Korean J. Chem. Eng., 33(12), 3330-3336 (2016)
DOI: 10.1007/s11814-016-0288-y
pISSN: 0256-1115
eISSN: 1975-7220

RAPID COMMUNICATION

Comparison of electrostatic charge and beta attenuation mass monitors for continuous airborne PM10 monitoring under field conditions

Panich Intra*,†, Artit Yawootti*, and Sate Sampattagul**

*Research Unit of Electrostatic Applications in Energy and Environment (RUEE), College of Integrated Science and Technology, Rajamangala University of Technology Lanna, Chiang Mai 50220, Thailand
**Center of Excellent on Energy, Economic and Ecological Management (3E), Science and Technology Research Institute, Chiang Mai University, Chiang Mai 50200, Thailand
(*Received 15 April 2016 • accepted 12 October 2016*)

Abstract−An electrostatic PM10 mass monitor (EPMM) used for wireless continuous airborne particulate matter monitoring was developed and evaluated in our previous work. However, differences in measured PM10 mass concentrations between the electrostatic charge and the beta ray attenuation methods due to the frequent occurrence of high humidity and temperature in the ambient air in Thailand's have not been extensively studied in our previous work; and in the literature, it would be necessary to compare the output of the EPMM against the beta ray attenuation mass monitor. In this study, we evaluated the performance of the EPMM simultaneously with a commercially available FH62C14 Beta gauge continuous ambient particulate monitor, Thermo Fisher Scientific Inc., for PM10 measurements at ambient condition in the field. The measurements were made at Yupparaj Wittayalai School, Si Phum, Mueang, Chiang Mai, Thailand from November 16-23, 2015. They showed that the averages of PM10 mass concentrations measured by the EPMM linearly correlate very well with the PM10 mass concentrations measured by the FH62C14. The slopes were 0.9620 and 1.0649 for 1 and 24-hour, respectively, and R^2 of 0.8634 and 0.9889 for 1 and 24-hour, respectively. Finally, this comparison proved to be particularly useful in the refinement and design of the EPMM.

Keywords: Particulate Matter, PM10, Mass Monitor, Electrostatic Charge, Beta Attenuation

INTRODUCTION

The U.S. Environmental Protection Agency (U.S. EPA) promulgated a regulation for the mass concentrations of PM10 that refers to particles smaller than 10 μm in aerodynamic diameters. PM10, both outdoors and indoors, can be measured by a mass concentration method in micrograms per cubic meter (μg/m^3) [1]. Generally, for PM10 standards, the Federal Reference Method (FRM) is based on gravimetric analysis of particles collected on filters over a period of 24 hr [2]. The gravimetric analysis was selected because most of the particulate data used for the epidemiological studies investigating associations between mortality and morbidity outcomes and ambient particle exposures are based on filter measurements [3]. However, a 24 hr average measurement may not adequately represent actual human exposure. Therefore, an automatic and continuous particulate mass monitor is essential for exposure assessment that can also provide accurate hourly measurements.

A number of techniques have been incorporated into instruments to achieve automatic and continuous (or at least near real time) particulate monitoring, including beta ray attenuation, light scattering, quartz microbalances, and electrostatic charge monitors [4-11]. These instruments are widely used to monitor airborne particulate matter and are wide-ranging in type, cost, flexibility, accuracy and resolution. A continuing research and development problem for manufacturers of such instruments and their users is the need to accurately record the true mass of particulate matter in ambient air over a given time. In Thailand's air quality monitoring network of the Pollution Control Department (PCD), now the hourly and daily PM10 mass concentrations are routinely measured by the automatic beta ray attenuation or TEOM mass monitors for 75 stations. However, these systems tend to be relatively large units, are not appropriate for integration within other compact devices, and are also expensive with typical starting prices greater than ten thousand U.S. dollars. Because of the large number of measuring stations distributed throughout Thailand, an air quality monitoring network of PM10 mass concentrations must have a low cost and be able to continuously give fast response measurement of ambient PM10 and the ease of moving a PM10 mass monitor should also be considered. It should be compact and easy to use, and its maintenance must be accomplished by relatively low skilled laborers. Therefore, a low cost wireless PM10 mass monitor is desirable to be placed in large numbers in the air quality monitoring networks of Thailand's PCD. Over the last decade, wireless monitor systems have been designed and developed to monitor real time particulate matter concentrations [12,13].

In our previous work [14], we developed and evaluated an electrostatic PM10 mass monitor (EPMM) for wireless continuous measuring of ambient particulate air pollution in the field at the air quality monitoring station of the PCD, Chiang Mai City Hall, Chi-

†To whom correspondence should be addressed.
E-mail: panich_intra@yahoo.com

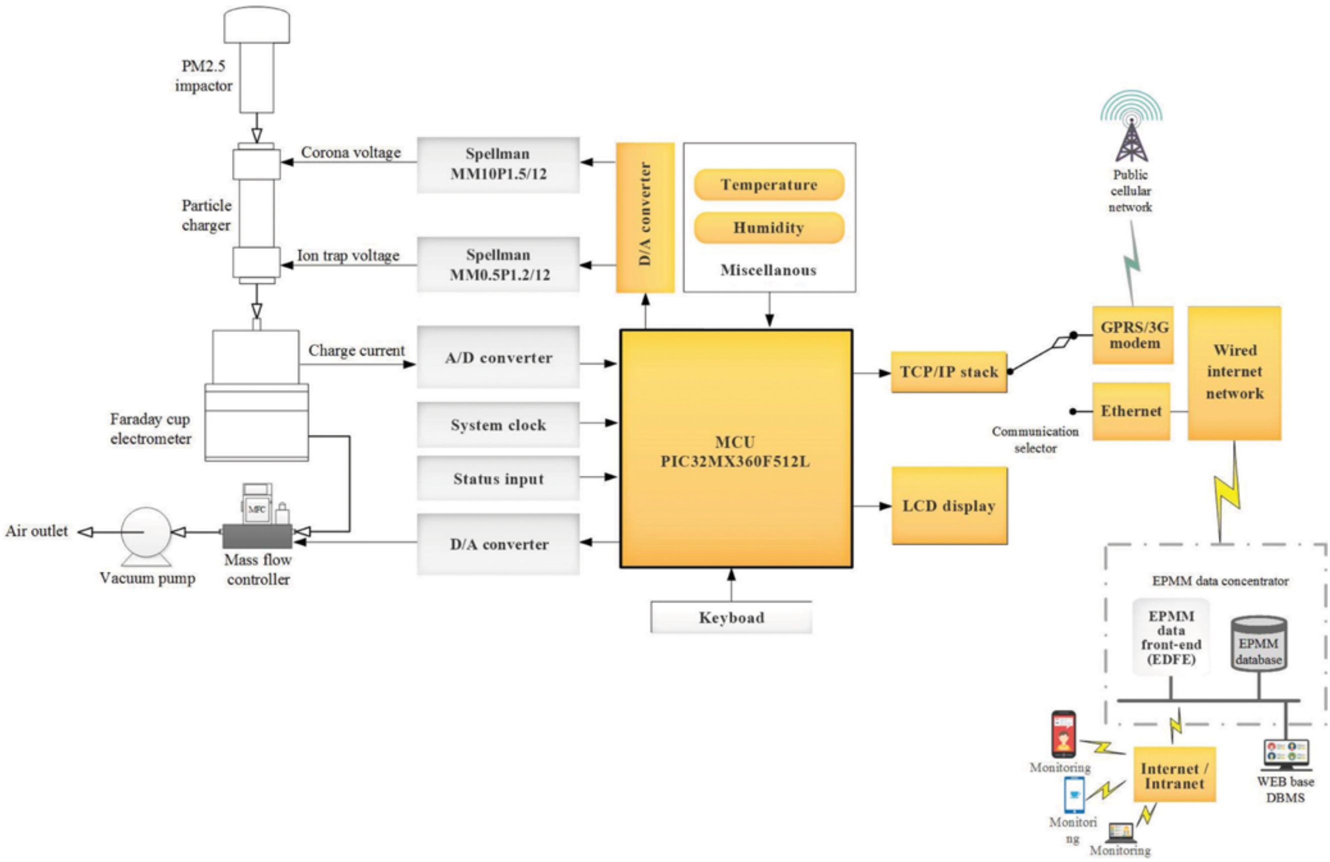

Fig. 1. Schematic diagram of the EPMM.

ang Mai, Thailand. This was an inexpensive, portable, and real-time instrument. The performance of the EPMM was evaluated simultaneously with a commercially available TEOM monitor for measurements at ambient conditions. Good agreement and high correlation were found between the EPMM and the TEOM in measuring ambient PM10. In researching the ruggedness and accuracy amongst all methodologies for real-time monitoring systems of the PM10 mass concentration unit, the time-tested methodology of beta ray attenuation was selected. In this technique, short-term samples are deposited on a relatively small collection area. Analysis is accomplished by determining the attenuation of low energy β-particles through the deposit and substrate, and comparing it with that of through the substrate alone. However, differences in measured PM10 mass concentrations between the electrostatic charge and the beta ray attenuation methods were not studied extensively in our previous work and in the literature. Also, due to the frequent high humidity and temperature of the ambient air in Thailand, it would be necessary to compare the output of the EPMM against the beta ray attenuation mass monitor on a site-by-site and season-by-season basis for environmental sampling. This comparison would particularly be useful in the refinement and design of the EPMM and help improve the regulatory compliance of the measurements using these devices.

In this study, the developed electrostatic PM10 mass monitor and a commercially available FH62C14 Beta Gauge Continuous Ambient Particulate Monitor, Thermo Fisher Scientific Inc., were installed in the same place, and the two monitors were compared using linear regression analysis of the collected data. The detailed description of the operating principle of the developed wireless PM2.5 mass monitor is also presented and discussed.

MATERIALS AND METHODS

1. Electrostatic PM Mass Monitor

The schematic diagram of the electrostatic PM10 mass monitor (EPMM) developed in this study is shown in Fig. 1. The monitor consisted of a PM10 impactor, particle charger, Faraday cup electrometer, flow system, high voltage power supply, data acquisition and processing system, and wireless communication system. The PM10 flow was regulated and controlled by thermal mass flow meters and controllers with a vacuum pump. Sampled particulate air was first passed through a PM10 impactor to remove particulates outside the measurement range based on their aerodynamic diameter, particulates with diameter larger than 2.5 µm. The particulate cut-off diameter at 50% collection efficiency, d_{50}, can be calculated by a following equation as [15]

$$d_{50}=\left(\frac{9\rho D^2 Stk_{50}}{\rho_p ReC_c}\right)^{1/2} \qquad (1)$$

where ρ is the gas density, D is the acceleration nozzle diameter, Stk_{50} is the Stokes number of a particle cut-off diameter at 50% collection efficiency, in case of the round jet impactor, Stk_{50} is 0.24

[15], ρ_p is the particle density, Re is the Reynolds number and C_c is the Cunningham slip correction factor.

Sampled PM10 was then directly introduced into the particle charger to electrostatically charge the particulates by attaching them to ions produced by the corona discharge inside the charger [16]. Based on the diffusion and field charging, the mean charge per particle, n_p, in a time period, t, by a particle diameter is approximately determined by the theory of White [17]

$$n_p=\frac{d_p kT}{2K_E e^2}\ln\left(1+\frac{\pi K_E d_p \bar{c}_i e^2 n_i t}{2kT}\right)+\left(\frac{3\varepsilon}{\varepsilon+2}\frac{Ed_p^2}{4K_E e}\frac{\pi K_E e Z_i n_i t}{1+\pi K_E e Z_i n_i t}\right) \tag{2}$$

where d_p is the particulate diameter, k is Boltzmann's constant (1.380658×10^{-23} J/K), T is the operating temperature, K_E is the Coulomb constant, ε_0 is the vacuum permittivity (8.854×10^{-12} F/m), $\bar{c}_i$ the mean thermal speed of the ions, e is the value of elementary charge on an electron (1.61×10^{-19} C), ε is the particle dielectric constant, E is the average electric field inside the charger, Z_i is the electrical mobility of ions, n_i is the ion number concentration, and t is the time of exposure of the particles to the ions.

The charged PM10 then entered into the Faraday cup electrometer where they were measured electrically downstream of the charger [18]. The readout of the data acquisition and processing system showed a relationship between time and the mass concentration of PM10. The mass concentration of PM10, m_p, on the filter in the Faraday cup as a function of the charged PM10 current, I_p, and PM10 diameter, d_p, could be calculated by [14]

$$m_p=\frac{\pi}{6}\frac{I_p}{eQ_p}\int\frac{\rho_p(d_p)d_p^3}{n_p(d_p)}dd_p \tag{3}$$

where m_p is the total mass concentration of PM10 (μg/m^3) and Q_p is the PM10 flow rate (m^3/s). Eq. (3) can be rewritten in the power law form [14]:

$$m_p=\left(\frac{\pi\rho_p d_p^3}{6n_p eQ_p}\right)I_p^n \tag{4}$$

In this study, the mass concentration of PM10 was determined empirically 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 PM10 sampling. The mass concentration of PM10 in μg/m^3 is adjusted upward using the formula:

$$m_p=47.124\times10^{12}\cdot I_p^{0.7609} \tag{5}$$

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 PM10 mass concentration and the average of the 1-hour and 24-hour PM10 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. Field Study Setup

2-1. Site Description

The field study was set up at the Air Quality Monitoring Station of the Pollution Control Department (PCD) during November 16-23, 2015. 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 FH62C14 were placed inside a trailer with their sample inlets located approximately 1 m above the trailer roof. The distance between the two inlets of both continuous mass monitors was greater than 1 m to avoid potential interferences. Inside the trailer, the temperature was controlled at about 20 °C to maintain suitable operation conditions for the electronic units of the real-time monitors. During the monitoring periods, the daily average temperature was from 27 to 35 °C and the daily average relative humidity was 70-85%.

2-2. Instrument Description

The performance of the EPMM was evaluated side by side with a Thermo Scientific Model FH62C14 Beta Gauge, Thermo Fisher Scientific Inc., readily available. PM10 mass measurements were done at ambient conditions [19]. To measure precise and accurate ambient aerosol concentrations, the FH62C14 is based on the principles of beta attenuation through a known sample area to continuously collect and detect the deposited mass. The FH62C14 is one of the few continuous monitors established as a U.S. EPA. equivalent method for PM10 monitoring (No. EQPM-1102-150CARB). The range of measurement of the PM10 mass concentration of the model 5014i beta was about 0 to 10,000 μg/m^3 with a resolu-

Table 1. Comparison between the EPMM and the FH62C14

Specifications	EPMM	FH62C14
Measurement technique	Electrostatic	Beta ray attenuation
Particulate size range	<10 μm	<10 μm
Mass concentration range	0-500 μg/m^3	0 to 1,000 μg/m^3 and 0 to 10,000 μg/m^3 (auto-ranging)
Resolution	0.01 μg/m^3	4 μg/m^3
Measurement time	0.1-3,600 sec	60-3,600 sec and 24 hr
Data averaging	Every 0.1 sec	Every 4 sec
Particulate flow rate	5 L/min	16.67 L/min
Operating temperature range	10-60 °C	−30-50 °C
Output	RS232/RS485, USB, TCP/IP	RS232/RS485, TCP/IP
Dimensions (L×W×H)	50×35×20 cm	48.3×33.0×31.1 cm
Weight	15 kg	18 kg
Electrical Requirements	100-240VAC 50 Hz	100-240VAC 50 Hz

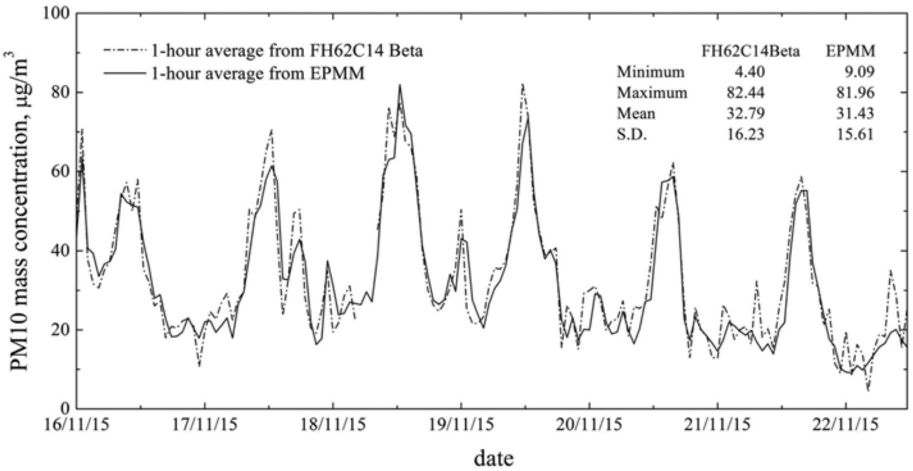

Fig. 2. Comparison of 1-hour averages from EPMM and FH62C14 at Yupparaj Wittayalai School during November 16-23, 2015.

tion of about 4 $\mu g/m^3$ and a measurement time of about 60 to 3,600 seconds and 24-hour (updated concentration every 4 seconds) [19]. Table 1 shows the comparison between the EPMM and the FH62C14.

2-3. Statistical Analysis

Linear regression relationships were calculated using the reduced major axis (RMA) method to investigate the comparability of monitors. Ayers [20] has shown RMA regression to be the appropriate method for comparing the air pollutant concentration data, since it does not assume that accuracy of the independent variable is error free. Standard linear regression using the least-squares method, which does make this assumption, is not a suitable tool with which to determine the equivalence of PM mass concentration monitors. For each possible pairing of instruments at each site using unprocessed data and on log-normally transformed ($\log_e$) values were calculated by RMA regressions.

FIELD STUDY RESULTS

The data used in this study were 1-hour and 24-hour PM10 mass concentration levels (in micrograms per cubic meter). The 1-hour and 24-hour average PM10 mass concentrations were calculated from data collected every 0.1 sec. The total observation time for Yupparaj Wittayalai School was 164 hours during November 16-23, 2015. The average of the 1-hour and 24 hour PM10 mass concentration was calculated to plot the time series to investigate the trend of the PM10 mass concentration. Fig. 2 shows the comparison of 1-hour averages from EPMM and FH62C14 at Yupparaj Wittayalai School during November 16-23, 2015. The trend of the average of the 1-hour PM10 mass concentration measured by the EPMM agreed to within small differences with the average of the 1-hour PM10 mass concentrations measured by the FH62C14. The 1-hour PM10 mass concentrations measured by the FH62C14 and EPMM were in the range of 4.4 to 82.44 $\mu g/m^3$. The maximum and minimum 1-hour PM10 mass concentrations measured by the FH62C14 were 82.44 $\mu g/m^3$ and 4.4 $\mu g/m^3$, respectively. The maximum and minimum 1-hour PM10 mass concentrations measured by the EPMM were 81.96 $\mu g/m^3$ and 9.08 $\mu g/m^3$, respectively. The 1-hour average EPMM mass concentration was about 31.36 $\mu g/m^3$ and the 1-hour average FH62C14 mass concentration was about 32.79 $\mu g/m^3$, with the EPMM to FH62C14 mean ratio of about 0.958. A comparison of 1-hour averages from EPMM and

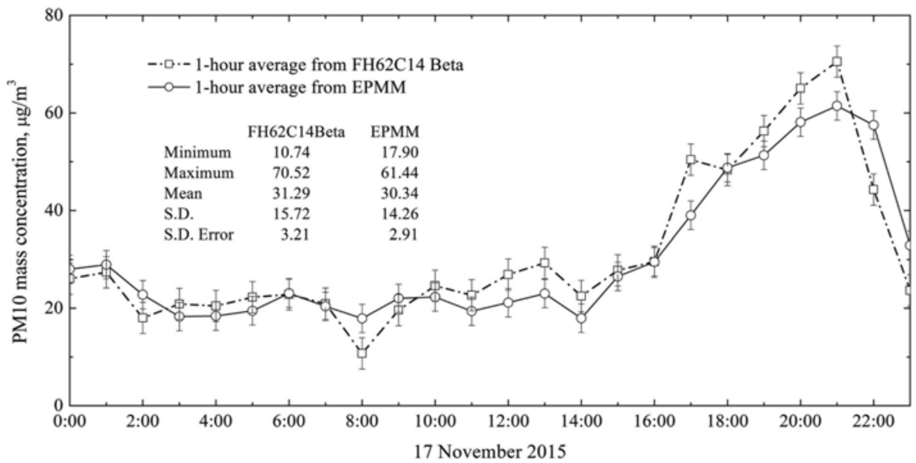

Fig. 3. Comparison of 1-hour averages from EPMM and FH62C14 at Yupparaj Wittayalai School on November 17, 2015.

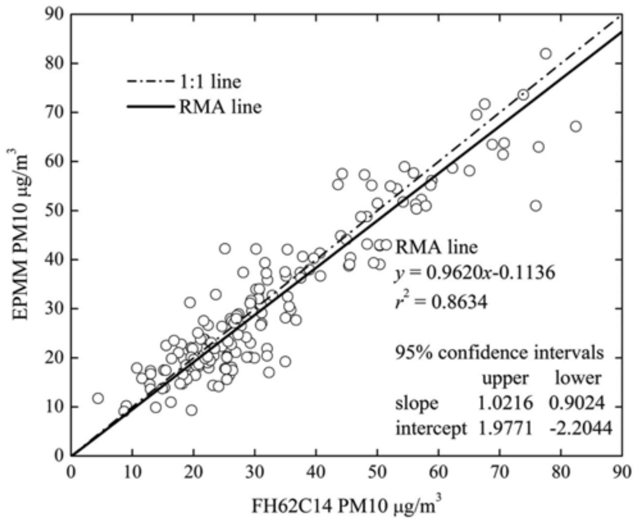

Fig. 4. Relationship between 1-hour PM10 mass concentrations for EPMM and FH62C14 at Yupparaj Wittayalai School during November 16-23, 2015.

FH62C14 on November 17, 2015 is shown in Fig. 3. The 1-hour PM10 mass concentrations measured by the FH62C14 and EPMM were in the range of 10.74 to 70.52 μg/m^3. The maximum and minimum 1-hour PM10 mass concentrations measured by the FH62C14 were about 70.52 μg/m^3 and 10.74 μg/m^3, respectively, with the standard error of about 3.21 μg/m^3. The maximum and minimum 1-hour PM10 mass concentrations measured by the EPMM were about 61.44 μg/m^3 and 17.90 μg/m^3, respectively, with the standard error of about 2.91 μg/m^3.

Fig. 4 shows the relationship between 1-hour average PM10 mass concentrations measured by the EPMM and FH62C14 at Yupparaj Wittayalai School during November 16-23, 2015. RMA regression analysis was used to determine the relationship of the slope of the regression between the EPMM and FH62C14. It is well known that RMA regression analysis is the method the U.S. EPA. uses to determine correlations between reference and candidate methods for particulate sampling and monitoring. Note that the correlation and slope of the reference method and the candidate PM10 method measurements must be ≥0.97, and 1.00±0.10, respectively [26]. Additionally, the maximum precision and accuracy for the candidate PM10 method must be 15%, and 5%, respectively [21]. Table 2 shows the RMA regression analysis results of 1-hour PM10 mass concentrations for EPMM and FH62C14. The 1-hour correlation was observed between the EPMM and the FH62C14 with R^2 of about 0.8634, with an RMA regression slope of about 0.9620 and the intercept of about −0.1136. The results showed that the average EPMM mass concentration was about 31.43 μg/m^3 and the average FH62C14 mass concentration was about 32.79 μg/m^3 with the EPMM to FH62C14 mean ratio of 0.959.

Table 2. RMA regression analysis results of 1-hour PM10 mass concentrations for EPMM and FH62C14

	FH62C14	EPMM
Mean	32.79	31.43
Standard error	1.267	1.219
Median	27.94	27.07
Standard deviation	16.23	15.61
Minimum	4.4	9.08
Maximum	82.44	81.99
Slope	0.9620	
Intercept	−0.1136	
R^2	0.8634	
n	164	

Fig. 5 shows the comparison of 24-hour averages between EPMM and FH62C14 at Yupparaj Wittayalai School during November 16-23, 2015. The 24-hour PM10 mass concentrations measured by the FH62C14 and EPMM were found in the range of about 20.98 to 44.51 μg/m^3. The maximum and minimum 24-hour PM10 mass concentrations measured by the FH62C14 were about 44.51 μg/m^3 and 23.58 μg/m^3, respectively. The maximum and minimum 24-hour PM10 mass concentrations measured by the EPMM were about 44.42 μg/m^3 and 20.98 μg/m^3, respectively. The 24-hour average EPMM mass concentration was about 32.64 μg/m^3 and the 24-hour average FH62C14 mass concentration was about 34.15 μg/m^3 with the EPMM to FH62C14 mean ratio of about 0.956.

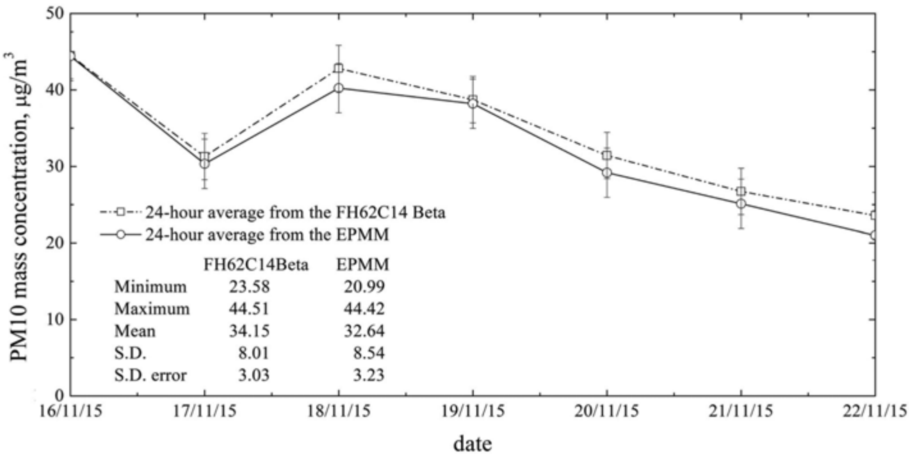

Fig. 5. Comparison of 24-hour averages from EPMM and FH62C14 at Yupparaj Wittayalai School during November 16-22, 2015.

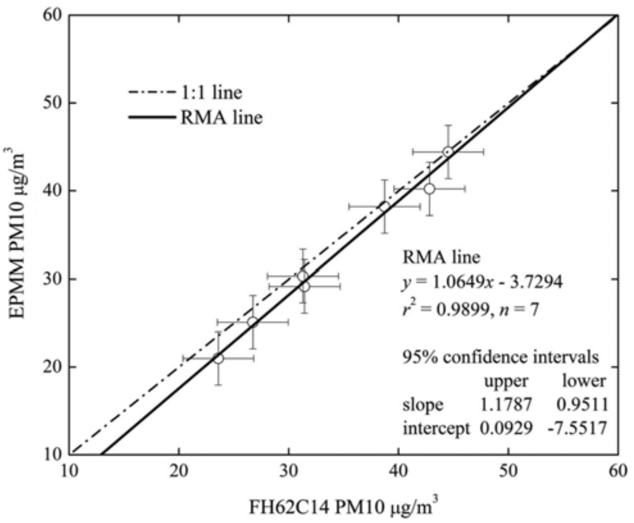

Fig. 6. Relationship between 24-hour PM10 mass concentrations for EPMM and FH62C14 at Yupparaj Wittayalai School during November 16-22, 2015.

Table 3. RMA regression analysis results of 24-hour PM10 mass concentrations for EPMM and FH62C14

	FH62C14	EPMM
Mean	34.15	32.64
Standard error	3.03	3.22
Median	31.42	30.33
Standard deviation	8.02	8.54
Minimum	23.58	20.99
Maximum	44.51	44.42
Slope	1.0649	
Intercept	−3.7294	
R^2	0.9889	
n	7	

Fig. 6 shows the relationship of 24-hour averages between EPMM and FH62C14 at Yupparaj Wittayalai School during November 16-22, 2015. The average of the 24-hour PM10 mass concentrations measured by the EPMM correlated linearly very well with the PM10 mass concentrations measured by the FH62C14. Table 3 shows the RMA regression analysis results of 24-hour PM10 mass concentrations for EPMM and FH62C14. The 1-hour correlation was observed between the EPMM and the FH62C14 with R^2 of about 0.9889, with a RMA regression slope of about 1.0649 and the intercept of about −3.7294.

However, the differences between EPMM and FH62C14 include (1) a different measurement method, the EPMM used the electrostatic charge technique and the FH62C14 used the radiometric technique, (2) the measurement times, the measurement time of the instrument and the sharpness (height to duration ratio) of the concentration peak between both instruments. The EPMM was set to record PM10 every 0.1 sec, averaged over 36,000 data points in 1-hour, while the FH62C14 recorded PM10 every 4 sec, averaged over 900 data points in 1-hour, (3) the cut-off aerodynamic diameter and the penetration curve of the inlet, (4) the deliquescence of aerosols, (5) the evaporation loss of volatile species of aerosol [22], and (6) deposited particles on the impaction surface or inner surface and the tip of corona-needle electrode of the charger may reduce particle penetration and charging efficiency. During the monitoring periods, slight particulates could be observed on the impaction plate of the PM10 impactor and the tip of corona-needle electrode of the charger, and there no visible particle was 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 (for calibration, cleaning etc.) may be greater than 500 hour of operation at relatively high mass concentrations of PM10.

Additionally, Speer et al. [23] reported that the 1-hour average PM10 mass concentrations from beta ray attenuation monitors were found to be insignificant under relative humidity lower than 70%, ambient PM10 mass concentration does not appear to be influenced by the change in the relative humidity, compared to the concentrations by the gravimetric method. Studies related the real-time mass measurement of liquid water content in particulates and the effect of water vapor on PM10 mass monitors have been carried out by numerous researchers [24-27]. In the beta ray attenuation method, the mass concentration of suspended and refined particulates are continuously measured using the radiometric principle of beta attenuation through a known area on a fibrous filter tape to continuously detect the mass of deposited ambient particles. It is possible that condensation of water vapor on the fibrous filter can cause errors in measuring the mass of matter deposited on the filter under high relative humidity conditions and also could result in over-estimation of PM mass concentration due to acid gas absorption on the glass fiber filter. Yawootti et al. [27] reported that the water vapor present in the air affected the corona onset field strength, the mobility of charge carriers, and the plasma chemistry inside the particulate charger in the electrostatic charge method. The corona discharge characteristics inside the charger was found to be insignificant under relative humidity lower than 80%, the corona onset field strength, the mobility of charge carriers, and the plasma chemistry does not appear to be influenced by the change in the relative humidity [27]. Therefore, a temperature and humidity control device is usually installed below the size selective inlet of the monitor to reduce these errors. However, heating of the air sample to a temperature between 10 °C and 20 °C above ambient (~50 °C) to remove particulate-bound water can further enhance losses of the semi-volatile constituents and ammonium nitrate of ambient particles. Therefore, an inlet heating tube heated above the dew point of the ambient air should be used for particle mass monitoring under high humidity conditions.

CONCLUSION

The performance of the EPMM was compared simultaneously with a commercially available Thermo Scientific Model FH62C14 Beta Gauge for measurements at ambient conditions. The site for the measurements was Yupparaj Wittayalai School, Si Phum, Mueang, Chiang Mai, Thailand November 16-23, 2015. Good agreement and small differences were found between the EPMM and FH62C14 in measuring ambient PM10. The average EPMM mass concentration was about 31.43 and 32.64 μg/m^3 and the average FH62C14 mass concentration was about 32.79 and 34.15 μg/m^3 with the EPMM to FH62C14 mean ratio of about 0.959 and 0.956 for 1-hour and 24-hour, respectively. The correlation between the EPMM and FH62C14 data resulted in a slope of 0.9620 and 1.0649 for 1 and 24-hour, respectively, and R^2 of 0.8634 and 0.9889 for 1 and 24-hour, respectively. This showed that an inexpensive and portable device proved to be particularly useful as a wireless monitoring system for the mass concentration of the PM10 under conditions prevalent in Thailand. Additionally, this comparison also proved to be particularly useful in the refinement and design of the EPMM and to help improve the regulatory compliance of measurements using these devices.

ACKNOWLEDGEMENTS

The 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. Rainer Zawadzki of Governor State University for the valuable contribution during the preparation of this article and also the Pollution Control Department (PCD) for the Thermo Scientific Model FH62C14 Beta Gauge data and permission to install the EPMM in the station.

REFERENCES

1. EPA, *National Ambient Air Quality Standards for Particulate Matter, Final Rule*, Federal Register, **62**, 38651 (1997).
2. D. W. Dockery, C. A. III. Pope, X. Xu, J. D. Spen-gler, J. H. Ware, M. E. Fay, B. G. Ferris and F. E. Speizer, *New Eng. J. Med.*, **329**, 1753 (1993).
3. Federal Register, *National Ambient Air Quality Standards for Particulate Matter*, 40 CFR Part 50.7, Section 8.2, Vol. 62, No. 138, July 18 (1997).
4. P. Babich, P.-Y. Wang, G. Allen, C. Sioutas and P. Koutrakis, *Aerosol Sci. Technol.*, **32**(4), 309 (2000).
5. W. Koch, W. Dunkhorst and H. Lodding, *Aerosol Sci. Technol.*, **31**(2), 231 (1999).
6. M. Lippmann, J. Q. Xiong and W. Li, *Appl. Occup. Environ. Hyg.*, **15**(1), 57 (2000).
7. C. Misra, M. D. Geller, P. Shah, C. Sioutas and P. A. Solomon, *J. Air Waste Manage. Assoc.*, **51**(9), 1309 (2001).
8. H. Patashnick and E. G. Rupprecht, *J. Air Waste Manage. Assoc.*, **41**(8), 1079 (1991).
9. J. H. Lee, P. K. Hopke, T. M. Holsen, D. W. Lee, P. A. Jaques, C. Sioutas and J. L. Ambs, *J. Aerosol Sci.*, **36**(1), 95 (2005).
10. P. Intra, A. Yawootti and N. Tippayawong, *Korean J. Chem. Eng.*, **30**(12), 2205 (2013).
11. TSI Incorporated, *Instruction Manual for Electrical Aerosol Detector Model 3070A*, Minnesota, U.S.A. (2002).
12. K. K. Khedo, R. Perseedoss and A. Mungur, *Int. J. Wireless and Mobile Networks*, **2**(2), 31 (2010).
13. D. Park, S.-B. Kwon and Y. Cho, *Int. J. Environ. Monit. Anal.*, **1**(1), 15 (2013).
14. A. Yawootti, P. Intra, N. Tippayawong and S. Sampattagul, *J. Electrostat.*, **78**(1), 46 (2015).
15. P. Intra, A. Yawootti, U. Vinitketkumnuen and N. Tippayawong, *Korean J. Chem. Eng.*, **29**(8), 1044 (2012).
16. P. Intra and N. Tippayawong, *J. Elec. Eng. Tech.*, **8**(5), 1175 (2013).
17. W. C. Hinds, *Aerosol Technology*, Wiley, New York, U.S.A. (1999).
18. P. Intra and N. Tippayawong, *Particul. Sci. Technol.*, **33**(33), 57 (2015).
19. Thermo Scientific Inc., *Instruction Manual for Thermo Scientific Model FH62C14 Beta Gauge Continuous Ambient Particulate Monitor*, U.S.A. (2014).
20. G. P. Ayers, *Atmos. Environ.*, **35**, 2423 (2001).
21. US EPA, *Revisions to the national ambient air quality standards for particulate matter*, 40 CFR Part 50, Federal Register, 52: 24634, July 1 (1987).
22. C. N. Liu, A. Awasthi, Y. H. Hung, B. Gugamsetty, C. J. Tsai, Y. C. Wu and C. F. Chen, *Atmos. Environ.*, **75**, 341 (2013).
23. R. E. Speer, H. M. Barnes and R. Brown, *Aerosol Sci. Technol.*, **27**, 50 (1997).
24. P. M. Young, A. Sung, D. Traini, P. Kwok, H. Chiou and H. K. Chan, *Pharmaceut. Res.*, **24**(5), 963 (2007).
25. C. N. Liu, S. F. Lin, C. J. Tsai, Y. C. Wu and C. F. Chen, *Atmos. Environ.*, **109**, 79 (2015).
26. C. N. Liu, S. F. Lin, C. J. Tsai, Y. C. Wu and C. F. Chen, *Atmos. Environ.*, **85**, 48 (2014).
27. A. Yawootti, P. Intra, N. Tippayawong and P. Rattanadecho, *J. Electrostat.*, **77**, 116 (2015).