ASEAN Engineering Journal

Full Paper

EVALUATION OF *ALPHASENSE OPC-N2* SENSOR FOR PM_{10} MEASUREMENT IN THE NORTH JAKARTA

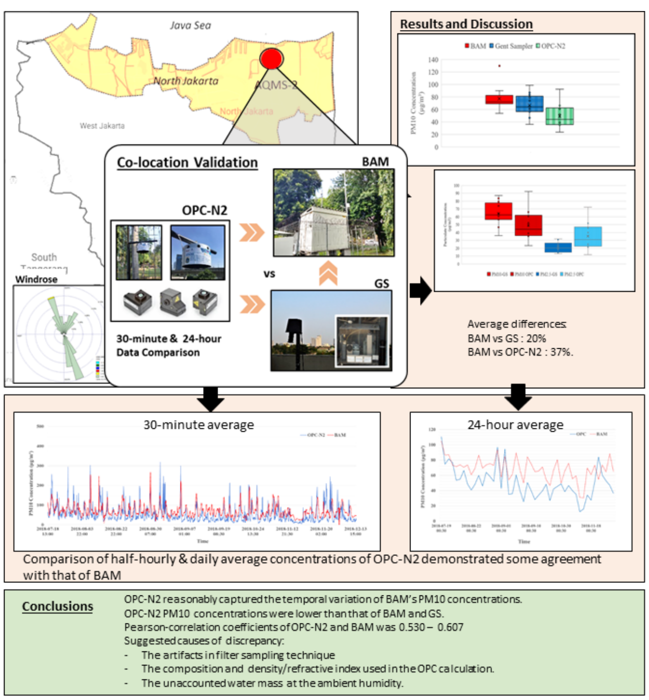
Ahmad Daudsyah Imami[a], Driejana[b*], Ernesto Reyes Villegas[c], Gordon McFiggans[d]

[a]Environmental Engineering Graduate Program, Faculty of Civil and Environment Engineering, Institut Teknologi Bandung, 40132, Bandung, Indonesia
[b]Air and Waste Management Research Group, Faculty of Civil and Environment Engineering, Institut Teknologi Bandung, 40132, Bandung, Indonesia
[c]Department of Earth and Environmental Sciences, School of Natural Sciences, Faculty of Science and Engineering, The University of Manchester, Manchester, United Kingdom
[d]Manchester Environmental Research Institute, Department of Earth and Environmental Sciences, the University of Manchester, Manchester, United Kingdom

Article history
Received
24 October 2021
Received in revised form
15 November 2021
Accepted
01 December 2022
Published online
31 May 2022

*Corresponding author
driejana@tl.itb.ac.id

Graphical abstract



Abstract

Spatial and temporal data of particulate matter (PM) are limited in Indonesia; hence cost-effective and robust instruments to monitor PM concentration could complete data coverage. The low-cost sensor (LCS) *Alphasense* OPC-N2 provides real-time PM concentration data and is relatively simple to install and deploy. This paper presents data from an OPC-N2 sensor collocated with a PM_{10} Beta Attenuation Monitor (BAM). The study was carried out at an air quality monitoring site in North Jakarta belonging to the provincial government. The location is considered suitable for evaluating the performance of OPC-N2 micro sensor as it is a representative of a typical Indonesian urbanized area with a range of pollutant sources, including sea-sourced aerosols. At the same site, a filter-based Gent Sampler (GS) measuring both PM_{10} and $PM_{2.5}$ was also deployed. The study showed that 30-minutely and daily average concentrations data for PM_{10} measured by OPC-N2 were lower than that of BAM measurements in both averaged durations by approximately 50%. The comparison between OPC-N2 and GS for PM_{10} showed that OPC-N2 measurement was underestimated but it was overestimated for $PM_{2.5}$. Nonetheless, correlations of OPC-N2 and BAM were 0.530 and 0.607 for PM10 and PM2.5, respectively. These results were comparable to other low-cost sensor evaluation studies in different countries, suggesting that the sensor can represent temporal variation of the reference measurement.

Keywords: Cost-effective method, Low-cost sensor, Micro sensor, Particulate matter, Indonesia

1.0 INTRODUCTION

The Sustainable Development Goals (SDG) has acknowledged the harmful effect of poor air quality. The direct relationship between SDGs and air pollution is mentioned in 2 issues; firstly, point 3.9 (Health) 'By 2030, Substantially reduce the number of deaths and illnesses from hazardous chemicals and air, water, and soil pollution and contamination'; and secondly, point 11.6 (Cities) 'By 2030, reduce the adverse per capita environmental impact of cities, including by paying special attention to air quality and municipal and other waste management.' [1].

Particulate matter is a criteria pollutant that has relatively high toxicity values [2]. Evidences had been well established for a range of its adverse health effects to the population in both developed and developing countries [3]. However, such evidences are difficult to find in developing countries due to inadequate air quality research and monitoring systems [4]. This circumstance is also observed in Indonesia. In Indonesia air quality is monitored using automatic reference method for the purpose of producing air quality index. However, the monitoring sites of the national network are only available in limited cities. Data gathered from air quality monitoring are used for air quality indexing system (called ISPU). In addition to PM_{10}, ISPU has four other criteria pollutants of CO, SO_2, NO_2, and O_3. The index published is the highest among indices calculated for each pollutant. ISPU formula was developed in 1995 when PM_{10} was the only parameter representing particulates. Another reason for only having PM_{10} in ISPU (at the time where this study was undertaken) was because data on finer particle parameters, e.g., $PM_{2.5}$ or PM_1, were relatively scarce [5].

Low-cost/microsensor monitoring (LCM) is an alternative method worth exploring in light of the shortage of PM monitoring. The method might be potential to fill in the PM pollution spatial information gap due to the limited air quality monitoring resources. This paper reports a preliminary investigation of LCM performance applied in the country. The Alphasense OPC-N2 instrument is a low-cost and compact optical particle counter allowing the retrieval of particle size distribution originated from the detected light backscatter of the red laser diode using a laser diffraction principle. Studies regarding this instrument have already been carried out in some countries [4],[6],[7],[8]. However, no literature was found to report its exposure to tropical climates.

The Alphasense OPC-N2 sensors were deployed in the Urban hybrid models for the AiR pollution exposure Assessment (UDARA) project, a 3-year research collaboration between Institut Teknologi Bandung and The University of Manchester. In order to deliver a challenging environment for the instrument, e.g., the hot and humid maritime tropical atmosphere, the monitoring location in North Jakarta that is nearest to the coast was chosen for co-locating the LCM. This location is also the site for one of the Air Quality Monitoring System (AQMS) owned by the Government of Jakarta Province.

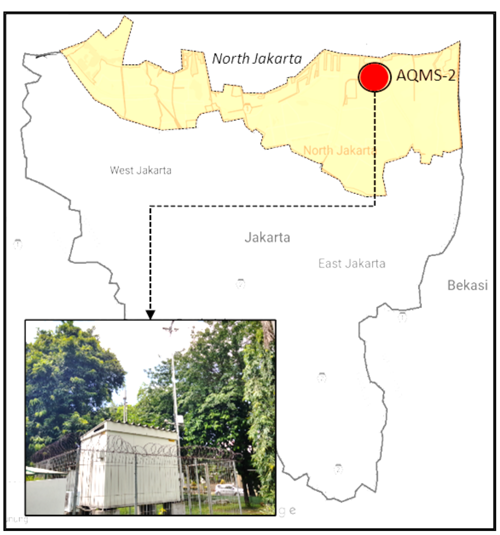


Figure 1 Map of the North Jakarta City (in yellow shading) and the location of AQMS DKI2

AQMS is a continuous automated monitoring system that generates data throughout the year as it is required for generating ISPU. In addition, there is also a set of meteorological measurements of wind speed and direction, temperature, and relative humidity (RH). This paper is a preliminary report of OPC-N2 performance in providing PM concentration measurement data and information on a broader range of particulate for its potential application in Indonesia.

2.0 METHODOLOGY

Area of Study

Jakarta is a special province that consists of 5 inland districts (cities) and one island district. North Jakarta district is a high-density region with 12,254 people/km^2, covering 146.7 km^2 areas [9]. Air quality for the whole area of North Jakarta is represented by one measurement location named AQMS DKI2. AQMS DKI2 station is located in Kelapa Gading sub-district (Longitude Latitude: 106.91, -6.154) as is depicted in Figure 1. The Java Sea borders the north to the northwestern side of the city, where to the South are the land of the other districts. Approximately 75% of the North Jakarta land use is residential. Office buildings (15%) and industrial (10%) cover the remaining areas [10].

The monitoring station at *Kelapa Gading* has a tropical-type marine climate, as it is located approximately 6 km from the north coast of Jakarta. It also surrounded by various emission sources, such as: i) Road with heavy vehicle activities associated with warehouses (*KBN Cakung*) around 3.5 km to the east; ii) Port activities (*Tanjung Priok*) approximately 6.0 km to the north; iii) Industrial activities (*JIEP Pulogadung*), approximately 4.0 km to the south; and iv) Manufacturing activities (*Sunter & Gaya Motor*) approximately 3.5km to the northwest of the site. Additionally, local transportation and highways emission sources in the residential areas around the monitoring site and main drainages of 5-to-6 m width at 100 m to the south of the monitoring site might also contribute to aerosol generation in the area.

Co-location Validation

Co-location validation is a field experiment process designed to identify unforeseen errors arising from the use of the sensor in the field, which is not adequately covered by the manufacturer's laboratory test. The reference measurement of AQMS DKI2 used Beta Attenuation Monitor (BAM) F-701-20. BAM F-701-20 particulate analyzer is a continuous monitoring instrument classified as a Class 3 Federal Equivalent Method (FEM) by US EPA [11] and EN15267 "Air Quality Certification of Automated Measuring System". The analyzer is regularly calibrated with blank and ranged standards once a month. The AQMS DKI2 reports PM_{10} as the single particulate size fraction at 30-minute intervals averaging from 5-minutely data. One LCM was co-located at the monitoring point. The field uncertainty was calculated by comparing the sensor results with the reference measurements using the methodology described in the guide to demonstrate equivalence [11].

During the UDARA project field survey, a Gent Sampler was also deployed at this site to measure PM_{10}, $PM_{2.5}$, and their composition [12]. The gravimetric filter-based measurement allowed cross-checking of $PM_{2.5}$ proportion in PM_{10} that could not be obtained as there is no automated $PM_{2.5}$ measurement at the site. Gent Sampler (GS) is an equivalent method used by the International Atomic Energy Agency (IAEA), a global network to investigate source apportionment of particulates. GS was designed by the University of Gent to measure fine and coarse particulates using two different filters that act as a dichotomous sampler [13, 14]. This method is able to validate the size distribution of particles. GS is a manual active method with a sampling interval of 24 hours per day to provide daily average PM concentration data. GS sampling during June – October 2018 resulted in 13 pairs of $PM_{2.5}$ and PM_{10} daily data.

Alphasense OPC-N2 using the light refractive principle at a particular time for particulate measurement [15]. The OPC-N2 continuously sizes and counts particles and allocates them to 16 discrete size bins. An algorithm is used to calculate and report particulate concentrations using the assumed value of material density for the three $PM_{1.0}$, $PM_{2.5}$, and PM_{10} size fractions [7]. The assumption used for the particle density value for calculating mass concentration was 1.6 g/cc. A unit of OPC-N2 was installed from July to December 2018, providing 1-minute concentration data in each size fraction.

Data Analysis Methodology

Three measurement methods used in this study resulted in PM concentrations of different sampling times, while the comparison required the exact duration of averaging data. For QA/QC analysis, the OPC's 1-minute data were analyzed using scatter plots and descriptive statistics.

After passed QA/QC processing, data cleaning, and screening, the averaging was carried out. Error-values and null were classified as not available (N/A). The analysis was done to evaluate the data capture capability of the sensor. Any extreme data observed in the plot were reviewed and might be considered as outliers then excluded from the calculation.

To get comparable data which is produced by BAM, the 1-minute OPC-N2 data were averaged to 30 minutes. Additionally, BAM and OPC-N2 data were also averaged to daily (24 hours) average to be compared to GS data. Co-location validation was done by comparing paired data obtained from the three methods at the same durations.

3.0 RESULTS AND DISCUSSION

Comparison of OPC-N2 to the Reference Method

Half-hourly average data of OPC-N2 and BAM (approximately 2708 pairs of data) were compared directly to see the agreement between both measurement method. OPC-N2 data demonstrated some agreement with BAM data as shown in Figure 2. Bias of OPC-N2 measurement was indicated by the densely clustered data above the 1:1 and 1:2 lines as shown in Figure 3.

Pearson correlation test was used to measure linear correlation of OPC-N2 and BAM data, while the paired t-test measured whether OPC-N2 can produce the same mean concentration with that of BAM. The null hypothesis (H_0) stated that the mean of PM_{10} concentrations are equal for both measurements. The H_0 is tested against the alternative hypothesis that stated both means are not equal.

The results in Table 1 indicated that there is moderately linear correlation with r= 0.530. However, the mean concentrations measured by the two methods were not equal, as can be seen in the value of the t-statistic and the p-value that showed H_0 was rejected. The statistics result indicated that OPC-N2 could moderately mimic the temporal fluctuation but not the mean values.

Table 1 Correlation and t-test Analysis of PM_{10} concentration between BAM and OPC-N2 measurement

Amount of Data	30-minute average			
	Pearson Correlation		Paired t-test	
2708 data	r-value	p-value	t -value	p-value
	0.530	0.000	29.78	0.000
	Daily average			
	Pearson Correlation		Paired t-test	
55 data	r-value	p-value	t -value	p-value
	0.607	0.000	11.72	0.000

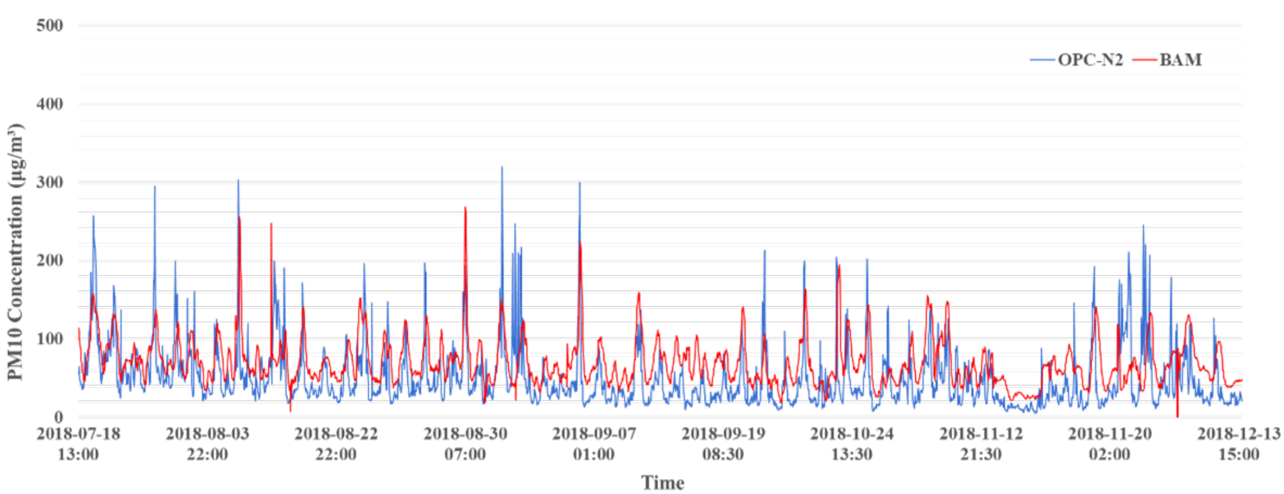


Figure 2 Temporal chart of PM_{10} 30-minute average concentration of OPC-N2 and BAM

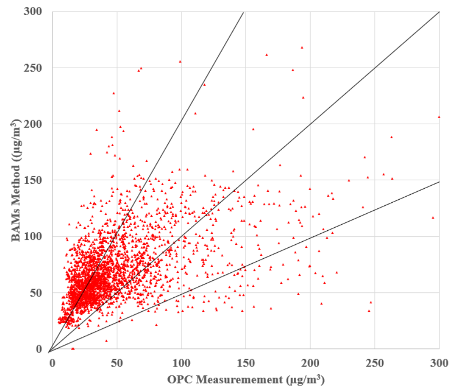


Figure 3 Scatter plots of 30-minute average concentrations of OPC-N2 vs. BAM (the grey lines represent 1:1 and 50% over and under values)

Daily average data is thought to smoothed out the variation, therefore it is expected to give better agreement of OPC-N2 to the reference method. It is also useful to investigate as it is the same as the duration of ambient air quality standards. To investigate the correlation of daily data, the 30-minute average data were converted into 24-hour average. The result shows that the Pearson correlation coefficient for daily data has somewhat increased (Table 1, bottom row).

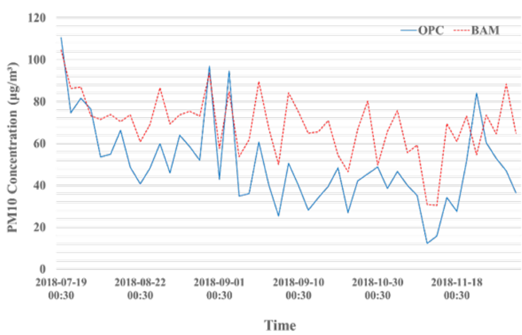


Figure 4 Line chart of daily average PM_{10} concentration between OPC-N2 and BAM measurements

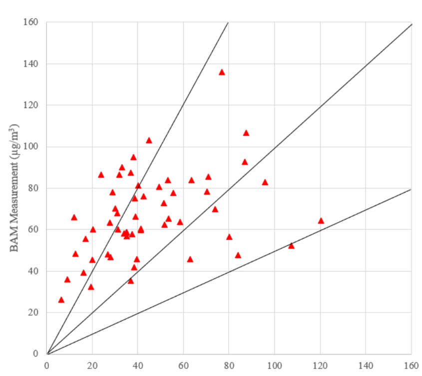


Figure 5 Scatter plot of daily average of OPC-N2 vs. BAM (the grey lines represent 1:1 and 50% over and under values)

Figure 4 shows that the OPC-N2 daily average concentrations also were lower than those of BAM by 40 - 50%; however, it could reasonably reproduce the temporal pattern of reference concentration, as is shown by Pearson correlation test of r= 0.607 (p-value: 0.000). Underestimation was relatively consistent (Figure 5, but it is better than in the 30-minute average (Figure 3).

The results in this study are in line with other studies. Air Quality Sensor Performance Evaluation Center (AQ-SPEC) of the South Coast Monitoring Division in California tested several PM low-cost sensor manufacturers and types, including OPC-N2 [16]. The study found that field correlation tests against Federal Equivalent Method (FEM) for PM_{10} showed lower values for all sensor types. The coefficient correlation of OPC-N2 to the reference method was relatively similar to that of AQ-SPEC studies, which found the coefficient of determinations (r^2) ranged between 0.45 – 0.57 (r = 0.67 – 0.75). The report stated that high humidity was found to be the cause of precision and accuracy decrement [16].

Ratios of $PM_{2.5}$ to PM_{10}

PM_{10} is defined as particles of 10µm size and below, so there is proportion of fine particles ($PM_{2.5}$) as part of PM_{10}. OPC-N2 collects particles in the size range of fine (0.38 µm) to coarse particles (17 µm) distributed into 16 bins [15]. Within that ranges, PM_{10} concentration is represented in 11 bins (0.38 – 9.00 µm). GS that was operated at the exact location measured daily average concentrations of both PM_{10} and $PM_{2.5}$. Using GS as the reference allows assessment of $PM_{2.5}$ proportion in PM_{10} ($PM_{2.5}/PM_{10}$ ratio) in both methods. Preceding the comparison, the accuracy of GS daily concentration measurement was evaluated by comparing its data to BAM daily average concentrations (n=13) [9]. The data distributions of the three methods are shown in Figure 6.

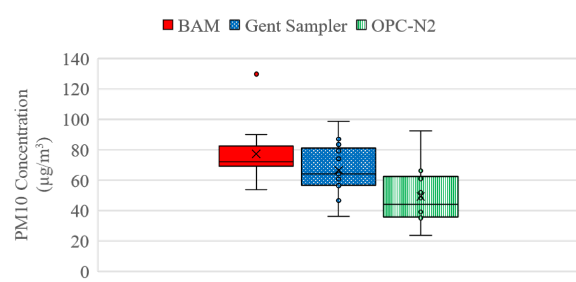


Figure 6 Box-plot comparison of PM_{10} daily average concentrations for BAM, GS and OPC-N2

All data set tended to positively skewed and the spread of OPC-N2 and GS data indicated similar deviation. BAM has the slightest variation of PM_{10} data. GS seemed to show closer values to BAM indicated by the upper quartiles of GS data fell within the range of the BAM mean value. Most of OPC-N2 data were generally lower compared to the other methods. The average error between BAM and GS was 20%, while difference of BAM and OPC-N2 was 37%. GS yielded measurement data around the mean value of BAM but with more variation. Apart from some outliers, generally, OPC-N2 values were lower than that of the two other methods.

GS data were then used as a reference to compare the relative proportion of $PM_{2.5}$ in PM_{10}. Figure 7 and Figure 8 show comparisons of PM_{10} and $PM_{2.5}$ concentrations of GS and OPC-

N2. The $PM_{2.5}$ of OPC-N2 was more resemble to the temporal trend of GS (Figure 7), while its PM_{10} tended to have different temporal patterns (Figure 8).

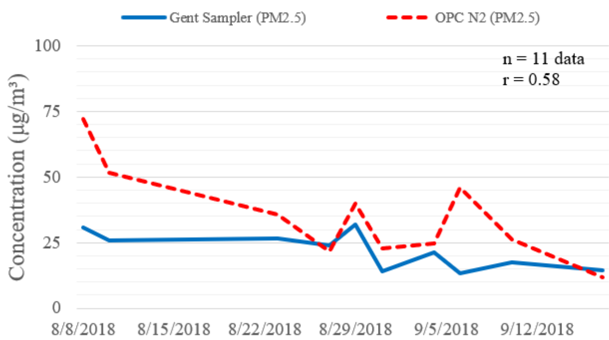


Figure 7 Comparison of $PM_{2.5}$ daily average concentrations of GS and OPC-N2

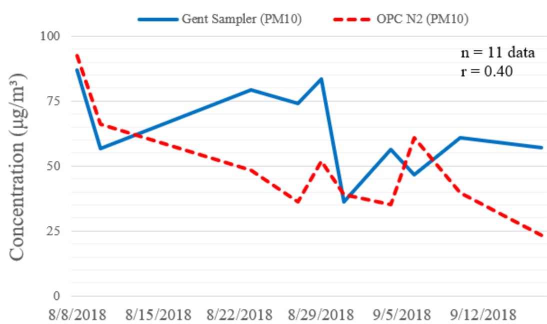


Figure 8 Comparison of PM_{10} daily average concentrations of GS and OPC-N2

This was confirmed by Pearson's correlation values (r) of 0.58 and 0.40 for $PM_{2.5}$ and PM_{10}, respectively. OPC-N2 PM_{10} values were lower than that of GS; however, were higher for $PM_{2.5}$ (Figure 9). In terms of the ratio $PM_{2.5}/PM_{10}$, significant difference was found in the ratio of OPC (69%) and of GS (34%) as also can be seen in Figure 10.

The difference in fraction might be caused by difference in composition between the fine and coarse PM, leading to a difference in the density or refractive index that should be applied in the OPC retrieval algorithm. The density of ammonium sulfate is 1.77 g/cc [16], while soot and sodium chlorides are around 1.8 g/cc and 2.16 g/cc, respectively [17]. The indices of organics are somewhere around 1.2 - 1.4 g/cc [18], and dust can be up to 3 g/cc [19].

The composition will change depending on the particle size, so a uniform density for each size bin may not be reasonably assumed. Other factor that is also needed to be considered in calculating the $PM_{2.5}$ mass concentration is particle sphericity or morphological dependence density. Mass of non-spherical aerosols such as soot aggregates and other ambient aerosols need to be recalculated using actual effective density depending on its shape, while OPC-N2 assumed all particles are spherical whereas atmospheric aerosol particles are often non-spherical [20].

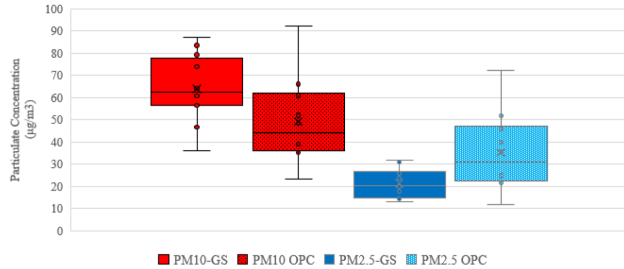


Figure 9 Box-plot comparison of PM2.5 vs PM10 daily average concentrations of GS and OPC-N2

The change in humidity inside the OPC-N2 also means that particles may sometimes be deliquesced - in this case, the particles will be in solution, and the density will be near 1 g/cc. The RH effect on BAM sampling results could be resolved by removing water vapor through the heating process and adsorption by silica gel before the sampled air flows into the analyzer column. This treatment was not available in OPC-N2.

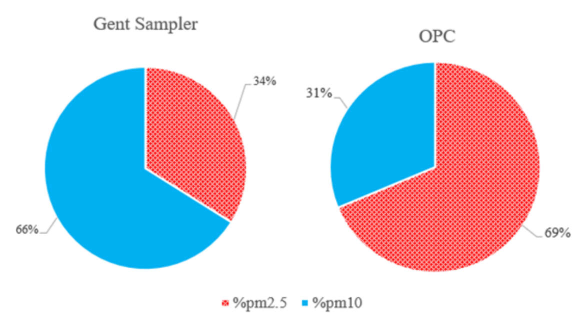


Figure 10 Fractions of particle mass according to size fraction in Gent Sampler and OPC-N2

Another possibility would be negative (possibly evaporative) artifacts in the GS filter sampling that also could add to the uncertainty. However, this might be less likely considering the difference between OPC-N2 and GS was almost double, while the proportion of evaporative aerosols (such as Cl) in the PM composition was much smaller [9].

Wind speed and direction data were also automatically recorded by AQMS DKI2. Windrose in Figure 11 indicates that the sampling location was affected by the northerly wind from the sea with 29% frequency of occurrence, while there was 20% frequency of occurrence of southerly wind from the land. Calm wind proportion was 42.4% (<0.5 m/s), so the overall wind speed was relatively low. The northern side of the sampling point is a coastal line. Significant sources of pollutant come from the port, arterial roads, and Jakarta - Banten highways that are in the northern side of the monitoring location. The zoning map of Jakarta [18] showed that the southern side of the monitoring site is highly populated residential areas and some industrial sites. The interferences of sea salt or secondary aerosols might affect the composition; hence the OPC-N2 reported values, which need further investigation.

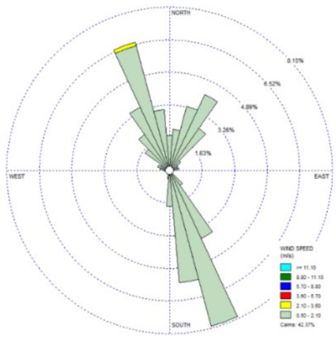


Figure 11 Windrose at sampling location from AQMS wind sensor in the same sampling period

4.0 CONCLUSIONS

OPC-N2 performance on PM_{10} measurement was evaluated by comparison to BAM and GS as the equivalent methods. OPC-N2 reasonably captured the temporal variations of BAM concentration. Pearson-correlation coefficients of OPC-N2 and BAM for 30-minute average and daily concentrations were 0.530 and 0.607, respectively. The results were similar to the correlation coefficients found in other studies that evaluated several PM sensors of different manufacturers [14].

OPC-N2 PM_{10} concentrations were lower than that of BAM and GS. OPC-N2 tended to have larger proportion of $PM_{2.5}$ (69%), compared to the that in GS (44%). This variation may arise from artifacts in the filter sampling technique of GS or changes in the composition that affect density/refractive index used in the OPC-N2 mass calculation. Another reason could be the unaccounted water mass at the ambient humidity. These results need further investigation as currently, comparison only carried out on one unit at one site.

Acknowledgement

Urban hybrid models for AiR pollution exposure Assessment (UDARA) project is a research collaboration *of Institut Teknologi Bandung* Indonesia (Principal Investigator: Dr. Driejana), with the University of Manchester, UK (Principal Investigator: Prof. G. McFiggans) in air pollution and health. The authors wish to thank *Lembaga Pengelola Dana Pendidikan* (LPDP, Indonesia Endowment Fund for Education), *Dana Ilmu Pengetahuan Indonesia* (DIPI, Indonesian Science Fund) and Newton Fund - Research Council UK (RCUK) for funding this work through grant No. 12/DIPI/2017, No.08/DIPI/2019 and No. NE/P014631/1. We are also grateful to the Environment Agency of DKI Jakarta Province for its support and assistance in accessing the monitoring site and data for the comparison.

References

[1] M. Elder, 2016. "Application of SDGs to Air Pollution," Paper presented at *The Atmospheric Pollution, Climate Change Nexus in Asia: Implications for a New Development Agenda*, Hayama, Japan,

[2] R. D. Ratnani, 2008 "Teknik Pengendalian Pencemaran Udara Yang Diakibatkan Oleh Partikel," *Jurnal Ilmiah Momentum*, 4(2): 27–32, [Online]. Retrieved from: https://publikasiilmiah.unwahas.ac.id/index.php/MOMENTUM/artice/view/612/7 . [Accessed August 2021]

[3] F. J. Kelly, and J. C. Fussell, 2012. "Size, source and chemical composition as determinants of toxicity attributable to ambient particulate matter," *Atmospheric Environment*, 60: 504–526, DOI: 10.1016/j.atmosenv.2012.06.039

[4] D. Priyanka, N. Victor, M. K. Jacqualine, E. S. Bruce,O. H. Wah, S. John, J. Roderic, and R. Carlo. 2017 "A Nairobi experiment in using low cost air quality monitors," *Clean Air Journal*, 27(2): 12-42 DOI : 10.17159/2410-972X/2017/v27n2a6

[5] M. Santoso, D. D. Lestiani, and A. Markwitz, 2013. "Characterization of airborne particulate matter collected at Jakarta roadside of an arterial road," *Journal of Radioanalytical and Nuclear Chemistry*, 297(2): 165–169, DOI : 10.1007/s10967-012-2350-5

[6] S. Feinberg, 2016. "CAIRSENSE Study : Real-world evaluation of low cost sensors in Denver, Colorado," Paper presented at *2016 National Ambient Air Monitoring Conference,* St. Louis, US.

[7] S. Sousan, K. Koehler, L. Hallett, and T. M. Peters, 2016. "Evaluation of the Alphasense optical particle counter (OPC-N2) and the Grimm portable aerosol spectrometer (PAS-1.108)," *Aerosol Science and Technology*, 50(12): 1352–1365, DOI : 10.1080/02786826.2016.1232859

[8] L. R. Crilley, M. Shaw, R. Pound, L. J. Kramer, R. Price, S. Young, and F. D. Pope, 2018 "Evaluation of a low-cost optical particle counter (Alphasense OPC-N2) for ambient air monitoring," *Atmospheric Measurement Techniques*, 11(2): 709–720, [Online]. Retrieved from: https://doi.org/10.5194/amt-11-709-2018 [Accessed June 2021]

[9] Driejana, N.K. Sari, and M. Santoso, *Characterization of dry-season particulate matter composition and its potential sources identification in Jakarta*, manuscript submitted for publication.

[10] L. Spinelle, M. Aleixandre, and M. Gerboles. *2013 JRC Technical Report:Protocol of evaluation and calibration of low-cost gas sensors for the monitoring of air pollution* [Online]. Available: https://ec.europa.eu/jrc/en/publication/eur-scientific-and-technical-research-reports/protocol-evaluation-and-calibration-low-cost-gas-sensors-monitoring-air-pollution [Accesed: June 2019]:

[11] S. Raja, S. R. Chandrasekaran, , Lin. L, X. Xia, P. K. Hopke, and K. T. Valsaraj, 2017 "Analysis of beta attenuation monitor filter rolls for particulate matter speciation," *Aerosol and Air Quality Research*, 17(1): 14–23,. DOI : 10.4209/aaqr.2016.03.0122

[12] P. K. Hopke, Y. Xie, T. Raunemaa, S. Biegalski, S. Landsberger, W. Maenhaut, and D. Cohen, 1997 "Characterization of the gent stacked filter unit pm10 sampler," *Aerosol Science and Technology*, 27(6): 726–735,. DOI : 10.1080/02786829708965507

[13] W.C. Hinds, 1999. *Aerosol Technology, Properties, Behaviour, and Measurement of Airborne Particles*, John Wiley & Sons Inc., New York,

[14] *Summary Tables and Reports, PM Sensor Evaluations*, [Online], Retrieved from http://www.aqmd.gov/aq-spec/evaluations/summary-pm[Accessed: September,2019]

[15] *Technical Specification OPC-N2 Particle Monitor*, [Online], Retrieved from http://www.alphasense.com [Accessed September 2019]

[16] D. O. Topping, G. B. McFiggans, and H. Coe, 2005 "A curved multicompo-nent aerosol hygroscopicity model framework: Part 1 – Inorganic compounds," *Atmospheric Chemistry Physic*, 5: 1205–1222,

[17] Jay G. Slowik, K. Stainken, Paul. Davidovits, L. R. William, J. T. Jayne, C. E. Kolb, Douglas R. Worsnop, Y. Rudich, Peter F. DeCarlo, and J. L. Jimenez, 2012. "Particle Morphology and Density Characterization by Combined Mobility and Aerodynamic Diameter Measurements. Part 2: Application to Combustion- Generated Soot Aerosols as a Function of Fuel Equivalence Ratio," *Aerosol Science and Technology*, 38(12): 1206-1222, DOI : 10.1080/027868290903916

[18] DKI Jakarta Government, 2014. *DKI Jakarta Regional Regulation No. 1/2014 : Detailed Spasial Plans and Zoning Regulation in DKI Jakarta Province*, Jakarta, Indonesia,

[19] BPS Kota Administrasi Jakarta Utara, *2019Kota Jakarta Utara Dalam Angka*, 2019 [Online]. Available: https://jakutkota.bps.go.id/publication.html. [Accessed August 2020]

[20] P. F. DeCarlo, J. G. Slowik, D. R. Worsnop, P. Davidovits, and J. L. Jimenez, 2004 "Particle morphology and density characterization by combined mobility and aerodynamic diameter measurements. Part 1: Theory," *Aerosol Sci. Technol.*, 38(12): 1185–1205, DOI: 10.1080/027868290903907.