Measurement of PM$_{10}$ concentration using hybrid cyclone separator and particle counter

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Abstract. Commercial air quality monitoring systems can measure PM$_{10}$ very precisely and accurately but are expensive to procure and maintain. The research objective was to design a portable, easy-to-handle, real-time PM$_{10}$ monitor using a particle counter PPD42NS, cyclone separator, vacuum pump, temperature, relative humidity, and air pressure sensors types BMP085 and DHT22. A comparative study of meteorological factors between Vantage Pro 2 and the BMP085 and DHT22 sensors shows a positive linear correlation. The sensor was used to correct the air sample flow rate in the PM$_{10}$ concentration formulation. The air sample flow rate is stabilized at 0.7 L min$^{-1}$ so that the cyclone separator can work optimally. The particle size analyzer (PSA) analysis results show that the cyclone separator can separate particles less than ten microns in size at locations with low, medium, and high PM$_{10}$ conditions. PM$_{10}$ obtained from the separation process was measured with a PPD42NS particle counter and was successfully converted into mass concentration using a mathematical formula on the microcontroller. The PM$_{10}$ monitoring system was tested for 24 hours in the wood processing area with a concentration of PM$_{10}$ 278.5 μg cm$^{-3}$, which was categorized as unhealthy.

1. Introduction

Air is an essential element to support human life. Air pollution describes a diverse and complex mixture of chemical, particulate, or biological materials in the ambient air, which can harm the living organisms. Particulate Matter (PM) is one of the dangerous pollutants, classified by size into PM$_{10}$, PM$_{2.5}$, and PM$_1$, which have a mass median aerodynamic diameter fewer than 10 μm, 2.5 μm, and 1 μm, respectively. PM$_{10}$ has a more comprehensive size range than other PMs, and it makes PM$_{10}$ has many health effects. Many epidemiologic studies have already proved that a high concentration of PM$_{10}$ (20 μg m$^{-3}$) causes more coughing, respiratory problems, bronchodilator use, and even mortality [1,2]. Therefore it is crucial to monitor the concentration of PM$_{10}$ to assess the ambient air quality.

There are at least two sampling methods for PM$_{10}$ concentration monitoring, namely the cascade impactor and the air sampler. The essential components of cascade impactor are several impactor stages, impaction plate, and nozzle. When accelerated in the nozzle, those particles with sufficient inertia will strike the impaction plate to be collected in a backup filter downstream stage by stage. Determine the mass of particles collected by weighing each stage before and after sampling [3]. Impaction substrates are usually coated with adhesive agents to minimize the bounce-off and re-entrainment of particles, which is a significant problem in applying impactors [4]. The air sampler consists of low volume air sampler (LVAS) and high volume air sampler (HVAS), where both apply the gravimetric principle. The
U.S. EPA has designed a reference method for total suspended particulate matter (TSP) and PM$_{10}$ using Andersen model GUV-16H high volume air samplers equipped with size-selective inlets and an adequate aerodynamic size of fewer than ten microns [5]. HVAS apparatus is provided with a vacuum pump to collect air samples. Like the impactor mechanism, a particulate matter in the air sample was trapped in a membrane-type filter before air entered the inlet manifold [6]. This method also has several difficulties, since the filter should be replaced regularly by the new one, so it is cost consuming.

Studies on low-cost particulate matter monitor using particle counters for outdoor or indoor have been intensively investigated in the last years. The corresponding particle counters’ advantages are their mobility, ease of use, and ability to measure particle concentrations over short time intervals. They can provide good approximations of real exposure in various situations [7]. The PPD42NS sensor from Shinyei Corp. has been widely used at some PM monitoring as it was done [8–10]. The PPD42NS sensor has a partially enclosed chamber with a single light-emitting diode, a plastic lens, and an optical receiver. The resulting signals from the detection of scattered light are passed through filtering and amplification circuitry that are externally visible on the PPD42NS [8,10]. The capability of the PPD42NS sensor can count particles that are larger than one micron in size. However, the flow rate and maximum length of lofted particles are not already specified, and it became a significant problem in its usage. Almost all previous research handles the situation using other data from the commercially available instrument to compare and do the calibration with their data. [8] Used the PPD42NS sensor to do field calibration using 24 h averages PM$_{2.5}$ data from a reference instrument with FEM status. [9] Characterized the PPD42NS in field conditions and against a variety of reference instruments. [10] Evaluated indoor air quality instruments compared with Dylos DC1100 pro.

Based on the facts mentioned earlier, the research objective was to design a more specific PM10 measurement system using a particle counter and cyclone separator. The cyclone separator’s ability to separate the corresponding particulate matter was examined by the Particle Size Analyzer (PSA) device. It is expected that this combination may lead to an accurate measurement result.

2. Material and Method

2.1. Device development
A low-cost and maintenance PM$_{10}$ measurement instrument was designed in such a way so it can be used continuously, and the measurement results can be obtained quickly. The main parts of this system were the PPD42NS sensor for counting the particle concentration and coupled with a cyclone separator as a PM$_{10}$ selector. The instrument was set up through several steps, which were a fabrication of cyclone separator and vacuum pump, acquisition of the electronic system, mechanic and electronic system, and calculation of PM$_{10}$ concentration (Figure 1).

2.2. Vacuum pump
A vacuum pump was designed to pump dust particles and air into the cyclone. According to the previous analysis, the flow rate must stable at 0.7 L minute$^{-1}$. The flow rate was affected by two parameters, battery voltage and Pulse Width Modulation (PWM) value. The vacuum pump was fabricated by 12 VDC motor. However, the microcontroller has a maximum voltage of 5 V. Voltage divider circuit can accommodate this gap by converting 12 V battery voltage to 3.31 V. Microcontroller read the analog to digital (ADC) value at the A1 pin. Changes in ADC value can detect any changes in motor speed caused by battery voltage drop. PWM controller was connected to the microcontroller using TIP-122 transistors for activating the PWM. When a vacuum pump has been used in several minutes, the battery voltage will drop (as displayed by ADC value), and it leads to the flow rate drop. The PWM should be set at a higher value to increase the flow rate to 0.7 L minute$^{-1}$. These steps are repeated to obtain a correlation between the PWM and ADC values.
Figure 1. Steps to develop the PM\textsubscript{10} measurement system

2.3. Cyclone separator

A vacuum pump draws the cyclone to separate PM\textsubscript{10} from dust particles in the air. Dust moves spherically inside the cyclone, and particles with a diameter size of more than ten microns will hit the cyclone wall and fall to the bottom of the cyclone, while PM\textsubscript{10} exit to the outlet then enters the inlet of the PPD42NS sensor. The ability of cyclone to separate particle size depends on volume flow rate and cyclone geometry [11]. For the geometry, a 2D2D model cyclone separator was used (Figure 2a and 2b), which its design has been proposed by [12,13]. Meanwhile, for the volume flow rate, according to [12,13], the volume flow rate on the 2D2D model cyclone should be 0.7 L minute\textsuperscript{-1} to obtain PM\textsubscript{10}.

Figure 2. The geometry of 2D2D model cyclone separator (a), cyclone simulation (b), and 3D printing of cyclone separator (c)

To ensure the particles that exit to the upper part of the cyclone have a diameter size of more than ten microns, they were diluted by 25 mL distillate water in impinger and analyzed by Particle Size Analyzer (PSA). The PSA gave an average of particle size ($D_{\text{mean}}$). A performance test of cyclone separator was needed to convince that cyclone works well. It was conducted at three different locations, i.e., Wageningan laboratory, Dramaga main road, and the wood processing site of Ciampea.
2.4. Shinyei PPD42NS sensor
The PPD42NS particle counter features a single light-emitting diode, plastic lens, and optical receiver at a 45° front angle. Dust particle which enters the PPD42NS sensor through the inlet will hit the infrared wave, which was emitted by a light-emitting diode and generate the scattered light. The optical receiver will detect this phenomenon so that the sensor will send digital logic as 0. Inversely, when there is no particle, the optical receiver will detect non-scattered infrared so that the sensor will send digital logic as 1. The relationship of 30 seconds integrated duty cycle was expressed by a full percentage scale (% FS) with a total particle number of more than 1 micron per 0.01 cubic feet. The microcontroller's tasks program was to measure % FS value to calculate dust concentration (pieces 283 mL⁻¹) and record the values into micro SD. The 30 seconds integrated duty cycle of this PWM signal has a positive correlation with cigarette smoke, has a zero intercept, and a slightly sub-linear response on higher concentrations [13]. The sampling on sensor performance tests conducted in the isolated state (the air could not pass in the sensor because of its cover), opened (the cover opened), and smoked (burning some papers) conditions.

2.5. BMP085 and DHT22 Sensor
The BMP085 and DHT22 sensors are used to measure temperature, pressure, and relative humidity [14] and stated that mass concentration in PM₁₀ corresponded with peaks on the relative humidity and the ambient temperature. Data from both sensors were used to correct the volume flow rate during measurement. This correction was needed because the metrology parameter may change during measurement, and it will influence the airflow. Eq. 1 state that volume flow rate correction at standard condition (25 °C, 760 mmHg), Qₛ is the corrected volume flow rate (m³ minute⁻¹), Qₒ was the tested volume flow rate (m³ minute⁻¹), Ts was the standard temperature (298 K), To was the tested temperature (K), Ps was the standard barometric pressure (101.3 kPa), and Po was the tested barometric pressure (kPa). The second correction was on a air volume using Eq. (2) where V was the air volume (m³), Qₛ₁ was the corrected volume flow rate 1, Qₛ₂ was the corrected volume flow rate, and T was the sampling time.

\[
Q_s = Q_o \cdot \left[ \frac{T_s - P_s}{T_o - P_o} \right]^{\frac{1}{2}}
\]

\[
V = \frac{Q_{s1} + Q_{s2}}{2} \cdot T
\]

Performance test of BMP085 and DHT22 sensors were needed to convince that sensor works well. The sensors are compared to the Vantage Pro 2 automatic weather station by Davis Instruments, a civil engineering and environmental department facility.

2.6. Integration of PM₁₀ instrument
The PM₁₀ measurement system was designed in two main steps to display real-time measurement results on alpha-numeric LCD: fabricating the electronic hardware and programming the system (Figure 3). Microcontroller programming using the C language developed by Arduino IDE 1.0.5. Data were formatted on micro SD media that was easier to be interpreted by the user. Figure 4 shows the integration scheme of the PM₁₀ measurement instrument. The instrument is attached to the enclosing box with an aluminium structure, which has a height of 1.5 m.

2.7. Calculation of PM₁₀ concentration
PM₁₀ measurement was conducted continuously (24 hours) at the wood processing site of Ciampea, Bogor. Measurements using PPD42NS produce concentrations in units of L⁻¹ pcs, whereas according to regulations, it must be µg m⁻³. On the cyclone separator's performance test, there was D_mean value, which was the average particle size (diameter size). D_mean was used to calculate the average particle volume using Eq. 3. If all particles, which were counted by using PPD42NS and measured by using PSA, were
spheres [15] with a mass density of 1.65 g cm\(^{-3}\) [16], that mass for one particle is obtained using Eq. 4. Total particle mass during measurement, which was obtained from one particle mass, was crossed by a total particle number (Figure 4) using Eq. 5.

\[
V_{\text{particle}} (m^3) = \frac{\pi}{6} \cdot [D_{\text{mean}}]^3
\]

(3)

\[
m_{\text{particle}} (\mu m) = \rho \cdot \left( \frac{g}{cm^3} \right) \cdot 10^{12} \cdot V_{\text{particle}}
\]

(4)

\[
C_{PM_{10}} (\mu g / m^3) = N_{PM_{10}} \cdot m_{\text{particle}}
\]

(5)

**Figure 3.** Electronics integration

**Figure 4.** Calculation Flowchart of PM\(_{10}\) concentration

3. Result and discussion

3.1. Vacuum pump performance

Table 1 shows time-series data from the vacuum pump's performance test, which is deployed about 509 minutes. The maximum value of battery voltage (fully charged battery) is 12.03 V, while the minimum value is 9.28 V. Then voltage divider converts them into 3.31 V and 2.46 V, respectively. This voltage value is converted into a digital value in the form of ADC without units. The PWM must be raised to a certain value to keep the volume flow rate stable at 0.7 L minute\(^{-1}\) (Figure 5b), compensate for the drop on battery voltage. Figure 5a shows the inversely proportional relation between PWM and ADC values. PWM and ADC values are in the range of 31 to 61 and 503 to 677, respectively. The linear regression of PWM to ADC is \(Y = -0.167x + 142.9\), where \(Y\) is PWM value, and \(x\) is ADC value. This equation
was then inserted into the microcontroller so that these PWM values will change automatically
appropriate with changes in ADC value. This equation is then entered into the microcontroller so that
the PWM value will change automatically according to the ADC value change so that the air volume
flow rate is stable at 0.7 L minute⁻¹. The air volume flow rate's stability must be maintained properly so
that the cyclone separator can work optimally to separate particulate sizes less than ten microns from
other dimensions. The vacuum pump and the cyclone separator mechanism are essential to ensure that
the particle counter detects and measures particulates under ten microns in size.

Table 1. The performance test result of the vacuum pump

| No | PWM (unit less) | ADC (unit less) | Voltage in A1 (Volt) | Battery Voltage (Volt) | Cyclone separator Flow rate (l/min) | Measurement time (min) | Time Accumulation (min) |
|----|----------------|----------------|----------------------|-----------------------|-----------------------------------|------------------------|------------------------|
| 1  | 31             | 677            | 3.31                 | 12.03                 | 0.7                               | 67                     | 67                     |
| 2  | 32             | 675            | 3.3                  | 11.84                 | 0.7                               | 178                    | 245                    |
| 3  | 33             | 655            | 3.2                  | 11.52                 | 0.7                               | 68                     | 313                    |
| 4  | 34             | 651            | 3.18                 | 11.46                 | 0.7                               | 68                     | 381                    |
| 5  | 35             | 636            | 3.11                 | 11.26                 | 0.7                               | 57                     | 438                    |
| 6  | 38             | 620            | 3.03                 | 11.02                 | 0.7                               | 20                     | 458                    |
| 7  | 40             | 612            | 2.99                 | 10.87                 | 0.7                               | 17                     | 475                    |
| 8  | 41             | 598            | 2.92                 | 10.68                 | 0.7                               | 14                     | 489                    |
| 9  | 47             | 567            | 2.77                 | 10.22                 | 0.7                               | 12                     | 501                    |
| 10 | 61             | 503            | 2.46                 | 9.28                  | 0.7                               | 8                      | 509                    |

Figure 5. Correlation between PWM and ADC (a), and stability of the air volume flow rate by
changing the PWM value automatically (b)

3.2. Cyclone separator
Analysis of PSA in areas with fewer particulate sources in the Wageningan Laboratory, the particulate
size ranges from 281.9-5890 nm with an average size of 1245.8 nm (Figure 6a). In the medium
particulate source area on the Dramaga highway, it ranges from 1622.2-4678.6 nm, with an average size
of 2802.4 nm (Figure 6b). In the area of high particulate sources at the wood processing site ranged from
102.4-9774.96 nm with an average size of 2170.8 nm each (Figure 6c). Based on the results of the
particle size analysis from three locations with different environmental conditions, it can be seen that
the particle size range does not exceed 10,000 nm or 10 microns. Therefore, the cyclone separator can
separate particles less than ten micro sizes for integration with the PPD42NS particle counter.
Figure 6. Distribution of particulate sizes in Wageningan Laboratory (a), Dramaga main road (b), and Wood processing sites (c)

3.3. PPD42NS performance
PPD42NS performance test in isolated conditions, as shown in Figure 7a. The lone state means that the sensor inlet and outlet are closed so that particles do not pass through the sensor inlet. The test results
show that the sensor performance is almost perfect, where the PM$_{10}$ concentration during testing is stable at 0.6 pcs (283 mL)$^{-1}$. Particle counter-performance test in an open state means particulate can pass through the outlet and inlet, as shown in Figure 7h, shows that the particles are in the range of 142.9 pcs (283 mL)$^{-1}$ to 4516.04 pcs (283 mL)$^{-1}$. Sensor performance test in the smoke condition, as shown in Figure 7c, the particles are in the range of 5050.12 pcs (283 mL)$^{-1}$ to 40747.09 pieces (283 mL)$^{-1}$. Based on the data, it can be concluded that the particle counter can work well in the conditions of few or many particles. Hence, the PPD42NS sensor has the potential to detect particulates in the air. Figure 7d shows the PPD42NS integrated into a plastic case.

![Figure 7](image)

**Figure 7.** Particle concentration data in the isolated state (a), in an opened state (b), in the smoked state (c), and illustration of PPD42NS particle counter performance test in isolated condition (d)

### 3.4. BMP085 and DHT22 Sensors

Comparison of the results of temperature, pressure, and relative humidity measurements using sensors BMP085 and DHT22 against Vantage Pro 2 for two hours at the Automatic Weather Station, Department of Civil and Environmental Engineering facility as shown in Figures 8a, b, c, and d shows the correlation of each are 0.93, 1.0, and 0.96, respectively. Figures 8e and 8f show the results of temperature, pressure, and air relative humidity for 24 hours on other days, respectively 26.95 °C, 99.09 kPa, and 83.2%. The maximum values are 32.6 °C, 99.24 kPa, and 88.9%, and the minimum values are 25 °C, 98.90 kPa, and 59.5%, respectively. Furthermore, the deviation values are 1.67, 107.09, and 6.57. Based on these results, the BPM085 and DHT22 sensors have the same measurement results and data patterns as the
Vantage Pro 2. Therefore, the BMP085 and DHT22 Sensors can be integrated with the cyclone separator and particle counter into a complete instrumentation system.

Figure 8. Fabrication of BMP085 and DHT22 sensors (a), comparison of temperature (b), comparison of air pressure (c), comparison of air relative humidity (d), temperature and air pressure measurement 24h (e), and air relative humidity measurement 24h (f)
3.5. Calculation of PM$_{10}$ concentration

After all parts of the system have been tested separately and show a good result, the next step is the final integration system. The performance test of it is conducted at the wood processing site, Ciampea, Bogor. Figure 9a shows the measurement result of PM$_{10}$ concentration every 3 seconds for 24 hours, and Figure 9b shows a similar result with a modified unit. There are three peaks marked by 1, 2, and 3, which occurred since the door sanding and woodcutting. The concentration of PM$_{10}$ at index 1, 2, and 3 are 0.58 $\mu$g m$^{-3}$, 0.6 $\mu$g m$^{-3}$, and 0.34 $\mu$g m$^{-3}$, respectively. The accumulation of PM$_{10}$ concentration after measurement, as seen in Figure 9c, is 278.5 $\mu$g m$^{-3}$, and this is the main value for calculating the air quality index. The air quality results are in the range of 101 - 199, which means that the air quality around the wood processing site at Ciampea Bogor belongs to the unhealthy category.

![Figure 9](image_url)

**Figure 9.** Dust concentration by PPD42NS sensor (a), dust concentration with a modified unit (b), and accumulated dust concentration (c)

4. Conclusion

In this study, the design and testing of the PM$_{10}$ measuring instrument were successful. The vacuum pump has worked well to keep the airflow rate at 0.7 L min$^{-1}$. This airflow rate is sufficient to separate PM$_{10}$ particles from other dust in the 2D2D model cyclone separator. The output data from the ppd42ns sensor can be converted into particulate concentration values in units of mass concentration. The PM$_{10}$ performance test was conducted at the Ciampea wood processing location with a PM$_{10}$ concentration of
278.5 μg m\(^{-3}\) and was categorized as unhealthy. A larger number of samples and PSA analyses are needed so that the research results are accurate. Besides, the PM\(_{10}\) measuring instrument needs to be calibrated with a standardized tool such as HVAS so that the measurement results can be validated so that the resulting data is accurate.

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