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Measurement of Aerosol Size Distribution in an Urban Park; a Case Study of Chulalongkorn Centenary Park in Bangkok, Thailand

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Abstract

This study investigated the particle size distribution (PSD) in the Chulalongkorn University Centenary Park, an urban park in Bangkok. Two continuous 7-day measurements were conducted during February to March 2023 by employing the Scanning Mobility Particle Sizer (SMPS) and the Optical Particle Sizer (OPS) to measure in the range of 10 – 10,000 nm. Observed $PM_{2.5}$ concentrations and local meteorological parameters were gathered for analysis. Ultrafine-mode concentrations exhibit diurnal pattern correlating with the traffic rush hours in the morning and in the evening. The statistics of geometric mean diameter also indicate minimum values twice daily in the morning and evening rush hours indicating the behavior of freshly emitted particles and subsequent growth. The number concentrations were significantly lower during the daytime than at nighttime highlighting the nighttime meteorological influence. The lumped number concentrations of particles larger than 80 nm (N80) correlates well with $PM_{2.5}$ data. Comparing between the two-measurement period, higher humidity is related to overall larger sizes that could be indicative of hygroscopic growth. Size distributions at chosen periods are presented to highlight the various influences of primary particle emission and microphysical processes. This work provides new information of the level of ultrafine particles that urban dwellers are exposed to in an urban park.

Keywords : size distribution; number concentration; particulate matter; urban park; meteorological parameter

Introduction

Poor urban air quality continues as major environmental issues that face contemporary society including Thailand. Over the past decade, the capital of Thailand has consistently experienced seasonal high $PM_{2.5}$ episodes with no obvious aim for abatement. Bangkok typically has severe $PM_{2.5}$ air pollution events from November to March due to a variety of factors including traffic, street vendors, transportation sectors, open burning, and industries [1]. Urban parks are currently one of the essential components of urban planning, and studies on air quality use them to give a background concentration of pollutants to offer the communities a variety of services and advantages [2-4]. The particle number concentration (PN), surface area concentration (PS), and mass concentration (PM), where PM is directly related to the particle volume concentration (PV), are commonly used to indicate the concentration of atmospheric particles [5]. Accumulating particles contribute significantly to the PS and PV while ultrafine particles typically dominate the PN [5]. Additionally, the recent studies [6, 7] descried the complex dynamic processes including meteorological data, emission sources, and atmospheric processes like nucleation, condensation, coagulation, and deposition contribute the concentration variability of ultrafine particle number size distribution (UFP-PNSD). Modes of four sizes used to describe the particle number size distribution (PNSDs) are nucleation (<25 nm), Aitken (25–100 nm), accumulation (100–1000 nm) [5], and coarse mode (<10000 nm) [8].

Suspended particulate matter has an adverse effect on the environment and human health. The PM_{10} and $PM_{2.5}$ fractions of particulate matter may pass through conductive airways and have a negative impact on the respiratory system and cause increased rates of cardiopulmonary mortality, shortened longevity, respiratory and cardiovascular disorders, as well as other adverse effects on human health [6, 9]. Recent epidemiological studies have shown a direct link between respiratory tract and cardiovascular diseases to airborne PM in urban environment [10]. Despite the chronic $PM_{2.5}$ problem, parallel efforts should be dedicated to advance our knowledge of ultrafine particles and aerosol number concentrations in line with the updated Air Quality Guidelines from WHO.

Several studies [11, 12] stated that the amount of pollution in the park majorly come from the sources in the surrounding area of this park. Moreover, the studies [2, 13] argued that the park in an urban area decreased turbulence of wind speed caused by the presence of its vegetation causing the increased pollutant concentration. Many air pollution studies focused on the case study of emission sources, measurement, simulation, and health risk assessment of particulate matter with the lack of particulate matter concentration and size distribution in urban parks in Thailand.

The objective of this study was to explore the aerosol number size distribution in an urban park locating in the Bangkok central business district. The measurement data will be analyzed together with $PM_{2.5}$, PM_{10}, and meteorological data measured at the park during the same period to provide further insights about the dynamics of the size distribution and level of ultrafine particles in the park.

Methodology

Case Study Area

The aerosol size distribution measurement was conducted in the Chulalongkorn University (CU) Centenary Park (13°44′22″ N, 100°31′25″ E), located in the central business district of Bangkok, Thailand. The site is at an elevation of 2 m above mean sea level and with a total area of 4.48 ha (0.048 square kilometers). The measurement work was conducted with the two measuring periods in the measurement spot (13°44'20.5"N, 100°31'26.1"E). The Park is located adjacent to the Chulalongkorn campus bordering with commercial and community areas. Right next to the park is an ongoing construction site and a community mall with restaurants and markets. Moreover, surrounded road network includes an expressway (West 270 m. away – annual average daily traffic (AADT) 319,180 veh/day), Banthat Thong rd. (adjacent West– AADT 27,500 veh/day), Rama IV rd. (South 375 m. away – AADT 110,397 veh/day), Phaya Thai rd. (East 465 m. away – AADT 61,600 veh/day) and Rama I rd. (North 765 m. away – AADT 46,582 veh/day). The park is open to the public for recreational uses between 5AM – 10PM. Often there are public venues and activities.

Measurements and Data Analysis

The continuous measurements of particle size distributions (PSD) were measured with the Scanning Mobility Particle Sizer (SMPS) model TSI 3910 in conjunction with the Optical Particle Sizer (OPS) model TSI 3330. The SMPS measures the particles covering the sizes of 10–420 nm while the OPS covers the range of 300–10,000 nm. The instruments measure aerosol number concentrations in various size bins and the mass and surface concentrations can be reported using an assigned particle density under a spherical shape assumption. The PSD samples were obtained at 1-minute time resolution. The measurements were carried out in two 7-day continuous periods from 20 February 2023 to 27 February 2023 and to 3 March 2023 to 10 March 2023. The measured PSD from the two instruments were merged using the Multi-instrument Manager (MIM) software and further analyzed and visualized using Microsoft Excel. Meteorological parameters and mass concentration of particles with aerodynamic diameter less than 2.5 μm ($PM_{2.5}$) measured by sensors installed at the CU Centenary Park are gathered for statistical analysis [14]. The sensor data which has native time resolution a scale of seconds was temporally averaged to 1-minute average data.

Results and Discussions

Particle size distributions

Figure 1 shows the aerosol number size distributions, dN/dlogDp, in unit of cm^{-3} with respect to sample timestamps. The 1-minute resolution data is displayed as color contour. The average particle number concentrations of 1st and 2nd period were 14,325 cm^{-3} and

11,961 cm^{-3} respectively. Overall, it can be observed that PSD from both measurement periods exhibit similar diurnal pattern. Typical PSD has a dominant mode at around 100 nm with repetitive occurrences of the peaking mode down to 30–50 nm sizes. We will discuss this diurnal pattern further in the next subsection.

Analysis of lumped number concentrations, $PM_{2.5}$, and meteorological factors

To allow comparative analysis of number concentrations in conjunction with other measurement data, the PSD is converted to lumped number concentrations, namely, N10, N40, N80, and N150, which mean total number concentrations of particles with diameter larger than 10 nm, 40 nm, 80 nm, and 150 nm, respectively, in a similar manner to [15]. Time-series of lumped number concentrations are depicted in Figure 2 a) – b) in comparison with the measured $PM_{2.5}$. It is visible that $PM_{2.5}$ correlates well with N80 because accumulation mode particles (Dp 100–1000 nm) overwhelmingly contribute to mass concentrations more than Aitken- and ultrafine-mode particles on the same particle number basis. We also presented the modal number concentrations obtained from the differences between the two lumped number concentrations. For example, N10-40 is the difference between N10 and N40 which highlight the ultrafine-mode concentrations. Figure 2 c) – d) are the plots for N10-40, N40-80, and N80-150. N10-40 displays diurnal cycles peaking twice at around 8AM and 7PM and hit the minimum twice at around 3AM and 2PM. We hypothesize these diurnal peaks to coincide with the traffic rush hour patterns in the morning and the evening and minimum to be associated with coagulation scavenging. Past studies identified the size of particles from traffic emission to center at 15 nm [16].

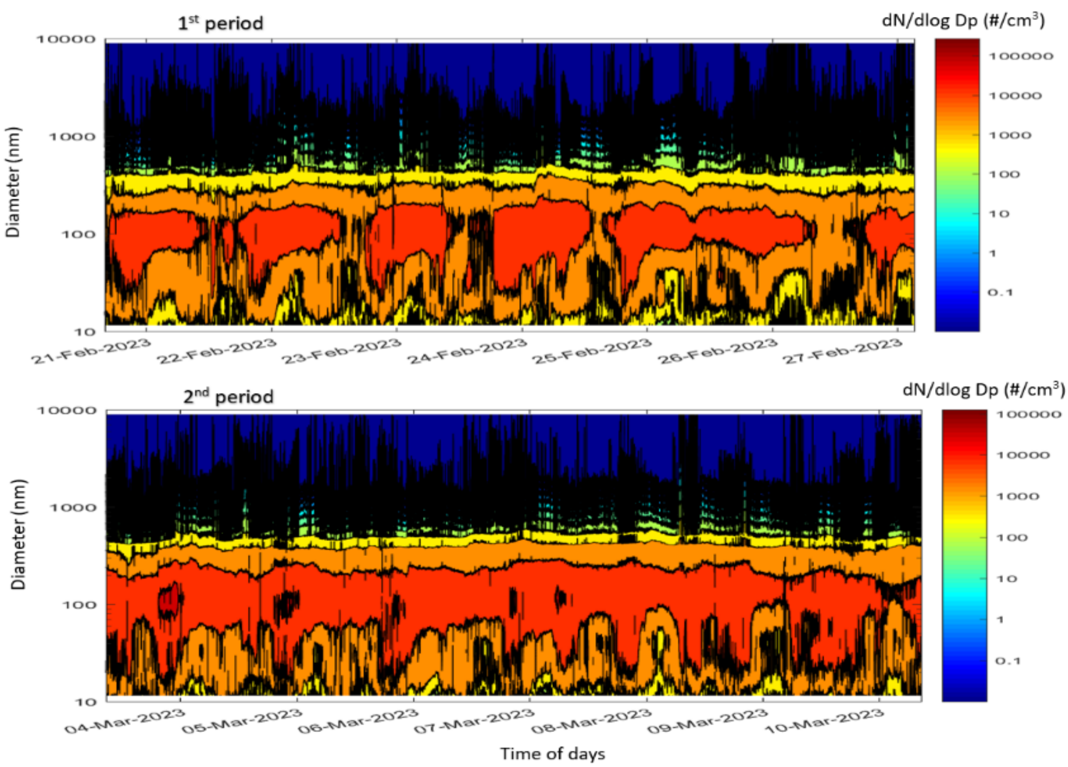

Figure 1 Time-series contour plots of aerosol number size distributions (dN/dlogDp) for the two measurement periods

We gather meteorological parameters measured at the park at the same as the PSD measurement. Temperatures during both measurement periods covered similar ranges of 23 to 39° Celsius and 26 to 38° Celsius. Relative humidity was slightly higher in the second period. Temperature, pressure, and relative humidity display diurnal cycle that closely linked to solar radiation levels. The plots indicate a general negative correlation between temperature and particle number concentrations and likewise with solar radiation. This can be explained with the higher chance of turbulence and atmospheric instability during the daytime that promote dilution of aerosol concentrations.

In addition, relative humidity usually reaches the maximum value of 75% in 1st period and 85% in 2nd period in this study. According to research [17], wet and dry deposition can induce fine particulate matter to coalesce, and several studies [18-20] stated that the high relative humidity may encourage gas-to-particle conversion, increasing the smaller PM fractions [21]. Past studies presented cases of nucleation events with high ultrafine concentrations persisting on the scale of hours followed by subsequent growth [22]. However, we only observe high ultrafine particles in 1-minute burst followed by a rapid growth to larger diameters. Thus, evidence seems to suggest we did not encounter new particle formation event which is probably understandable given the lack of conditions with low preexisting particles. The effect of higher relative humidity in the 2nd period can contribute to the overall larger diameters of the PSD compared to the 1st period this is because water vapor can condense onto hygroscopic particles and grow their sizes.

As mentioned above that solar radiation negatively correlates with lumped number concentrations. However, there are some incidences of high lumped number concentration during the daytime, for example, 21 February 2023 14:15. Locally emitted particles may be the reason but further investigation and data will be needed to shed more light on such event. During both the daytime and nighttime, wind speed has a significant impact on the particle number concentration. The wind speed was found with the highest speed of 4 m/s in 1st period and 2.9 m/s in 2nd period in the daytime, respectively. The wind speed in the measurement is generally higher in the daytime than the nighttime due to the solar radiation. Moreover, the reduction of number concentration in N10, N40, N80 and N150 was observed in both periods of measurement when the wind speed is very high in the daytime. However, a significant increasing in the magnitude of N10, N40, N80 and N150 was observed at nighttime when the wind speed is weak due to the lack of solar radiation. In this case, the evident case was found that the higher wind speeds can also increase the dispersion of particulate matters and other precursor gases. As such the wind direction is another important factor that affects the particle number concentration and size distribution in the atmosphere during both daytime and nighttime [23]. By showing Figure 2 m) – n) for wind direction, the average wind direction was found with the degree value of 348.75 - 11.25 degrees (north direction being 0 degree) in both periods of measurement. There is no clear correlating pattern of wind directions and number concentration because the aerosol concentrations involve various factors, such as the source strength, meteorological conditions, and other topography of the measurement area.

In Figure 1, the highest nucleation-mode particles concentration was significantly dispreading at night as compared to daytime. The fraction with Dp <100 nm showed higher particle number concen-trations (dN/dlog Dp) during daytime and nighttime in both periods often above 105 particles/cm^3. Then, particulate matter with diameters ranging from 10 nm to 10 μm portray similar particle number concentration values throughout the sampling periods. Figure 3 illustrates the diurnal distributions of geometric mean diameters (GMDs) of particles, with an average range spanning from 70 nm to 110 nm during both measurement periods. Furthermore, it is noteworthy that there exists no significant disparity between the highest GMD values observed during the daytime and nighttime in both periods. The traffic emission can influence low GMD every day around 8am and 7pm in the traffic rush hours. The average geometric mean diameters (GMD) in daytime and nighttime were observed to be 83.5 nm and 86.2 nm in the 1st period and 84.4 nm and 95.6 nm in the 2nd period, respectively. This suggests no particular contrast of particle number situations between the two sampling periods. The average geometric mean of nighttime is slightly greater than the daytime average value suggesting that nighttime humidity can contribute to condensational growth. In addition, the average geometric mean values for morning traffic rush hours (7-9AM),

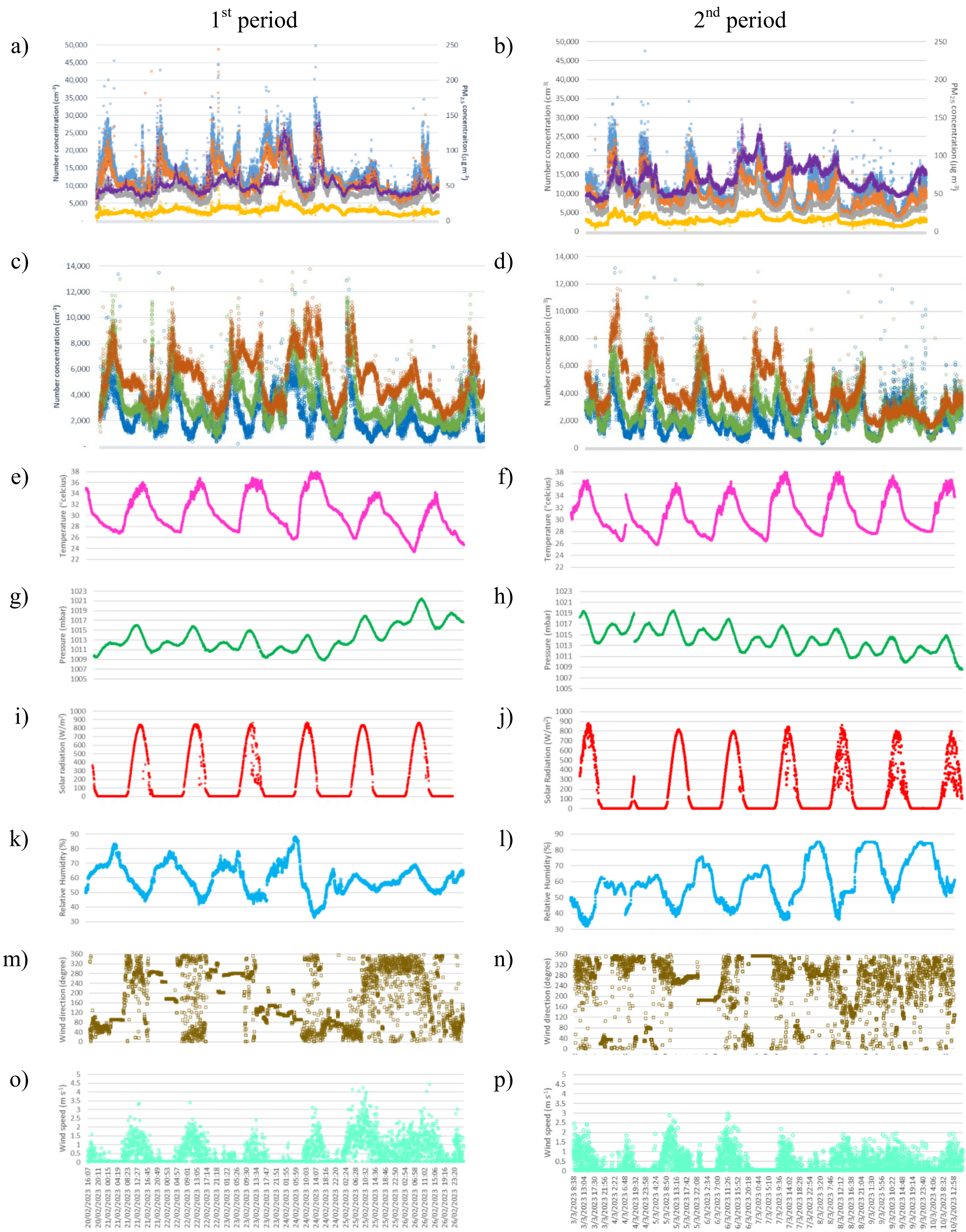

Figure 2 Time-series plots of lumped number concentrations, $PM_{2.5}$ concentrations, modal number concentrations, and meteorological parameters in both measurement periods; a)-b) N10, N40, N80 and N150 and $PM_{2.5}$, c)-d) N10-40, N40-80, and N80-150; e)-f) temperature; g)-h) air pressure, i)-j) solar radiation; k)-l) relative humidity; m)-n) wind direction; o)-p) wind speed.

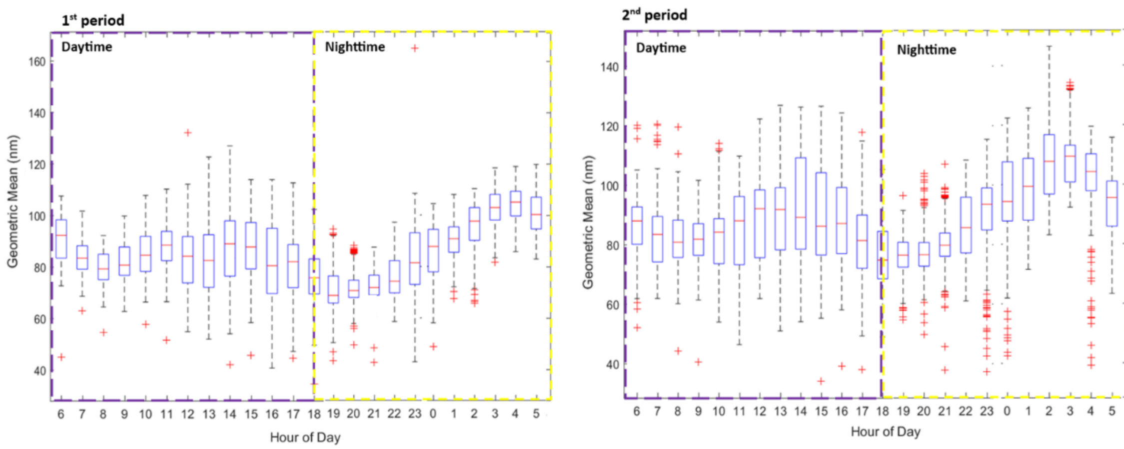

Figure 3 Box plots of geometric mean diameters of PSD in the two measurement periods

mid-day (9AM-6PM), evening rush hours (6-8PM), and nighttime (8PM-7AM) are 81.1 nm, 83.9 nm, 70.9 nm, 87.8 nm, respectively, for the 1st period and 81.8 nm, 84.9 nm, 76.7 nm, and 97.5 nm, respectively, for the 2nd period. The contrast of rush hours and non-rush hours is more notable with the smaller rush hours GMD. This is in accord with the published influence of fresh emission at 15 nanometers. Then after the rush hours, lower traffic means there is fewer supply of freshly-emitted particles and the existing particles grow through coagulation and condensation.

Figure 4 shows the particle size distribution over several selected timestamps in the first period and the second period respectively. In Figure 4a), the typical number concentrations at midday tend to be like PSD of 21 February 2023 12:55 centering at 80 nm and the higher ultrafine concentrations, PSD show bimodal feature with high peak centering around 50 nm and a lower peak at 15 nm such as that on 21 February 2023 17:20. The presence of 15 nm peak may suggest the influence of traffic emission and the second peak may be a result of growing via coagulation. Nighttime size distribution, such as that of 21 February 2023 21:07, peaking at 100 nm could be a result of ultrafine particles emitted during the evening rush hour. It is worth noting that the 2nd period coincided with particularly high $PM_{2.5}$ on multiple days. Apart from the typical shape of PSD centering at the 80 – 90 nm like that in Figure 4b), there is some instance of bimodal distribution with high peak at 30 nm and a lower peak at 150 nm on 4 March 2023 21:28. These insights underscore the complexity of aerosol microphysical dynamics, shaped by multifaceted factors. While the current analysis provides valuable data, it also prompts considerations for further investigation. Future studies may delve into the intricate interplay of meteorological conditions, geographical influences, and seasonal variations on particle size distribution. Additionally, comparing these findings with existing research could enrich our understanding of regional aerosol dynamics.

According to good practices statement of WHO air quality guideline 2021, control of ultrafine particle sources shall be prioritized by the levels of UFPs being low PNC (<1,000 particle/cm^3 (24-hour mean)) or high PNC (>10,000 particle/cm^3 (24-hour mean) or >20,000 particle/cm^3 (1-hour mean)) [24] Figure 5 displays the mean values of total particle number concentrations (all with diameters larger than 10 nm). The results indicate high number concentrations in term of 24-hour mean values throughout both measurement periods. However, high 1-hour mean PNC occasionally occur in the evening and consistently more frequently during the first period. This finding should prompt more attention dedicated to monitor number concentration on a regular basis.

a) b)

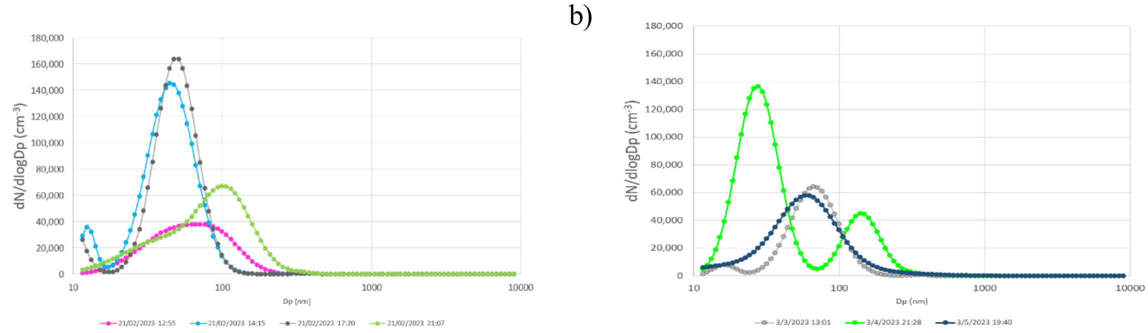

Figure 4 Size distribution of selected times for a) first period and b) second period

a) b)

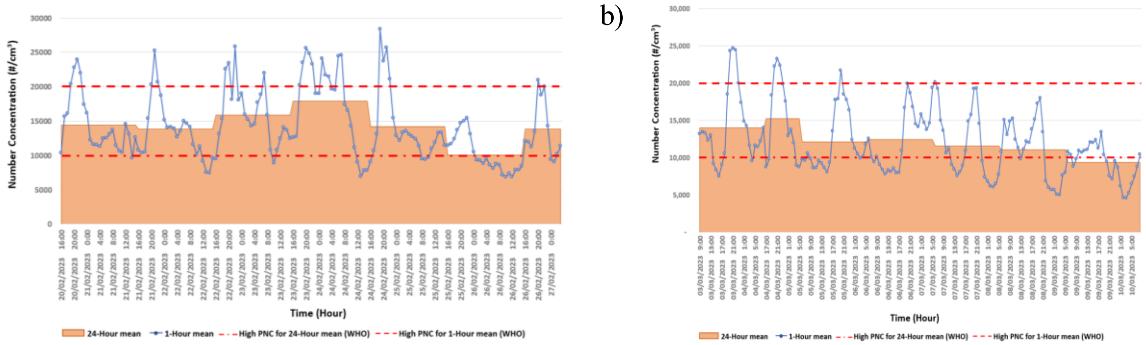

Figure 5 Total number concentrations for a) 1st measurement period and b) 2nd measurement period. The blue line symbols display 1-hour mean and the orange area shows 24-hour mean values. The red continuous broken line marks the WHO recommended high PNC for 1-hour mean and the red dash dot line marks the high PNC for 24-hour mean

Conclusion

Number size distributions were measured in Chulalongkorn University Centenary Park in Bangkok for two continuous 7-day periods in February and March 2023. The results suggested that meteorological conditions had some influence on the particle. Local traffic emissions and adjacent construction site were also anticipated to contribute to ultrafine particle concentrations in the park. Ultrafine particles concentration demonstrated peak patterns in agreement with the morning and evening rush hours. Nighttime increase of concentrations was consistently observed. The statistics of particle geometric mean diameters also exhibit the diurnal pattern of minimum at morning and evening rush hours indicating the influence of fresh emission (low GMD) and subsequent growth (higher GMD). The study also analyzed the lumped number concentration of particles (N10, N40, N80 and N150) and found good correlation of N80 with PM2.5. N80 variability patterns do not show clear correlation with diurnal solar cycle or road traffic activities because the involvement of long-range transport that brought $PM_{2.5}$ into the study area. Also, it was found that higher relative humidity may be the reason for overall larger particles due to hygroscopic growth in the 2nd period. In reference to the recommended benchmarks outlined in the 2021 WHO guideline, the 24-hour mean particle value featured in this investigation surpassed the threshold of 10,000/cm^3, thereby indicating exclusively high PNCs. Additionally, the analysis revealed occasional exceedances the 1-hour mean value of 20,000/cm^3 especially at night. Finally, this study was concluded that meteorological conditions greatly influence the particle concentrations and local traffic emissions plays an important role in the ultrafine concentrations. Aerosol microphysics is a complex process that is essential to consider in the context of understanding and managing ultrafine particles pollution. This work provides new information and good practices of the level of ultrafine particles that urban dwellers are exposed to in an urban park.

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References

[1] Heshani ALS, Winijkul E. 2022. Numerical simulations of the effects of green infrastructure on PM2.5 dispersion in an urban park in Bangkok, Thailand. Heliyon. Aug 31;8(9):e10475. https://doi.org/10.1016/j.heliyon.2022.e10475. PMID: 36097489; PMCID: PMC9463594.

[2] Xing, Y. and Brimblecombe, P. 2020. Trees and parks as "the lung of cities". Urban For. Urban Green. 48, 126552: 1-13. https://doi.org/10.1016/j.ufug.2019.126552.

[3] Frumkin H, Bratman GN, Breslow SJ, Cochran B, Kahn PH Jr, Lawler JJ, Levin PS, Tandon PS, Varanasi U, Wolf KL, Wood SA. Nature Contact and Human Health: A Research Agenda. Environ Health Perspect. 2017 Jul 31;125(7): 075001. PMID: 28796634; PMCID:PMC5744722. https://doi.org/10.1289/EHP1663.

[4] Hartig T, Mitchell R, de Vries S, Frumkin H. Nature and health. Annu Rev Public Health. 2014;35:207-28. Epub 2014 Jan 2. PMID:24387090. https://doi.org/10.1146/annurev-publhealth-032013-182443.

[5] Young, L.-H., Hsu, C.-S., Hsiao, T.-C., Lin, N.-H., Tsay, S.-C., Lin, T.-H., Lin, W.-Y., Jung, C.-R. 2022. Phenomenology of ultrafine particle concentrations and size distribution across urban Europe. Science of the Total Environment 856, 159070: 1-13. https://doi.org/10.1016/j.envint.2023.107744.

[6] Schikowski T, Sugiri D, Ranft U, Gehring U, Heinrich J, Wichmann HE, Krämer U. Does respiratory health contribute to the effects of long-term air pollution exposure on cardiovascular mortality? Respir Res. 2007 Mar 7;8(1): 20. PMID: 17343725; PMCID:PMC1821323. https://doi.org/10.1186/1465-9921-8-20.

[7] Bousiotis, D., Pope, F. D., Beddows, D. C. S., Dall'Osto, et al. 2021. A phenomenology of new particle formation (NPF) at 13 European sites, Atmos. Chem. Phys., 21, 11905-11925, https://doi.org/10.5194/acp-21-11905-2021.

[8] Wu, S.L., L.J. Mickley, D.J. Jacob, D. Rind and D.G. Streets. 2008. Effects of 2000-2050 changes in climate and emissions on global tropospheric ozone and the policy-relevant background surface ozone in the United States. J. Geophys. Res., 108, D18312. https://doi.org/10.1029/2007JD009639.

[9] Klejnowski K, Krasa A, Rogula-Kozłowska W, Błaszczak B. Number size distribution of ambient particles in a typical urban site: the first Polish assessment based on long-term (9 months) measurements. Scientific World Journal. 2013 Oct 27;2013: 539568. https://doi.org/10.1155%2F2013%2F539568. PMID: 24288492; PMCID: PMC3826294.

[10] Pope CA 3rd, Burnett RT, Thurston GD, Thun MJ, Calle EE, Krewski D, Godleski JJ. Cardiovascular mortality and long-term exposure to particulate air pollution: epidemiological evidence of general pathophysiological pathways of disease. Circulation. 2004 Jan 6;109(1): 71-7. https://doi.org/10.1161/01.cir.0000108927.80044.7f. Epub 2003 Dec 15. PMID: 14676145.

[11] Evgenieva, T., Winman, B.L., Kolev, N.I., et al. 2011. Three-point obdrvation

in the troposphere over sofia-plana mountain, Bulgaria. Int. J. Rem. Sens. 32(24): 9343-9363. http://dx.doi.org/10.1080/01431161.2011.554456.

[12] Xing, Y. and Brimblecombe, P. 2019. Role of vegetation in deposition and dispersion of pollution in urban parks. Atmos. Environ. 201, 73-83. https://doi.org/10.1016/j.atmosenv.2018.12.027.

[13] Long, X., Bei, N., Wu, J., Li, X., Feng, T., Xing, L., Zhao, S., Cao, J., Tie, X., An, Z. and Li, G. 2018. Does afforestation deteriorate haze pollution in Beijing–Tianjin–Hebei (BTH), China?, Atmos. Chem. Phys., 18, 10869-10879. https://doi.org/10.5194/acp-18-10869-2018.

[14] Sanphet, C., Sirima, P. and Garavig, T. 2017. Particulate Matter Monitoring Using Inexpensive Sensors and Internet GIS: A Case Study in Nan, Thailand. Thailand Research Fund. http://dx.doi.org/10.4186/ej.2018.22.2.25.

[15] D'Andrea, S. D., Häkkinen, S. A. K., Westervelt, et al. 2013. Understanding global secondary organic aerosol amount and size-resolved condensational behavior, Atmos. Chem. Phys., 13, 11519-11534. https://doi.org/10.5194/acp-13-11519-2013.

[16] Stanier, C., Khlystov, A. and Pandis, S.N. "Ambient Aerosol Size Distributions and Particle Number Concentrations Measured during the Pittsburgh Air Quality Study", Atmospheric Environment, Vol 38, 2004, 3275-3284. https://doi.org/10.1016/j.atmosenv.2004.03.020.

[17] Li. S., Ren, A., Guo, B., Du, Z., Zhang. S., Tian, M. and Wang, S. 2015. Influence of meteorological factors and VOCs on $PM_{2.5}$ during servere air pollution period in Shiiazhuang in winter; In: Proceedings of the 2015 2nd International Conference on Machinery, Materials Engineering, Chemical Engineering and Biotechnology. Atlantis Press. 588-592. https://doi.org/10.2991/mmeceb-15.2016.116.

[18] Zhao, D., Xin, J., Gong, C., Quan, J., Liu, G., Zhao, W., et al. 2019. The formation mechanism of air pollution episodes in Beijing city: insights into the measured feedback between aerosol radiative forcing and the atmospheric boundary layer stability. Sci. Total Environ. 692, 371-381. https://doi.org/10.1016/j.scitotenv.2019.07.255.

[19] Han, B., Zhang, R., Yang, W., Z., Ma, Z. and Zhang, W. 2016. Heavy haze episodes in Beijing during January 2013: Inorganic ion chemistry and source analysis using highly time-resolved measurements from an urban site. Sci. Total Environ. 544, 319-329. https://doi.org/10.5194/acpd-15-11111-2015.

[20] C.L. Zilli Vieira and P. Koutrakis. 2021. The impact of solar activity on ambient ultrafine particle concentrations: An analysis based on 19-year measurements in Boston, USA. Environmental Research 2021, 201. https://doi.org/10.1016/j.envres.2021.111532.

[21] Sirithian, D. and Thanatrakolsri, P. Relationships between Meteorological and Particulate Matter Concentrations ($PM_{2.5}$ and PM10) during the Haze Period in Urban and Rural Areas, Northern Thailand. Air, Soil and Water Research. 2022;15. https://doi.org/10.1177/11786221221117264.

[22] Wang, K., Ma, X., Tian, R. and Yu, F. 2023. Analysis of new particle formation events and comparisons to simulations of particle number concentrations based on GEOS-Chem–advanced particle microphysics in Beijing, China, Atmos. Chem. Phys., 23, 4091-4104. https://doi.org/10.5194/acp-23-4091-2023.

[23] Brzezina. Jáchym; Klaudia. Köbölová; Vladimír Adamec. 2020. "Nanoparticle Number Concentration in the Air in Relation to the Time of the Year and Time of the Day" Atmosphere 11, no. 5: 523. https://doi.org/10.3390/atmos11050523.

[24] World Health, O. 2021. *WHO global air quality guidelines: particulate matter (PM2.5 and PM10), ozone, nitrogen dioxide, sulfur dioxide and carbon monoxide*. World Health Organization. https://apps.who.int/iris/handle/10665/345329.