Performance Evaluation of a Portable and Cost-effective Atmospheric Particulate Matter Monitor

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Abstract

Low-cost particulate matter (PM) sensors offer high potentials in air quality monitoring. Their performance, however, strongly depends upon the materials used, their design and on the sampling and operational conditions. In this work we evaluate the performance of the latest Alphasense PM sensors under real-life outdoor and indoor conditions. Our observations highlight differences in the accuracy of these sensors, especially when sampling aerosol particles that have different properties from those used for calibration and under real-life conditions, but also high potentials for improvements.

Keywords: Low cost PM sensors; Air quality; Indoor/Outdoor exposure

1. Introduction

Airborne particulate matter (PM) affects the climate (IPCC, 2013), while having implications on the human health as they can cause cardiovascular and respiratory diseases (Anderson, Thundiyil and Stolbach 2012). Recent progresses in aerosol instrumentation have lead to the development of low-cost and lightweight sensors for measuring the concentration and the size of ambient PM (Morawska et al., 2018). Such sensors can be employed for probing the concentration and size of PM in both indoor and outdoor environments (Kumar et al., 2015; Kumar et al., 2016a), as well as for personal exposure monitoring (Koehler and Petters, 2015). By exploiting the main advantages of these sensors (i.e., low-cost and portability), the spatiotemporal resolution of air quality monitoring can be significantly increased (e.g., by forming dense networks of these sensors), thereby providing great potential in the field.

The majority of these PM sensors count and size of the sampled aerosol particles based on the light they scatter when illuminated. In contrast to their laboratory-grade counterparts, low cost sensors make use of rather cost-effective components (e.g., lasers, mirrors, photodetectors) and peripherals (e.g., very simple or even passive flow system, data acquisition electronics, etc), while they are commonly accompanied by very basic user interfaces (e.g., software). For these reasons, low cost-sensors are extensively and systematically being tested by a number of research groups and first results on how they compare with the more expensive laboratory-grade instruments are becoming available.

Based on the published studies so far, the performance of these low-cost PM sensors depends on: i) Their design characteristics (e.g., optical and flow system, mode of transport of particles in the detector; e.g., Manikonda et al., 2016), ii) deterioration of their components leading to performance drifts over time (e.g., Mukherjee et al., 2017) and/or when the sensor is exposed to different environments (e.g., wider concentration range; Zheng et al., 2018), as well as iii) sampling and operational conditions. The latter is specifically important even for laboratory grade instruments, as, for instance, the sampled aerosol particles need to be dried before being measured(GAW report N0. 227, 2016), since any absorbed water on their surface will affect their chemical composition and size. In this aspect, most of the low-cost sensors are limited by their simplistic and underpowered flow systems, which do not produce enough pressure difference to allow connection with pre-treatment and sampling lines, which are common in air quality monitoring stations.

In order to address demands for cost-effective PM monitoring we have recently integrated a low-cost sensor/Optical Particle Counter (OPC) in a cost-effective prototype instrument; i.e., a standalone measuring device, combining the PM sensor and the necessary peripherals for its operation (Bezantakos et al. 2021). The promising Alphasense N2 Optical Particle Counter (OPC; Sousan et al., 2016; Bezantakos et al., 2018) was used as a PM sensor, combined with power supply and storage system, data acquisition, collection and storage interfaces, and networking capabilities. In this work, the newest models of the Alphasense OPCs are tested in real-life outdoor and indoor conditions in order to identify which is the most promising of use in integrated cost-effective instruments.

2. Methods

2.1. Sampling

The performance of the low-cost OPCs was assessed by outdoor collocated measurements with a Tapered Element Oscillating Microbalance (TEOM; Rupprecht and Patashnick Inc., Model 1400a) carried out at a traffic observational site in Nicosia. In addition, tests against a laboratory-grade Optical Particles Sizer (OPS, TSI Model 3330), were carried out under real indoor environment conditions. In this case, all the instruments were used in a household where different activities, including frying and vacuum cleaning, took place.

2.2. Data Analysis

Raw measurements from the reference instruments, namely the TEOM and OPS, were inverted directly by their firmware/software to mass concentrations and number size distributions (i.e., dN/d$_p$), respectively. More specifically for the TEOM, which directly measures the mass concentration of the sampled particles, the measurements are directly provided in terms of mass concentrations for two size fractions (i.e., $PM_{2.5}$ and PM_{10}). For the low-cost OPCs, the recorded data correspond to particle counts per size channel, which need to be converted to particle size distributions by utilizing the flow rate through the detector and the sample period as:

$$N_i = \frac{n_i}{SFR\ SP}\,. \qquad (1)$$

where n_i stands for the particle counts at each size channel (#), whereas *SFR* and *SP* represent the flow rate through the detector (cm^3/s) and sampling period (s), respectively.

Further analysis of our measurements involved the calculation of the total number concentration (applicable only to the low-cost OPCs and the reference OPS), the estimation of the normalized size distributions (i.e., dN/dlogd_p), as well as the estimation of the $PM_{2.5}$ and PM_{10} mass concentrations (i.e., applicable to the low-cost OPCs and the reference OPS, only). The latter were estimated for an apparent aerosol density of 1.65 g/cm^3. For the outdoor measurements, a direct comparison can be made only in terms of mass fractional concentrations (i.e., PM_{10} and $PM_{2.5}$). For the indoor measurements, a direct comparison can be made between the number and mass concentrations of the sampled aerosols.

3. Results and discussion

3.1. Outdoor measurements

Scatter plots of the PM_{10} and $PM_{2.5}$ mass concentrations estimated from the low-cost OPCs vs. those directly measured by the TEOM are shown in Figure 1. Based on the estimated values, the low-cost Alphasense R1 model exhibits a better performance than the Alphasense N3, because the latter understimates the mass concentration of both PM_{10} and $PM_{2.5}$ fractions, especially above 30 μg/m^3 (cf. AQ-SPEC, 2021). Since these low-cost OPCs measure directly only the particle number and size, the observed differences between the N3 and R1 models can be attributed to differences in the sizing of the particles and/or in their counting. For instance, if the low-cost OPC is accurately measuring the size of the sampled aerosols but significantly underestimates their number, then the resulted mass concentrations will be lower than the actual. If the low-cost OPC is accurately measuring the number concentration of the sampled particles but underestimates their size, then the estimated mass concentrations will be lower than the actual.

3.2. Indoor measurements

The total number concentration of aerosols measured indoors when there was no human activity, and while cooking (frying) and vacuum cleaning took place, is shown in Figure 2.

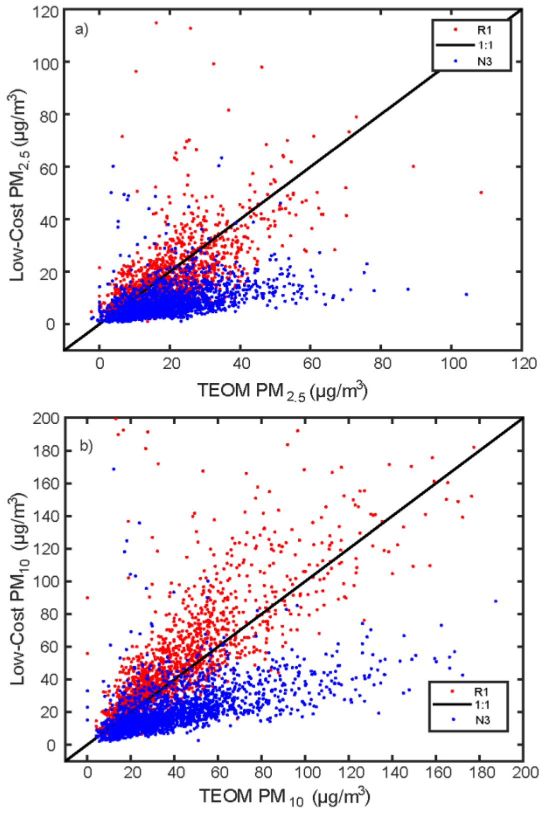

Figure 1: $PM_{2.5}$ (a) and PM_{10} (b) mass concentrations estimated by the low-cost OPCs vs. the reference instrument, i.e., the TEOM. Note for the estimated mass concentrations by the low cost OPCs we assumed an apparent aerosol density of 1.65 g/cm^3.

In addition, the estimated mass fraction concentrations (i.e., $PM_{2.5}$ and PM_{10}) at the same conditions are also depicted in Figure 3. As indicated by the measurements shown in Figure 2, the N3 model significantly underestimates the total number concentration of particles in almost all cases, and especially during cooking, when the reference total number concentration peaks at ca. 5000 #/cm^3. On the other hand, the R2 OPC is over-estimating the total number particle concentration by ca. 15 to 90% depending on the concentration. These discrepancies may be attributed to the different detection efficiencies of the instruments at the different sizes as discussed above. Note, that the intensity of the scattered light is related to the physicochemical properties of the aerosols (i.e., size, shape, chemical composition) and on the characteristics of the light source and detector (e.g., wavelength, angle of detection). As a result, all the instruments that rely on the optical detection of particles are calibrated with standard particles (i.e., standard size and optical properties). For instance, while all the instruments used in this work have a nominal lowest detection size of approx. 0.3 μm, their detection efficiency for the sampled aerosols (i.e., different from those they were calibrated with) may be different than 100%.

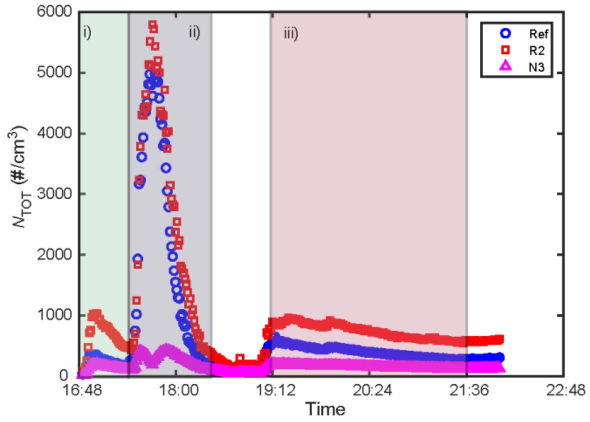

Figure 2: Total number concentrations measured indoors by the low-cost OPCs and the reference OPS (i.e., TSI Model 3330), during non-activity (i), cooking (ii) and vacuum cleaning (iii). Note that both the low-cost sensors and the reference OPC are directly measuring the aerosols number concentration, and are all based on the same operating principle (i.e., optical aerosol detection).

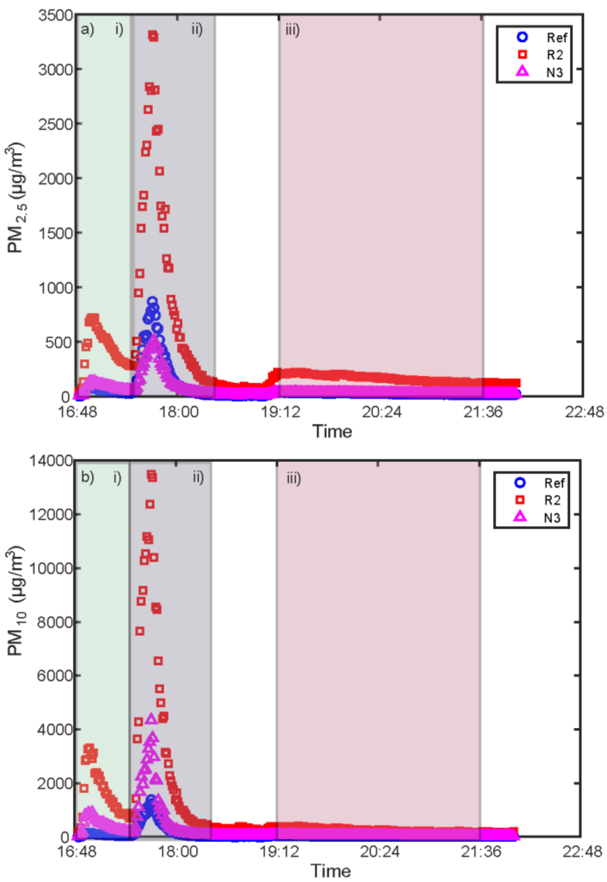

Figure 3: Mass fraction concentrations determined during the indoor measurements when the low-cost OPCs and the reference instrument were sampling aerosols during non-activity (i), cooking (ii) and vacuum cleaning (iii). Note: Apparent particle density used to convert the number to mass of the particles is 1.65 g/cm^3.

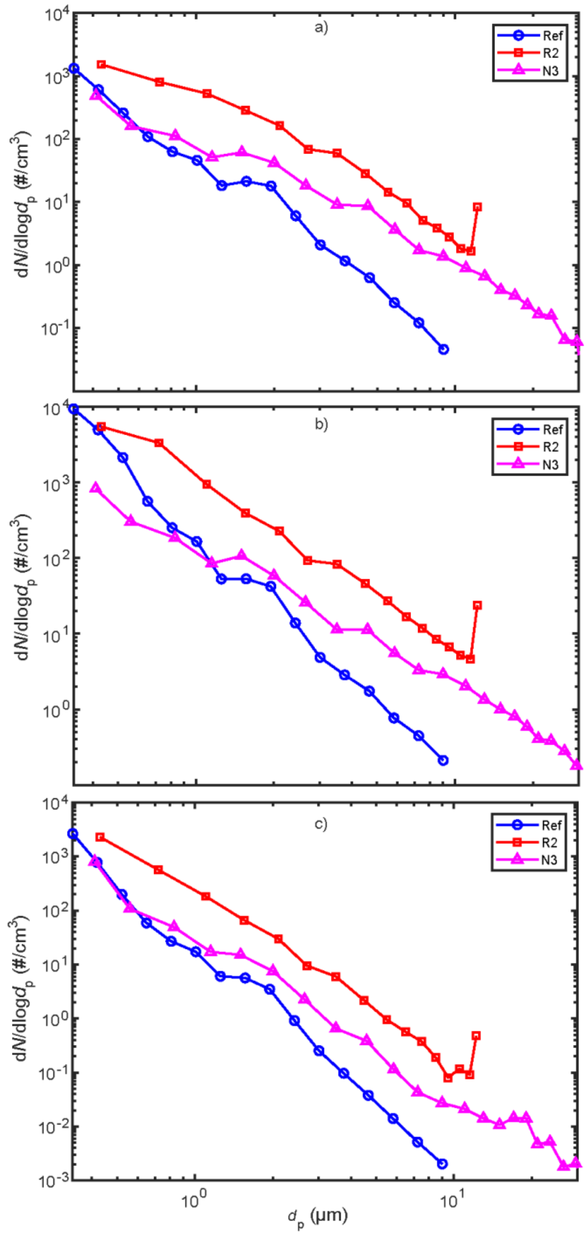

Figure 4: Averaged measured size distributions when both the low-cost and reference instruments were sampling indoor aerosols during non-activity (a), cooking (b) and vacuum cleaning (c).

The discrepancies in counting and sizing between the low-cost sensors and the reference instrument are more pronounced when the measured size distributions are used for estimating the mass concentration fractions (i.e., PM_{10} and $PM_{2.5}$; cf. figure 3). To further explore whether the exhibited discrepancies between the measured total number and mass concentrations can be attributed to differences in the detection efficiencies of the different sizes of the sampled aerosols we depict the averaged size distributions per activity interval in Figure 4. Based on the measured size distributions, the low-cost OPC R2 overestimates the number of particles at all of its size bins, and especially at the higher sizes, with respect to the reference OPC; something which explains both the exhibited overestimations in the particles total number and mass concentrations (cf. Figures 2 and 3). In contrast, the low-cost OPC N3 underestimates the number of particles residing at its lowest size channels (especially during the cooking activity), while it slightly overestimates for bigger particles. This can explain the underestimation of the total number aerosol concentration (cf. Figure 2), since in all these indoor activities the majority of the particles resides in the sub-500 nm range, according to the reference OPC. On the contrary, the estimated mass concentrations by the OPC-N3, which depend both on particle size and number, are comparable to the reference instrument for the sub-2.5 μm particles (cf. Figure 3a) and overestimated for the sub-10 μm particles (cf. Figure 3b), due to the overestimation of the aerosol number concentrations at higher than 500 nm sizes.

4. Conclusions

The performance of the latest models of the Alphasense low-cost PM sensors is evaluated under real-life conditions, in both outdoor and indoor measurements, in order to cover a wide range of conditions where low-cost PM sensors can be used. Our results highlight the discrepancies, especially under certain conditions, between the low-cost sensors and laboratory grade reference instruments. These discrepancies can be attributed to differences in the design, operating principle (i.e., OPCs vs. TEOM), components and interpretation of the raw signals of the sensors. With respect to mass concentration measurements, we underline the fact that all the optical sensors do not directly measure mass but number concentration at different sizes, so it is expected that their accuracy will be inferior, especially under conditions deviating much from those used during their calibration, when compared with reference mass concentration instruments (i.e., TEOM). On the other hand, all optical instruments provide direct information on the size distributions of the sampled particles, and therefore a more direct comparison is possible. From this perspective it appears that low-cost instruments can exhibit different performances when subjected to real-life conditions and when sample aerosols with a different chemical composition than that used for their calibration. Our observations highlight the fact that the potential instrument developer/user should account the advantages (e.g., low cost, portability, energy efficiency) with respect to the required accuracy. For instance, if the intended use of such a sensor is to act as part of an early warning system for air quality, then the cost, together with the consistency and repeatability of the measurements it can provide, together with its long term reliability in the given space are more important than its absolute accuracy.

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