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Suitability of Low-Cost Particulate Matter Sensors for Measurements in Ventilation Systems

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ABSTRACT

Particulate matter (PM) is one of the most critical pollutants affecting indoor air quality (IAQ). Hence, reducing the exposure of occupants to indoor PM pollution is critical. Ventilation systems for commercial and residential buildings are instrumental for achieving this goal.

Current developments in digital micro-electronics make available an increasing variety of low-cost PM sensors. These devices work on the principle of light scattering, and they open new possibilities for measuring and assessing indoor particle concentration. The least expensive ones are bare units integrated into consumer-grade products to measure PM concentration in still air.

Their cost makes them appealing also for evaluating the PM concentration inexpensively along ventilation ducts. Combining them with cheap dedicated electronic equipment makes it possible to transmit measured data and develop Internet of Things applications. The availability of real-time particle concentration could allow automated control actions in smart buildings to minimize indoor PM pollution. Moreover, the data obtained from these sensors are also helpful for assessing the performance of ventilation systems components during their operation.

To assess the potential use of low-cost PM sensors in ventilation ducts, we tested two samples of three different types of those sensors in a test duct studying their response in different controlled conditions. We evaluated the impact of particle concentration, different PM sources (synthetic aerosol and atmospheric one), and airflow rates.

We present and discuss the experimental data obtained from this study and the correlation with PM mass concentration measured data provided by other two laboratory instruments used as a reference.

INTRODUCTION

The most important indoor pollutant for human health in residential and commercial buildings in industrialized or high-traffic areas is airborne particulate matter (PM), according to an increasing number of studies (Logue et al., 2012; Chen et al., 2012; Ji & Zhao, 2015). The reduction of exposure to indoor PM can provide substantial health and economic benefits (Bekö et al., 2008; Montgomery et al., 2015; Zhao et al., 2015; Chan et al., 2015). The ability to measure and to know indoor particle concentrations produces several benefits. For example, real-time feedback on indoor PM concentrations can be an effective means of increasing behaviors to reduce indoor sources (Klepeis et al., 2013). Real-time measurements of indoor PM combined with other parameters influencing the indoor environmental quality and human occupancy and activity with

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smart building automation and control systems can adapt building operation to save energy and improve indoor air quality (IAQ) (Bushby, 1997; Snoonian, 2003; Zavala, 2013; Zhao et al., 2013; Rackes & Waring, (2013, 2014); Chen et al., 2014). However, airborne PM concentrations have been measured in buildings seldom because of the significant equipment costs involved (Heinzerling et al., 2013).

The availability of a wide variety of portable air pollution monitors, including many low-cost PM sensors commercially available, changes this situation (Snyder et al., 2013; Piedrahita et al., 2014; Williams et al., 2014; Wang et al., 2015). However, challenges remain regarding the possibility of using low-cost PM sensors for measuring the particle concentration in ventilation ducts or inside air handling units. Those devices' manufacturers engineered them to measure PM concentration in still air. We studied the behavior of three different models of low-cost PM sensors operating in an air stream to assess their potential and what adaptations could be necessary to deploy them extensively also inside HVAC systems. Such possibility is appealing because the effectiveness of air-cleaning systems and the PM reduction obtainable by their use could be much more easily assessed if cheap measuring instruments able to transmit the data remotely could be included as a routine device. The actual efficiency of air filtration systems during their operation has obviously become even more critical due to the Covid-19 pandemic.

MATERIALS AND METHODS

Low-cost PM sensors

We compared three different types of low-cost PM sensors, using two samples of each one. Table 1 summarizes their characteristics. All tested models are mainly intended to measure PM mass concentration in still air and work on a similar operating principle. A stream of sample air is drawn through an optical chamber built into the sensors. The particles in the air stream scatter the light emitted by a light source. The intensity of the scattered light is proportional to the characteristics (particle number, size, and refraction index) of the aerosol and is detected by a photodiode generating a pulsating signal, which is then processed by a microcontroller. Proprietary algorithms based on the Mie Theory (Li, 2019) generate the sensor's output.

Sensors A and B provide a digital output with the PM_{2.5} and PM₁₀ mass concentrations. Sensor B also provides the mass concentration for PM₁ and PM₄, the particle count in four different size ranges, and the average particle size. Differently from the above-mentioned sensors, sensor C provides an analogue signal (voltage), which is proportional to total particle mass concentration.

Table 1. Characteristics of the Sensors Studied

	Sensor A	Sensor B	Sensor C
Light source	Laser diode	Laser diode	Infrared emitting diode
Resolution	8 bit	8 bit	N/A
Supply voltage [V]	5 ± 0.3	5 ± 0.5	5 ± 0.5
Supply current [mA]	70 ± 10	<80	<20
Dimensions [mm]	70x71x23	41 x 41 x 12	46 x 34 x 17.6
Mass concentration range [µg/m ³]	0 – 999.9	0 - 1000	0 - 580
Lowest detectable particle size [µm]	0.3	0.3	N/A

We used two identical electronic modules based on an ESP-32 micro-controller unit to get the data from all three sensors simultaneously. Sensors A and B were connected to the ESP-32 board using a universal asynchronous receiver/transmitter (UART) communication protocol, while the output from sensor C was obtained using the dedicated analog-to-digital converter of the ESP-32, with a 12-bit resolution. The digital data from sensor C was then converted into particle mass concentration values by following the procedure provided by its manufacturer.

The boards were programmed to read the sensors every second and send them through serial communication to a terminal emulator program running on a personal computer (PC). The program logged the data on a text file stored on the local hard drive. We saved one separate data log for each sensor module during each one of the tests performed.

Reference instruments and test aerosols

We employed two research-grade laboratory instruments as references. We used a TSI OPS 3330 as the primary

reference for both PM₁₀ and PM_{2.5} measurements. Its measuring range is between 0.3 µm and 10.0 µm particle size and was configured to use 12 size channels. Additionally, a PMS LAS X-II was also used as a reference for PM_{2.5} measurements only. Its measuring range is between 0.09 µm and 7.5 µm, and its size range was divided into 18 size bins equally spaced on a logarithmic scale. We will refer to these two instruments as Ref1 and Ref2, respectively.

Both reference instruments provide particle counts per channel as raw output. This information is used to determine the mass-weighted concentration per channel, assuming that the measured aerosol is made of spherical particles with constant density, using the equation (Görner et al., 2012)

$$m = \rho \frac{\pi D_{pv}^3 c}{6tQ} \phi \quad (1)$$

where the volume-weighted particle diameter for each channel is given by

$$D_{pv} = LB \left[\frac{1}{4} \left(1 + \left(\frac{UB}{LB} \right)^2 \right) \left(1 + \left(\frac{UB}{LB} \right) \right) \right]^{\frac{1}{3}} \quad (2)$$

The total mass concentration of PM_{2.5} and PM₁₀ was obtained as the sum of the mass-weighted concentrations for all channels with particle sizes below or equal to 2.5 µm and 10 µm, respectively.

Laboratory tests

Figure 1 shows the scheme of the laboratory setup. We used a test rig for air filters compliant with ISO 16890-2 (2016) to simulate the conditions inside a ventilation duct. The outdoor air intake labeled as Inlet 2 is located approximately 11 m above the ground level and approximately 90 m apart from road traffic. The sensor modules were installed inside the test duct attached to the isokinetic sampling probe (TSI 1130011) used with the Ref1, as showed in Figure 2. A second identical isokinetic sampling probe was installed 3.3 m downstream and connected to Ref2. Both probes were placed in the midplane of the test duct so that the instruments sampled the airflow from its centerline. The reference instruments were connected to the sampling probes using conductive silicone hoses to avoid losing particles due to electrostatic charges. During the first 17 short-duration tests, the sensors were placed within an enclosure box. For the rest of the tests, we exposed them directly to the air stream. We did not find significant differences between the results obtained with and without the enclosure. Thus, we do not discuss this aspect further.

Table 2 summarizes the test conditions used during our study. The initial part consisted in short tests with a duration between 300 s and 8 h to assess the response of the sensors under different particle concentrations using Di-Ethyl-Hexyl-Sebacate (DEHS) synthetic aerosol and atmospheric aerosol in the outdoor air.

Table 2. Test Conditions Studied

Test duct air velocity [m/s] – [ft/min]	Mean total mass concentrations measured with Ref1 [µg/m ³]	Test aerosol type	Temperature [°C]	Relative humidity [%]
0.50 – 98.4	33	DEHS	22	39
0.75 – 147.6	8/23/30/50/80/111/123/310	DEHS	22	30-39
0.75 – 147.6	14/48	Outdoor air	20	37
0.00 – 0.00	13.8	Outdoor air	20	38
1.50 – 295.3	7-45	Outdoor air	21-23	30
2.50 – 492.1	6 - 45	Outdoor air	14-21	22-38

The DEHS aerosol was generated using a Laskin nozzle fed with compressed oil-free air. We varied the compressed air pressure to control the particle mass concentration inside the test duct. The uniformity of DEHS aerosol concentration in the test section had been verified before following the protocol described by ISO 16890-2:2016 standard.

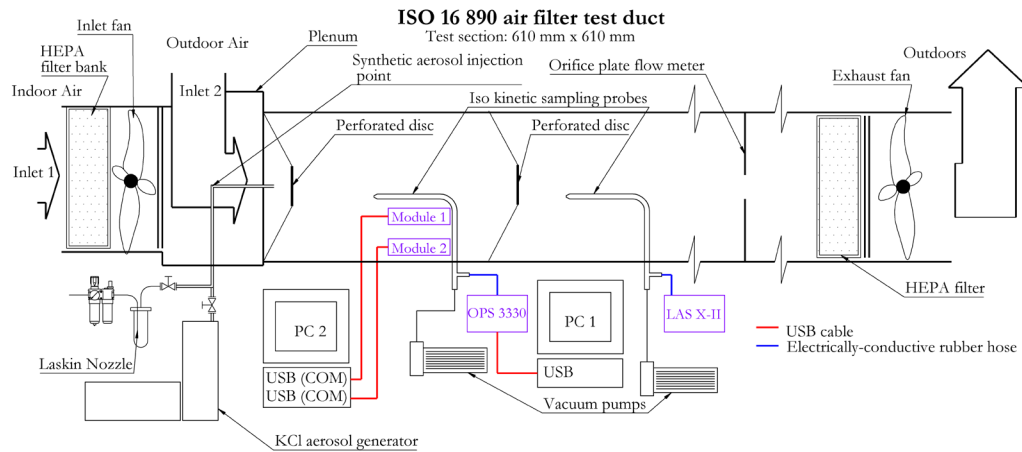


Figure 1 Laboratory setup used for the characterization of the sensors.

The short tests were carried out with air flow rates equal to 670 m³/h and 1000 m³/h, corresponding to low air velocities (0.50 m/s (98.4 ft/min) and 0.75 m/s (147.6 ft/min), respectively) recommended by the manufacturers of sensors A and B. When using DEHS aerosol, indoor air was drawn from Inlet 1 through the High-Efficiency Particulate Air (HEPA) filter bank shown in Figure 1. The rotational speed of the fans was set to achieve the desired airflow rate while maintaining the duct at a higher pressure than the room. This setup guaranteed that only DEHS particles with a stable concentration were present in the test duct during the experiments. The reference mass concentration was obtained from Ref1 considering a particle density of 0.912 g/cm³ for DEHS particles (ISO 16890-2:2016 standard).

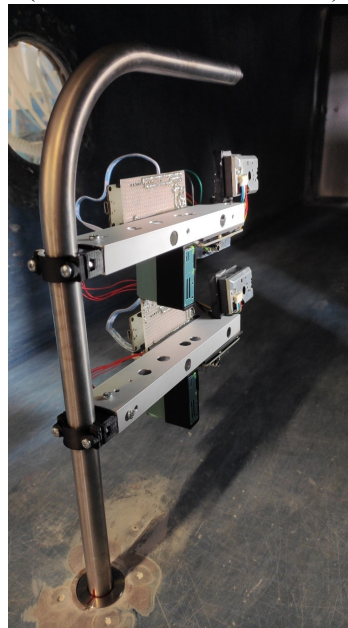


Figure 2 Upstream isokinetic sampling probe of Ref1 and the tested sensors attached to it.

An additional test using still outdoor air was done, performing a previous purge drawing air from Inlet 2 by turning on the downstream test rig fan for a few minutes and then performing the test without any imposed flow rate. To obtain the mass concentration of outdoor air, we assumed a particle density of 1.65 g/cm^3 . Weijers et al. (2004) based on the study by Tuch et al. (2000) proposed this density value. Tittarelli et al. (2008) also used it to estimate the particle mass concentration in outdoor air in the city of Turin, Italy, using a particle spectrometer.

After the preliminary tests, we carried out the experiments at higher air flow rates (2000 and $3400 \text{ m}^3/\text{h}$) during more extended periods (20 min, 1 h, 60 h, and 88 h) using unfiltered outdoor air to study the performance of the sensors in operating conditions such as those of a ventilation duct.

Throughout all tests, we controlled the rotational speed of the fans by a Programmable Logical Circuit (PLC) to maintain a constant airflow rate, regardless of ambient conditions such as relative humidity and temperature. The sampling flow rate of Ref1 was constant (1 l/min) for all tests. In the case of Ref2, sample flow rates of 95 and $10 \text{ cm}^3/\text{min}$ were used when sampling DEHS aerosol and outdoor air, respectively.

RESULTS

We present the overall results from the short-duration tests with constant DEHS aerosol concentration comparing the response of the low-cost PM sensors response and our reference instruments. Then, we present the results from the tests simulating the operation inside a ventilation duct at constant airflow rates.

Synthetic aerosol tests at constant particle mass concentrations

Figure 3 shows an example of the data collected during the short tests using stable concentrations of DEHS aerosol.

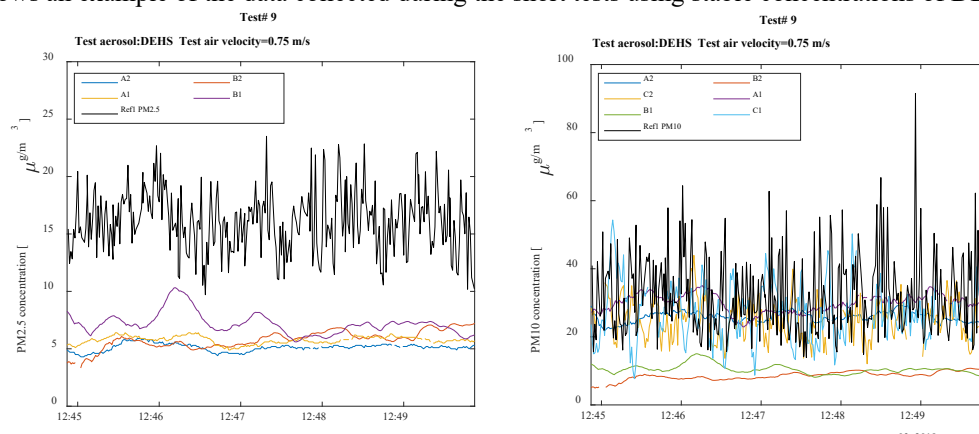


Figure 3 PM mass concentration data collected from the low-cost PM sensors and calculated from the reference instruments during short tests using stable concentrations of DEHS aerosol at low test air velocity (0.75 m/s (147.6 ft/min)).

We determined the mean mass concentration obtained by each sensor for each test as the arithmetic average of the data points collected from it during the test. All data points more than three standard deviations apart from the mean measured value were not considered in the computations. Next, we compared the mean mass concentrations obtained from each sensor against the mean mass concentration output from Ref1. We distinguished between $\text{PM}_{2.5}$ and PM_{10} results to consider the dedicated channels in type A and B sensors separately. The output from C sensors was compared only against PM_{10} mass concentration values from Ref1 because we did not detect particles larger than $10 \mu\text{m}$.

Figure 4 shows the linear regression fittings for the $\text{PM}_{2.5}$ and PM_{10} data from the sensors and the percentage errors as a function of the PM_{10} mass concentration obtained from the output of the reference device. In general, with DEHS aerosol, the sensors showed lower mass concentration values than the reference instrument. However, they demonstrated a good linear

correlation with the Ref1. Despite that, the distribution of percentage errors shown in Figure 4 c) indicates that a linear fit might not be adequate to calibrate the PM₁₀ readings from sensors A1, C1 and C2, especially when the mass concentrations change over a wide range of values. This is because the percentage deviation from reference of their PM₁₀ readings changed significantly over the range of concentrations studied.

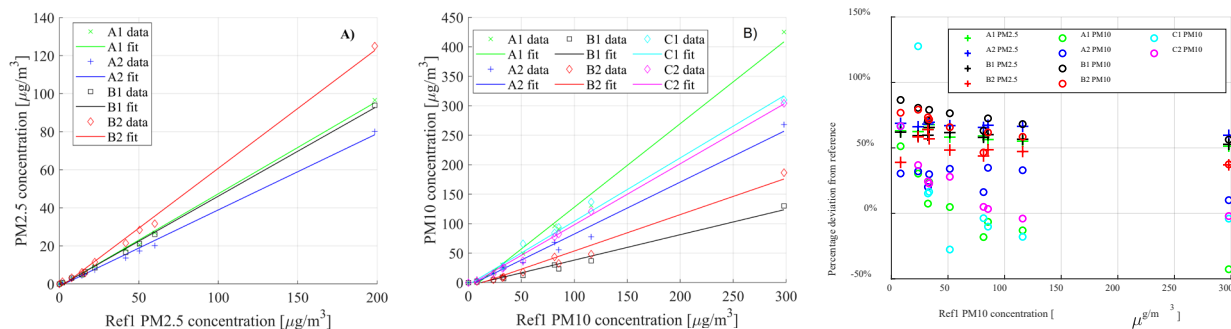


Figure 4 Mean particle mass concentration values obtained from the low-cost PM sensors and Ref1 from the tests with DEHS aerosol. a) PM_{2.5} mass concentration readings from the low-cost PM sensors as a function of reference device PM_{2.5} concentration. b) PM₁₀ mass concentration readings from the low-cost PM sensors as a function of reference device PM₁₀ concentration. c) Percentage of deviation of the sensor readings from the reference plotted against PM₁₀ mass concentration values obtained from Ref1. Note the different y-axis scales.

Table 3 contains the parameters of the linear regression of PM_{2.5} and PM₁₀ readings from the low-cost PM sensors and the ones obtained from Ref1. The adjusted coefficient of determination (Kotz et al., 2006) is also provided as an indicator of the goodness of the linear fit. For sensor types A and B, PM_{2.5} measurements showed a more significant linear correlation with the reference data than PM₁₀. We can also see slight differences between two sensors of the same model. Those are evident from the changes in slope and interception of the linear regression lines.

Table 3. Linear fit parameters of the low-cost sensors compared with Ref1 in DEHS measurement

Sensor	Interception	PM _{2.5} Slope	$\bar{R}^2$	Interception	PM ₁₀ Slope	$\bar{R}^2$
A1	-1.262	0.486	0.997	-13.841	1.418	0.988
A2	-1.197	0.401	0.995	-5.693	0.881	0.985
B1	-1.122	0.472	0.998	-4.998	0.431	0.978
B2	-2.111	0.629	0.996	-8.072	0.617	0.972
C1	-	-	-	-3.531	1.076	0.983
C2	-	-	-	-5.505	1.036	0.996

Simulating the working conditions inside a ventilation duct

The tests performed using outdoor air drawn from Inlet 2 of the test rig showed a different sensor behavior compared with the tests using DEHS aerosol. In this case, the low-cost sensors overestimated the PM concentration to Ref1 and Ref2.

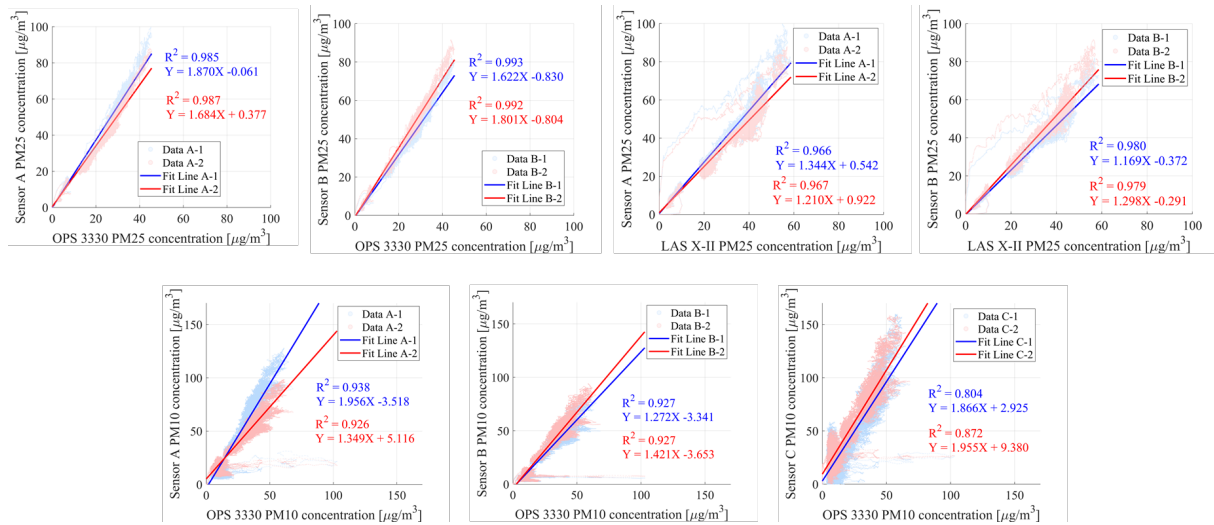


Figure 5 Correlation between measured concentrations with low-cost sensors and reference instruments, linear fit parameters for measured PM2.5 and PM10 from outdoor air at 1.5m/s.

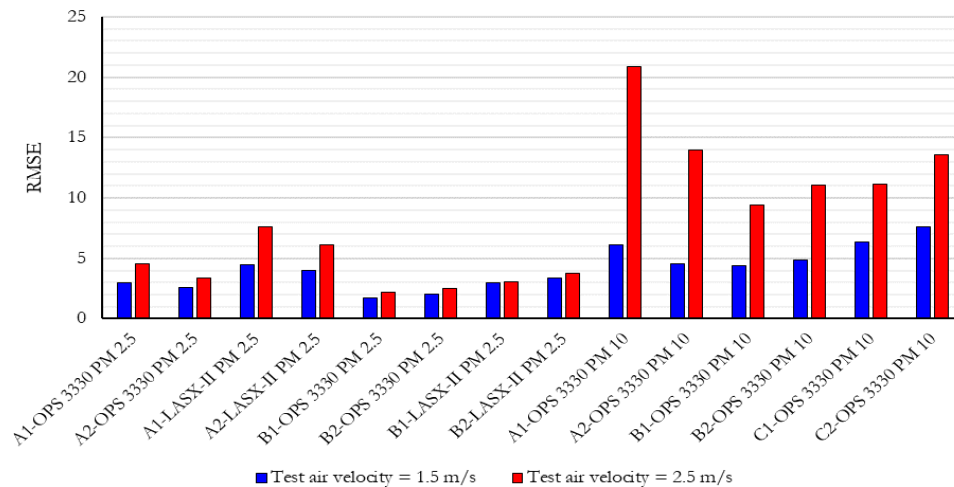


Figure 6 Root mean square error [%] of particle mass concentrations measured with tested sensors to reference instruments under two different test air velocities.

DISCUSSION

The PM sensor's detection relies on the measured scattered light caused by the particles crossing a light beam, so it provides an indirect measurement of the particle mass concentration.

The comparison of the behavior of the low-cost PM sensors with reference instruments using made a DEHS or an atmospheric aerosol leads to different conclusions. The difference between the underestimation and the overestimation respectively of the particle mass concentration can be probably associated with the algorithm converting the measured signal into a particle mass concentration. This algorithm is chosen by the sensor's manufacturer and it is influenced by the refraction

index and the density of the aerosols used during the design and calibration of the low-cost PM sensors.

The most straightforward way for comparing the measurements provided by the low-cost PM sensors and the reference instruments is the analysis of the parameters of linear regression statistics. In our case the R^2 values were between 0.804 and 0.996. Therefore, the relationship between the measurements is linear and direct. The slope of the linear regression represents the over or underestimation of the measurement. For example, values higher than one means overestimation, and values lower than one means underestimation.

Test performed with synthetic aerosol showed a linear correlation between measurements provided by the low-cost PM sensors and the reference instruments, either for $PM_{2.5}$ or for PM_{10} . Regarding absolute particle mass concentration, the low-cost PM sensors provided lower particle mass concentration measurements of $PM_{2.5}$. Instead, there is not a clear trend for PM_{10} measurements.

Tests performed with outdoor air (atmospheric aerosol) showed a consistent overestimation of the measured mass concentration all over the particle size range with both air velocities tested.

The ratio of the air stream velocity to the sampling air velocity, turbulence, and the position, shape, size, and orientation of the inlet can influence the sampling efficiency of the aerosol measuring instrument (Kulkarni et al., 2011). The change in sampling efficiency increases with higher air stream velocities and can cause higher inaccuracies on measured concentrations in this case. The higher the air stream velocity, the higher is the difference between the low-cost PM sensors and the reference instruments. Such difference is even higher for PM_{10} measurements for which isokinetic conditions are important.

CONCLUSIONS

The data obtained with this study showed that low-cost PM sensors provide more reliable $PM_{2.5}$ data than PM_{10} data, especially if air velocity is higher than 1 m/s. Despite the recommendation of the manufacturer about the maximum air velocity for their operation, the tested low-cost PM sensors can be used in ventilation ducts providing reasonably reliable data. The measured particle mass concentration values are not as accurate as the ones provided by the reference instruments. However, a further calibration procedure could be accomplished, either by changing the properties of the sampled PM for each specific application or by laboratory measurements.

Low-cost PM sensors are very convenient for detecting high and dangerous levels of PM concentrations. They can evaluate also the filtration performance of particle filters in operating conditions. Their low price tag and ability to be easily adapted to a data acquisition system make them a good value option for ventilation system assessment and management. In fact, to assess the performance of air filters, it is essential to provide a reliable ratio between the particle concentration upstream and downstream of the filter bank. For measuring the filter efficiency what matters mostly is the reduction rate of particle concentration, not the particle concentrations absolute values. The air velocity could affect strongly the data provided by low-cost PM sensors. Therefore, such sensors can be used reliably to assess filtration efficiency only when upstream and downstream air velocities are close enough.

Further studies are needed to compare air filter efficiency measured with low-cost PM sensors and laboratory instruments.

NOMENCLATURE

PM_X	=	particulate matter with dimensions below or equal to X in μm .
m	=	mass weighted concentration per channel.
ρ	=	particle density.
D_{pv}	=	Volume-weighted particle diameter.
LB	=	lower channel boundary.
UB	=	upper channel boundary.
c	=	particle counts per channel.
t	=	sample time.
Q	=	sample flow rate.
ϕ	=	dilution factor.
R^2	=	coefficient of determination.
$\bar{R}^2$	=	adjusted coefficient of determination.

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