Technical Note

‘EnvilutionTM’ Chamber for Performance Evaluation of Low-cost Sensors

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Graphical abstract

Environmental-pollution (‘EnvilutionTM’) chamber

* Depends on the PM/gaseous pollutants and reference instrument limits

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ABSTRACT

The emergence of low-cost sensors (LCSs) has rapidly changed the landscape of air pollution monitoring. Unlike regulatory standards with comprehensive processes for performance evaluation and certification for reference equipment, no accreditations or regulatory standards exist for LCSs. Hence, calibration and performance assessment of the LCSs are carried out via co-location experiments with reference instruments under limited ranges of environmental conditions and pollution concentrations. We designed and tested an environmental-pollution (referred to as 'EnvilutionTM') chamber to generate controlled environment for temperature and relative humidity (RH) along with different concentrations of particles so that varied real-world environmental conditions and pollution concentrations can be generated for the performance evaluation of LCSs. The custom-made 125L EnvilutionTM chamber consists of a humidifier/dehumidifier system, heat pump, particulate matter (PM) generator, a connection for gaseous air pollutants and reference measuring instruments. In the experiments under controlled conditions, the chamber was able to maintain diverse ambient and indoor environmental conditions (temperature range from 5 to 40°C and RH from 10 to 90%) and stable pollution concentrations, thereby enabling the use of chamber as a reference environment for LCSs' testing. For demonstration, the assessment was conducted based on temperature/RH (HDC1000 digital) and PM_{2.5} (HPMA115S0 Honeywell) sensors. A Vaisala HMT120 temperature/RH sensor and optical particle counter (Grimm EDM 107) were employed as reference instruments. The evaluation of LCSs, which were placed inside small enclosure kits, showed excellent correlation for temperature ($R^2 > 0.96$), RH ($R^2 = 0.99$), and PM_{2.5} ($R^2 = 0.97$) with the reference instruments. The LCSs also demonstrated high linearity agreement ($R^2 > 0.98$) among themselves at temperature (5-35°C), RH (20-80%), PM_{2.5} (65-200 $\mu\text{g}/\text{m}^3$) measurement ranges. The unique features of the chamber, including affordable cost, small size and

lightweight, low maintenance/operational costs and ease of operation, has the potential to make it an on-demand package for LCSs' testing.

KEYWORDS

Environmental-pollution chamber; Air quality measurement; Performance evaluation; Gaseous/particle pollutants; Low-cost sensors.

1. INTRODUCTION

Unlike more expensive instruments used for regulatory purposes, there has been an emerging trend for using low-cost sensors (LCSs), due to the rising demand for affordable air quality monitors (Morawska et al., 2018; Rai et al., 2017). The affordability, flexibility and portability associated with the LCSs, which are generally small in size, with low power consumption and offering the possibility for more spatial data and higher temporal frequency whilst easing the data transmission/collection and recovery process (Austin et al., 2015; Kumar et al., 2015; Snyder et al., 2013), make lower-cost portable monitors available to the public. In addition, deploying a network of LCSs under known atmospheric conditions and emission sources can assist in (i) detecting pollution hotspots; (ii) assessing real-time exposure for designing mitigation strategies; and (iii) creating pollutant bottom-up emission inventories (Kumar et al., 2015). As a result of this emerging technology, new projects have been funded to establish LCS networks for trial purposes in both the European Union and the US (e.g., CITI-SENSE; iSCAPE; USEPA Air Pollution Monitoring for Communities Grants) (CITI-SENSE, 2016; iSCAPE, 2019; USEPA, 2016). Additionally, air pollution as a highly topical subject has attracted substantial interest from companies to innovate using these types of LCSs in the Internet of Things applications to create disruptive solutions for consumers and business. However, due to the lack of uncertainty, certifications and standards, users are unaware of the performance of LCS under different

environmental conditions and pollution concentrations. In fact, they have hardly any alternative options for calibration other than co-location against reference instruments, which is costly and covers only a limited range of variations (environments and concentrations) under uncontrolled/narrow conditions. Hence, evaluating the performance of LCS for both research and environmental awareness as a function of environmental parameters has been an emerging research topic in recent years.

In characterising performance, the cost and inflexibility of field experiments noted earlier (e.g., calibration using co-location) means that environmental-pollution (referred to as ‘EnvilutionTM’) chambers that can control both environmental conditions and pollution concentrations can be instrumental for evaluating the performance of LCSs. EnvilutionTM chamber, hereafter referred in this manuscript to as ‘Chamber’, can generate controlled environments for ambient temperature, relative humidity (RH), and other parameters (e.g., atmospheric pressure, air pollutant concentrations), become an increasingly useful tool for this space. Chambers, as a state-of-the-art tool, offer the ability for studying/testing a single or a range of meteorological conditions and known concentrations of different pollutants during LCS testing (Austin et al., 2015; Papapostolou et al., 2017; Wang et al., 2015).

Although global market of LCSs is growing by more than \$3 billion annually towards the year of 2027 (IDTechEx, 2019), this expected growth in sensor technology is due to the interest of agencies or citizens who are unable to track individual’s exposure under different microenvironment conditions (Williams, 2019). Current research studies revealed the importance of test chambers for performance validation due to poor to modest performance of LCSs compared with reference instruments employed by regulatory agencies. In addition, to cover the global

market and end-user prospective, companies need to cover a wide range of testing to minimise the risk and time to market before developing products based on LCSs. Hence, the ability to use a chamber controlling single environmental variables at a time is perceived to offer a faster rate of development, through the ability to quickly test components, iterate and validate to solve issues before moving into the more complex field environment. The laboratory chamber designed by Air Quality Sensor Performance Evaluation Centre at South Coast Air Quality Management District in US (Papapostolou et al., 2017) and the chamber used by the National Physical Laboratory in UK (NPL, 2019) are the most comprehensive and the most recent state-of-the-art testing units for this purpose around the world. However, the high associated costs with a chamber of this type mean that this approach becomes prohibitive for most research laboratories around the world. Hence, simpler designs for limited studies, e.g. Wang et al. (2015) for particle testing, Jayaratne et al. (2018) for RH testing, and Ren and Cao (2020) with a transparent chamber equipped with a visualisation device for indoor experimental and modelling studies on CO₂ concentration have likewise been developed.

Compared to the available simple and detailed chambers in the market (Alpert et al., 2017; Bernard et al., 2016; NPL, 2019; Papapostolou et al., 2017; Weiss Technik et al., 2019), a chamber has been designed and manufactured at the Global Centre for Clean Air Research (GCARE), University of Surrey, UK, to generate required atmospheric conditions (temperature/RH), various pollutant types and concentrations (fine particulate matter (PM_{2.5}; fraction of particles with an aerodynamic diameter $\leq 2.5 \mu\text{m}$), nitrogen dioxide (NO₂), nitric oxide (NO), sulphur dioxide (SO₂), and carbon monoxide (CO) – see Table S1) for LCSs’ testing with unique features, such as state-of-the-art technology (3D printed components), lightweight and small size, affordable cost

(around £10k, see Table S2), low maintenance/operational costs and automated bringing ease in operation.

The chamber has been designed to operate with a number of pollutants, such as PM_{2.5}, CO, NO, NO₂, and SO₂ pollutants due to the rising demands of their high spatiotemporal resolution monitoring in local environments, which can aggravate pre-existing conditions such as asthma and cause sufferers to be admitted to hospitals as well as the mortality risk from cardiovascular diseases (Morawska et al., 2018; Northcross et al., 2013; Sousan et al., 2016a). This paper describes design details and performance assessment of the chamber, while preliminary assessment of six LCSs in terms of two environmental parameters (temperature and RH) and PM_{2.5} concentration is included for demonstration.

2. MATERIALS AND METHODS

2.1 Chamber

Figure 1 shows a schematic diagram of the chamber with a list of major components. This 125L chamber (interior dimensions of 50 cm × 50 cm × 50 cm) was made of acrylic sheets sprayed with Teflon, which is isolated by 100 mm of Styrofoam. The sheets were used to minimize surface reactions for gaseous and aerosol experiments (Liu et al., 2016). The interior edges of the chamber were sealed with rubber strips as well as silicone sealant to prevent leakage. The chamber has been designed to be able to maintain a stable and reproducible range of temperature (from 5 to 40°C) and RH (from 10 to 90%) conditions using a loop-powered Vaisala HMT120 sensors (Vaisala, Finland) with known gases (Table S1) and particle concentrations.

The pollutants are premixed before entering the chamber from the top centre part of the chamber (100 mm pipe). The inflow pipe is equipped with three baffles (non-centric perforated sheets) for

further and complete mixing of gaseous and PM pollutants with zero-air prior to entering the chamber. However, there is a built-in fan inside, which facilitate mixing to maintain the uniform environment inside the chamber. To avoid particle loss via deposition between the chamber and reference instruments, a 40 mm diameter outlet pipe was used to draw air samples to the reference instruments. The outlet pipe is located at the centre of the chamber and at the same level, where the LCSs will be placed for testing. An adjustable platform for LCSs was designed and placed inside the chamber, which can hold various sensors with different dimensions as close as possible to the height of the outlet pipe. In addition, the chamber is equipped with a transparent door which is sealed to the wall using one-sided self-adhesive Neoprene tape. The transparent door allows monitoring the interior parts, especially those related to LCSs, such as battery levels, possible alarms, etc. For the placement of temperature/RH/pressure sensors, inflow/outflow/pressure safety pipes, thermistor wires, and the heat pump, proper holes were drilled, and silicone sealant was used for sealing.

As shown in Figure 1, in addition to major components of the chamber, the entire testing facility is composed of: (i) RH system, including (a) a dry and particle/gaseous pollutants (ozone (O_3), NO, NO_2 , SO_2 , hydrogen sulphide (H_2S)) free air (zero-air or dehumidifier system), which contain three different scrubbers and a high-efficiency particulate air (HEPA) filter and (b) a sealed deionized (DI) water bath (humidifier system) to generate RH using air bubbles; (ii) flow controllers to precisely measure flow rate of zero-air and different gaseous pollutants; (iii) a heat pump to maintain hot/cold temperatures with a controller (see Figure S1), which is equipped with a mixing fan; (iv) temperature and RH sensor and indicator; (v) pressure sensor; (vi) an aerosol generator and a certified gaseous pollutant; (vii) two reference instruments for PMs and gaseous pollutant; (viii) integrated computer programs that control various environmental parameters and

log data from the reference instrument software. All parts are either made of Teflon, coated with Teflon, stainless steel or other inert/unreacted materials to prevent any unwanted reactions during the experiments. The details regarding the chamber components are presented in the supplementary file.

2.2 LCS Testing for Demonstration

The performance of six LCSs named as Badboy, Dougal, Florence, Zebedee, Dylan, and Ermintrude, were assessed using reference instruments for changes in temperature, RH, and PM_{2.5}. The specification of factory-calibrated temperature/RH sensor (HDC1000, Texas Instruments) and laser-based PM sensor (HPMA115S0, Honeywell) are described in Table S3. The sensors are placed inside small enclosure kits for mobile applications in indoor environments. The sampling interval of the sensors was set to 1 Hz, because they capture variations across the sampling period better at this rate. A cell phone application was used to communicate with the sensors over Bluetooth. The application allowed the user to remotely control the sensors, plot the graphs, and transfer the recorded data to a Firebase cloud database via the mobile network.

2.3 Experimental Plan

The heat pump and RH system (a combination of the zero-air/DI water bath) were used to create a uniform environment inside the chamber. For performance demonstration purpose, the PM concentrations were set according to the threshold limits defined by the major standard organisations, such as World Health Organisation, Department for Environment, Food & Rural Affairs (UK) and National Ambient Air Quality Standards (US). The concentrations vary from as low as typical ambient environment up to very high conditions (up to 200 µg/m³ of PM_{2.5}), which was achieved by multiplying the standard limits by some factors.

169 Due to the low volume of the chamber (125L), considering ~2-5 LPM of flow rate, the residence
170 time in the chamber is around 25 min to 1 hour. However, the built-in fan could facilitate proper
171 and fast mixing inside the chamber. Hence, any step change in the input variables occurs only after
172 reading steady concentration values as well as recording enough measurements. It is worth noting
173 that the steady condition is reached when the parameters do not change and/or change periodically
174 in a certain cycle with time. For sensor testing, a number of LCSs were placed inside the chamber
175 (on top of the adjustable platform), where they sampled the air at the same level as the reference
176 instruments. After each experiment, the system was cleaned with isopropyl alcohol (IPA) and set
177 to be flushed with the zero-air. The base condition for the experiments was the laboratory
178 temperature (20°C) and RH of about 40%.

179 The chamber was designed to create various environmental conditions and pollution
180 concentrations to evaluate the performance of LCSs. However, failure in maintaining extreme
181 environmental conditions have been reported earlier (Jayaratne et al., 2018; Sohn et al., 2008;
182 Wang et al., 2010; Wang et al., 2015). Very high/low temperature and RH could be crucial
183 parameters to maintain in chambers due to their impacts on the performance of both reference
184 instruments and LCSs. For example, the Grimm EDM 107 optical particle counter (Grimm-
185 Aerosol GmbH & Co., Germany) is manufactured to operate between +4 to +40°C, RH < 95%,
186 non-condensing, non-corrosive or explosive gases conditions. In case of LCSs, generation of water
187 mists as a result of RH generators, potential water condensation at low-temperatures (Sohn et al.,
188 2008; Wang et al., 2010), and enlargement of the particles size (Chakrabarti et al., 2004; Fischer
189 et al., 2007) could reduce the performance and sensitivity of gas sensors and overestimation of the
190 particle mass concentration in optical particle sensors. Additionally, extreme temperatures could
191 impact on LCS circuit boards, which resulted in improper readings (Wang et al., 2015). To address

these concerns, the designed chamber is equipped with well-engineering features and accessories to keep temperature and RH experiments running smoothly within the designed ranges of instruments.

2.4 Data Analysis and Quality Control

For performance analysis, recorded data during the experiments were assessed using RStudio 1.2.1335 with ‘openair’ 2.6-5 (Carslaw and Ropkins, 2012) and ‘psych’ 1.8.12 (Revelle, 2018). Different parameters, such as mean, standard deviation (SD), median, trimmed, mad, min, max, range, skew, kurtosis, standard error (SE), relative standard deviation (RSD%) were used during chamber performance testing (see Table S4). In comparison between reference instruments and LCSs, factor of two (FAC2), mean bias (MB), mean gross error (MGE), normalised mean bias (NMB), normalised mean gross error (NMGE), root mean square error (RMSE), Pearson coefficient (r), coefficient of efficiency (COE), and index of agreement (IOA) were determined for analysis (see Table S5). Since the sensors and reference instruments sampled with different data frequency, a greater median reading than the sampling frequency was considered for data analysis.

3. RESULTS AND DISCUSSION

The capability of the chamber is demonstrated in a series of experiments on both temperature/RH control and PM_{2.5} concentrations as elaborated below.

3.1 Temperature/RH for Reference instrument versus LCSs

Figure 2 shows the recorded data by the temperature/RH sensor (Vaisala) and LCSs during the experiments of the environmental parameters. The Vaisala temperature/RH sensor was placed close to both the outlet pipe and the location designed for the LCSs (Figure 1), so it can fairly measure the temperature/RH inside the chamber.

During the temperature test (Figure 2 (top)), the temperature was ramped up to 40°C and remained constant to reach a steady condition. Then the temperature was ramped down to the first set point (35°C) and again reduced on step-basis of 10°C covering a range of 35 to 5°C. The experimental conditions at each step were remained constant and required data sets were recorded during the test (the plot in black). The RSD%, based on the chamber measurements and set points, were 1.0, 2.2, 4.8, and 6.7 for the temperature set points of 35, 25, 15 and 5°C, respectively. The temperature fluctuations among the recorded values were less than 2.8°C (see 'range' values in Table S4), which were due to the performance of the temperature controller in maintaining desired temperatures. Very low standard error (SE) values (Table S4) show the closeness of relationships among the results, which signify the capability of the system in maintaining temperature during the experiments. Similar accuracies have been reported in other chambers by Zhao et al. (2015) and Papapostolou et al. (2017), where the temperature was maintained within acceptable ranges of 5% (RSD%) and $\pm 2^\circ\text{C}$, respectively.

A similar procedure was followed to test the RH system. The RH was operated by adjusting airflow between humidification (DI water bath) and dehumidification (zero-air) systems. In order to validate the performance of the RH system, the chamber condition was maintained at the base condition and then RH was ramped up to 80%. The required time to reach 80% from the ambient condition (40% of RH at 20°C) was about 30 minutes. Then, using the dehumidification system, zero-air, the RH was reduced to 20% at 20% intervals. The recorded average data is plotted against the time in Figure 2 – bottom (the plot in black). Statistical analysis of the measured RH values at the certain set points showed very close relationships among the recorded values (see Table S4). For example, at 20% of RH, the RSD% value was only 0.3%, while fluctuation between 20-23% at similar conditions has been reported in Papapostolou et al. (2017). The RSD% measured for all

the set points were below 3.1%. A similar approach was used by Zhao et al. (2015) and Papapostolou et al. (2017) during chamber testing experiments, where they maintained RH conditions within the RSD of 5% and acceptable RH fluctuations of up to $\pm 3.9\%$, respectively.

The performance of six LCSs in response to changes in temperature set points (top) and five LCSs in response to changes in RH set points (bottom) are also plotted in Figure 2. Due to malfunctioning of the Florence, the RH data of this LCS was not available for the analysis. The figures demonstrate that the LCSs were able to follow the changes during the experiments as illustrated by time series plots.

For a better understanding regarding the evaluation of LCSs in relation to temperature and RH changes, the *hexbin* plot, which is a form of scatterplot permitting the visualisation of big data points, is used (Figure 3). In the *hexbin* plot, each data point is linked to a hexagon, whereas the frequency of occurrence of data points in each hexagon is counted and plotted using a colour ramp (Lewin-Koh, 2011). The figures show where most of the data points lie close to the set points in warm colours, where a high number of counts compared to the total counts is observed. Figure 3 also reveals a clearer indication of the linear relationship between the LCSs and the reference instruments, whereas the R^2 lied between 0.96 to 1.00 (slopes between 0.97 and 1.1) in case of temperature testing, and $R^2 = 0.99$ (slopes between 0.86 and 0.97) in case of RH testing.

For further demonstration, Taylor diagram was implemented for the entire dataset during both temperature and RH experiments. Figure 4 reveals the interesting performance of all LCSs in terms of temperature (top)/RH (bottom) experiments, where the SD and centred RMSE (it is centred because the mean values of the observed and predicted data are subtracted first (Pirani et al., 2014)) values were comparable among all the sensors. In Taylor diagram, the observed variability (e.g.

the SD) is plotted on the x-axis (specifically, the magnitude of the variability is measured as the radial distance from the origin of the plot), correlation is shown on the black arc, whereas the centred RMSE is specified by the concentric gold dashed lines originating from the observed point in purple (Pirani et al., 2014). Using a system of polar coordinates, the degree of similarity between the LCSs and the reference instrument can be easily evaluated. Taylor diagram showed a quite similar performance (correlations greater than 0.96 and less than 5 of centred RMSE) on the entire temperature sensor dataset and Vaisala reference instrument. Among the temperature sensors, only Dougal had correlation value less than the others. Similar performance with more uniform centred RMSE of the RH sensors vs. reference instrument was observed (Figure 4 – bottom). Further statistical analysis on the entire datasets regarding the performance of HDC1000 sensor vs. Vaisala is provided in Table S5.

3.2 PM_{2.5} for Reference instrument versus LCSs

Under certain ambient environment (20°C and 40% of RH), the chamber and LCS performances in maintaining four PM_{2.5} concentrations were demonstrated as shown in Figures 5. The PM_{2.5} concentrations were varied from high to low (200–65 µg/m³) in a step-wise approach. The high to low levels are defined based on the standard guidelines (DEFRA, 2019; Omidvarborna et al., 2018; WHO, 2018) and the highest/lowest concentrations that can be generated by the sources and/or detected accurately by the reference instrument (Kumar et al., 2018). The study results (the plot in black – Figure 5) showed that the chamber performance on PM_{2.5} was comparable with Papapostolou et al. (2017). For example, considering two similar set points, the chamber was able to maintain PM_{2.5} at 119.8±3.8 and 201.5±4.8 µg/m³, which are in the same ranges as 125.7±3.2 and 229.7±4.3 µg/m³ in similar environmental conditions by Papapostolou et al. (2017). In addition, RSD% values for other concentrations set points (150 and 65 µg/m³) during the

performance assessment of the chamber were obtained as 3.0 and 6.0, respectively. Similarly, the time series of the PM_{2.5} concentrations measured by six LCSs (the plots in colour) closely follows the Grimm (the plot in black) during the performance demonstration.

Figure 6 shows the *hexbin* plot and correlation among the PM_{2.5} sensors against the reference instrument, whereas higher number of counts in warmer colours represent the four set points (65, 120, 150, and 200 µg/m³). The correlation of the HPM115S0 sensors among themselves ($R^2 > 0.99$ – see Figure S5) and between sensors and Grimm ($R^2 > 0.97$ – see Figure 6) showed a high relationship, which is comparable with the previous studies (Hapidin et al., 2019; Sousan et al., 2016b; Wang et al., 2015). The reliable performance of the sensors (linear response) could be due to the use of air flow system, which facilitates particles transport into the laser detection area (Wang et al., 2015). The air flow system can speed up the movement of the particles compared to random diffusion method, which results in faster response time and improves the overall sensor performance.

The correlation coefficients (Figures 6 and S5) of all sensors are in good agreement with the reference instrument. However, the measured centred RMSE values (between 50 and 100) of the Taylor diagram (Figure 7) revealed sensor bias, which has to be corrected to reduce errors from the observed value. It is worth noting that relatively similar correlation factors and slopes were obtained during the demonstration experiments for PM₁₀, which are not repeated in here.

4. CONCLUSION

Generating and maintaining different environmental conditions and pollution concentrations by using an affordable EnvilutionTM chamber is a highly useful facility to evaluate the performance of LCS. Here, we describe the engineering design, specifications and performance of the chamber.

A set of experimental studies was designed and conducted to demonstrate its performance in maintaining stable conditions including meteorological parameters and PM_{2.5} pollutant. The results demonstrated the performance of the chamber via statistical analysis compared to the available studies in the literature.

For demonstration, the chamber was utilised to evaluate the performance of six temperature/RH (HDC1000) and PM_{2.5} (HPMA115S0, Honeywell) sensors, whereas Vaisala and Grimm were employed as the reference instruments. Good correlation towards the reference instrument, with R² values above 0.96, 0.99, and 0.97 were observed for temperature, RH, and PM_{2.5}, respectively. In addition, the described chamber also offers additional features that are not presented by others, such as affordable cost in both manufacturing and operation, small size and lightweight, low maintenance, and less-complicated in operation. Since the required characteristic parameters in our several experiments have been met, the chamber is expected to regenerate repeated experiments in similar environments and pollutant concentrations. Thus, the chamber can provide a wide community of sensor users an affordable and scientifically robust means for self-evaluation the performance of LCS under various conditions.

ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available on the journal website. This includes detailed design parameters, specifications, extra figures and statistical analysis associated with the chamber and LCSs' testing.

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329 **Author Contributions**

330 Prashant Kumar conceptualised the concept and design, and secured funding and needed resources.
331 Arvind Tiwari and Hamid Omidvarborna implemented it with the support from the University of
332 Surrey's workshop staff. All the authors contributed equally to the development of this manuscript.

333 **Notes**

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446

448 **Figure 1.** Schematic diagram of the chamber system with the main components. The components
449 are not illustrated in their actual size. The purple and green lines demonstrate process flows and
450 electric wires, respectively.

Figure 2. (top): Recorded temperature (30-sec average) by Vaisala and LCSs under atmospheric pressure at four set points (35, 25, 15, and 5°C) at 40% of RH. The Y-axis demonstrates chamber interior temperature (°C) and X-axis demonstrates operating time (sec); (bottom): 1-sec average results of the RH system recorded by Vaisala and LCSs under atmospheric pressure at four set points (80, 60, 40, and 20%) at 20°C. The Y-axis demonstrates chamber interior RH (%) and X-axis demonstrates operating time (sec).

Figure 3. (top): Correlation matrix among Vaisala and six LCSs during temperature testing. The higher number of counts represent the higher number of data points at that certain temperature level; (bottom): Correlation matrix among Vaisala and five LCSs during RH testing.

Figure 4. Taylor diagram of the entire dataset illustrating the statistics of comparison between temperature (top) and RH (bottom) sensors and reference instruments. The X- and Y-axes of the top and bottom plots represent SD in ($^{\circ}\text{C}$) and ($\%$), respectively.

468
 469 **Figure 5.** Recorded concentrations of PM_{2.5} by Grimm (the plot in black) at a sampling frequency
 470 of 6 seconds under atmospheric pressure at four different set points of 65, 120, 150, and 200 µg/m³
 471 vs. six LCSs (the plots in colour). The y- and x-axes represent concentration in (µg/m³) and time
 472 in (sec), respectively.

Figure 6. Correlation matrix among Grimm and six LCSs during PM_{2.5} performance demonstration.

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477 **Figure 7.** Taylor diagram of the entire dataset illustrating the statistics of comparison between
 478 PM_{2.5} sensors and Grimm. The X- and Y-axes represent SD in ($\mu\text{g}/\text{m}^3$).