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Original Article

Development of an online particulate monitoring system for measurement of the mass and number concentrations and size distributions of ambient PM10, PM2.5 and sub-400 nm particles

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Abstract

An online particulate monitoring system for measuring the mass and number concentrations and size distributions of ambient particulate matter was developed and field tested in this study. The developed monitoring system consisted of electrostatic PM mass monitor (EPMM), NanoScan-SMPS, data acquisition and wireless communication systems, and monitoring station structure with an air conditioning system. In this study, the monitoring station was placed and field evaluated in Chiang Mai University Mae-Hia, Mae-Hia, Mueang Chiang Mai District, in Chiang Mai Province, Thailand. The field study results showed that the trend of the average of the particle number concentration measured by the NanoScan-SMPS agreed to within small differences with the particle mass concentration of PM10 and PM2.5 measured by the EPMM. The 1hour-average PM10 and PM2.5 mass concentrations measured by EPMM were about 32.07 µg/m^3 and 28.64 µg/m^3, respectively, and the 1hour-average number concentration of sub-400 nm particle measured by the NanoScan-SMPS was found about 5,262.00 particles/m^3. Particle size distribution measured by the NanoScan-SMPS was found in the size range from about 11.5 to 365.2 nm. This proved the developed system particularly useful as an online, low cost continuous monitor for the measurement of the mass and number concentrations and size distributions of ambient PM10, PM2.5 and sub-400 nm.

Keywords: online, particulate matter, monitoring system, PM10, PM2.5

1. Introduction

A law for the PM10 and PM2.5 mass concentrations was disseminated by the U.S. EPA. It quotes to particulate matter less than 10 and 2.5 µm in aerodynamic diameters. Both outdoors and indoors, measuring for PM10 and PM2.5 can be carried out by a mass concentration method in micrograms per cubic meter (µg/m^3) (Environmental Protected Agency [EPA], 1997). However, there are various sources of nanoparticles, including a large variety of anthropogenic origin such as engineered nanoparticles and particles from materials synthesis, biotechnology, semiconductor manufacturing, pharmaceutical products, combustion, and various industrial processes. Nanoparticles are also emission in ambient air, both indoors and outdoors. The key parameters in the determination of their risk were demonstrated by the size distribution, number concentration, and surface area of such nanoparticles, as has been identified by various recent health studies (Hinds, 1999).

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For the PM10 and PM2.5 standards generally the Federal Reference Method (FRM) is based on a gravimetric analysis of particles collected on filters over a period of 24 hrs (Federal Register, 1997). Because of the epidemiological studies considering relationships between mortality and morbidity outcomes and ambient particle exposures used particulate data, the gravimetric analysis was selected. However, a 24 hrs-average measurement might not sufficiently demonstrate actual human exposure. For nanoparticles, the differential mobility analyzer (DMA) has become the most common instrument used in classifying and measuring nanoparticles based on the electrical mobility technique (Hinds, 1999). A typical design of a general DMA configured as coaxially cylindrical electrodes between which a DC high voltage is applied and a gas flows through them (Intra & Tippayawong, 2008). An aerosol flow containing charged particles is introduced adjacent to one of the cylindrical electrodes. A particle-free sheath of gas flow initially separates the aerosol flow from the opposite cylindrical electrode. According to their electrical mobility which is related to their size, the electrical field formed between the cylindrical electrodes causes the charged particles to move toward the opposite cylindrical electrode across the gap between the cylindrical electrodes. Charged particles within a narrow range of electrical mobility diameter, exit the DMA through the monodisperse sample flow, these particles are indicated to as the monodisperse aerosol. The monodisperse aerosols are then entered to the particle counter where the number concentration of the particles is counted. All the remaining particles exit the DMA via the excess flow (Intra & Tippayawong, 2007).

An automatic and continuous PM and nanoparticles monitor for measuring the mass and number concentrations and the size distributions of ambient PM10, PM2.5 and sub-400 nm particles is necessary for an exposure evaluation that can give accurate hourly and daily monitoring. For the PM10 and PM2.5, a number of techniques have been incorporated into instruments to obtain automatic and continuous PM measurements including the beta ray attenuation, the light scattering, the quartz microbalances, and the electrostatic charge monitors (Babich, Wang, Allen, Sioutas, & Koutrakis, 2000; Intra, Yawootti, & Tippayawong, 2013; Khedo, Perseedoss, & Mungur, 1999; Lee *et al*., 2005; Lippmann, Xiong, & Li, 2000; Misra, Geller, Shah, Sioutas, & Solomon, 2001; Patashnick & Rupprecht, 1991; TSI Incorporated, 2002). For nanoparticles an overview of the recent development of the nanoparticle detector and analyzer for measurements of the number concentration and the size distribution of nanoparticles was proposed by Intra and Tippayawong (2007, 2008). Available commercial instruments to obtain automatic and continuous nanoparticle measurements including the electrical aerosol analyzer, the scanning mobility particle sizer, the electrical aerosol spectrometer, the engine exhaust particle sizer, the differential mobility spectrometer, and the NanoScan-SMPS (Intra & Tippayawong, 2007, 2008). These analyzers are widely used to automatic and continuous measure airborne PM and nanoparticles and are wide-ranging in type, cost, flexibility, accuracy and resolution. For online or wireless PM mass and number monitor system, a continuing research and development problem for manufacturers of such instruments and their users is the need to accurately record the actual mass and number concentration of ambient PM in air over a given time period. Over the last decade, wireless PM mass and number monitor systems have been designed and developed for monitoring real time PM mass and number concentrations (Al-Ali, Zualkernan, & Aloul, 2010; Bhattacharya, Sridevi, & Pitchiah, 2012; Khedo, Perseedoss, & Mungur, 2007; Park, Kwon, & Cho, 2013; Zhang & Li, 2015). At the present time, the automatic beta ray attenuation or TEOM mass monitors were used to routinely measure the hourly and daily PM10 and PM2.5 mass concentrations for 75 stations in Thailand's air quality monitoring network of the Pollution Control Department (PCD). However, the size distribution, number concentration, and surface area of ambient nanoparticles are not carried out and unavailable in the PCD air quality monitoring stations and these stations tend to be relatively large units, are not suitable for incorporation within other compact devices; they are also fairly expensive with typical starting prices greater than ten thousand U.S. dollars. An air quality monitoring network of ambient PM mass concentrations must have low cost and be able to continuously give fast response measurement because of the large number of measuring stations distributed throughout Thailand. The ease of moving a PM 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. The simultaneous measurement of mass and number concentrations and size distributions of ambient PM10, PM2.5 and nanoparticles has not reported in the previous work and literature. Thus, it is an incentive for study and the low cost wireless monitoring system for measuring the mass and number concentrations and size distributions of ambient PM10, PM2.5 and nanoparticles are desirable to be placed in large numbers in the air quality monitoring networks of Thailand's PCD.

In the present study, a low cost, wireless, online particulate monitoring system for measuring the mass and number concentrations and size distributions of ambient PM 10, PM2.5 and sub-400 nm was developed and field tested. The detailed description of the operating principle of the system as well as the preliminary field testing results of ambient PM10, PM2.5 and sub-400 nm were also introduced and discussed.

2. Description of the Online Particulate Monitoring System

The schematic diagram of the online airborne particulate matter monitoring system developed in this study is shown in Figure 1. The online airborne particulate matter monitoring system includes an electrostatic PM mass monitor (EPMM) that monitors the mass concentration of particulate matter in the size fraction of PM10 and PM2.5, a NanoScan-SMPS that monitors the number concentration and the particle size distribution of sub-400 nm particle, a data acquisition and wireless communication system, and a monitoring station structure with the air conditioning system. A detailed description of main components of the online airborne particulate monitoring system is given below.

2.1 EPMM

The EPMM was used as the measurement technique of the charged particle current via the high efficiency particulate air filter developed by Yawootti, Intra, Tippayawong and Sampattagul (2015). This was an inexpensive, portable,

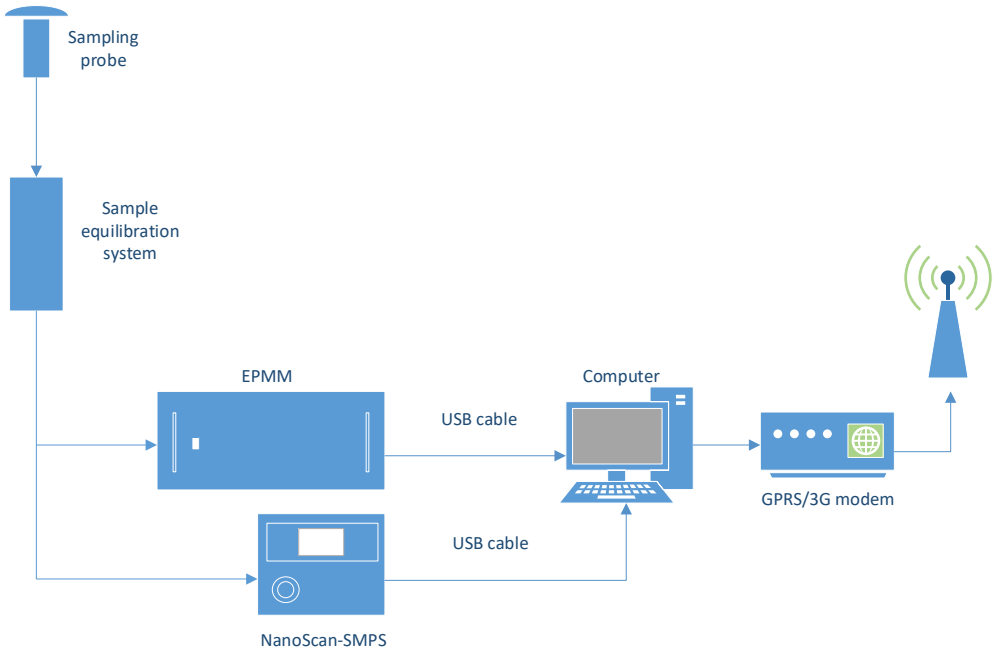


Figure 1. Schematic diagram of the online particulate monitoring system developed in this work.

and real-time instrument. The EPMM consists of a PM impactor, a PM charger, a charged PM detector, a flow system, a high voltage power supply, and a data acquisition and processing system. The PM flow was regulated and controlled by thermal mass flow meters and controllers with a vacuum pump. Sampled PM was first passed through a PM impactor to remove particulates outside the measurement range based on their aerodynamic diameter, particulates with diameters larger than 10 µm or 2.5 µm (Intra, Yawootti, Vinitketkumnuen, & Tippayawong, 2012). After the PM impactor, Sampled PM were then directly introduced into the PM chargers to electro statically charge the particulates by attaching them to ions produced by the corona discharge inside the PM charger (Intra & Tippayawong, 2013). The charged particulates then entered into the charged PM detector downstream of the charger where they were measured electrically (Intra & Tippayawong, 2015). The output signal from PM detector was in the range of 0 to +10V. It was then sent to the ADAM-4017 analog input module that converted the signal from analog to digital, a 16-bit, 8 channel analog input module, controlled and data sampled by an external personal computer via a RS-485 to USB converter interface. The EPMM could be used in detecting the mass concentration of PM10 and PM2.5 of approximately 0.1 to 1,000 µg/m^3 with a time resolution of less than 1s. Additionally, the collected PM10 and PM2.5 on the filter in the EPMM could be further analyzed for physical and chemical properties. Chemical composition of the size resolved particles could also be studied. The performance of the EPMM was evaluated simultaneously with a commercially available Thermo Scientific TEOM 1400ab and 5014i Beta monitors for PM10 and PM2.5 measurements at ambient conditions. Good agreement and high correlation were found between the EPMM, the TEOM 1400ab and 5014i Beta. The comparison between the EPMM, the TEOM 1400ab and 5014i Beta data values resulted in R^2 of 0.9697 and 0.9811 for PM10 and PM2.5, respectively (Yawootti *et al*., 2015).

2.2 NanoScan-SMPS

The NanoScan-SMPS has been designed for multiple applications such as measuring of industrial process emissions and workplaces, mobile studies, in-vehicle and outdoor air quality measurements (TSI Incorporated, 2002). Number concentration and size distributions of nanoparticles in the range between about 10 and 420 nm can be achieved. The NanoScan-SMPS consisted of an inlet cyclone, an unipolar diffusion charger, a radial DMA (rDMA), and an isopropanol CPC. On entering the instrument, the aerosol flow of about 0.75 L/min was pre-conditioned to remove large particles by the cyclone which has a cutoff point of about 550 nm. After that, the polydisperse aerosol entered the unipolar corona jet type charger (Medved, Dorman, Kaufman, & Pocher, 2000). This unipolar charger worked through the introduction of an opposed charger flow that was filtered with both an active carbon filter and a HEPA filter. After passing over the charger needle, a jet of positive ions flowed into the field-free mixing chamber, allowing the interaction of ions with the polydisperse sample flow using the opposed flow technique, improving mixing and charge repeatability. After flow splitting, the sample flow of about 0.25 L/min entered the rDMA. The remaining flow entered as a particle-free sheath air from the bottom outside edge of the rDMA into a circular channel. The polydisperse sample flow was introduced tangentially through an inlet channel at the top. The top plate of the rDMA was at ground, and the bottom plate was at a high negative voltage, thus creating an electric field. The size classified aerosol exited through bottom center port of the rDMA and continued to the isopropanol-based Condensation Particle Counter (CPC). The excess flow exited through the top center port of the rDMA. During the course of a measurement the DMA's voltage was ramped up to scan the entire particle size range. During every 60 secondsof sampling time there was a 45 second up-scan in which the measurement occurred, and a 15

second down-scan. The electrical mobility diameter of monodisperse particle could be set by the operator to particle sizes between 10 and 420 nm (TSI Incorporated, 2002).

2.3 Data acquisition and wireless communication system

Figure 2 shows the schematic diagram of the wireless communication system. Both EPMM and NanoScan-SMPS were controlled and data sampled by an external personal computer through a USB cable. Software running on an external computer was developed based on Visual Basic programming. The software was capable of displaying the variation of time, and the mass and number concentrations, and size distributions of ambient PM10, PM2.5 and sub-400 nm, and the average of the 1hour- and 24hour-PM10, -PM2.5 mass concentrations, and the number concentration of sub-400 nm. For wireless continuous monitoring, the EPMM and NanoScan-SMPS were also capable of connecting to the GPRS/3G modem via TCP/IP through the internet and a public cellular network to transfer data. In this study, the cloud storage services, Dropbox, was used for the data storage for time, date and level of the mass and number concentrations, and size distributions of PM10, PM2.5 and sub-400 nm, respectively. The central server was responsible for the collection, processing and storage of data from the station. Data from the EPMM and NanoScan-SMPS were first written to text files in comma-separated values (CSV) format and every time new data generated they were appended to the end of the previous file at each predefined time interval. The data storage and processing was the function of by the SQL server. In the website design, the website rendered a quick, simple, a user-friendly way for viewing particulate matter data such as tables and line graphs, and also generated reports on an hourly or daily basis. Figure 3 shows the home page display of the data from the online airborne monitoring system. The current day particulate matter link showed the current date and time when the data was uploaded to the web. Additionally, the PM2.5, PM10 and sub-400 nm measurement data could be used as predictive modeling or forecasting models for predictive volume and behavior of the particulate matter in near-real-time.

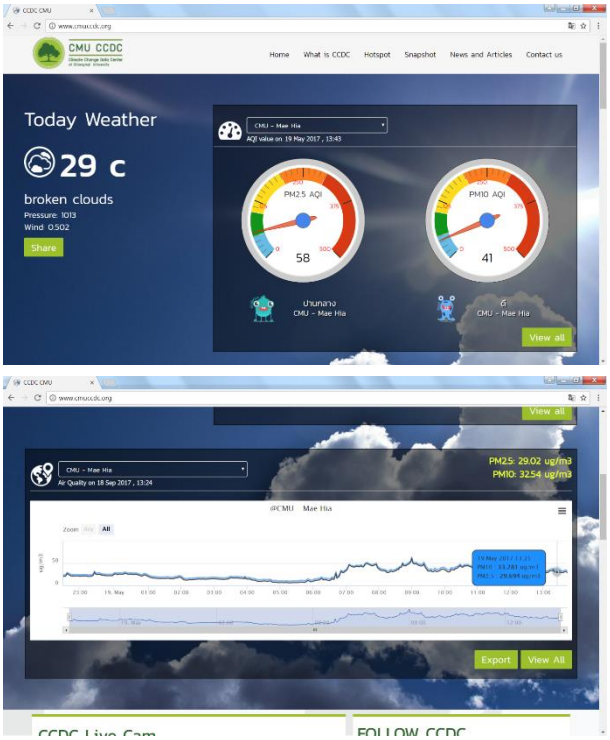


Figure 3. Home page display of the data from the online airborne monitoring system.

2.4 Monitoring station

In this study, the monitoring station was located in Chiang Mai University Mae-Hia, Mae-Hia, Mueang Chiang Mai District, in Chiang Mai Province, Thailand. The geographical coordinate information of the monitoring station at that location is 18°78'23.8"N and 98°93'73.9"E. Figure 4(a) shows the monitoring station. Both the EPMM and the NanoScan-SMPS were installed in a modular fashion to facilitate easy maintenance and upgrades inside a3 (W) × 3 (L) × 3 (H) m trailer (Figure 4(b)). The PM sample inlets were located ap-

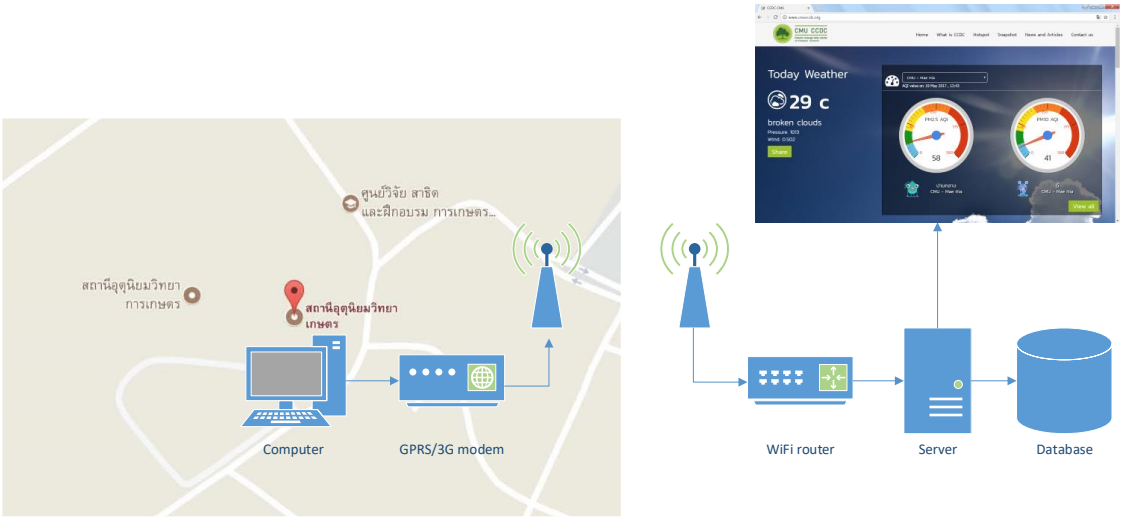


Figure 2. Schematic diagram of wireless communication system developed in this work.

(a) Monitoring station

(b) EPMM and NanoScan-SMPS

Figure 4. Developed monitoring station and EPMM and NanoScan -SMPS.

proximately 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. The sample flow first passed through the sample equilibration system to water vapor and reduced humidity levels. The dried sample then entered both EPMM and NanoScan-SMPS. Inside the trailer, the air conditioning unit had been mounted to maintain the suitable operation temperature conditions, about 25 ºC, for the electronic units of both the EPMM and the NanoScan-SMPS monitors. Comparison between this station and the PCD air quality monitoring station is shown in Table 1.

3. Field Study Results

Figure 5 shows the comparison between the measured particle number concentration from NanoScan-SMPS and the measured particle mass concentration of PM10 and PM2.5 from EPMM at Chiang Mai University Mae-Hia during May 18–20, 2017. During the monitoring periods, the daily average temperature ranged from 27 to 35ºC and the daily average relative humidity from 70–85%. As shown in Figure 5, the trend of the average of the particle number concentration measured by the NanoScan-SMPS agreed to within small differences with the particle mass concentration of PM-10 and PM2.5 measured by the EPMM. Figure 6 shows the comparison of 1 hr-average particle number concentrations measured by the NanoScan-SMPS and the particle mass concentration of PM10 and PM2.5 measured by EPMM at Chiang Mai University Mae-Hia during May 19 – 20, 2017. The 1 hour-PM10 and -PM2.5 mass concentrations measured by the

Table 1. Comparison between this work and the PCD air quality monitoring station.

Specifications	This work	PCD air quality monitoring station
Particulate size range	PM10, PM2.5 and sub-400 nm particles	PM10 and PM2.5
Mass concentration range	0.01 – 1,000 µg/m^3	0.1 – 10,000 µg/m^3
Mass concentration resolution	0.01 µg/m^3	0.1 µg/m^3
Number concentration range	1,000,000 particles/cm^3	-
Number concentration resolution	1 particles/cm^3	-
Measurement time	0.1 – 3,600 sec and 24 hr	60 – 3,600 sec and 24 hr
Data averaging	Every 0.1 sec	Every 1 sec
Particulate flow rate	5 L/min for EPMM 0.75 L/min for NanoScan	16.67 L/min
Operating temperature range	10 – 60 ºC	-30 – 50 ºC
Communication system	RS232/RS485, USB, TCP/IP	RS232/RS485, TCP/IP
Electrical Requirements	100 – 240VAC 50 Hz	100 – 240VAC 50 Hz

EPMM were in the range of 7.05 to 47.93 µg/m^3. The maximum and minimum 1 hour-PM10 mass concentrations measured by the EPMM were 47.93 µg/m^3 and 10.67 µg/m^3, respectively. The maximum and minimum 1 hour-PM2.5 mass concentrations measured by the EPMM were 44.41 µg/m^3 and 7.05 µg/m^3, respectively. The maximum and minimum 1hour-sub-400 nm particle number concentrations measured by the NanoScan-SMPS were 13,761.76 particles/m^3 and 1,916.35 particles/m^3, respectively. The 1 hour-average PM10 and PM-2.5 mass concentrations measured by EPMM were32.07 µg/m^3 and 28.64 µg/m^3, respectively, and the 1hour-average sub-400 nm particle number concentrations measured by the NanoScan-SMPS was about 5,262.00 particles/m^3.

Figure 7 and 8 show the 1 hr-average particle size distributions measured by NanoScan-SMPS at Chiang Mai University Mae-Hia during May 19–20, 2017. Particle size distribution obtained by the NanoScan-SMPS was in the range of about 11.5 and 365.2nm. As shown in Figure 7, the peak number concentration of particles on May 19, 2017 during 00: 00 to 11:00 was about 15.4 nm at 8:00 and the peak number concentration of particles was about 36.5 nm at 12:00 during 12:00–23:00. As shown in Figure 8, the peak number concentration of particles on May 19, 2017 during 00:00 to 11:00 was about 27.4 nm at 10:00 and the peak number concentration of particles was about 86.6 nm at 12:00 during 12:00 to 23:00. Figure 9 shows the comparison of the 1 hr-average particle number concentrations from NanoScan-SMPS and the particle mass concentrations from EPMM for PM10, PM2.5 and sub 400 nm at Chiang Mai University Mae-Hia during May 19–20, 2017. The trend of the 1hr-average of the concentrations of particle sizes ranged between 11.5 and 365.2 nm measured by the NanoScan-SMPS and it agreed to within small differences with the particle mass concentration of PM-10 and PM2.5 measured by the EPMM. On May 19, 2017, the 1 hour-average particle number concentrations measured by

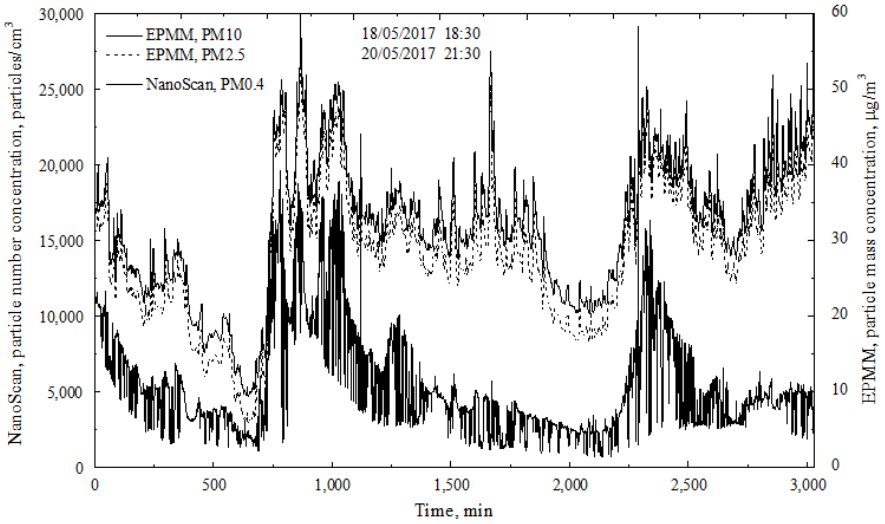
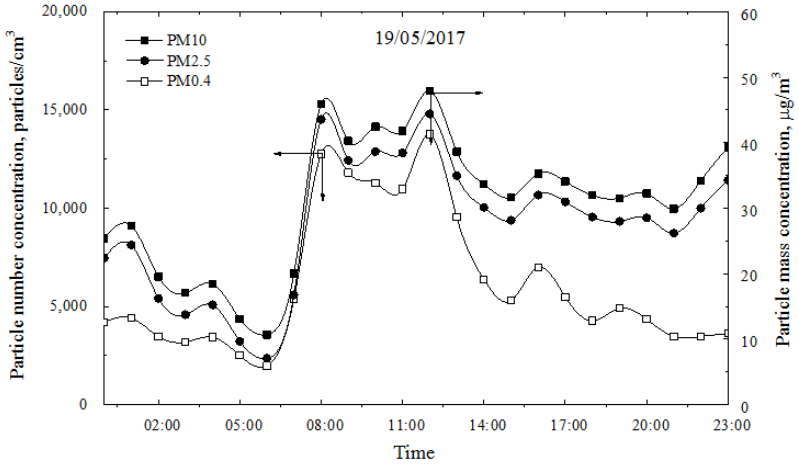
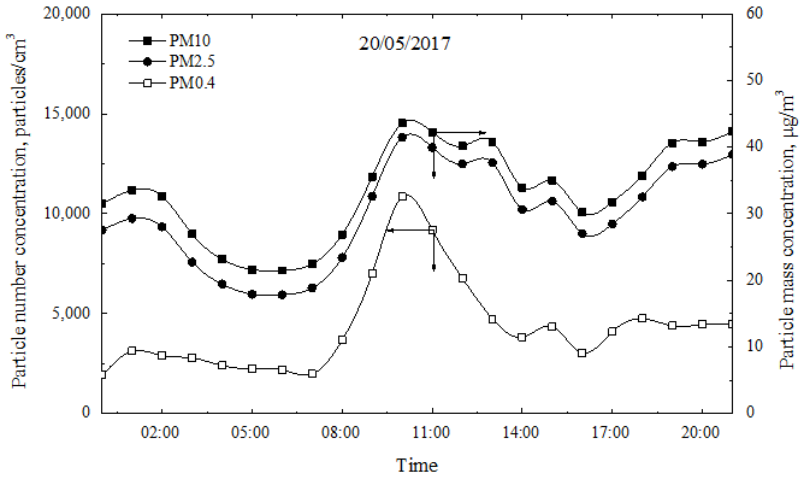


Figure 5. Comparison between the particle number concentration from NanoScan-SMPS and the particle mass concentration from EPMM at Chiang Mai University Mae-Hia during May 18 – 20, 2017.

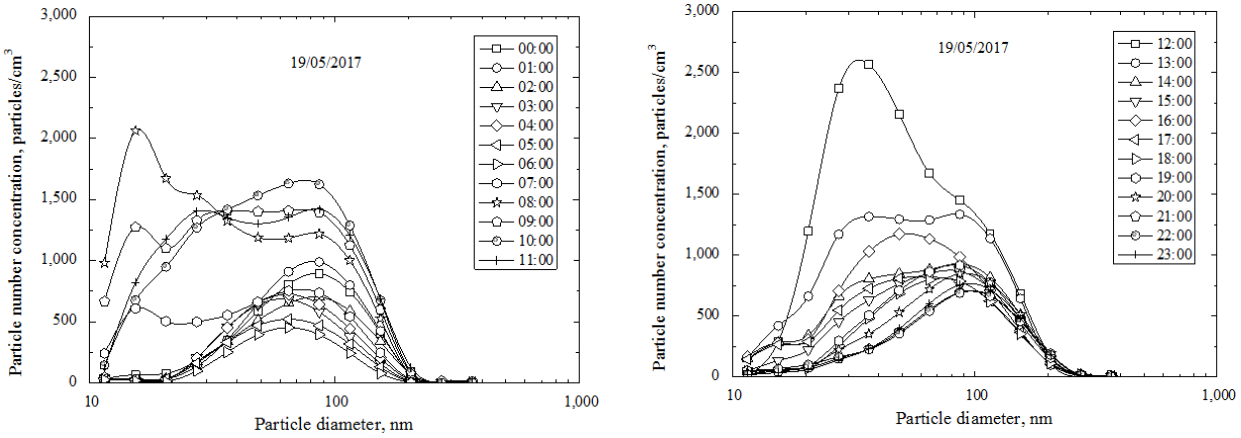


(a) 19/05/2017



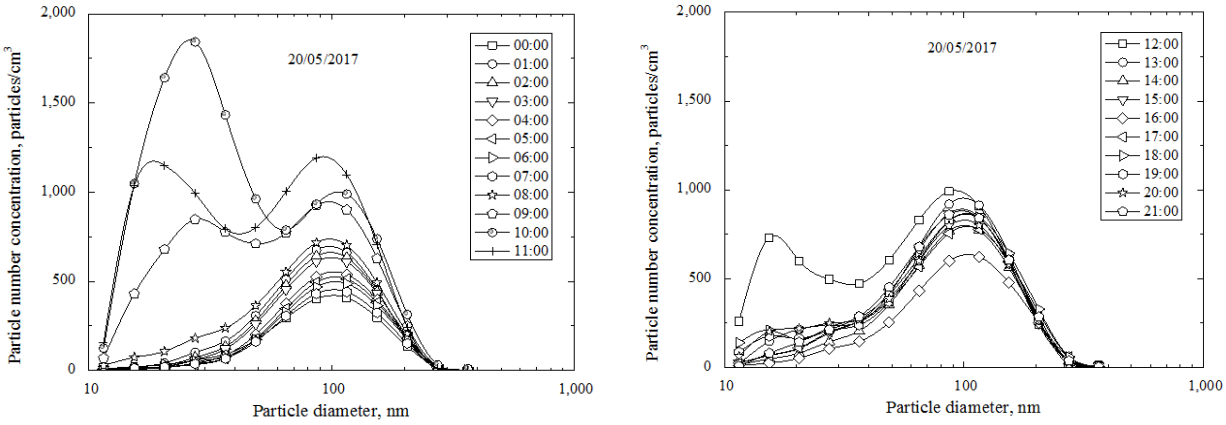
(b) 20/05/2017

Figure 6. Comparison of 1 hr-average particle number concentrations from NanoScan-SMPS and the particle mass concentration from EPMM at Chiang Mai University Mae-Hia during May 18 – 20, 2017.



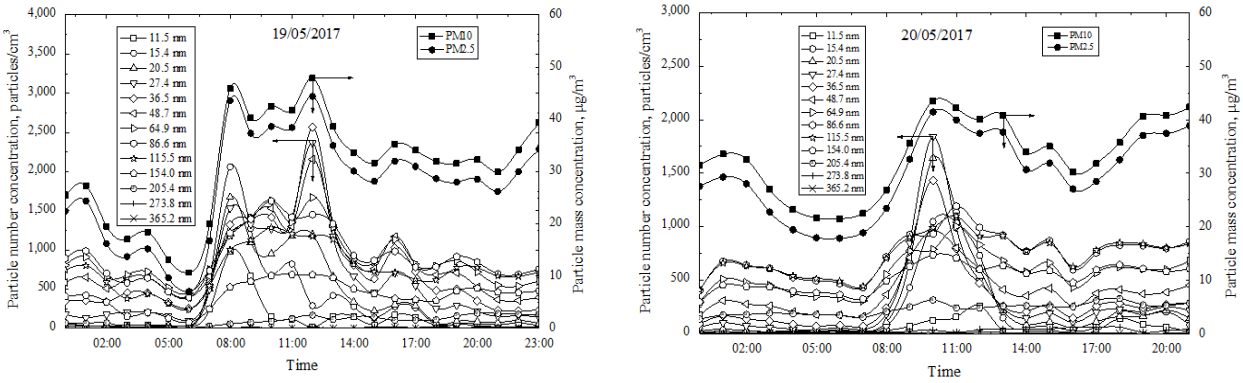
(a) 00:00 – 11:00 (b) 12:00 – 23:00

Figure 7. Measured particle size distribution from NanoScan-SMPS at Chiang Mai University Mae-Hia in May 19, 2017.



(a) 00:00 – 11:00 (b) 12:00 – 23:00

Figure 8. Measured particle size distribution from NanoScan-SMPS at Chiang Mai University Mae-Hia in May 20, 2017.



(a) 19/05/2017 (b) 20/05/2017

Figure 9. Comparison of 1 hr-average particle number concentrations from NanoScan-SMPS and the particle mass concentration from EPMM for PM10, PM2.5 and sub 400 nm at Chiang Mai University Mae-Hia during May 19 – 20, 2017.

the NanoScan-SMPS were respectively about 135.25, 317.50, 380.02, 596.73, 736.21, 836.31, 907.96, 920.63, 752.88, 426.01, 100.86, 7.40 and 3.09 particles/m^3 for each particle size of 11.5, 15.4, 20.5, 27.4, 36.5, 48.7, 64.9, 86.6, 115.5, 154, 205.4, 273.8 and 365.2 nm. On May 20, 2017, the 1 hour-average particle number concentrations measured by the NanoScan-SMPS were respectively about 46.07, 189.35, 240.44, 286.84, 298.62, 389.77, 566.35, 735.92, 730.15, 519.58, 226.46, 26.87

and 3.40 particles/m^3 for particle size of about 11.5, 15.4, 20. 5, 27.4, 36.5, 48.7, 64.9, 86.6, 115.5, 154, 205.4, 273.8 and 365.2 nm.

4. Conclusions

In this study, an online particulate monitoring system was developed and field tested for measuring the mass and number concentrations and size distributions of ambient particulate matter and sub-400 nm. The developed monitoring system consisted of electrostatic PM mass monitor (EPMM), NanoScan-SMPS, data acquisition and wireless communication system, and monitoring station structure with an air conditioning system. In this study, the monitoring station was located and field evaluated in Chiang Mai University Mae-Hia, Mae-Hia, Mueang Chiang Mai District, in Chiang Mai Province, Thailand. It was shown from the field study results that the trend of the average of the particle number concentration measured by the NanoScan-SMPS agreed to within small differences with the particle mass concentration of PM10 and PM2.5 measured by the EPMM. The 1 hour-average PM10 and PM2.5 mass concentrations measured by EPMM were about 32.07 µg/m^3 and 28.64 µg/m^3, respectively, and the 1 hour-average sub-400 nm particle number concentrations measured by the NanoScan-SMPS was about 5,262.00 particles/m^3. Measured particle size distributions from the NanoScan-SMPS were found to be in the size range of about 11.5 to 365.2 nm. It was shown that the developed online particulate monitoring system was simple, efficient and reliable in the simultaneous measurement of mass and number concentrations and size distributions of ambient PM10, PM2.5 and nanoparticles and features real-time particulate air pollution monitoring and wireless sensor system functions.

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