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REAL TIME PARTICULATE MATTER CONCENTRATION MEASUREMENT USING LASER SCATTERING

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ABSTRACT

Particulate Matter (PM) is the sum of all solid and liquid particles suspended in air. It can be classified into PM1.0, PM2.5, and PM10 based on the size of the particles. Smaller particles are extremely hazardous as they can penetrate into our respiratory system causing adverse health effects. In this paper, a real time, portable and cost effective PM sensor system is designed for the monitoring of air particulate matter concentration. To achieve the objectives, a particulate matter monitoring device was constructed using PM Sensor SEN0177, Temperature and Humidity Sensor DHT11, Arduino Mega, DS1307 RTC and TFT LCD for data visualization. The system can simultaneously measure the concentration of PM at varying sizes. Besides, it is also equipped to measure RH and ambient air temperature. Built in real time clock and data logging system was also included as added function. The system employs a real time monitoring system for particulate matter using laser scattering technique and interfaced using MIE theory algorithm. The completed prototype was tested with TE 600 PM10 Air Sampler and General consumer for accuracy test. The system offers particulate matter detection based on laser scattering principle with a considerable accuracy of 87.7% in comparison when being compared with the TE6001 PM10 air sampler. The main advantage of this system is its ability to provide real time monitoring to obtain in situ data on the PM concentration together with RH and temperature readings which are crucial factors in the air quality monitoring.

Keywords*:* particulate matter, air quality monitoring, MIE scattering, real time monitoring.

1. INTRODUCTION

Particulate matter (PM) is a type of pollution that are made up of a mixture of solid particles and liquid particles originated from incomplete combustion processes [1]. PM exist in various range of sizes and made up of hundreds of different chemicals originating from various sources which maybe directly emitted known as primary PM or formed in the atmosphere by transformation of gaseous emissions known as secondary PM[2].

Primary PM is originates from both human and natural activities. Human activities include agricultural development, construction, demolition activities and entrainment of road dust into the air while natural activities include volcanic eruption, windblown dust and wildfires [2] whereas secondary PM is originates from indirect formation of particles by the intermediate reactions of gases in the atmosphere such as Sulphur Oxides, Nitrogen Oxides and Ammonia are which is considered as precursors to PM formation.

Scientifically, a particulate matter can be classified based on their aero-dynamic diameter which describe its transportation ability in the air as well as its ability to navigate through respiratory organism [3]. Environmental Protection Agency, United States (EPA) categorizes Particulate matter in two size categories which are PM 10 and PM2.5. These particles is categorize based on their predicted penetration capacity into the lung. PM10 is an inhalable particles, with diameters ranging from 10 μm and smaller whereas PM2.5 which is a fine inhalable particles, with diameters ranging from 2.5 μm and smaller [3].

The fact that the size of particulate matter is small enough to penetrate our respiratory system makes it a threat towards the cardiovascular system. A report by Shah *et al*.,(2013) indicated that at least two millions death occur worldwide annually in relation to the effect of air pollution damaging the lungs and respiratory system whereby around 2.1 and 0.47 millions of this incidences are caused by fine particulate matter [4] and ozone[5]. In another study, acute health effects was observed from directly injected PM2.5, including rapid inflammation, oxidative damage, and routine-behavioral changes [6]. Meanwhile, various studies have presented the negative impact of particulate matter to our health [7][8].

World Health Organization (WHO) in one of their article stated that PM2.5 in particular reduces life expectancy of the population of the region by about 8.6 months on average[1]. Numerous epidemiologic studies have documented associations between long-term exposure to fine particulate matter mass (PM2.5) air pollution and increased mortality in urban populations [1]. The concern towards the effect of particulate matter exposure has introduced the need for a more robust PM monitoring system.

A real-time monitoring system would be useful for immediate response for necessary preventive measure. Making a device that is portable will allow continuous monitoring by the general user hence increasing awareness towards particulate matter exposure. These concern has motivated this study to come up with a practical low-cost instrumentation which provide in situ data of PM concentration together with Relative Humidity (RH) and temperature readings.

2. RELATED STUDIES

Conventional particulate matter detection system

The most common ways of monitoring particulate matter concentration is using the federal reference method (FRM). This method used filter based gravimetric analysis [9] to determine the PM concentration based on their mass distribution. The monitoring system works by continuously sampling airborne particulate matter onto a polytetrafluoroethylene (PTFE) teflon sample filter paper [10] over a 24 hours period. After 24 hours, the filter is weight before the concentration is determined using on gravimetric analysis.

Alternative to the FRM monitoring system is using the beta attenuation monitor (BAM) which uses radioactive decay for determination of particulate matter concentration. The detection system works by emitting Carbon-14 radioactive through an air flow. Some of the radiation will be absorbed by the particle during the process. The amount of radiation will then be used to determine the particle concentration in hourly temporal resolution [11].

Although both of the conventional detection method can accurately provide particulate matter monitoring system, these system are however usually expensive and inaccessible by the general users. This prevents continuous robust monitoring of PM. Another issue faced by the conventional method is the FRM method does not provide real-time monitoring of PM. The BAM method also proposed health concern from radioactive exposure. Due to this, many studies have been conducted in attempt to improve the conventional detection methods. Some of the studies is presented in the following section.

Studies on improvement of particulate matter detection system

The limitations proposed by the conventional method of particulate matter monitoring have driven researchers from across the globe to create a better particulate matter monitoring system. The advancement of technology had enables many breakthroughs in the construction of low-cost particulate matter monitoring system using off-the-shelf consumer electronics. The most common approach to this is using optical based sensor. Many studies have shown a very promising results of Particulate matter monitoring system using optical based sensor with a considerable accuracy [12]–[15].

A study conducted by[13] showcased a real-time measurement of concentration and size distribution of airborne dust particles using ARM7 microcontroller board on optical scattering basis with promising performances although further study is require to improve the detection sensitivity. In another study by[16] an airborne particle measurement using integration of enhanced light scattering technique and inertial filtering were designed showcasing 30% agreement to the theoretical expectations. Meanwhile a remarkable stability of the Arduino platform with the Sharp GP2Y1010AU0F dust sensor were shown by [17].

One of the concerns that arise from using low-cost particulate monitoring device is in term of its accuracy and reliability in reporting the actual concentration of particulate matter. This issue however can be resolved through proper calibration which is presented in various previous studies such as by [18] whom documented the ability of low-cost PM sensor in evaluating mass concentration of single composition particle with good accuracy.

This study is motivated by various studies conducted by previous researcher with a slight modification and improvement to the previous system. The aim of this study is to develop a real time particulate matter monitoring system using off-the-shelf consumer electronics with ease of handling. The constructed system should be able to read the real-time reading of PM1.0, PM 2.5 and PM 10 concentrations with added function of RH and temperature monitoring and data logging system. Based on the literature review, a real-time particulate matter monitoring system was designed. The following section describes the design of the system.

3. DESIGN OVERVIEW

This study features a bleeding edge real time Particulate Matter monitoring system with a promising accuracy and ease of handling. The design of this system is comprised of hardware and software integration. The system is designated to offer robust monitoring of PM with embedded temperature and humidity sensors for calibration and scientific related studies purposes. Real Time Clock (RTC) and on-board data logging system is integrated to the system to allow continuous temporal monitoring of PM with minimal handling effort. For easy data collection, a TFT display with simple Graphical User Interface (GUI) was integrated into the system to make the system more practical and user friendly. Additional sound notification as feedback mechanism was also added. Overall, the system is arranged in a stacked formation making it relatively smaller than the conventional PM detection device hence making the system ergonomic and portable. The block diagram of the system design is shown in Figure-1.

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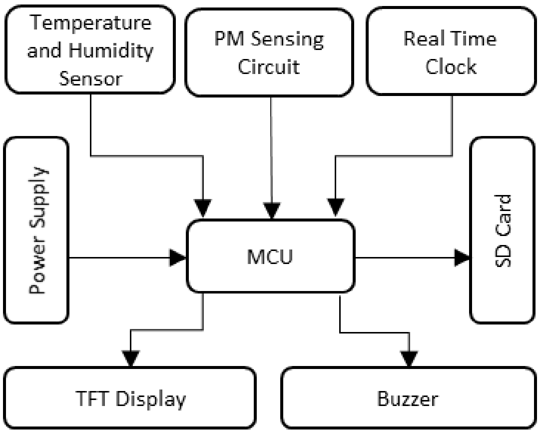

Figure-1. Block diagram of the design system.

4. HARDWARE DESIGN

Hardware overview

The hardware design of the system showcase a synergy between off the shelf consumer electronics that are able to provide monitoring of PM, RH and Temperature in the most ergonomics way. This section describe the building block of the detection system composing of the sensor used, data logger and the enclosure of the prototype.

Sensor system

PM sensor: The system showcase a PM detection device based on laser scattering principle. The sensor used was PM2.5 laser dust sensor with model number of SKU: SEN0177 from DFRobot. The SEN0177 sensor offers a real time measurement of particle size distribution based on the laser scattering principle. This sensor is capable of measuring particle concentration up to minimum diameter size of 0.3 micron with maximum volume concentration of 500 µg /m^3 at less than 10 s response time. The SEN0177 comes in a very compact size of 65 × 42 × 23 (mm) making it suitable to be integrated as portable device. Table-1 shows the specification of the sensor.

The hardware design of the PM Sensing circuit is composed of few components. Firstly is the exhaust fan which function to draw in ambient air creating air flows. Secondly is the detection chamber which isolates the stray light from the detection system. Thirdly is a laser diode source which acts as incident light to induce light scattering and finally a photodetector which detects the scattered light intensity. The symbiosis between all of these components creates a particulate matter detection system based on light scattering and the overall design of the system is shown in Figure-2.

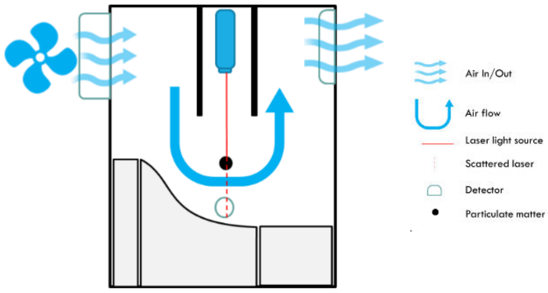

Figure-2. PM sensor detection mechanism.

The PM detection by the SEN0177 works by firstly, drawing in ambient PM through an exhaust fan. The exhaust fan creates air flows allowing the PM to flow through a stream of laser beam within the sensor detection chamber inducing light scattering. The detection chamber is design to isolate the laser from the ambient light to avoid error. The scattered light is then detected by a photodiode at a specific angle which generates a current pulse proportional to the scattered light intensity. A graph of time against the intensity of the scattered light was then plotted where the variation in signal peak with amplitude depends on the particle size.

The next stage of the detection is determination of particulate distribution and this is done by firstly applying Fourier transform to the time against the intensity graph through which the frequency of signal is obtained. The duality relationship between the time domain and frequency domain can be acquired using Equation.(1)

$$X(\omega) = \int_{t=\infty}^{\infty} x(t)e^{-j\omega t}\, dt \tag{1}$$

which can be rearrange as Equation.(2)

$$x(t) = \frac{1}{2\pi}\int_{\omega=\infty}^{\infty} X(\omega)e^{j\omega t}\, dt \tag{2}$$

The analyzed frequency from the Fourier transform represents the frequency distribution function of particle size, $f(a)$ which can then be used to detect the number of particle based on Mie Scattering as shown in Equation.(3)

$$I(v) = \int_{a_{min}}^{a_{max}} K(v,a)f(a)\, da \tag{3}$$

$K(v,a)$ is the scattering intensity as a function of the angle of the scattered light, v and radius of the particle, a. The Light intensity data, $I(v)$ is measured by the photodetector and the inverse problem of particle size measurement is used to obtain the expression of particle size distribution $f(a)$ from $I(v)$[19].

The PM sensor is connected to the microprocessor by an adapter through serial communications line. The sensor transmits data to the microprocessor in the form of 32-bit data which represents the concentration of PM 1, PM 2.5 and PM 10. This signal is then processed by the microprocessor using the FFT and

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MIE scattering algorithm before the data is display to the TFT display.

Temperature and humidity sensor: Temperature and Humidity sensor was added to the system to aid in further scientific study of PM distribution as well as for calibration purposes. Previous study have shown that there is strong correlation temperature and humidity towards the PM distribution [20]–[22] hence the integration of these sensor will further enhance the detection system. The sensor offers reliable continuous monitoring of Humidity and temperature with accuracy of ±5 %RH for humidity and ±2 ◦C for temperature. The sensor has a similar response time with the PM sensor making it compatible with the detection system operation. On normal condition, the sensors have the capability to detect humidity up to 80 %RH and temperature up to 50 ◦C which is within the desired range of detection system. The sensor is connected to the microprocessor via Serial interface (Single-Wire Two-Way) transmitting 40-bit data which represents the ambient RH and Temperature information.

Data logger

Real time clock: Integration of real time clock (RTC) onto the system operation is to provide temporal resolution of particulate matter monitoring. Various studies have shown that the distribution of PM varies depending on the time of the day[23]–[25] hence the addition of RTC allows continuous temporal analysis of the PM monitoring system. The RTC offers continuous counts of seconds, minutes, hours, date of the month, month, day of the week, and year with leap-year compensation valid up to 2100 with 4.7V operating voltage. The RTC unit is connected to the Arduino via I^{2}C interface transferring data serially through an I^{2}C, bidirectional bus.

Data logging: To provide on-board real-time data logging system, an SD card function is implemented to the overall design of detection system. This is to allow continuous monitoring of PM with minimal handling effort thus making the detection system semi-autonomous. The data logger saves all the data in the form of txt. File which can easily be access by general CPU consumer. All the data will be uploaded at a rate of every 10 minutes and can retain up to 1440 data.

Enclosure

A custom made 3D printed enclosure was design from a light weight material to accommodate all the sensor in a compact portable form. This study utilizes the 3D printing technology to allow customization of the enclosure so that the sensor can be placed ergonomically within the unit. The enclosure is printed with durable PLA materials which protects the sensor from environmental factors with minimal weight compensation. The dimension of the enclosure is as shown in Figure-3.

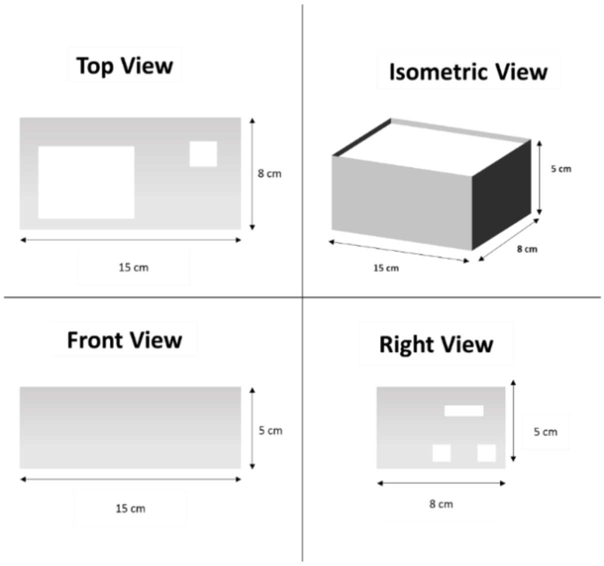

Figure-3. 3D view of the system enclosure.

Overall, a compact enclosure was constructed with a 3D printer. The weight of the integrated enclosure and detection system is less than 700 g making it portable and convenient for in-situ monitoring usage. The final product of the printed enclosure is as shown in Figure-4.

Figure-4. Completed 3D printed enclosure.

Main controller

The micro processing unit used in the detection system is Arduino mega 2560. This controller is used instead of the conventional Arduino Uno board to accommodate the number of digital pins needed for the overall system operation. The Arduino mega come with a bigger Random access Memory which is needed to support the system complex algorithm. The Arduino board acts as the central processing unit, encoding all the information from the sensor before displaying the data onto the TFT display .The Arduino board also acts as a regulated power supply that supply the sensor with 5 V voltage supply. The left out Available I/O pin can be used to connect more sensors in the future. Table 2 shows the summary of the microcontroller specifications.

Display

TFT display is used to provide interactive monitoring of all the readings as well as for easy data collection. Real time reading obtains from each the sensor is displayed on the TFT at every one minute interval. Time

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and date are also displayed to allow temporal monitoring. An interchangeable color ring meter was integrated on the display to make the detection system more interactive. The overall graphical user interface is shown in Figure 5.

Figure-5. System graphical user interface (GUI).

5. SOFTWARE DESIGN

The software design provides smooth symbiotic system integration between all the sensors. The program that is used to construct the system software design is basic C programming language on an Arduino IDE platform. The software works by firstly initializing the microcontroller board all the sensor unit. Once initialized, the reading of RTC, Temperature and Humidity and PM will be obtained. This data will then be send to the data logging system before display onto the TFT display.

Additional PM quality control function is integrated into the software design to send alert if certain threshold limit is exceeded. The execution time for the overall system software can be done under one minute, however, to avoid accumulation of data, the software is set to refresh at every 10 minutes interval. The flowchart of the software design is as shown in Figure-6.

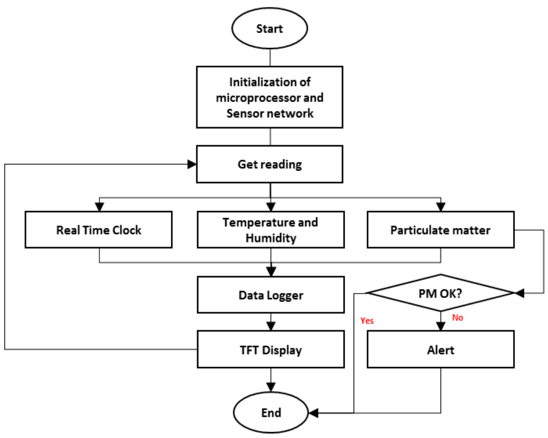

Figure-6. Flowchart of software design.

6. RESULTS

Preliminary accuracy assurance of developed prototype To ensure the accuracy of the constructed monitoring system, a calibration test was conducted by comparing data from the system with the gravimetric method. This is essential step in the development of the system since previous study documented a slight deviation between the result obtain from laser scattering and the conventional gravimetric measurements method when the size distribution of the airborne particles differs significantly from the size distribution of the test aerosol [26].

In this study, the constructed system was tested with TE 6001 PM10 Air Sampler which is a federal reference instrument used to determine the concentration of particulate matter in industrial scale. The TE 6001 is only capable of reading PM 10 concentration using gravimetric method thus test was conducted by comparing the PM 10 concentration obtained from both system over a period of 24 hours. The test was conducted at an outdoor environment at Marina Café, University Malaysia Sabah (UMS) to simulate the real-life application of both systems. The test was conducted within two days to obtain 24 hours period from 11:00 AM to 18:30 PM for the first day and 05:30 AM to 11:30 AM on the second day. The results of the PM calibration test are as shown in Table-3.

The test is conducted within 24 hours period by obtaining 29 sets of data from the developed system and 1 sample data from the TE 6001 PM10 Air Sampler through the conventional gravimetric method. The data from the develop sensor was then averaged and compared with the reference instrument. Based on the results, it was observed that the accuracy of the PM sensor compared with the reference instrument is 87.7 %. This is an acceptable range of accuracy for the develop system although longer monitoring period is needed to validate this information. The Temperature and humidity sensor were also tested simultaneously using the digital hygrometer. The test was conducted on the same day as the PM sensor calibration over a period of 24 hours. Figure-7 shows the temperature and humidity reading obtained from the DHT11 and digital hygrometer plotted against time.

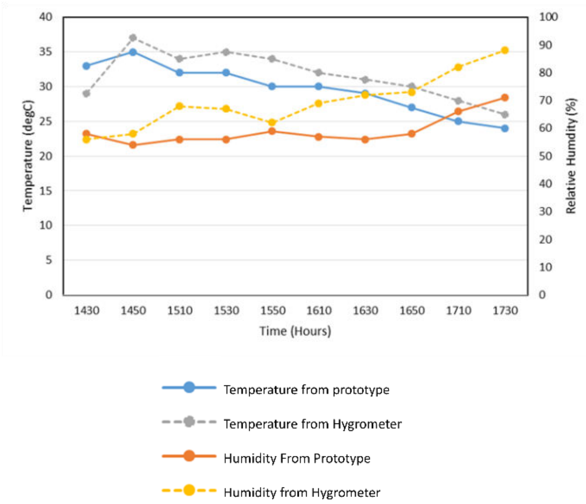

Figure-7. Graph of temperature and humidity against time.

A graph of correlation for temperature and humidity was plotted to see the relationship between the temperature and humidity of the developed system and the hygrometer. Figure-8 shows correlation analysis between the two sensors.

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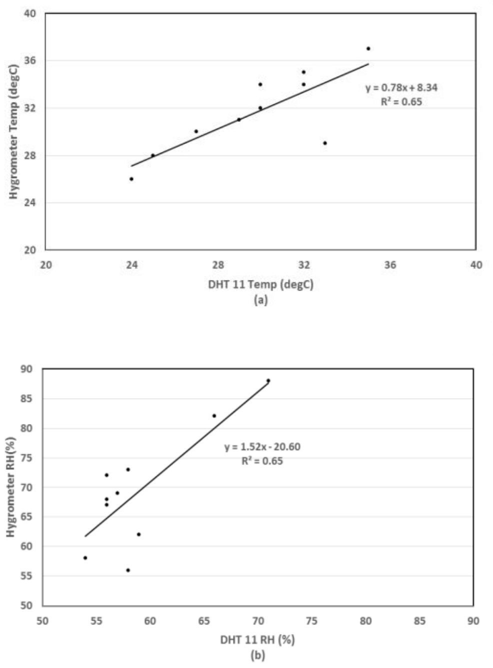

Figure-8. Correlation analysis between DHT 11 sensor and hygrometer.

The results obtained for the correlation between the DHT 11 and Hygrometer for temperature (a) and humidity (b) reading shows a positive R^2 trend line > 0.65 suggesting a one-to-one positive regression. The developed prototype is able the mimic the reading of the conventional digital Hygrometer with a slight deviation of around ±2 °C for temperature and around ±8 %RH for humidity. Overall, the preliminary test conducted in this study show promising results for real application of the However, further studies is needed to validate the data before it can be used for industrial purposes

7. CONCLUSION AND FUTURE WORK

This study had presented a novel real-time particulate matter monitoring system in the form of portable device with ease of handling using off-the-shelf consumer electronics. The systems offers particulate matter detection based on laser scattering principle with a considerable accuracy of 87.7 % in comparison with the TE6001 PM10 air sampler which uses the conventional gravimetric method.

The state of the art of this system is its ability to provide an in line monitoring to obtain in situ data on the PM concentration. To add in the functionality of the detection system, temperature and humidity sensor was added which allow further scientific related study of PM distribution as well as for calibration purposes. The embedded on-board data logging system enables continuous monitoring of PM with minimal handling effort thus making the system a semi-autonomous system. Integration of TFT display with interactive graphical interface makes the system more convenient for users from all backgrounds.

In future works, the detection system will be added with internet of things (IoT) functions via cloud database application. This is to allow remote monitoring of PM and to make the data more accessible for general and scientific use. To achieve a high-end monitoring system, more robust calibration will be conducted. Once conducted, data correction will be made to meet the needs of industrial accuracy. The final product of this study is aimed to provide transparency in particulate matter monitoring with ease of handling.

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