Songklanakarin J. Sci. Technol.
40 (2), 347-353, Mar. - Apr. 2018

http://www.sjst.psu.ac.th

*Original Article*

# Field evaluation of an electrostatic PM2.5 mass monitor

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Received: 2 November 2016; Revised: 7 December 2016; Accepted: 1 January 2017

**Abstract**

An electrostatic PM2.5 mass monitor (EPMM) used for wireless continuous airborne particulate matter monitoring was developed and field evaluated in our previous work. Developed electrostatic PM2.5 mass monitor was consisted of a 2.5 impactor, a particle charger, a Faraday cup electrometer, a flow system, a high voltage power supply, and data acquisition, processing, and wireless monitor system. The monitoring data of the EPMM was connected to the internet through a GSM connection to a public cellular network. In this study, the EPMM performance was simultaneously evaluated and compared with a commercially available Thermo Scientific Model 5014i Beta Continuous Particulate Monitor for PM2.5 measurements at ambient conditions. The monitoring station was located in Yupparaj Wittayalai School, Si Phum, Mueang, Chiang Mai, Thailand, during October 15 to November 5, 2015. The two different instruments showed good results that were highly correlated. It was found that the comparison between the EPMM and the Thermo Scientific Model 5014i Beta data values were $R^2$ of 0.8230 and 0.9811, and a slope of 1.0231 and 0.8802 for 1-hour and 24-hours, respectively. Particularly, it was showed that the EPMM proved its advantages in measuring and detecting PM2.5 particulate air pollution for mass concentrations in the range from 0 to 500 µg/m$^3$ and with greater than 500 hours of operation.

**Keywords:** particulate matter, PM2.5, mass monitor, electrostatic, wireless

## 1. Introduction

A regulation for the PM2.5 mass concentrations was promulgated by the U.S. Environmental Protection Agency (U.S. EPA). It was defined to as particulate matter (PM) with an aerodynamic diameter less than or equal to 2.5 µm. Both outdoors and indoors, PM2.5 measuring and sampling could be performed by a mass concentration method in micrograms per cubic meter (µg/m$^3$) (EPA, 1997). Generally, the federal reference method (FRM) for the PM2.5 standards is based on the gravimetric analysis, determination of particulate concentration based on weight difference, of particulate collected on filters over a period of 24 hour (Dockery *et al.*, 1993). The gravimetric analysis was selected because most of particulate data used for epidemiological studies investigating relationships between mortality and morbidity outcomes and ambient PM2.5 exposures are based on filter measurements (EPA, 1997).

However, disadvantages of the PM2.5 FRM were presented the following as i) a sequential sampling unit for collecting PM2.5 2 to 7 daily samples per week is desired; ii) it desires both an environmental control balance room and extensive laborer for weighting the filters; and iii) it does not provide fast response or real time measurements. High investment and laborer costs could be significant for implementing the fine particulate mass standard, while very small will be studied about the diurnal variability of the mass concentrations of fine particulate (Babich *et al.*, 2000). A 24-hour average measurement of PM2.5 may not sufficiently indicate human exposure actually. Therefore, an automatic and continuous particulate mass monitor was desired. It was capable to provide accurate hourly PM2.5 measurements are essential for

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exposure assessment. For both understanding particulate health effects and developing sound mitigation strategies, detailed instantaneous information is desired. Since its sensitivity, the gravimetric method might not be sufficient to obtain fast response or real time measurements, less than 1 to 24 hour. Additionally, attempts to obtain a finer resolution on mass concentrations of ambient PM2.5 on a regular basis using filter based methods for large monitoring networks are cost-prohibitive and impractical. Finally, the proposed PM2.5 FRM cannot provide the immediate data that are necessary to calculate the air quality index (AQI) (Babich *et al.*, 2000).

A number of techniques have been incorporated into instruments to achieve automatic and continuous (or at least near real-time) airborne PM2.5 mass monitoring. Some of these instruments include the beta ray absorption, the light scattering, the quartz microbalances, and the electrostatic charge monitors. Each instrument has been used more or less successfully by specific researchers, but all those instruments for particulate monitoring somehow have significant disadvantages (Babich *et al.*, 2000; Koch *et al.* 1999; Lee *et al.*, 2001, 2005; Lippmann *et al.*, 2000; Misra *et al.*, 2001; Patashnick & Rupprecht, 1991;). Over the past decade, a new technology has occurred providing a new method for fast response monitoring of PM2.5 mass concentration. The technique bases itself on an electrostatic charge method. Typically, an electrostatic charge method includes two main components, one for particulate charging and the other for detecting the electrostatic charge current on the particulate with an ultra-low current ammeter. The output signal of the ammeter depends strongly on the particulate charging technique used. Intra and Tippayawong (2007) have reviewed the recent aerosol instrument developments based on an electrostatic technique. These instruments are widely used for detecting and measuring airborne aerosol particles, and providing fast response and high resolution measurements (Fatokun *et al.*, 2008; Intra *et al.*, 2013; Johnson *et al.*, 2002; Lanki *et al.*, 2011; Lee *et al.*, 2001; Li *et al.*, 2009a, 2009b; Murtomaa *et al.*, 2005; Ntziachristos *et al.*, 2004; Rostedt *et al.*, 2009; TSI Incorporated, 2002; Wei, 2007). However in measuring and monitoring of PM2.5, the ease of moving a PM2.5 mass monitor should be considered. It should be portable and easy to use, and its maintenance must be possible by relatively low skilled laborers. Therefore, a wireless portable particulate mass monitor is desirable for continuous ambient air pollution measurements. In the last decade, wireless particulate monitor systems have been designed and developed by numerous researchers for measuring real-time particulate mass concentrations (Al-Ali *et al.*, 2010; Bhattacharya *et al.*, 2012; Khedo *et al.*, 2007; Park *et al.*, 2013; Zhang & Li, 2015). However, these systems tend to be relatively large units, not suitable for integration within other compact devices. They are also fairly expensive with typical starting prices greater than ten thousand U.S. dollars. Because of the large number of measuring stations distributed in the region, a wireless monitor system of particulate mass concentration must have an inexpensive and continuously give fast response measurement of ambient particulate matter. In our previous work, Yawootti *et al.* (2015) was evaluated in a field study of an electrostatic PM10 mass monitor (EPMM) for continuous measuring of ambient particulate air pollution. In the authors work, the performance of the EPMM was field evaluated simultaneously with a commercially available TEOM (Tapered Element Oscillating Microbalance) series 1400ab ambient particulate monitor, Thermo Fisher Scientific Inc., for measurements of PM10 mass concentration at ambient conditions. Good agreement and high correlation was found between the EPMM and the TEOM in measuring ambient PM10. However, a field study of ambient continuous PM2.5 monitoring and comparison of the EPMM with other particulate measuring devices has not been extensively studied in our previous work and literature.

Therefore, an electrostatic PM2.5 mass monitor used for wireless continuous ambient PM2.5 measurements at an inexpensive than commercially available instruments was developed and field evaluated and comparison of the real-time PM2.5 measuring between the monitor and a radiometric or beta ray absorption was carried out in this study. The novel instrument features real-time PM2.5 mass concentration monitoring and wireless monitor system functions. In field evaluation, the developed wireless PM2.5 mass monitor and an existing commercial Model 5014i Beta Continuous Ambient Particulate Monitor, Thermo Fisher Scientific Inc., were installed in the same place, and the two monitors was compared using a simple linear regression analysis on the collected data. The detailed description of the operating principle of the developed wireless PM2.5 mass monitor is also presented and discussed.

## 2. Materials and Methods

### 2.1 Electrostatic PM2.5 mass monitor

The schematic diagram of the electrostatic PM2.5 mass monitor (EPMM) developed in our previous work is shown in Figure 1 (Yawootti *et al.*, 2015). The EPMM consisted of a 2.5 impactor, a particle charger, a Faraday cup electrometer, a flow system, a high voltage power supply, data acquisition, processing, and wireless monitor system. In the EPMM, the mass flow controller and a vacuum pump were used to regulate and control the particulate flow rate in the EPMM system. Sampled particulate was first drawn through a PM2.5 impactor for removal of particulate outside the measurement range, particulates with aerodynamic diameter larger than 2.5 µm. Sampled PM2.5 was then directly introduced into the particle charger for electrostatically charging the particulates by attaching them to ions produced by the unipolar corona discharge inside the charger. After the charger, the charged PM2.5 then entered into the Faraday cup electrometer for measuring electrically charge PM2.5 in a Faraday cup electrometer downstream of the charger. A relationship between time and the mass concentration of PM2.5 was processed and showed by the data acquisition and processing system. The PM2.5 mass concentration, $m_p$, from the Faraday cup electrometer as a function of the charged PM2.5 current, $I_p$, and PM2.5 diameter, $d_p$, could be calculated by (Yawootti *et al.*, 2015)

$$m_p = \frac{\pi}{6}\frac{I_p}{eQ_p}\int \frac{\rho_p(d_p)d_p^3}{n_p(d_p)}\mathrm{d}d_p \qquad (1)$$

where $m_p$ is the PM2.5 mass concentration (µg/m$^3$) and $Q_p$ is the PM2.5 flow rate (m$^3$/s). Equation (3) can be rewritten in the power law form:

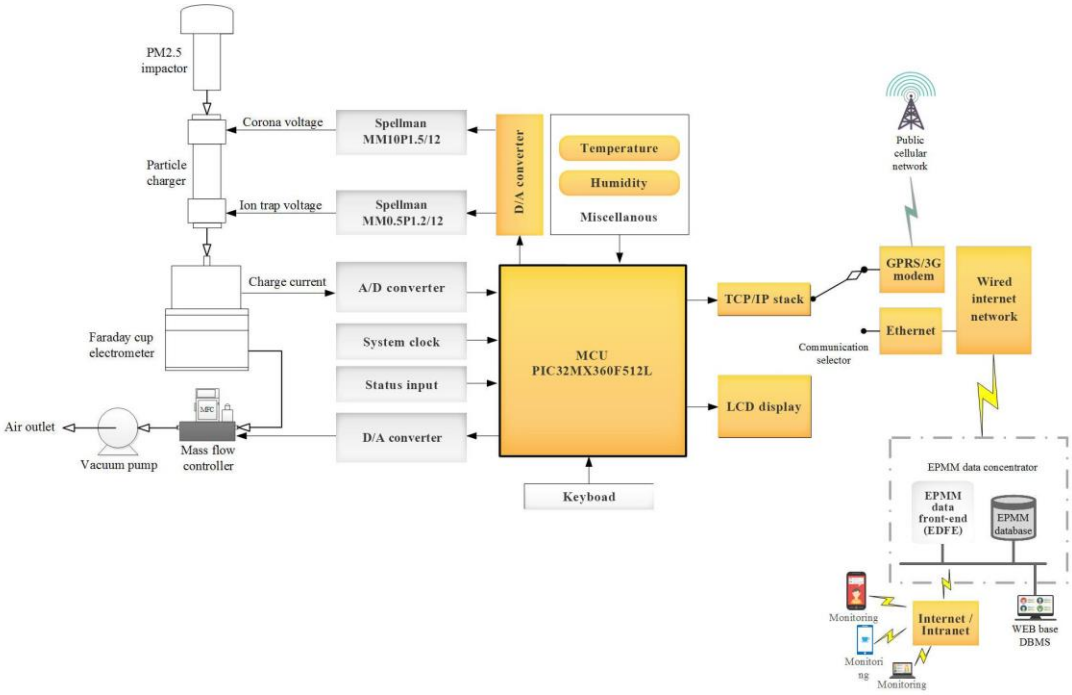



Figure 1. Schematic diagram of the EPMM.

$$m_p = \left( \frac{\pi \rho_p d_p^3}{6 n_p e Q_p} \right) I_p^n \quad (2)$$

In this study, the PM2.5 mass concentrations were empirically determined through regression analysis of the data gathered. Regression analysis is the method by which the U.S. EPA determines correlations between reference and candidate methods for PM2.5 sampling. The PM2.5 mass concentration in μg/m$^3$ is adapted upward using the Equation:

$$m_p = 25.57 \times 10^{12} \cdot I_p^{0.8685} \quad (3)$$

The EPMM could be controlled and data sampled by an external personal computer through a USB/RS-232 port cable. Software running on an external computer was developed based on Visual Basic programming. The software was capable to display the variation of time and PM2.5 mass concentration and the average of the 1-hour and 24-hour PM2.5 mass concentration. For wireless continuous monitoring, the EPMM was also capable connect to the GPRS/3G modem via TCP/IP through the internet and a public cellular network.

## 2.2 Field study setup

The performance of the EPMM was evaluated side by side with a Thermo Scientific Model 5014i Beta Continuous Ambient Particulate Monitor, Thermo Fisher Scientific Inc., readily available. Measurements of PM2.5 mass concentration were done at ambient conditions (Thermo Scientific Inc, 2014). Table 1 shows the comparison between the EPMM and the Thermo Scientific Model 5014i Beta. The Thermo Scientific Model 5014i is one of the few continuous monitors established as an U.S. EPA equivalent method for PM2.5 monitoring, No. EQPM0609-183. The Thermo Scientific Model 5014i Beta continuous ambient particulate monitor is continuously measured the PM2.5 mass concentration of suspended and refined particulates by using the radiometric principle of beta attenuation through a known area on a fibrous filter tape for continuously detecting the mass of deposited ambient particles. The measurement range of the PM2.5 mass concentration of the Thermo Scientific Model 5014i beta was about 0 to 10,000 μg/m$^3$ with a resolution of about 0.1 μg/m$^3$ and a measurement time of about 60 to 3,600 seconds and 24-hour (Thermo Scientific Inc, 2014).

The inter-comparative study of both mass monitors was evaluated in a field study at the air quality monitoring station of the Pollution Control Department (PCD). This station is located in Yupparaj Wittayalai School, Si Phum, Mueang, Chiang Mai, Thailand. The geographical coordinate information of the EPMM at that location is 18°47'29.1" N and 98°59'19.1" E. Both the EPMM and the Thermo Scientific Model 5014i Beta were collocated inside a trailer with their sample inlets located approximately 1 m above the trailer roof. To avoid potential interferences, the distance between two inlets of both continuous mass monitors was greater than 1 m. Inside the trailer, temperature was controlled at about 25 ºC to maintain suitable operation conditions for the electronic units and the monitors. During the monitoring periods, the daily average temperature was from 27 to 35ºC and the daily average relative humidity was 70–85%. Chiang Mai, Thailand was facing a haze episode that primarily occurs every year towards the end of the dry season between February and April, the average PM2.5 rates were considerably above the country's safety level of 100 μg/m$^3$, peaking at about 200 μg/m$^3$. In this study, the field study was conducted during

Table 1. Comparison between the EPMM and the Thermo Scientific Model 5014i Beta.

| Specifications | EPMM | Thermo Scientific Model 5014i Beta |
|---|---|---|
| Measurement technique | Electrostatic | Radiometric |
| Particulate size range | < 2.5 µm | < 2.5 µm |
| Mass concentration range | 0.01 – 500 µg/m$^3$ | 0.1 – 10,000 µg/m$^3$ |
| Resolution | 0.01 ug/m$^3$ | 0.1 ug/m$^3$ |
| Measurement time | 0.1 – 3,600 sec | 60 – 3,600 sec and 24 hr |
| Data averaging | Every 0.1 sec | Every 1 sec |
| Particulate flow rate | 5 L/min | 16.67 L/min |
| Operating temperature range | 10 – 60 ºC | -30 – 50 ºC |
| Output | RS232/RS485, USB, TCP/IP | RS232/RS485, TCP/IP |
| Dimensions (L x W x H) | 50 × 35 × 20 cm | 58.4 × 42.5 × 21.9cm |
| Weight | 15 kg | 19 kg |
| Electrical Requirements | 100 – 240VAC 50 Hz | 100 – 240VAC 50 Hz |

October 15–November 5, 2015, that was a non-haze episode in Chiang Mai. However, this field study site at Yupparaj Wittayalai School was urban area. Therefore, the main emission source of the PM2.5 in this station came from road traffic, household activities, energy production, building work, shipping and small-scale industry. The urban population is particularly exposed to traffic emissions as these are relatively close to the ground and in the near vicinity of housing. Traffic emissions involve both primary and secondary particles.

## 3. Field Study Results

In this study, the data used were 1-hour and 24-hour average PM2.5 mass concentration levels (in micrograms per cubic meter). The average of the 1-hour and 24-hour PM2.5 mass concentrations were calculated from data collected every 0.1 sec. The total observations for Yupparaj Wittayalai School were 507 hours or 21 days during October 15 to November 5, 2015. The average of the 1-hour and 24-hour PM2.5 mass concentration was calculated to plot the time series for investigating the trend of PM2.5 mass concentration. Figure 2 shows the comparison of 1-hour averages from EPMM and Thermo Scientific Model 5014i Beta at Yupparaj Wittayalai School during October, 15, to November, 5, 2015. There was good agreement for the comparative study. The measured mass concentrations of ambient PM2.5 for both monitors were in the range of 0 to 58 µg/m$^3$. The maximum PM2.5 mass concentrations were about 58 and 49 µg/m$^3$, and the minimum PM2.5 mass concentrations were about 0 and 5 µg/m$^3$, respectively, for the Thermo Scientific Model 5014i Beta and EPMM. Figure 3 shows the comparison of 24-hour averages from EPMM and Thermo Scientific Model 5014i Beta at Yupparaj Wittayalai School during October, 15, to November, 5, 2015. Good agreement was found for the comparative study. The measured mass concentrations of ambient PM2.5 for both monitors were in the range of about 7.5 to 35 µg/m$^3$. The maximum PM2.5 mass concentrations were about 33 and 35 µg/m$^3$, and the minimum PM2.5 mass concentrations were about 8.5 and 7.5 µg/m$^3$, respectively, for the Thermo Scientific Model 5014i Beta and EPMM.

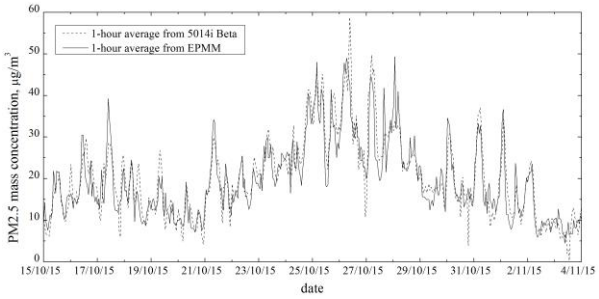



Figure 2. Comparison of 1-hour averages from EPMM and Thermo Scientific Model 5014i Beta at Yupparaj Wittayalai School during October, 15, to November, 5, 2015.

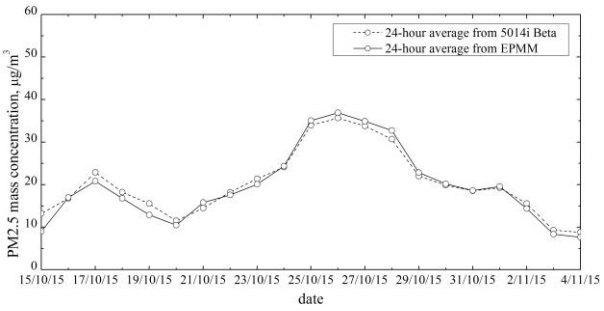



Figure 3. Comparison of 24-hour averages from EPMM and Thermo Scientific Model 5014i Beta at Yupparaj Wittayalai School during October, 15, to November, 5, 2015.

Figure 4 and 5 show the relationship between 1-hour and 24-hour PM2.5 mass concentrations for EPMM and Thermo Scientific Model 5014i Beta at Yupparaj Wittayalai School during October, 15 to November, 5, 2015. Simple linear regression was used for determining the relationship between the EPMM and Thermo Scientific Model 5014i Beta monitors with the slope of the regression. It was well known that the regression analysis is the method the U.S. EPA used for determining the correlations between reference and candidate methods for particulate sampling and monitoring (EPA, 1997). The two monitors were showed good agreement and were highly correlated.

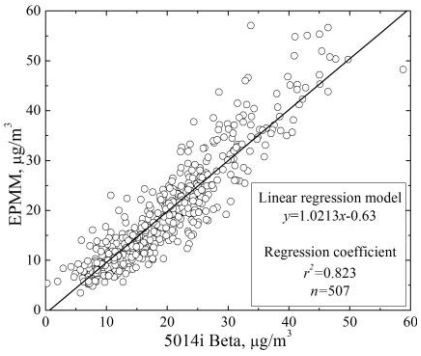



Figure 4. Relationship between 1-hour average PM2.5 mass concentrations for EPMM and Thermo Scientific Model 5014i Beta at Yupparaj Wittayalai School during October, 15, to November, 5, 2015.

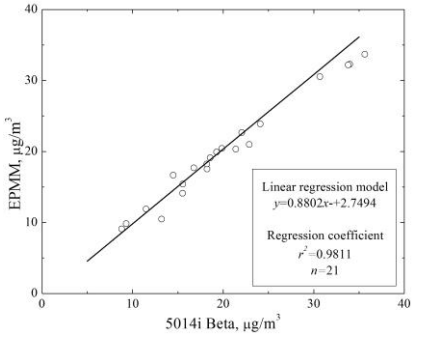



Figure 5. Relationship between 24-hour average PM2.5 mass concentrations for EPMM and Thermo Scientific Model 5014i Beta at Yupparaj Wittayalai School during October, 15, to November, 5, 2015.

Table 2 provides the results of the EPMM and Thermo Scientific Model 5014i Beta monitor measurements. The average EPMM mass concentration for 1-hour was about 19.79 µg/m$^3$ and the average Thermo Scientific Model 5014i Beta mass concentration was about 20.02 µg/m$^3$ with the EPMM to Thermo Scientific Model 5014i Beta mean ratio of 0.9885. The average EPMM mass concentration for 24-hour was about 19.80 µg/m$^3$ and the average Thermo Scientific Model 5014i Beta mass concentration was about 20.18 µg/m$^3$ for the same time period with a EPMM to Thermo Scientific Model 5014i Beta mean ratio of 0.9811. The comparison between the EPMM and Thermo Scientific Model 5014i Beta data resulted in $R^2$ of 0.8230 and 0.9811, and a slope of 1.0231 and 0.8802 for 1-hour and 24-hour, respectively. The difference between 1-hour and 24-hour average is due to the difference in measurement method and time response between both monitors. The EPMM used the electrostatic charge technique and the Thermo Scientific Model 5014i Beta used the radiometric technique or beta ray absorption technique. As shown in Figure 6, the EPMM was set to record PM2.5 every 0.1 sec, averaged over 36,000 data points in 1-hour, while the Thermo Scientific Model 5014i Beta recorded PM2.5 every 1 sec, averaged over 3,600 data points in 1-hour.

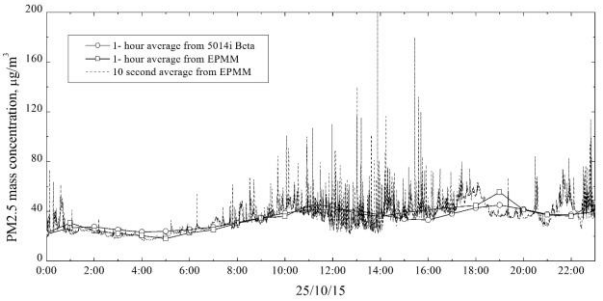
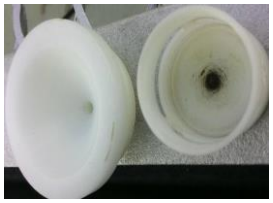



Figure 6. Comparison of 1-hour and 10 second averages from EPMM and Thermo Scientific Model 5014i Beta at Yupparaj Wittayalai School at October 15, 2015.

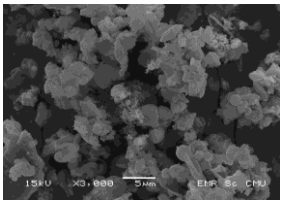
Figure 7 shows the particulate deposition on the impaction plate of the PM2.5 impactor and the corona-needle electrode and ion trap electrode of the particle charger for measuring time of about 507 hours or 21 days. Slightly particulate was deposited on the impaction plate of the PM2.5 impactor and the tip of corona-needle electrode of the charger could be observed and there is no visible particle deposited on the ion trap electrode. The continuous operation of the EPMM did not result in any measurable changes in the performance of the EPMM. This indicated that the maintenance interval (calibration, cleaning, etc.) may be greater than 500 hours of operation at relatively high mass concentrations of PM2.5.

Table 2. Results of EPMM and Thermo Scientific Model 5014i Beta measurements.

| | Average EPMM Concentration (µg/m$^3$) | Average Model 5014i Beta Concentration (µg/m$^3$) | EPMM/ Model 5014i Beta Ratio | Valid sampling day | Correlation ($R^2$) | Slope |
|---|---|---|---|---|---|---|
| 1-hour | 19.79 | 20.02 | 0.9885 | 507 | 0.8230 | 1.0231 |
| 24-hour | 19.80 | 20.18 | 0.9811 | 21 | 0.9811 | 0.8802 |



(a) PM2.5 impactor



(b) Typical particulate morphologies on the impaction plate.

(c) Corona-needle electrode

(d) Ion trap electrode

Figure 7. Particulate deposition inside the PM2.5 impactor and particle charger for measuring time of about 507 hour or 21 days.

## 4. Conclusions

In this work, the EPMM used for wireless continuous airborne particulate matter monitoring was developed and evaluated in a field study. The EPMM included the 2.5 impactor, the particle charger, the Faraday cup electrometer, the flow system, the high voltage power supply and the data acquisition, processing and wireless monitor system. The particulate flow system of the EPMM was regulated and controlled by mass flow controllers with a vacuum pump in this study. Sampled particulate was first passed through a PM2.5 impactor to remove particulate outside the measurement range. After the impactor, sampled PM2.5 was then directly introduced into the particle charger for electrostatically charging the particulates. The charged PM2.5 then entered into the Faraday cup electrometer and was measured electrically in a Faraday cup electrometer downstream of the charger. The readout of the data acquisition and processing system showed a relationship between time and the mass concentration of PM2.5. The measurement data of the monitor connected to the internet through a GSM connection to a public cellular network. The EPMM proved particularly useful for measuring and detecting particulate air pollution, for mass concentration of PM2.5 in the range between 0 and 500 $\mu g/m^3$.

In this study, the performance of the EPMM was evaluated simultaneously with a commercially available Thermo Scientific Model 5014i Beta for PM2.5 measurements at ambient conditions. The monitoring station was located in Yupparaj Wittayalai School, Si Phum, Mueang, Chiang Mai, Thailand, during October, 15, to November, 5, 2015. Good agreement and high correlation was found between the EPMM and the Thermo Scientific Model 5014i Beta in measuring ambient PM2.5. The average EPMM mass concentration for 1-hour was about 19.79 $\mu g/m^3$ and the average Thermo Scientific Model 5014i Beta mass concentration was about 20.02 $\mu g/m^3$ with the EPMM to Thermo Scientific Model 5014i Beta mean ratio of 0.9885. The average EPMM mass concentration for 24-hour was about 19.80 $\mu g/m^3$ and the average Thermo Scientific Model 5014i Beta mass concentration was about 20.18 $\mu g/m^3$ with a EPMM to Thermo Scientific Model 5014i Beta mean ratio of 0.9811. The comparison between the EPMM and Thermo Scientific Model 5014i Beta data resulted in $R^2$ of 0.8230 and 0.9881, and a slope of 1.0231 and 0.8802 for 1-hour and 24-hour, respectively.

## Acknowledgements

Authors gratefully acknowledge the National Science and Technology Development Agency (NSTDA) (Research contract no. P-14-50757) for the financial support. The authors wish to thank the Center of Excellence for Renewable Energy, Chiang Mai University, the Center of Excellent on Energy, Economic, and Ecological Management (3E), Science and Technology Research Institute, Chiang Mai University and Dr. R. Zawadzki for his valuable contribution during the preparation of this article and also the Pollution Control Department (PCD) for the Thermo Scientific Model 5014i Beta data and permission to install the EPMM in the station.

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