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Impact of ambient air filters on PM concentration levels at an urban traffic hotspot (Stuttgart, Am Neckartor)

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ABSTRACT

Air pollution can have severe impacts on public health. A novel approach to lower the local particle concentrations at urban hotspots is ambient air filtration. This study presents experimental investigations into the effectiveness of air filters to lower ambient particle concentration levels at two different locations. Seventeen outdoor filtration devices with a total flow rate of 170.000 m^3/h were installed beside federal highway B14 at Stuttgart "Am Neckartor" targeting to reduce PM_{10} concentration levels within a 300 m × 50 m area around the urban pollution hotspot. Further measurements were conducted at the residential area "Bleyle Areal" to show the capabilities of a single filter device under relatively defined conditions. By periodically switching the filters on and off while monitoring the particle mass concentrations with optical particle counters, the effects of the filters on the PM_{10} and $PM_{2.5}$ concentration levels were determined. A long term investigation at the Neckartor installation site (466 h) yielded an average PM_{10} reduction of 10.4% (6.3 μg/m^3) at the official Neckartor measurement station. Additional in situ measurement campaigns showed that the PM reduction effect decreases with increasing distance to the filter devices. However, the effect is clearly measurable in the walkway areas across the installation site.

1. Introduction

Adverse health effects of fine dust particles are well-known (Leopoldina, 2019; WHO, 2005; WHO, 2016). Today, a large fraction of the world's urban population is exposed to elevated concentration of fine dust regularly. Statutory limits for particulate matter are derived from recommendations by the World Health Organization, where the exact limits may vary from nation to nation. In order to control these immission limits, governments operate measurement stations at key locations (e.g. in urban environments). Emission regulation (e.g. Federal Ministry of Justice and Consumer protection, 2020; BMU, 2002) has been driven by statutory limits for particulate matter (PM) concentration levels to reduce the overall impact of the industry and transport sectors on citizens and the environment. Apart from emission regulation, additional measures to improve local air quality can be undertaken (Ionescu et al., 2013). E.g. Amato et al. (2010), discussed several publications on the effectiveness of road sweeping as a means to reduce the PM concentration level, however the results were inconclusive. Employing ambient air filters to improve the fine dust concentration level in distinct outdoor areas is a novel approach. A first commercial application ("smog free tower") was erected by Studio Roosegarde in Rotterdam, Netherlands, in 2015, with several follow-up applications in urban parks across the world (Studio Roosegarde, 2015). Scholastic studies on the effects of outdoor air filters are still rare. Blocken et al. (2016), employed CFD simulations to investigate the effect of a large network of electrostatic precipitators erected in parking garages on the air quality in the city center of Eindhoven, Netherlands. Other authors numerically investigated the impact of filtering updraft towers on the PM concentration level (Tan et al., 2017). Nevertheless, to the best of the author's knowledge, no studies have been published addressing the experimental proof of concept of outdoor air filter devices, neither in terms of methodology nor by providing significant measurement data. This work is hence intended to close this gap by presenting methodology and results of respective concepts for filter installations in and around the city of

Abbreviations: OPC, optical particle counter; PM, particulate matter; LUBW, Landesanstalt für Umwelt Baden-Württemberg.

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Stuttgart, Germany. An overview of past measures to improve air quality at one of Germany's nation-wide pollution hotspot (Stuttgart, Am Neckartor) can be found in the supplementary information.

The key challenge for outdoor air filter impact measurements is the handling of the ever changing influencing factors and boundary conditions in the outdoor environment (e.g. meteorological conditions). For identifying these influencing factors on the PM concentration profile within a limited area around outdoor air filters, one can draw on well-established models for contaminant dispersion for continuous point or line emission sources with super-imposed convection (e.g. Zhou and Levy, 2007). In these models, the spatial concentration profile is typically influenced by diffusional properties of the contaminant, convectional transport, the emission strength as well as initial and boundary conditions (i.e. urban background concentration level and wind flow across the boundaries). Also, further emission sinks/sources play an important role. In outdoor air filtration, these key parameters relate mainly to the wind and filter-induced flow field in the observed area, the filters' volumetric flow rate, the filter outlet concentration and road/-vehicle emissions, respectively. This spectrum of influencing factors poses a challenge for theoretical/numerical work as well as for experiments. E.g., Blocken et al. (2016), found that the spatial PM concentration distribution in their complex city model depended massively on their input parameters, especially the Schmidt number. While numerical methods and parameters suffer from uncertainty due to the lack of validation of their parameters and models, experiments suffer from the necessity to either perform the measurements under extremely well-monitored, steady conditions (with non-generalizable results) or to resort to long term experiments and descriptive statistics for quantitative analysis. The experimental and statistical aspects presented in this paper were compiled to provide a reliable framework for future effectiveness studies on outdoor filtration devices (or similar controllable decentralized emission sinks or sources). The key element of our investigation is a specific test during which the filters are periodically switched on and off to determine their impact on ambient particle concentration levels.

2. Material & methods

2.1. MANN + HUMMEL Filter Cube

The Filter Cube consists of up to three stacked cubical filter modules mounted on a concrete pedestal (Fig. 1). Each cube has an edge length of 94 cm and is equipped with a radial fan, an ePM_1 55% filter element (as per ISO 16890, 2016) and an additional water separator.

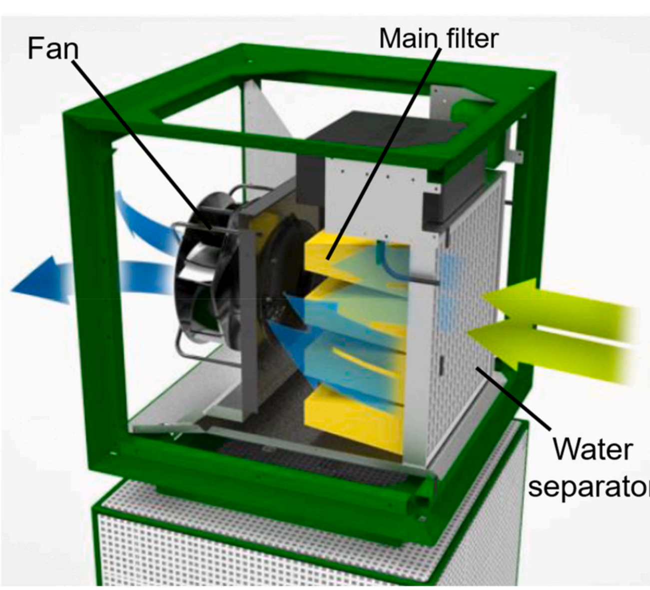

Fig. 1. MANN + HUMMEL Filter Cube schematic component view.

The filter elements contain 16.6 m^2 of microglass media per unit. ISO 16890 specifies filtration efficiency tests for HVAC elements with KCl and DEHS aerosols under controlled laboratory conditions. The results are expressed as gravimetric efficiencies ePM_1, $ePM_{2.5}$ and ePM_{10} for the respective size fractions. In addition to the standard procedure, which puts new as well as electrostatically discharged elements under test, dust loaded filters from the Neckartor site were tested with the same methodology to evaluate the evolution of fractional efficiency over filter lifetime (Table 1).

As with most non-charged, fiber based air filters, the filtration efficiency increases during operation, i.e. with increasing amount of accumulated particles (Brown, 1993). The rotational speed of the fans can be controlled remotely. While the Filter Cube units are designed for flow rates of up to 4.200 m^3/h/cube (500 W), the devices are optimized for a default flow rate of 3.400 m^3/h (300 W) in terms of power consumption and noise emission. Flow rate and differential pressure of the filter element are monitored with sensors, respectively. Occasionally, filter operation is automatically interrupted when precipitation is detected by a rain sensor to protect the filter from excessive water ingress.

2.2. Filter installation at Stuttgart Am Neckartor

The filter network at Stuttgart Am Neckartor was composed of 17 MANN + HUMMEL Filter Cube III units distributed along a 300 m stretch of six-lane Federal Highway B14 (see Fig. 2). The cumulated volumetric flow rate amounts to 4.000.000 m^3/d. The distance between curb and filters was 0.5 m. Spacings between neighboring filter units ranged between 12 m and 40 m. In order to avoid direct interference between filters and the measurement equipment of the official immission measurement station (operated by the Landesanstalt für Umwelt Baden-Württemberg, LUBW), its immediate surroundings were left blank. The closest Filter Cube was hence positioned 16 m off the measurement station. In order to comply with German noise immission legislation (BMU, 1998), two filters erected directly before a residential building on the South-Western end of the installation were turned off between 10 p.m. and 6 a.m.

Preceding the installation of the filters, numerical simulations with the MISKAM model (Eichhorn, 1989; Eichhorn and Kniffka, 2010; Müller and Warth, 2020) under various wind and contamination scenarios were conducted by a simulation laboratory. The calculations predicted PM_{10} reductions of 10–30% in the southward walkway areas and, more specifically, a reduction of 10–15% at the LUBW measurement station when presuming borderline (50 μg/m^3) ambient pollution situations. Although we relate to these reference values as orientation later, the simulations themselves are not covered in the present work to keep the focus on the experimental aspects.

2.3. Filter installation at Bleyle quarter Ludwigsburg

In addition to the air pollution hotspot at the "Neckartor" roadside, three Filter Cube II (2 cubes per unit) were installed close to a housing complex in Ludwigsburg, Germany (Fig. 3). The overall situation of the housing area within "Bleyle Areal" quarter with regards to particle

Table 1
ISO 16890 filtration efficiency values of new and used filter elements (4 months). ePM_x values indicate the fraction of separated particles (mass based) in the particle size range between 0.3 μm and x μm.

	ePM_1	$ePM_{2.5}$	ePM_{10}
New element	55%	65%	87%
New element after iso-propanol discharging	55%	64%	87%
Element after 4 months of use	74%	81%	94%

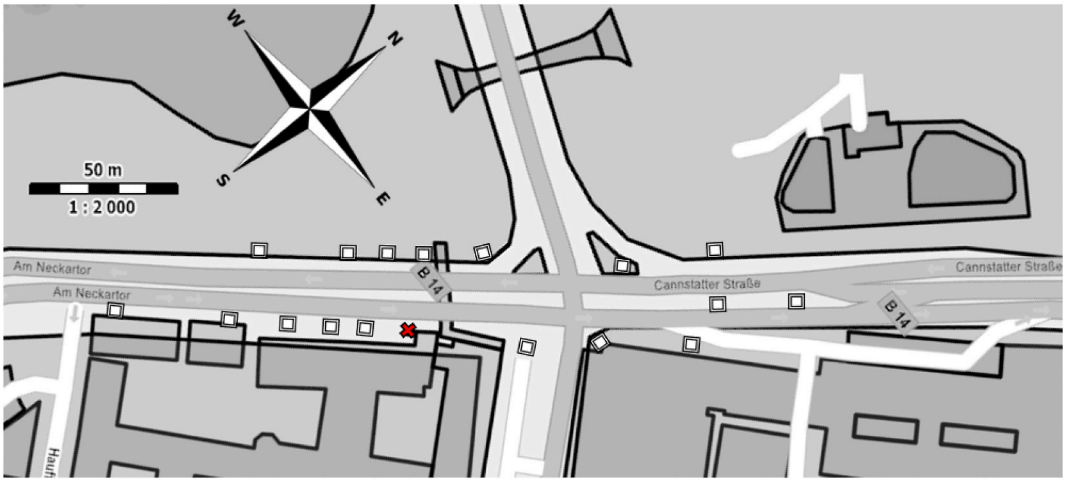

Fig. 2. Map of the Stuttgart Neckartor installation positions (square symbols, not true to scale). The X marks the position of the LUBW measurement station. Map source: OpenStreetMap and Contributors.

Fig. 3. Map of Bleyle Areal Ludwigsburg, indicating the positions of the Filter Cube II devices (square symbols, not true to scale) and their air flow orientations (arrows).

concentration and vehicle traffic differs greatly from Neckartor. Although the PM_{10} concentration levels are lower, the absence of highly dynamic vehicle emission and the wind protected placement within a U-shaped housing complex facilitate short term experiments, especially by improving their reproducibility. Thus, the "Bleyle Areal" installation is suitable for experimental investigations focusing on the effectiveness of a single Filter Cube.

3. Theory/calculation

3.1. *Experimental challenges and methodology*

Typically, the effect of pollution reduction measures is evaluated by drawing comparisons between the contaminant concentration levels after their implementation and either historical data or data from similar (but unaffected) sites (Umweltbundesamt, 2009). However, for the

Neckartor case, such comparisons are incapable of differentiating between the effects of the filters and those resulting from the other simultaneous interventions (see supplementary information for list of past measures to improve air quality at "Am Neckartor"). Hence, the remote control options of the Filter Cubes were exploited in a straightforward fashion that removed the handicap of such potentially biased reference data. The approach was to periodically change the filters' state of operation (ON and OFF state) while monitoring the PM concentrations at specific spots in the proximity of the filters. The key to obtain significant data in such alteration tests is to identify the alteration interval best suited for the respective experiments. For this, it is imperative to balance the dynamics of PM concentration levels and those of the PM measurement itself. This, in turn, requires a thorough assessment of the boundary conditions and dynamic PM characteristics on-site when preparing measurement campaigns.

3.1.1. Particulate matter concentration and measurement dynamics

A necessary prerequisite for statistically meaningful test results is that the sample distributions for the ON and OFF state are obtained under comparable boundary conditions. However, the local PM concentrations at the Neckartor roadside are subject to fluctuations on different time scales potentially leading to bias between these boundary conditions. Fig. 4 shows the average daytime-related trend for PM_{10} data measured at the Neckartor LUBW station and at two urban background measurement spots. A detailed characterization of the ambient aerosol at the Neckartor roadside (including SEM analysis, EDX analysis and particle size distributions) can be found in the supplementary information. At the hotspot, traffic induces a distinct daily evolution with higher amplitude than the background locations, both in absolute and relative terms. Concentration changes of several $\mu g/m^3$ per hour must hence be anticipated. Samad and Vogt also measured highly fluctuating PM concentrations in close proximity to sources of particle emissions (Samad and Vogt, 2020). These high change rates are problematic for alteration tests, as they potentially exceed the predicted effect of the filters (10%–30%), especially on days with low or moderate absolute concentrations. In turn, this implies the need to aggregate large samples in quantitative measurements to prevent bias between the sample distributions for the ON and OFF state. Changing the alteration pattern frequently (e.g. daily) further helps to reduce the potential bias from the repetitive concentration evolution (e.g. rush hours). If high concentration changes occur during short term measurements, the only option to compensate these changes is to use an additional reference measurement point just outside the range of effect of the filter columns.

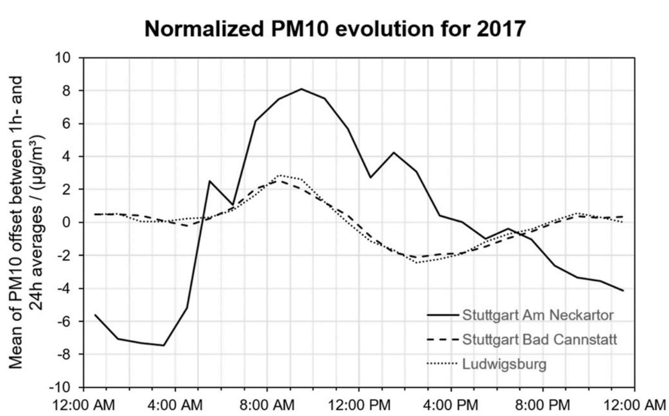

Fig. 4. Annual average of the difference between the hourly PM_{10} concentrations and their 24 h mean at the LUBW station Stuttgart Neckartor.

While the temporal change of operating conditions suggests short alteration intervals (and hence short measurement intervals) to be advantageous, disadvantages may also arise from insufficient durations of measurement intervals. PM levels in the walkway areas are subject to short term fluctuations, as depicted in Fig. 5. Especially PM_{10} concentrations are heavily fluctuating, showing distinct peaks over the course of several minutes measurement time. Most of these peaks can be attributed to passing vehicles (i.e. traffic light phases) and singular sources, such as smokers or heavy trucks. An appropriate measurement interval should contain several of the periodic short term events, in order to avoid bias between ON and OFF states. At "Stuttgart Neckartor", traffic light cycles spanned several minutes. At moderate and low levels of PM_{10}, short term averages also suffer from high variance due to the high impact of singular large particles from the largest particle size bins. As the OPC bins in the $PM_{2.5}$ size range typically contain a much higher number of particles, optically measured $PM_{2.5}$ values have a much lower relative standard deviation and thus require a shorter averaging interval to aggregate reliable mean values. The same is valid when using the particle number concentration C_n. Resorting to these smaller particle fractions hence allows to shorten the alteration intervals, thus reducing the duration of the measurements. This proves advantageous when measurement campaigns require specific concentrations levels or weather conditions that are only available within a limited timeframe.

3.1.2. Dynamics of PM distribution and aerosol homogenization

When conducting measurements with abrupt local concentration changes, it has to be considered that changes in the ambient concentration profiles will not happen instantaneously. During operation, filtered air mixes with ambient air, thus creating a spatial concentration gradient with low PM concentrations in the proximity of the filters and higher concentrations at increasing distance. After switching the filters off, concentrations steadily increase again, provided there are emission sources available. The higher the distance of a measurement spot to the filters, the longer it will take until PM concentrations have leveled out. In an ideal experiment, measurement of the ON and OFF state concentration would only start after the concentration has leveled out. Otherwise, the measured averages would be lower in the OFF state and higher in the ON state, respectively (Müller and Warth, 2020). Hence, starting the measurement immediately after changing the operation state systematically reduces the difference of means. However, this approach was used in the current work, because the required pause between state change and measurement is hard to predict, as it depends on wind, traffic-induced turbulence as well as the distance between the filter and measurement spot. Also, reducing the measurement duration between two state changes would again reduce the accuracy of the measurement.

3.2. Statistical aspects of alteration tests

The alteration tests result in average values for the PM concentrations $\bar{c}$ in the OFF and ON states. Welch's t-test (Welch, 1947) can be used to evaluate the expected accuracy of the obtained difference. The respective null hypothesis states that the difference of means Δc is less than or equal to a hypothetical difference ω. Using the standard deviations s and the number of intervals n of the ON and OFF state data, respectively, one obtains:

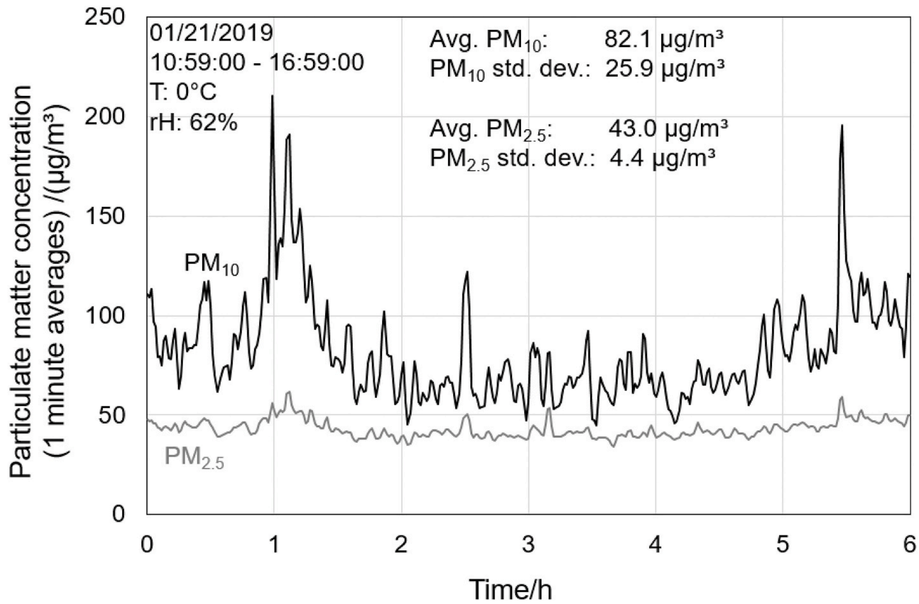

Fig. 5. Short term PM_{10} and $PM_{2.5}$ fluctuations at the Neckartor roadside (1 min average values).

$$H_0 : \Delta c = \overline{c_{OFF}} - \overline{c_{ON}} \le \omega$$

$$SE_{\Delta c} = \sqrt{\frac{s^2_{OFF}}{n_{OFF}} + \frac{s^2_{ON}}{n_{ON}}}$$

$$t = \frac{\Delta c - \omega}{SE_{\Delta c}}$$

$$df = \frac{SE^4_{\Delta c}}{\frac{1}{n_{OFF}-1}\left(\frac{s^2_{OFF}}{n_{OFF}}\right)^2 + \frac{1}{n_{ON}-1}\left(\frac{s^2_{ON}}{n_{ON}}\right)^2}$$

$SE_{\Delta c}$ is the standard error for the difference of means. t is the test statistic and df denotes the degrees of freedom as per the Welsh-Satterthwaite equation (Satterthwaite, 1946) Using historical PM_{10} data from the LUBW obtained using the optical particle counter (OPC) at the Neckartor measurement station one can estimate the margin of error for the difference of means (Table 2) as a function of the experiment's duration. A comparison between the expected absolute PM reductions and their corresponding margins of error signify that long term tests are necessary to obtain statistically reliable data for Δc. Consequently, short term experiments are merely suited to visualize certain aspects of the system behavior non-quantitatively. Only under steady boundary conditions (i.e. if low variances occur in reference measurements) the data from short experiments can also be used to demonstrate semi-quantitative trends.

3.3. Conclusions regarding the proposed proof of concept methodology

An ideal experimental setup capable of observing the temporal and spatial effect of the filters would consist of multiple accurate PM measurement devices suited for continuous outdoor air monitoring thus enabling multivariate spatial analysis. Considering their cost, such devices are rarely available in abundance, so practitioners have to resort to cheaper portable fine dust measurement devices to gather spatially resolved data in addition to singular long term spots. Therefore, two types of alternating state tests were conducted to gain spatially resolved as well as long term data:

a) Long term alternating state test with 1 h alteration interval, synchronized with the data from the LUBW station "Am Neckartor" for long term validation and proof of concept regarding the effectiveness of the Filter Cubes.
b) Short term, in situ measurement campaigns with 15–30 min alteration intervals, aiming to characterize the filters' spatial effect (semi quantitative analysis) using multiple mobile optical particle counters.

4. Results and discussion

4.1. Field test in Bleyle quarter (singular Filter Cube under defined conditions)

Measurements with four Palas OPCs (3x Fidas Frog, 1x Fidas 200s) were conducted to evaluate the effectiveness of a single Filter Cube at

Table 2
Statistical parameters of OPC 30 min average values of the LUBW Am Neckartor station for the year 2019 and associated margins of error (two-sided) calculated for hypothetical alteration test durations (assumptions: reductions of 10% for PM_{10} and 7.5% for $PM_{2.5}$ for the respective mean and standard deviation in the ON state).

				Expected 95% margins of error for Δc [µg/m³]			
Pollutant	Annual average [µg/m³]	Standard deviation [µg/m³]	Estimated difference of means [µg/m³]	10 days	30 days	100 days	1 year
PM_{10}	24.5	20.4	2.45	±7.1	±4.1	±2.2	±1.1
$PM_{2.5}$	11.4	16.6	0.86	±6.3	±3.6	±2.0	±1.0

different axial distances (Fig. 6) under the well-defined ambient conditions of the “Bleyle Areal" in Ludwigsburg. Due to the low PM variance, sample intervals for ON and OFF states can be relatively short (see also chapter 3.2.). All Fidas Frog devices were calibrated against the Fidas 200s before and after the experiments and generally were in good agreement ($r^2 > 0.94$).

During the experiments, the Filter Cube was switched on and off every 15 min to determine the difference in spatial PM concentration with and without the influence of ambient air filtration. Fig. 7 shows concentration averages during each phase for PM_{10}, $PM_{2.5}$ and particle number concentration C_n, respectively. In addition to absolute values, normalized data is reported to compensate for the concentration decay over the course of the experiment. As reference, the Fidas 200s was positioned outside of the effective range of the Filter Cube.

The effect of the Filter Cubes on the downstream concentration is visualized through the amplitude of the curves between the ON and OFF states. Amplitudes were found to differ between the observed dust fractions. 1.5 m behind the cubes, PM_{10} concentration was reduced by approx. 40% (7–8 μg/m^3), $PM_{2.5}$ by approx. 30% (4–5 μg/m^3) and C_n by approx. 25% (75–120 #/cm^3) when compared to their average values during the OFF phase. This is a consequence of the size dependent fractional efficiencies of the employed filters as per Table 1. As described above, short term PM_{10} measurements suffer from high variance and hence do not strictly follow the clear trend observed for $PM_{2.5}$ and C_n. While $PM_{2.5}$ and C_n almost reach the reference value in the OFF state, PM_{10} values do not swing back to their reference level, indicating a slower PM_{10} homogenization.

The amplitude (i.e. the observable effect of the filters) decays with increasing distance from the Filter Cube, indicating the formation of a steep concentration gradient downstream from the filter. Fig. 8 shows the average reduction in absolute PM for all ON phases as a function of distance from the Filter Cube. At an average reference ambient $PM_{2.5}$ concentration of 13–15 μg/m^3, the reduction 5 m downstream from the filter drops below 1 μg/m^3. Considering the flow rate of 1.8 m^3/s at the filter outlet, it may be concluded that mixing in the downstream areas with ambient air is highly intense during filter operation. Consequently, the concentration decay resembles that of a point or line source rather than that of a jet stream, in which almost constant particle concentrations would have been expected.

4.2. Field test at the Neckartor roadside (spatial effect on PM of filter installation)

In order to investigate the lateral concentration profile with increasing distance from the filters, multiple OPCs were deployed at the Neckartor installation site. An alteration test with a 30 min alteration

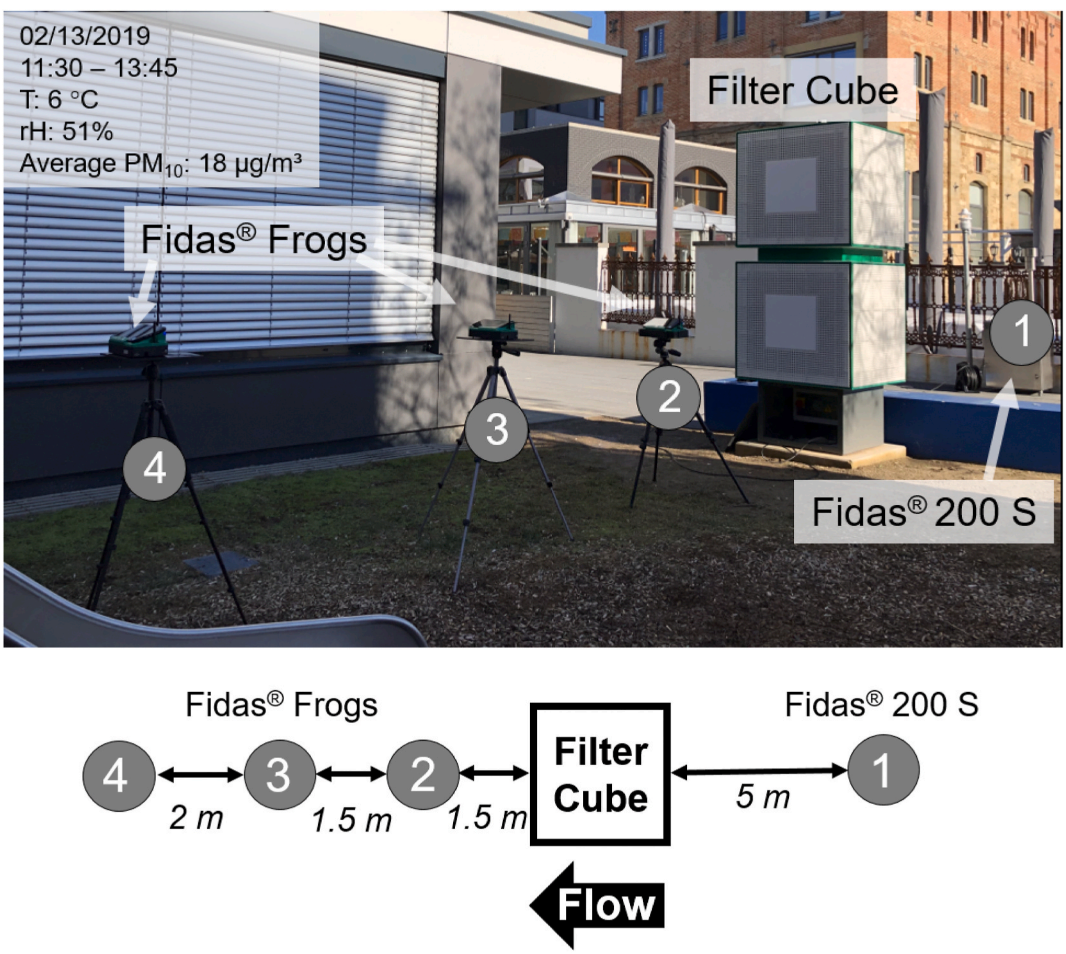

Fig. 6. Photograph and schematic drawing of the test setup at the Bleyle quarter.

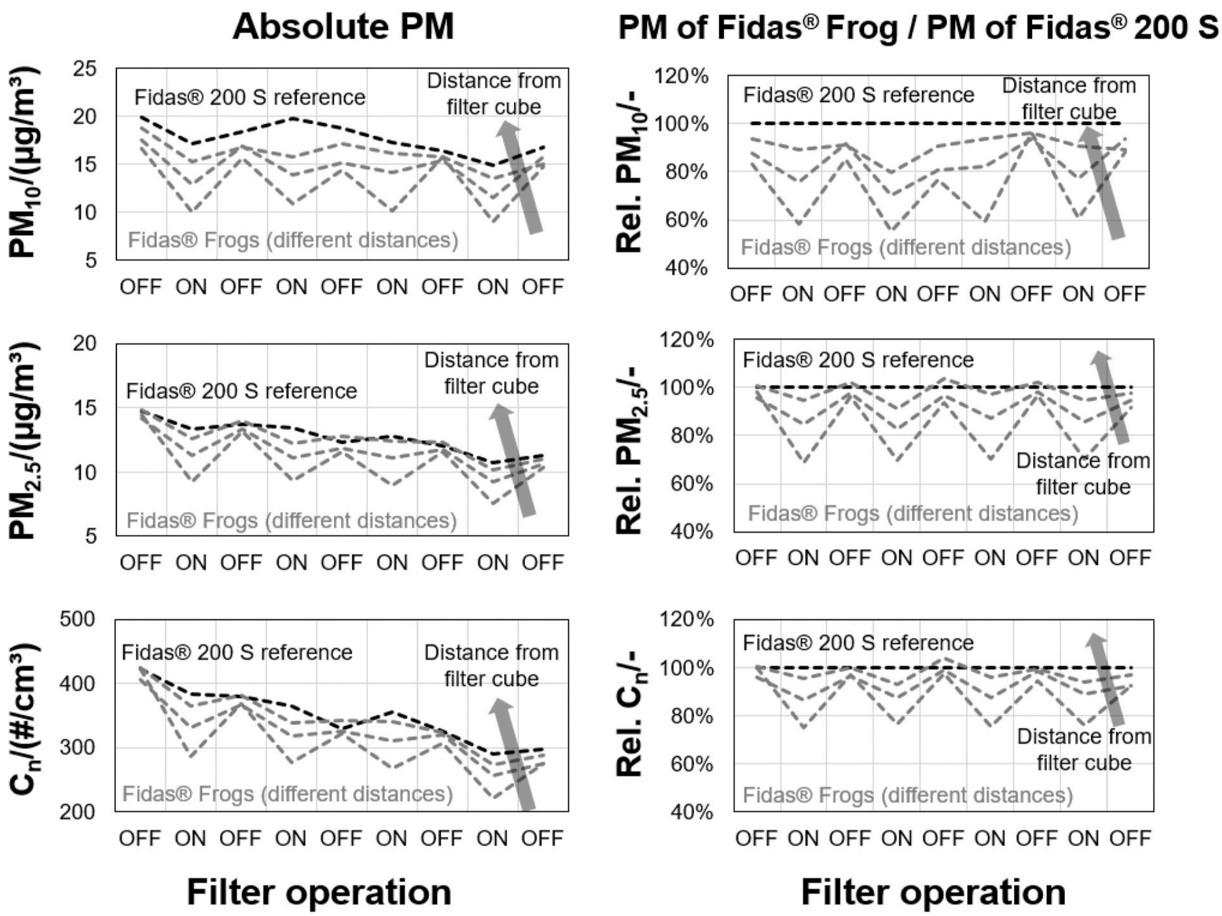

Fig. 7. Results of PM and particle number concentration during the experiments at the Bleyle quarter (02/13/2019, 11:30–13:45; Temperature: 6 °C; Relative humidity: 51%; Average PM_{10}: 18 μg/m^3).

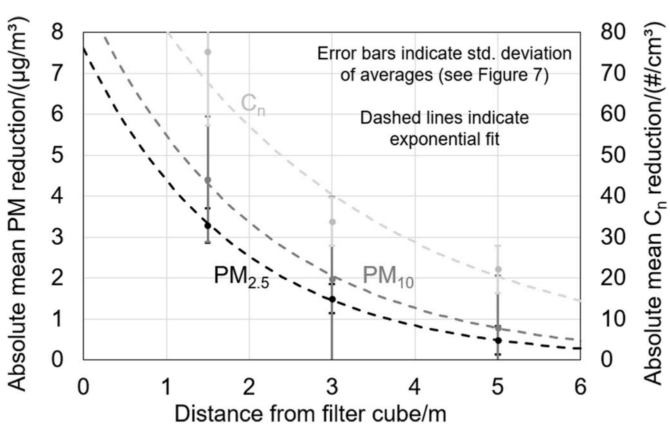

Fig. 8. Absolute mean particle concentration reduction as a function of distance from the Filter Cubes. The displayed concentration reductions are the mean values of the difference between the reference concentration (outside the effect range of the Filter Cube) and the respective Fidas Frog at each position for all ON states.

interval was conducted. The setup of the measurement devices is shown in Fig. 9. All OPC inlets were set on the same height (1.4 m), except the one on the LUBW station. $PM_{2.5}$ and PM_{10} OPC data from the latter were kindly provided by LUBW.

A reference device was located approximately 100 m off the rest of the devices, on the southwestern edge of the installation. Its concentration evolution (Fig. 10, bottom left) shows the general trend of the traffic-affected concentrations and appears to be unaffected by filter operation. The incremental changes measured are on the same order as the expected effective PM reduction. Hence, all further data in Fig. 10 were related to their counterparts from the reference device. Across all devices, only the $PM_{2.5}$ data measured directly behind the filters (Pos. 4) showed the steady, repetitive pattern found at "Bleyle Areal". Partially, a zig-zag trend was also observed at the filter inlet, which may however originate from recirculation as well as from the sampling (probing was done perpendicularly to the rapid inlet flow). The particle number concentrations C_n show a more distinct trend than $PM_{2.5}$, with repetitive concentration reductions during filter operation (Fig. 10; number concentration of official measurement station not available). Again, the amplitude and hence the reduction wears off with increasing lateral distance from the Filter Cube. At the LUBW station, the $PM_{2.5}$ trend even appears to be inverted. This supports the results from the MISKAM simulations, which predicted the effect at the LUBW station to be significantly lower than in the other regions on the southwestern roadside. The distinct $PM_{2.5}$ drop after the first activation of the filters is remarkable, as it goes against the trend at the reference location and might be an indicator, that the concentration within the effective range of the filters is shifted towards lower values for the whole duration of the

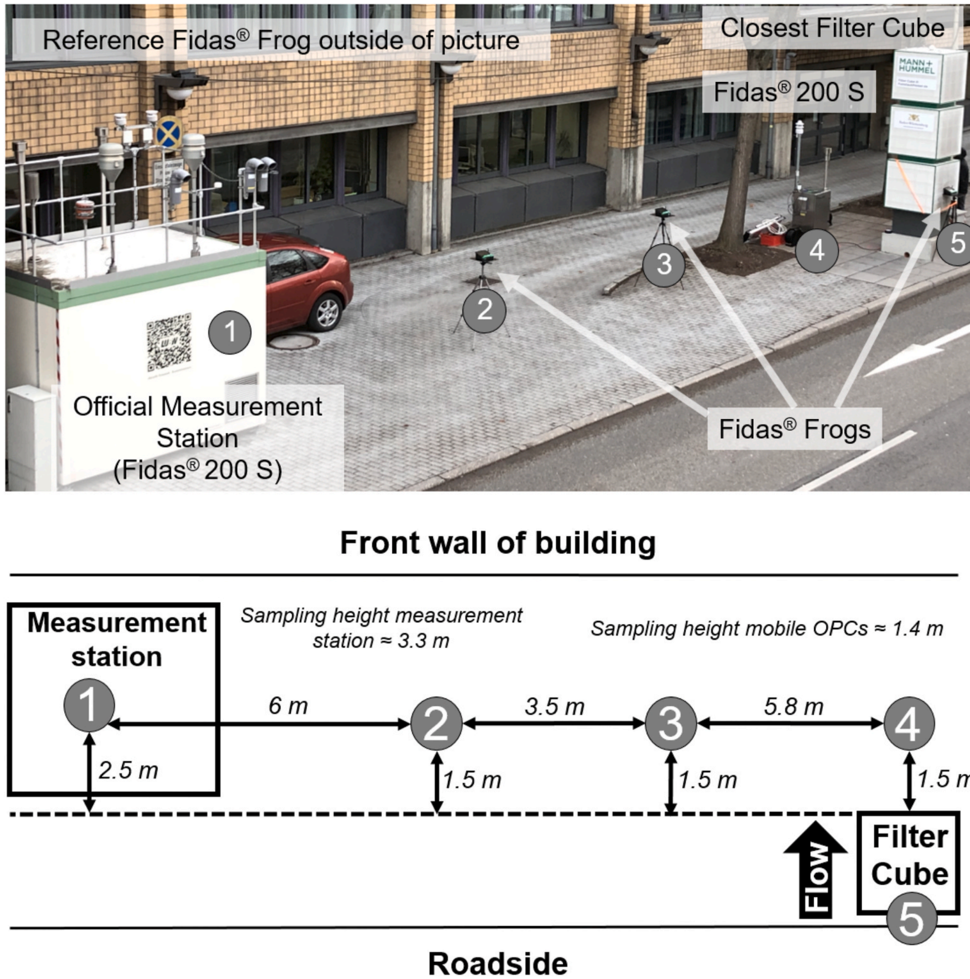

Fig. 9. Photograph and schematic drawing (bird's eye view) of the test setup from 01/18/2019 at the "Neckartor" roadside to investigate the lateral PM reduction of the Filter Cubes. Conditions: Temperature: 3 °C; rel. humidity: 62%, avg. PM_{10}: 47.8 μg/m^3. The reference was located outside of the estimated range of the Filter Cubes close to the edge of the housing complex at the street corner "Am Neckartor – Hauffstraβe" (see Fig. 3).

test. This means, that the alteration interval might be too short for the PM fractions to swing back to their original level.

The presented experiments were done under comparatively steady ambient conditions. Additional experiments were conducted with different test setups, the majority of which however failed to deliver conclusive results, primarily due to meteorological effects (rain, snow) or extreme concentration changes.

4.3. Long term alteration test and data analysis

A long term alteration test with 1 h alteration intervals was conducted between 01/19/2019 and 02/28/2019 to investigate the effect of the Neckartor installation on the PM values observed at the LUBW station. The change of operation was conducted manually via a remote servicing feature of the Filter Cubes. Data from hours during which significant precipitation occurred (i.e. above the threshold of the Filter Cube rain sensors), were excluded from the data set. Ultimately, a total of 32 days with 8–21 h of useable data were aggregated (Fig. 11). The whole installation was either switched on or off in the corresponding interval. Table 3 shows the respective average values for PM_{10}, $PM_{2.5}$ and, merely as a neutral reference, for NO_2 data, which should be unaffected by the filters. Overall reductions of 10.4% (6.3 μg/m^3), 5.1% (1.2 μg/m^3) and 0.1% (0.1 μg/m^3) were found for the concentrations of PM_{10}, $PM_{2.5}$ and NO_2, respectively. Also, statistical parameters required for the Welch test are given as well as results from three statistical tests:

a) One-tailed *t*-test on $H_0 : \Delta c \leq \omega$
b) One-tailed *t*-test on $G_0 : \Delta c \leq 2.5\ \mu g/m^3$ (only meaningful for PM_{10})
c) Two-tailed *t*-test to determine the 95% confidence interval for Δc

The Hypothesis H_0 can be rejected at a confidence level > 99% for PM_{10} and 95% for $PM_{2.5}$. Hence, the filters reduce the PM concentrations at the LUBW station position with statistical certainty. H_0 cannot be rejected for NO_2, thus indicating that the filters are unlikely to affect the NO_2 concentration at the LUBW station. An influence of the filters on this reference contaminant might have occurred if the flow pattern induced by the filters had altered the measured concentration in the ON state. For PM_{10}, a 95% confidence level is also found for rejecting hypothesis G_0, meaning that the difference between the ON and OFF states is likely to exceed 2.5 μg/m^3 or 4.1% in relative terms, respectively. The

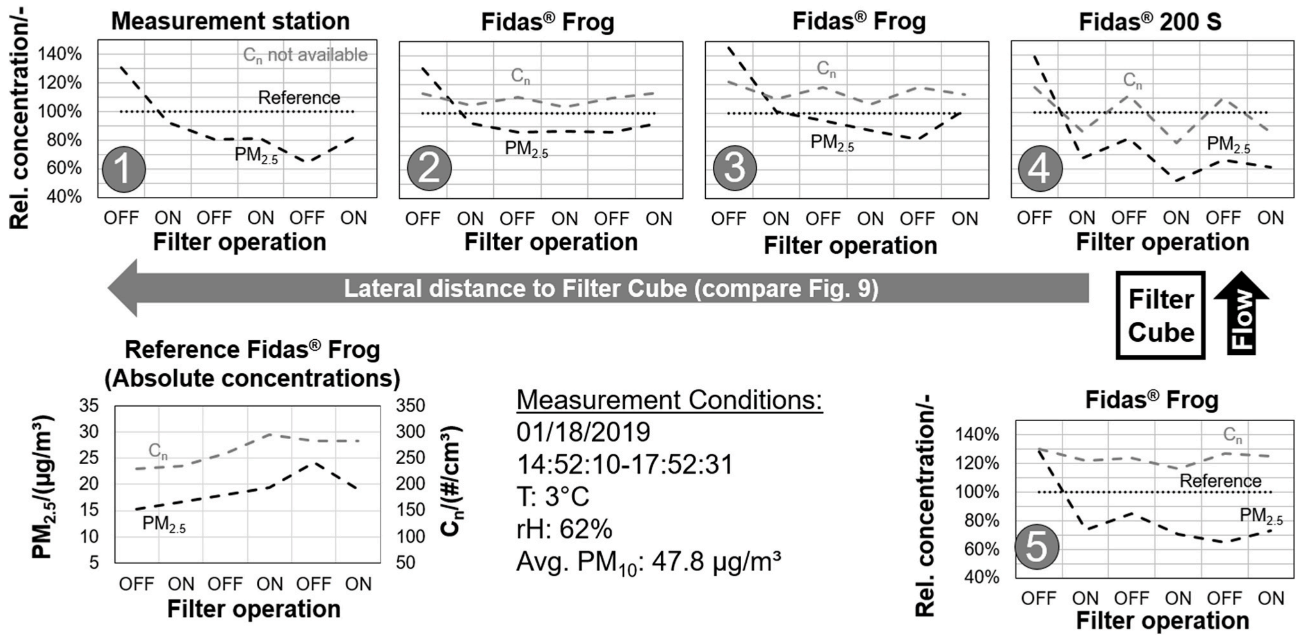

Fig. 10. Spatial PM levels detected during the measurement campaign on 01/18/2019. Alteration interval was 30 min.

95% confidence interval for Δc is 6.3 ± 4.5 μg/m^3 for PM_{10}, and 1.2 ± 1.4 μg/m^3 for $PM_{2.5}$. In contrast to the short term measurements no benefit in terms of accuracy can be obtained when using $PM_{2.5}$ instead of PM_{10}. This effect may be attributed to the low absolute differences in $PM_{2.5}$ in relation to the high relative standard deviation arising over the long test duration.

Fig. 11 shows a day by day representation of the test results. A reduction of PM_{10} during the ON phase was observed on the majority of test days. Extreme results on both ends of the scale are not only linked to statistical variance of PM_{10} concentrations but frequently coincide with exceptional meteorological conditions. High reductions occur in situations with limited air exchange, whereas minor reductions/neutrality can be observed on windy days (e.g. 03/02 and 10/02, the windiest days in the test period with average wind speeds of >2 m/s at the closest public meteorology station (Stuttgart, Bad Cannstatt)). In the latter situations, convection leads to a stronger dilution of the clean air into a higher volumetric flow rate of contaminated air, resulting in steeper spatial PM_{10} gradients. Hence, on windy days, the effect of the filter is only measurable in close proximity of the filter. No meteorological measurement equipment was available to the authors during the

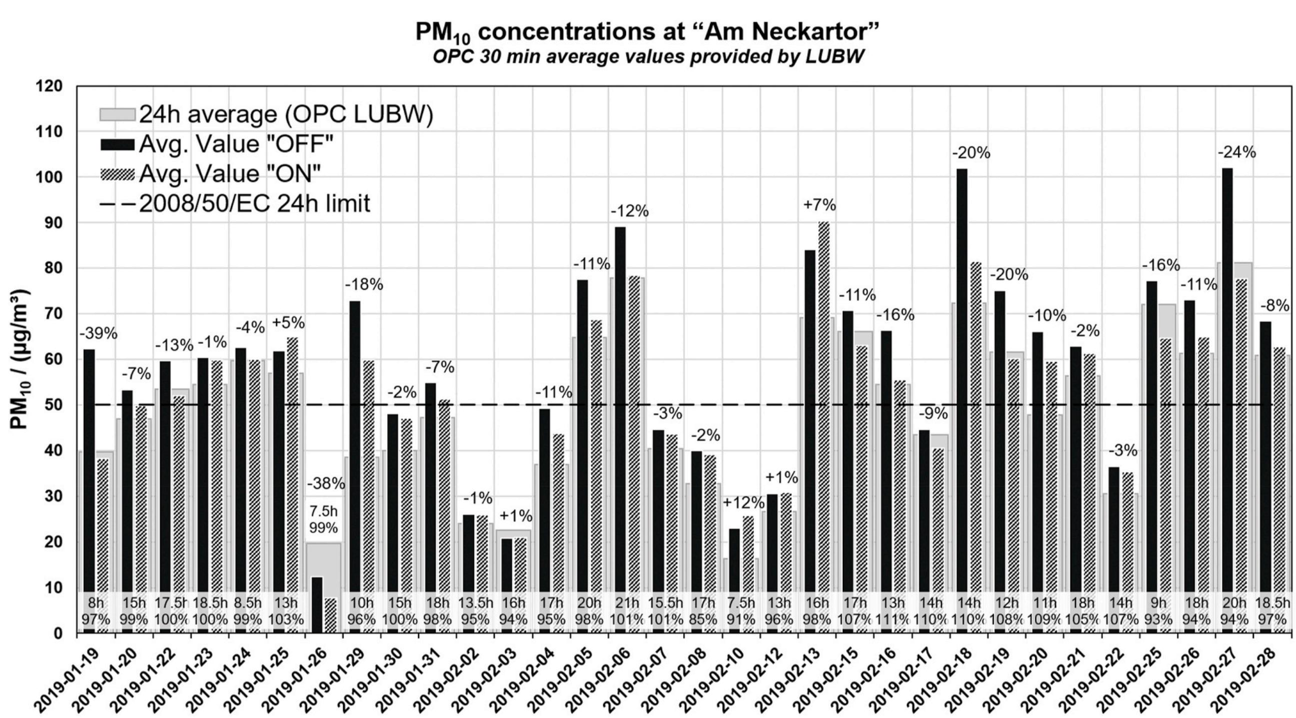

Fig. 11. Day by day results of the long term alternating state test. Values in the lower end captions denote the cumulated duration of useable data for the respective day and the achieved average flow rate of the filter installation related to its nominal performance.

Table 3
Long term test results, based on 1 h alteration interval and 30 min averaging intervals.

	Pollutant		
	PM_{10}	$PM_{2.5}$	NO_2
Mean value ON ($\overline{c_{ON}}$) [μg/m³]	**54.4**	**21.7**	**82.2**
Mean value OFF ($\overline{c_{OFF}}$) [μg/m³]	**60.7**	**22.8**	**82.3**
Difference of means (Δc) [μg/m³]	6.3	1.2	0.1
Reduction $\Delta c/\overline{c_{OFF}}$	**10.4%**	**5.1%**	**0.1%**
Number of 30 min intervals ON	482	482	447
Number of 30 min intervals OFF	450	451	422
Standard deviation ON [μg/m³]	32.2	10.2	26.7
Standard deviation OFF [μg/m³]	38.0	10.8	27.8
Standard error for the difference of means [μg/m³]	2.3	0.7	1.9
t-value of a one-sided *t*-test @ $\omega = 0$, H_0	2.73	1.69	0.31
p-value of a one-sided *t*-test @ $\omega = 0$, H_0	0.0033	0.049	0.38
t-value of a one-sided *t*-test @ $\omega = 2.5\ \mu g/m^3$, G_0	1.69	–	–
p-value of a one-sided *t*-test @$\omega = 2.5\ \mu g/m^3$, G_0	0.05	–	–
95% confidence interval for Δc, two-sided *t*-test [μg/m³]	**6.3 ± 4.5**	**1.2 ± 1.4**	**0.1 ± 3.6**

measurement campaign. In later investigations (conducted with different filter devices, not covered by this article) a continuous meteo spot was installed on the northwestern park side at 1.4 m height. Typically, wind velocities of <0.5 m/s were observed, predominantly in the direction of traffic. The meteorological situation close to the ground at the "Neckartor" site hence remains unaffected by the macro-meteorological situation. This statement holds as long as the wind speeds are not excessively high. Although our data exhibits particularly low effect at high wind speeds, the amount of data is not sufficient to substantiate a clear correlation between the effect of the filters and the wind speed observed at several meteorological monitoring stations in the Stuttgart area. However, the results in Fig. 11 signify the potential of reducing the power consumption of outdoor air filter devices by implementing a sensor-based, demand oriented operation scheme.

5. Conclusions

The effect of MANN + HUMMEL “Filter Cube” outdoor air filtration devices on their ambient PM_{10} concentration was investigated at two different locations. The general test approach was to repetitively change the operation status while measuring PM concentrations with optical particle counters. In order to achieve meaningful results within a limited time frame, the periodicity of the status changes must be adapted to the boundary conditions and the system behavior. Optimizing the alteration interval requires knowledge of the dynamics of the local air pollution and of the dynamics of the system reaction to the state changes (i.e. contaminant homogenization). These factors must then be balanced against the achievable accuracy of the measured PM averages within the available time frame. Thorough in-situ measurements to characterize the respective dynamic system behavior should hence be conducted prior to starting similar testing activities in comparable applications.

A long term alteration test at Stuttgart Neckartor was conducted using the data from the public measurement station operated by the Landesanstalt für Umwelt Baden-Wuerttemberg (LUBW). At the location, 17 Filter Cube III devices were operated along a 300 m × 50 m stretch of federal highway B14 accumulating a nominal flow rate of 4.000.000 m^3/day obtained at 14.7 kW of electric power. After 466 h of aggregated test time, an average PM_{10} reduction of 10.4% (6.3 $\mu g/m^3$) at the LUBW station was observed ($PM_{2.5}$: 5.1% or 1.2 $\mu g/m^3$), matching a prognosis of 10–15% from MISKAM simulations. Welch type t-tests yielded very high confidence (>99.5%) for a positive effect ($\Delta c > 0$ $\mu g/m^3$) on the ambient PM_{10} concentration and 95% for a PM_{10} reduction of at least 4.1% ($\Delta c > 2.5\ \mu g/m^3$). Day by day values showed a reduced effectiveness at low and moderate PM_{10} concentrations, thus indicating the potential of demand based control schemes to reduce the power consumption, e.g. by monitoring the local PM concentrations.

Short term semi-quantitative investigations on the axial and lateral concentration profile in the ON and OFF states of the filters revealed high concentration reductions in the proximity of the Filter Cube which decay with increasing distance to the filter, both axially and laterally. The decay is a result of the homogenization of filtered and ambient air. The key challenges for short term PM measurements were the dynamically changing ambient concentrations as well as the long time to aggregate accurate PM_{10} measurement data at low and moderate ambient concentrations. A workaround for both problems was found in resorting to the finer particle fractions of the employed OPCs ($PM_{2.5}$, particle number concentration C_n) for semi-quantitative analyses. This approach proved advantageous due to better diffusive mixing and quicker aggregation of reliable averages of the respective particle classes. Also, at the test locations, the fine particle fractions exhibited lower relative variances than PM_{10}.

Ultimately, the presented results demonstrate the capability of outdoor air filter installations of the Filter Cube devices to reduce PM levels in a distinct area when filters are arranged in a tight grid. The potential of PM level reduction by outdoor air filtration is closely linked to the convective and turbulent mixing of ambient air at the target location across the installation site boundaries. At increased concentration levels, higher absolute PM reductions may be achieved at the same expense (cost, power, space). It can hence be concluded that locations characterized by limited air exchange and high PM values (e.g. train/subway stations) hold the highest potential for an efficient application of outdoor air filtration technology.

Author statement

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Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Dr. Thilo Konrad Müller and Dr. Tobias Warth are currently employed by MANN + HUMMEL GmbH and worked on the project.

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Appendix A. Supplementary data

Supplementary information to this article can be found online at https://doi.org/10.1016/j.apr.2021.101059.

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