by these sensors are easily deteriorated if one of this assumption is violated. In order to ensure accuracy of the reported mass concentration by these sensors, the correct density factor must be applied, and this density factor is unique to every location due to the complexity of particle distribution. Therefore, the sensor must be evaluated in the environment that they will be used beforehand and so far, no such evaluation was ever conducted within the South East Asia region prior to the literature of this research study.

Another concern when using these low-cost PM sensors is the effect of humidity on their performance. Previous studies have showcased significant impact of humidity on the performance of low-cost PM sensor due to the change of the scattering coefficient (Wang *et al.,* 2015a; Zheng *et al.*, 2018). However, this limitations can be overcome by using correction model as presented by previous researcher (Soneja *et al.*, 2014; Tan, 2017). Malaysia is a tropical country and is known for having high humidity with annual average of 80 %RH, therefore, it is crucial to evaluate the effect of humidity on the performance of these low-cost PM sensor within this region to ensure the right correction model is applied.

In this study, the potential of these low-cost PM sensor was utilized by integrating them into a real-time and portable particulate matter measuring instrument for microenvironment monitoring. The developed instrument is small enough to be used for personal monitoring and have the capability to report real-time $PM_{1.0}$, $PM_{2.5}$ and $PM_{10.0}$ concentration simultaneously as well as particle distribution within the range of 0.3 to 10.0 micron thus overcoming the temporal limitations of the conventional method.

To ensure data reliability, the developed instrument was deployed in three types of environment namely indoor, outdoor and factory settings. The density factor from each location was determined based on the relationship between particle distribution and particle mass concentration. This density factor is crucial for the conversion of particle distribution to mass concentration thus ensuring data reliabilities. The performance of the developed instrument was further evaluated on their climate susceptibility response by manipulating the ambient humidity from low to high in a chamber experiment. The relationship between humidity and the sensor output was then used to develop a humidity correction model.

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In conclusion, this instrument was targeted towards overcoming the limitations of the conventional method for PM monitoring by integration of low-cost PM sensor with the capability of reporting PM mass concentration at a high reliability and accuracy. The compactness and simplicity of developed instrument operation also make it highly compatible for personal exposure assessment thus overcoming the spatial limitations of the conventional method. To ensure data reliability, the instrument was evaluated through laboratory and field evaluation against reference instrument and results were used to develop a model to improve the performance of the instrument.

1.3 Research Objectives

The objectives of this research are highlighted as follow:

1. To develop a particulate matter (PM) measuring instrument applying Laser Light Scattering (LLS) technique for monitoring $PM_{1.0}$, $PM_{2.5}$ and $PM_{10.0}$.
2. To evaluate the linearity, intra-model variability, climate susceptibility and density factor of developed particulate matter measuring instrument through laboratory and field experiment.
3. To validate the performance of the calibrated particulate matter measuring instrument against Federal Equivalent Method (FEM) instrument.

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1.4 Research Scope

In this study, the potential of low-cost PM sensor was utilized by integrating them into a real time and portable particulate matter measuring instrument for microenvironment monitoring. Microenvironment refers to immediate small-scale environment; environment where everything is represented in the micrometer unit. This monitoring instrument was developed using low-cost Commercial off the shelf (COTS) consumer electronics making it highly reproducible for large scale production thus promoting establishment of more monitoring networks which will creates unique opportunity for citizen-participatory sensing (Jovašević-Stojanović *et al.*, 2015). By making the developed instrument in compact and portable form with built in data logger, assessment of particle exposure in a more personal level can be achieved thus enabling better understanding on the role of PM chemical components in causing adverse health effects which is not achievable by the conventional method. To ensure data reliability, the instrument was evaluated in both laboratory and field deployment