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Atmospheric Measurement Techniques
Discussions

Evaluation of a Low-Cost Dryer for a Low-Cost Optical Particle Counter

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Abstract. The use of low-cost sensors for air quality measurements has become very popular in the last decades. Due to the detrimental effects particulate matter (PM) has on human health, PM sensors like photometers and optical particle counters (OPC) have been widely investigated. The negative effects of high relative humidity and fog events in the mass concentration readings of these types of sensors are well documented. In the literature, different solutions to these problems - like correction models based on the Köhler theory or machine learning algorithms - have been applied. In this work, an air pre-conditioning method based on a low-cost, thermal dryer for a low-cost OPC is presented. The study was conducted in the laboratory under two different scenarios. In one case, we tested the efficiency of the low-cost dryer in the presence of fog. In the second case, we studied to which extent the low-cost dryer hinders the hygroscopic growth of inorganic aerosols. The results show that the sensor with the low-cost dryer at its inlet measured an average of 64 % less PM2.5 concentration during the experiments with fog compared to a sensor without the low-cost dryer. In the experiments with hygroscopic aerosols, the sensor with the low-cost dryer measured 59 % less PM2.5 concentration compared to a sensor without it. In light of these results, we believe that a low-cost, thermal dryer is a cost-effective add-on that can improve the accuracy of low-cost sensors under high relative humidity or during fog events. With the proposed air pre-conditioning method, the typical overestimation of the mass concentration readings is avoided, i.e., the sensor data are improved without the need for complex data post-processing. We believe that these low-cost dryers are very promising for the application of sensors in citizen science, in sensor networks for supplemental monitoring, and for epidemiological studies.

1 Introduction

The use of particulate matter (PM) sensors has increased significantly in the last decade. They are widely applied in citizen science projects (Lukeville, 2019; Schaefer et al., 2020), as part of sensor networks (English et al., 2020; Gulia et al., 2020), and also for educational purposes in schools and universities to raise awareness about air quality in the young generations (Castell et al., 2021; Höfner and Schütze, 2021). Moreover, new fields of application are emerging as sensors achieve better performances thanks to new sensor developments and new methods for data post-processing. Researchers are currently investigating the use of low-cost sensors for smart city management (Toma et al., 2019), supplemental monitoring for official measurement stations (Castell et al., 2017; Liu et al., 2019), and personal exposure (Steinle et al., 2015; Novak et al., 2020). The accuracy needed for certain applications is at this moment the limiting factor for the use of low-cost sensors.

The most widely used measurement principle of PM low-cost sensors is light scattering, and the most common type of low-cost sensors used in air quality research are photometers (usually nephelometers) and optical particle counters (OPCs). Photometers measure relative concentrations by detecting the combined light scattered from many particles at once (Hinds, 1999). In nephelometers, particles pass through a sensing volume as a group of particles, and the particle concentration is determined by the intensity of the total scattered light registered by the photodetector. On the contrary, in OPCs individual particles generate a pulse on the photodetector. The number of pulses is proportional to the number of particles per unit volume and the intensity of the pulses to the size of the particles (Li, 2019). The accuracy of outdoor air measurements with light scattering instruments is seriously influenced by the relative humidity (RH) due to the water uptake of hygroscopic aerosols, and due to fog events (Jayaratne et al., 2018).

Fog is defined as visible aerosols consisting of tiny water droplets or ice crystals in the order of micrometres suspended in air (Spiridonov and Ćurić, 2021). During fog events, the air is saturated with water vapor and the relative humidity is around 100 %. Water droplets can substantially falsify the number and the size of the particles detected with light scattering instruments. An example can be seen in Fig. 1a, where the PM concentration registered by a light scattering aerosol spectrometer, model 1.108 from the company GRIMM (Germany), during a fog event is presented. As can be seen, mass concentrations are extremely high, especially the PM10 values, which reach magnitudes of 10^4-10^5 µg m^{-3}. In Fig. 1b it is shown that most of the detected particles during that fog event were smaller than 1 µm. However, there was a considerable number of particles between 1 and 10 µm which are responsible for the large effect seen on the PM10 mass distribution. This effect can be observed in Fig. 1c where the normalized mass distribution versus the size distribution is presented.

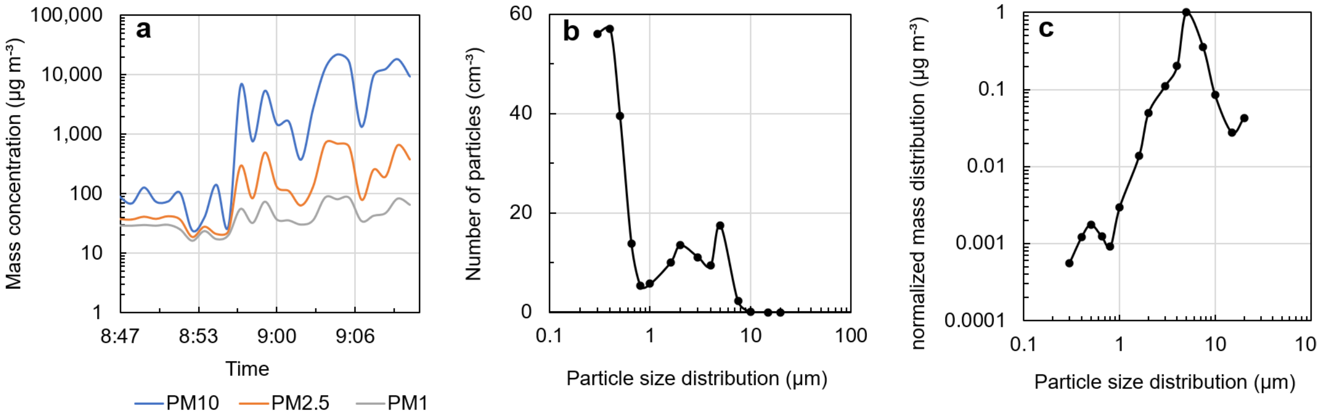

Figure 1. (a) Time series of the mass concentration, **(b)** number of particles per particle size, and **(c)** normalized mass distribution per particle size during a fog event in Stuttgart (Germany) on 23 January 2020.

Hygroscopicity is an aerosol property that measures its ability to attract and hold water molecules in the condensed phase and determines the variations of aerosol size, and physical and optical properties with relative humidity (Boucher, 2015). The

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hygroscopic growth factor (*g*) is defined as the ratio between the diameter of the particle at a certain RH and the diameter under dry conditions (Laskina et al., 2015). The hygroscopic growth factor follows a hysteresis (Wise et al., 2005; Li et al., 2014): increasing the RH, one observes a sudden change in the size of the hygroscopic particle due to water uptake. The RH at which this change happens is called the deliquescence point. Up to this point, a further increase in the RH increases the diameter of the particle, as shown in the study carried out by Wise et al. (2005). If the RH decreases from this point, the particles constantly lose water until the efflorescence point, where a sudden loss of water and, consequently, a sudden reduction of the size of the particles back to the size under dry conditions occurs.

A lot of research has been done to study the influence of RH on sensor readings (Holstius et al., 2014; Gao et al., 2015; Wang et al., 2015; Jayaratne et al., 2018). However, most of the studies do not differentiate between the growth of hygroscopic particles and fog droplets being detected as particles. Only Jayaratne et al. (2018) investigated both effects separately and raised the question of whether it was possible to correct the particle number and mass concentrations reported by the low-cost sensors in the presence of high humidity and fog.

In Table 1 some of the possible methods to avoid the negative effect of high RH as well as their main advantages and disadvantages are listed. Some research groups have tried to reduce the overestimation of the PM concentrations when relative humidity is high by using a correction factor based on the κ-Köhler theory (Di Antonio et al., 2018; Crilley et al., 2018). The outcomes show that by applying this correction factor, good results for in situ measurements can be obtained. However, the re-location of the sensors in other places where they are exposed to new environments with different particle compositions limits the transferability of the method. Regression models containing the RH as an independent variable are widely used (Badura et al., 2019; Venkatraman Jagatha et al., 2021; Hong et al., 2021). Nevertheless, researchers indicate the concentration range and specific ambient condition at which the calibration was performed; for any other conditions, a good performance cannot be guaranteed. Machine/deep learning techniques are nowadays the most advanced methods in sensor calibration. These computer-based models have a lot of potentials to remove meteorological effects, cross sensitivities, and sensor drifts (Wang et al., 2020; Kumar et al., 2020). However, they also have limitations such as the high dependency on the quality of the training data and the extensive computational resources required.

The pre-conditioning of the inlet air is not a new method. Federal Equivalent Method (FEM) instruments are usually equipped with drying systems like Nafion™ membranes, diffusion dryers, or thermal dryers. The use of Nafion™ membranes is not very popular in the field of PM sensors, most likely because it makes the sensor system incompatible with the term “low-cost” due to its high price. In the case of diffusion dryers, the regeneration process is the main disadvantage as it makes difficult their use in continuous measurements. In this context, a heated inlet appears to be the most reasonable air pre-treatment method. Samad et al. (2021) investigated a low-cost dryer for a medium-cost sensor, the OPC-N3 from the company Alphasense (UK). Laquai and Kroseberg (2021) studied the effect of a low-cost dryer in a cheap PM sensor, the SDS011 from the company Nova Fitness (China), which is a nephelometer. Therefore, we propose to apply a low-cost, thermal dryer as an air pre-conditioning method for the sensor OPC-R1, an optical particle counter from the company Alphasense (UK). Its cost of approximately

100 € makes this sensor an ideal candidate for applications where a certain level of accuracy is expected and a lot of sensors are needed with a limited budget, for instance in sensor networks for supplemental monitoring or in epidemiological studies.

Table 1. Review of possible methods to avoid the negative effect of high RH on sensor readings.

Methods	Advantages	Disadvantages	References
κ-Köhler theory	• Consistent results if particle composition is known and constant • Fewer resources needed	• A change in air masses may lead to over- or underestimations • Limited transferability to other locations	• (Crilley et al., 2018; Di Antonio et al., 2018; Crilley et al., 2020)
Regression models	• Consistent results within the calibration range • Relatively simple	• Data extrapolation may lead to wrong results • Lack of sensitivity	• (Badura et al., 2019; Hong et al., 2021; Barkjohn et al., 2021)
Machine/Deep Learning	• Multiple options for algorithms possible • Practical for large-scale deployments	• Performance depends on the quality of the training data • Limitation to predict uncommon events • Extensive computational resources	• (Zimmerman et al., 2018; Wang et al., 2020; Si et al., 2020)
Diffusion dryers	• Minimal cost of construction and use • No energy consumption	• Regeneration needed • Not suitable for long-term measurements	• (Masic et al., 2020)
Nafion^{TM} membrane	• No or little maintenance • Acceptable size and shape	• A vacuum system or a drying agent is needed • Expensive	• (Cai et al., 2014; Karali et al., 2021)
Thermal drying	• Drying efficiency variable • Low construction costs	• Excess heating could evaporate volatile and semi-volatile species	• (Samad et al., 2021; Laquai and Kroseberg, 2021)

The aim of this study is to present a prototype of a low-cost dryer built for a low-cost OPC. The first experiments have been carried out under laboratory conditions. The quantification of the effect of the low-cost, thermal dryer has been evaluated by comparing the PM2.5 concentrations readings of the sensor with a low-cost dryer with the readings of an additional sensor from the same model without a low-cost dryer and with the results of a reference instrument with an aerosol drying system.

2 Methodology

2.1 Instrumentation and experimental set-up

The experiments were performed in a particle chamber made from a greenhouse glass with aluminium frames. A schematic set-up of the particle chamber is presented in Fig. 2. The chamber was 2.57 m long, 1.93 m wide, and 1.95 m high in the middle/highest point. Two OPC-R1 sensors, with and without a dryer, as well as a professional light scattering aerosol spectrometer, model Fidas® 200 from the company Palas GmbH (Germany), were placed in the middle of the chamber. For a detailed analysis of the OPC-R1 performance, we refer the reader to the evaluations carried out by Bulot et al. (2020) and Demanega et al. (2021). The OPC-R1 can measure particles ranging from 0.35 up to 12.4 µm in 16 channels (Alphasense Ltd.,

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2019), whereas the Fidas® 200 has a measuring range covering from 0.18 to 18 µm in 64 channels (Palas GmbH, n.d.). The Fidas® 200 was chosen due to its Intelligent Aerosol Drying System (IADS). The IADS is an air pre-conditioning system consisting in a thermal dryer that is controlled using temperature and RH data from an external weather station. Another advantage is that it allows the user to work in "expert mode", where the user can decide the heating temperature. Two fans were used inside the particle chamber to make sure that the particles were homogeneously distributed.

The experiments to evaluate the dryers under hygroscopic growth conditions were carried out with the help of an atomizer, model 3073 from TSI (US), which generates hygroscopic aerosols from solutions. For that purpose, solutions of the following salts were used: sodium chloride, potassium chloride, ammonium sulphate, and ammonium nitrate. For the experiments with fog, an ultrasonic air humidifier, model U350, from the company Boneco (Switzerland) was used. According to the manufacturer, it produces water droplets with a diameter up to 4 µm.

In the first experiments, it was observed that reaching RH higher than 65 % happened slowly when using only the atomizer or the ultrasonic air humidifier. Moreover, the number of particles generated was very high, thus increasing the chances of coincidence errors in both the sensors and the reference instrument. A coincidence error means that there are too many particles in the sensing volume at the same time so the device is not able to resolve every single particle. There is an overlapping of the single particle signals which causes an underestimation of the particle number concentration and an overestimation of the particle size and consequently of the particle mass concentration. Therefore, coincidence errors need to be avoided. To solve this problem, wet towels were used to increase the RH quickly without increasing the number of particles.

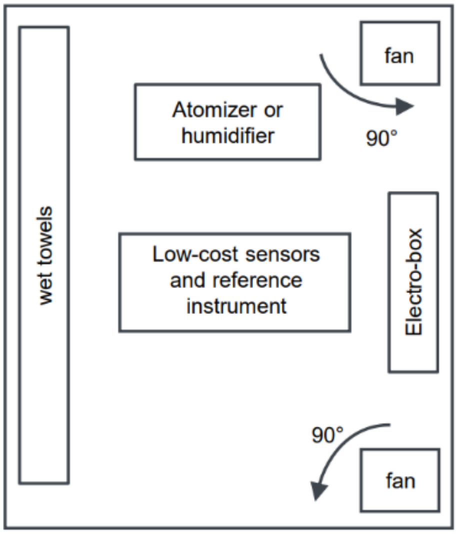

Figure 2. Schematic set-up of the particle chamber.

2.2 The low-cost dryer

The low-cost dryer for the OPC-R1 consists of a brass tube of 50 cm in length, with an inner and outer diameter of 9 and 10 mm, respectively. The inner diameter was chosen so that the sampling flow rate did not deviate more than 2% from that measured without the dryer. A ceramic tape is first pasted onto the brass tube to facilitate heat distribution. Next, a wire with a conductor resistance of 0.975 Ω m^{-1} is wound around leaving 5 cm on each side for ease of handling. To achieve a target power of 10 W with 12 V, 10 windings per cm are needed (see Fig. 3). In order to attach the dryer to the sensor inlet, the tube was soldered to a copper plate and fixed at the sensor with screws. Another important part of the dryer is the insulation. Here, three layers of Thermolam 272 material (100% polyester) are used and the insulated dryer is placed inside a PVC tube as shown in Fig. 3a. The total cost of the material for the construction of the low-cost dryer was approximately 50 €.

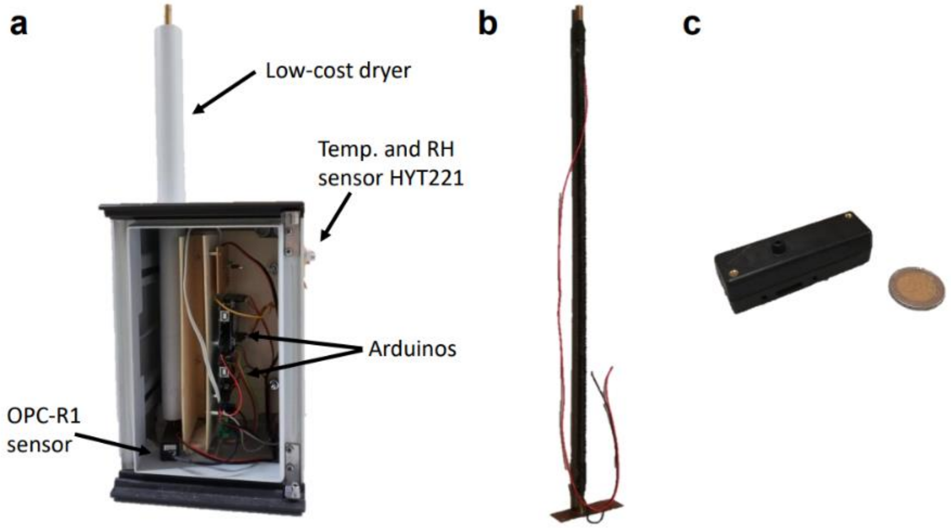

Figure 3. (a) Sensor box with low-cost dryer, **(b)** low-cost dryer without isolation, and **(c)** OPC-R1 sensor.

The dryer is controlled by an Arduino Uno microcontroller using the RH data of an ambient temperature and RH sensor model HYT221 from iST (Switzerland) and the temperature sensor inside the OPC-R1 (T_{OPC}). The Arduino Uno controls the heating using a loop: if RH is equal or more than 65 %, an electrical current will be passed through the wire resistance so that the dryer will be heated. In a second step, the temperature inside the OPC-R1 is used to control the heater. If T_{OPC} is equal or more than 35 °C the dryer will be switched off and start cooling down to avoid overheating. Once T_{OPC} is equal or less than 34 °C and RH is still equal or more than 65 % the dryer will be switched on again.

To quantify the effect of the dryer, two different drying efficiencies (η_r, η_s) were calculated in order to compare the PM2.5 concentrations of the sensor with the low-cost dryer to the PM2.5 concentrations of the reference instrument which also has a dryer (equation 1) and also to the PM2.5 concentrations of the sensor without dryer (equation 2),

$$\eta_r\,(\%) = \frac{\sum_{i=1}^{n}\left(1 - \frac{\mathrm{PM2.5}_{d,i}}{\mathrm{PM2.5}_{r,i}}\right)}{n} \cdot 100, \tag{1}$$

$$\eta_s\,(\%) = \frac{\sum_{i=1}^{n}\left(1 - \frac{\mathrm{PM2.5}_{d,i}}{\mathrm{PM2.5}_{s,i}}\right)}{n} \cdot 100, \tag{2}$$

where $PM2.5_{d,i}$ is the PM2.5 concentration of the sensor with the low-cost dryer at a specific time i, $PM2.5_{r,i}$ correspond to the PM2.5 concentration of the reference instrument at a specific time i, and $PM2.5_{s,i}$ is the PM2.5 concentration of the sensor without the low-cost dryer at a specific time i for n number of samples. The time used for determining the dryer efficiency corresponds to the period of time between switching the dryer on and switching the dryer off. To better compare the drying efficiency, the one-minute averages of the PM2.5 concentrations of both OPC-R1 sensors were calibrated with a linear regression against the reference instrument under low RH (the low-cost dryer and IADS dryer were off). The coefficient of correlation R^2 was higher than 0.90 in all cases.

3 Results and discussion

3.1 Experiments with water droplets

Several experiments with the ultrasonic air humidifier were carried out in the particle chamber to test the efficiency of low-cost dryers to remove water droplets. Figure 4 shows the calibrated PM2.5 concentration of two OPC-R1, with the dryer (red line) and without the dryer (blue line). The PM2.5 readings of the reference instrument (black line) are shown for comparison. The results correspond to two different experiments: in Fig. 4a, the IADS of the reference instrument was kept in automatic mode whereas in Fig. 4b, it was set at 70 °C using the expert mode. In the secondary axis, the relative humidity (blue dots), as well as the time when the low-cost dryer was on (green line), can be observed. As shown in Fig. 4a, once the air humidifier was on, water droplets were generated, and RH slowly increased. After reaching a PM2.5 mass concentration of 300 µg m^{-3}, the air humidifier was switched off and the sedimentation curve started. However, the increase in RH was still not enough to start the dryer and wet towels were used to reach a RH higher than 65 %. Immediately after that, a remarkable increase in the PM2.5 concentration was observed, possibly due to the increase of the water droplets which were too small to be detected at lower RH. Once the RH reached 65 %, the low-cost dryer of the OPC-R1 started heating. The mean drying efficiencies η_s and η_r were 64 % and 52 %, respectively. In contrast to what is expected, the reference instrument did not completely reduce the water droplets and behaved similarly to the OPC-R1 without a dryer. This finding can be explained by the heating power used by the IADS, which was less than 25 % of the total power (90 W) during the whole experiment. The IADS regulates the heating considering the relative humidity in the air, which in this experiment did not reach more than 75 %, and therefore, the IADS considered sufficient a heating power of less than 25 %. In Fig. 4b, the IADS was set using the expert mode at 70 °C. In this case, the reduction of the fog droplets was clearly observed for both the reference instrument and the OPC-R1 with a dryer, reaching the latest a mean drying efficiency (η_s) of 57 % compared with the OPC-R1 without a dryer.

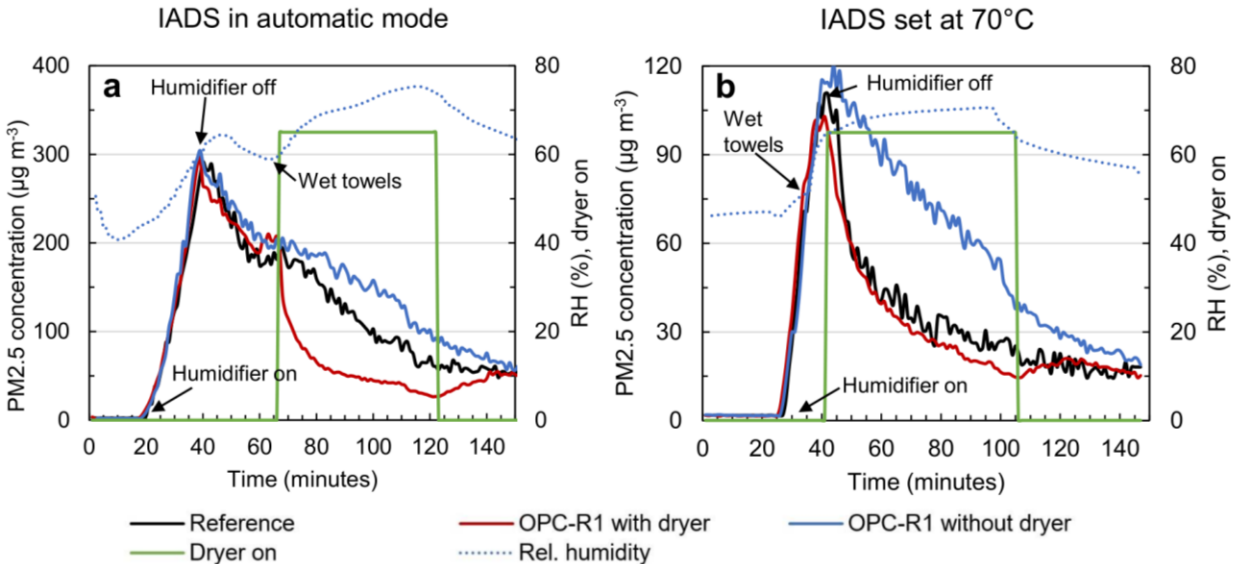

Figure 4. Experiments with an air humidifier **(a)** keeping the IADS in automatic mode and **(b)** IADS set at 70 °C.

Figure 5 illustrates the size distribution of the water droplets generated with the ultrasonic air humidifier measured with the reference instrument. As can be seen in Fig. 5, the mean diameter of the generated water droplets was below the detection limit of the reference instrument (0.18 µm) and the OPC sensors (0.35 µm). As shown in Fig. 1c, fog events in the field have a different size distribution with particles ranging also from 1 to 10 µm. Another limitation that was found during these experiments is the fact that it was not possible with the proposed set-up to reach RH close to 100 % without having coincidence errors. Therefore, for future research with fog droplets, other types of fog generation like the ones suggested by Angelov (Angelov et al., 2017) but also field measurements in real fog conditions are recommended.

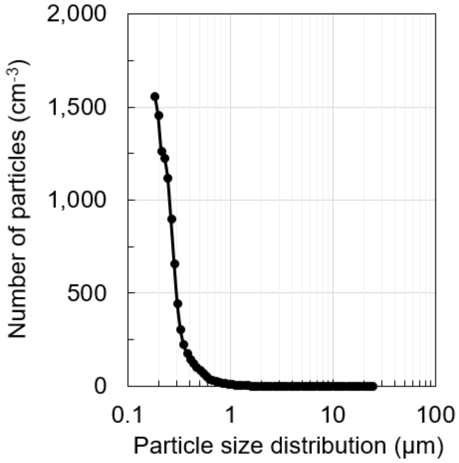

Figure 5. Number of particles per particle size measured with the reference instrument during the experiments with the air humidifier.

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These experiments demonstrate the positive effect of the low-cost dryer to remove water droplets and hence decreasing the overestimation of the PM2.5 concentration during fog events. The energy needed to remove the water droplets is significant and even the reference instrument is not able to remove all the droplets when working in automatic mode. This outcome is similar to that reported by Jayaratne et al. (2018) who wrote "The corresponding increase in the TEOM reading…suggests that, in the presence of fog, the dryer at its inlet has a limited efficiency in terms of removing the liquid phase of the particles". The WMO/GAW guidelines recommend modest heating using temperatures that do not exceed 40 °C to minimize the loss of semi-volatile species (WMO/GAW, 2016). However, the findings from these experiments suggest that temperatures higher than 40 °C are needed in order to observe a clear reduction of the mass concentration during fog events. Consequently, an optimum has to be found between the efficient removal of fog and the minimization of the loss of semi-volatile species. This has special implications in regions where fog formation is abundant in terms of probability, frequency, and duration.

3.2 Experiments with hygroscopic aerosols

Figure 6 shows the results of an experiment carried out to test the dryer against hygroscopic growth. A solution of $(NH_4)_2SO_4$ (80 g l^{-1}) was atomized at 400 hPa using an aerosol generator. $(NH_4)_2SO_4$ has a deliquescence point of 80 % at 298 K (Gu et al., 2017). Once constant concentrations were reached in the particle chamber, wet towels were introduced to increase the RH quickly. The effect of the sudden increase in the RH can be clearly seen at minute 45 in Fig. 6a by the simultaneous increase in the PM2.5 concentration in all the devices. As soon as 65 % RH is reached, the dryer switched on automatically and after one minute the PM2.5 concentration measured by the OPC-R1 drastically decreased. This sudden decrease was not observed in the data from the reference instrument, which ran in automatic mode. This was due to the reaction time of the RH sensor that controls the IADS of the reference instrument (in brown dots in Fig. 6a) that reacts slower compared to the RH sensor (blue dots in Fig. 6a) that controls the low-cost dryer. Consequently, the IADS increased the heating power much slower. A decrease in the PM2.5 concentration of the reference was observed between minute 46 and minute 60) after the wet towels were introduced into the particle chamber. However, this was also observed in the OPC-R1 without the dryer as well as in the OPC-R1 with the dryer, which means that the decrease could have other reasons, for instance, the sedimentation of the heavier particles. From minute 60 until the end of the experiment the PM2.5 concentration of the reference instrument did not vary significantly.

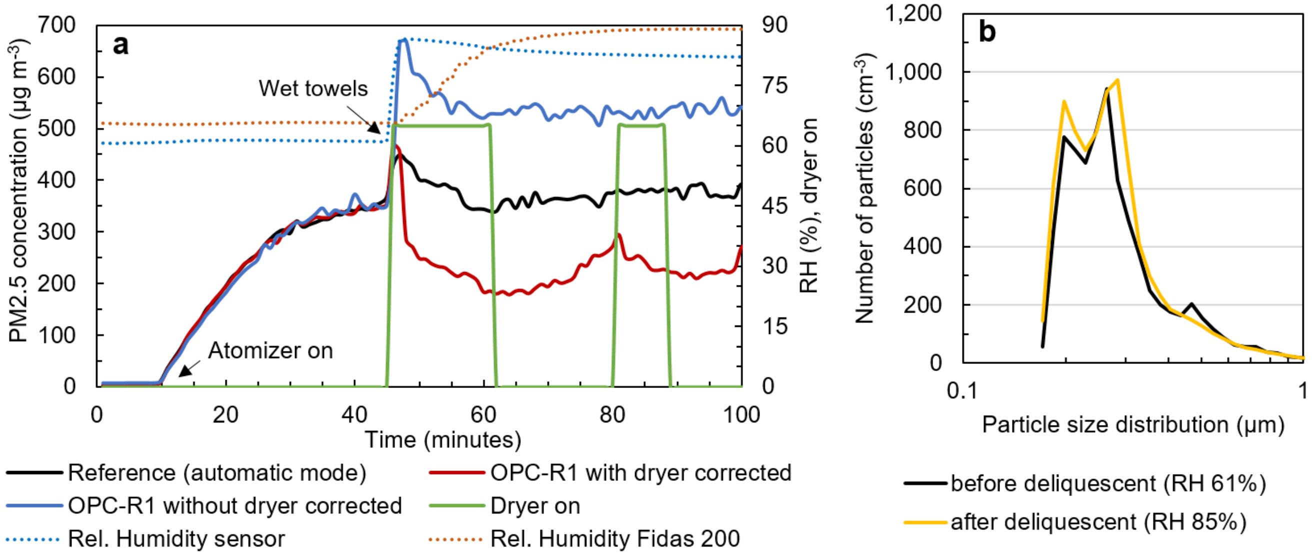

Figure 6. (a) Time series of the PM2.5 concentration during an experiment with $(NH_4)_2SO_4$ particles, **(b)** size distribution of the reference instrument before and after deliquescence.

The drying efficiency of the low-cost dryer, when compared with the reference instrument (η_r), was 39 %, whereas it was 59 % when compared with the low-cost sensor without dryer (η_s). An interesting observation is that in the periods when the low-cost dryer was switched on (marked with a green line in Fig. 6a), the PM2.5 concentration measured by the OPC-R1 with the dryer decreased and increased again when the dryer was switched off. This pattern is not observed in the reference instrument, whose PM2.5 concentration readings remained constant at around 380 µg m^{-3}. This should be further investigated as an apparent excess of heating in the low-cost dryer could cause the evaporation of volatile organic compounds during field measurements. Moreover, it should be considered that the water uptake is higher at higher RH and that the drying efficiency is dependent on the size of the particle and the amount of water absorbed. Therefore, adaptive heating according to the RH should be considered for new versions of the low-cost dryer. Furthermore, the temperature profile inside the dryer must be investigated. Similarly, the IADS did not use its full heating power but adapted the heating power to the relative humidity (the higher the RH, the more heating power). The highest heating power the IADS used was 70 % of 90 W for a 4.7 l min^{-1} flow, whereas the low-cost dryer used always 100 % of the available power (10 W) for a 0.24 l min^{-1} total flow rate. In Fig. 6b it can be observed that the reference instrument almost completely avoided the shifting of the curve to the right after the deliquescent point when comparing the particle size distribution of the $(NH_4)_2SO_4$ particles before and after the deliquescent point. A more detailed analysis of the particle size distribution of the low-cost sensors is ongoing.

4 Conclusions

Fog events and the ability of hygroscopic aerosols to uptake water cause an overestimation of the mass concentrations in low-cost sensor readings based on light scattering. Low-cost sensors are already and will be a game changer in the future of air pollution monitoring. Finding a solution for these problems will make the sensor data more accurate, expanding possible application fields to those where a high level of accuracy is required, e.g., in supplemental monitoring or in epidemiological studies. The present study provides an overview of the work carried out for the evaluation of a self-constructed, low-cost dryer for a low-cost optical particle counter under laboratory conditions. It was shown that low-cost, thermal dryers can be a cost-effective solution to avoid the negative effect of hygroscopic growth and fog droplets on the mass concentration readings of low-cost optical particle counters. They do not eliminate the need for calibration but because of their simplicity, low-cost dryers for PM sensors are very promising for applications where complex data post-processing is too difficult/expensive, e.g., in citizen science projects. Moreover, the design of the dryer can be easily adapted to other models or types of sensors, including, for instance, electrochemical sensors for gases.

During the experiments, some challenges were encountered. Some of these were the impossibility of reaching relative humidity of 100 % in the particle chamber without causing coincidence errors and the difficulties in the generation of water droplets that could simulate the size distribution of real fog. The mean diameter of the generated fog droplets was < 1 µm, whereas fog observed during field measurements and what has been found in the literature have a bigger fraction of droplets between 1 and 10 µm. Another challenge encountered was simultaneously (a) removing of fog droplets, (b) minimizing the effect of the hygroscopic growth, and (c) avoiding the evaporation of volatile organic compounds. Future investigations should address the temperature profile inside the low-cost dryer and its effect during field measurements. Furthermore, more research is required to optimize the energy consumption, and to create an adaptive heating based on the real need for heating according to the meteorological conditions.

Code availability

The Arduino codes are available at https://github.com/MiriamChacon/OPC-R1_with-air-dryer (last access: 12 April 2022) and archived on Zenodo (DOI: 10.5281/zenodo.6460181).

Data availability

The data of this study are available from the authors upon request.

Author contributions

MCM drafted the manuscript. MCM and BL designed the research plan. MCM and BL carried out the experimental work. MCM performed the data analysis. UV and CS supervised the project. UV secured the funding. BL, UV, and CS provided extensive comments on this manuscript. All authors had read and approved the final manuscript.

Competing interest

The authors declare that they have no conflict of interest.

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