Journal of Aerosol Science 150 (2020) 105644

Contents lists available at ScienceDirect

Journal of Aerosol Science

journal homepage: http://www.elsevier.com/locate/jaerosci

Simultaneous measurement of spatially resolved particle emissions in a pilot plant scale baghouse filter applying distributed low-cost particulate matter sensors

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ARTICLE INFO

Keywords:
Low-cost PM-sensors
Emission measurement
Dust separation
Surface filtration
Baghouse filtration
Smart filter

ABSTRACT

Baghouse filters are widely applied in industrial gas cleaning, for example in waste incineration plants and the cement industry, to meet particle emission standards and for product recovery. The global particle emission of pulse-jet cleaned surface filters is typically monitored end of pipe (e.g. in the stack). Since the particulate matter emission of baghouse filters originates often from leaks and incorrectly installed or damaged filter bags, operators would greatly profit from online measurement technology that monitors the emission contribution of individual filter bags or at least a subset of all installed filter elements to the total emission. Low-cost particulate matter sensors can be deployed inside filter houses in larger quantities due to their compact design and low asset cost compared to conventional aerosol measurement technology. The ability of several low-cost sensors to detect the characteristic PM emission behavior of surface filters has been shown in previous investigations in a filter test rig. This study shows first results regarding the emission contribution of individual filter bags of a pilot plant scale baghouse filter employing distributed low-cost sensors of the model OPC-N3 from the manufacturer Alphasense. A Promo® 2000 aerosol spectrometer with a welas® 2100 sensor serves as reference regarding the particulate matter concentration detected by the low-cost sensors and as end of pipe measurement equipment to monitor the global emission. The selected filter medium was a membrane filter medium with sealed seams to provide low emission levels and defined conditions on the clean gas side. The employed low-cost sensors detect an emission peak right after cleaning of the corresponding filter bag only. The global emission measured in the clean gas duct consists of the overlay of the individual emission peaks detected locally at the corresponding filter bags. By exchanging one filter bag with a filter bag made from a non-membrane filter medium without sealed seams, an increase of the total continuous emission can be detected, both end of pipe in the clean gas duct and locally via the low-cost particulate matter sensor. This demonstrates the applicability of the measurement technology for the detection and identification of leaks and damaged filter bags that serve as emission hotspots in baghouse filters.

1. Introduction

Pulse-jet cleaned surface filters remain state of the art technology for industrial gas cleaning, where particle mass concentrations in

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https://doi.org/10.1016/j.jaerosci.2020.105644
Received 29 April 2020; Received in revised form 15 July 2020; Accepted 4 August 2020
Available online 14 August 2020

the region of multiple grams per cubic meter have to be separated from dust-laden gas streams in order to fulfill emission standards. The key advantage of surface filters is the continuous operation, where a dust cake with a high separation efficiency is formed by collecting particles on the surface of a filter medium. The formation of the filter cake increases the differential pressure between the raw-gas side and the clean gas side. Thus, the cake has to be removed periodically, e.g. by a jet-pulse from the clean gas side, after a specified time has passed (Δt-controlled operation) or a maximum differential pressure is reached (Δp-controlled operation). The filter medium is often confectioned in the form of a filter bag and multiple filter bags are arranged inside a filter house dependent on the volume flow of the dust-laden gas.

Continuously tightening emission standards for technical facilities as well as the inclusion of particle size resolved immission limits in the form of $PM_{2.5}$ and PM_{10} mass concentrations put high demands on plant operators. An optimal operating strategy for surface filters would combine low emissions with a low energy consumption. In this context, the operation and emission behavior of baghouse filters is still subject of research. Here, filter tests are typically performed inside standardized test rigs [e.g. Binnig et al., 2009; Bach & Schmidt, 2007; Höflinger and Laminger, 2013; Sobich et al., 2018], that do not necessarily represent the operating conditions of industrial baghouse filters.

The usual end of pipe particle emission that can be detected in the clean gas duct of filter houses consists of a continuous baseline emission in addition to emission peaks after jet-pulse cleaning of the filter bags. The origins of the continuous emission are for example leaks or defects of filter bags and the plenum plate, incorrectly installed filter bags and the seams of the filter bag (Kurtz et al., 2017). Process conditions, especially the intensity of the cleaning pulse and the interval between cleaning pulses, can also play a role. Insufficiently short cleaning intervals may not grant enough time for cake buildup of the previously cleaned bag, so that the dust emission detected in the clean gas duct originates from multiple bags. This emission behavior is not reflected in filter tests, where mainly the emission of particle penetration through the filter medium itself contributes to the emission (Binnig et al., 2009).

Simon et al. studied the complex flow conditions inside a pilot filter unit and discussed the impact of newly regenerated filter bags on the total particle emission (Simon et al., 2010). Kurtz et al. showed the high impact of leaks on the global emission detected at the end of the pipe of baghouse filters (Kurtz et al., 2017). Similar investigations were led by Bach et al. who studied the influence of pinhole leakages in a filter test rig (Bach & Schmidt, 2007).

Due to the dominating role of leaks on the total particle emission, new methods for an easy on-line detection that help identify different emission levels within the baghouse can greatly help plant operators. Conventional methods for the detection of leaks include triboelelectrical measurements and the use of fluorescent dust, both of which have drawbacks. Triboelectrical sensors enable on-line measurement of the global dust concentration on the clean gas side. Due to their size and comparably high cost, tribolelectrical sensors are difficult to implement on multiple measurement points within the baghouse, thus offering no local information about the location of emission hotspots. The identification of leaks via fluorescent dust requires a temporary shutdown of the filter house and considerable troubleshooting concerning the location of the source of the PM emission (e.g. leaks, damaged filter media or plenum plate,

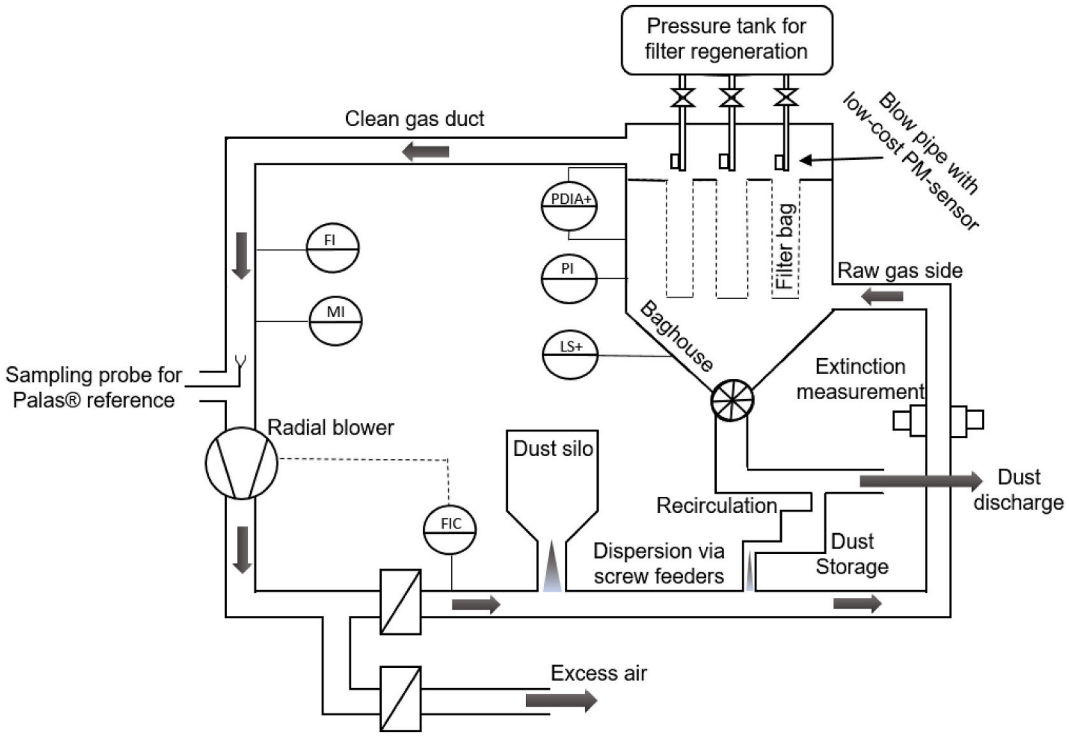

Fig. 1. Flow sheet of the pilot plant scale baghouse with nine filter bags.

incorrect installation of bags, etc.).

With increasing popularity of low-cost sensors for the determination of local particulate matter concentrations with respect to immission measurement, cheap and compact measurement technology is available that could potentially be used inside filter houses to detect local dust emissions of individual filter bags (Schwarz et al., 2018). Many publications exist that investigate sensor performance for the immission application, e.g indoor and outdoor air quality, detailing challenges regarding sensor accuracy, inter-sensor variability and impact of measurement conditions (e.g. relative humidity) [e.g. Asbach et al., 2018; Badura et al., 2019; Budde et al., 2018; Crilley et al., 2020; Feenstra et al., 2019; Karagulian et al., 2019; Kelly et al., 2016; Zou et al., 2020].

In previous publications, the suitability of low-cost sensors to characterize the typical emission behavior of surface filters have been investigated in a filter test rig. The characteristic emission peak after jet-pulse cleaning of the filter medium could be detected by the low-cost sensors. Additionally, different emission levels from different filter media could be identified from PM measurements using low-cost sensors (Bächler et al., 2019a, 2019b; Schwarz et al., 2018).

This publication presents first results regarding the local particle emission contribution of individual filter bags in a pilot plant scale baghouse employing spatially distributed low-cost sensors for simultaneous measurement of the local PM concentration with high temporal resolution.

2. Experimental set-up, procedures and materials

2.1. Pilot plant scale baghouse

A pilot plant scale baghouse filter serves as the testing facility for the experiments. The corresponding schematic set-up is shown in Fig. 1. Contrary to typical filter test rigs, where circular filter coupons are investigated, the filter medium is confectioned as filter bags similar to the industrial application.

A total of nine filter bags (diameter 11.7 cm; length: 125 cm) are installed inside the baghouse. The bags are fixed on the plenum plate via MikroPul Venturi bayonet fittings and double beaded ring clamps, thus separating the raw and clean gas side of the testing facility. Each of the nine bags can be cleaned individually by a jet pulse from a blow pipe that is connected to a pressure tank. A radial blower recirculates the air flow through the testing facility. The air flow is adjusted to set an overall filter face velocity of approximately 120 m/h. Dust is fed in the raw gas duct via dosage from screw feeders at two different locations. A storage silo ensures that a sufficient amount of test dust is available. Additionally, collected dust is mostly recirculated to enable a more economic test operation. The dust dosage is controlled by an extinction measurement, which is calibrated to a gravimetric raw dust concentration of 5 g/m^3. To determine the global particle emission in the clean gas duct, a Promo® 2000 aerosol spectrometer in combination with a welas® 2100 sensor from the manufacturer Palas® (https://www.palas.de/prod) draws a sample flow via an isokinetic probe in the downflow pipe of the clean gas.

The local PM emissions of the nine individual filter bags are measured via nine low-cost PM-sensors of the model OPC-N3 from the manufacturer Alphasense (http://www.alphasense.com), which are described in detail in the following chapter. One sensor is attached to each blow pipe for filter regeneration according to Fig. 2. A small hose is attached to the sensor outlet to be able to draw a sample closer to the outlet of the venturi nozzle of the individual bag and avoid lateral interferences and dispersion effects on the clean gas side. The sampling hose is fixed on the inside of the venturi nozzle.

In addition to emission measurement, other process parameters like the differential pressure between raw-and clean gas side, the signal of the extinction measurement, the total volume flow, temperature and the pressure inside the pressure tanks for filter regeneration are monitored by an independent process control system. The employed process parameters are summarized in Fig. 3. To

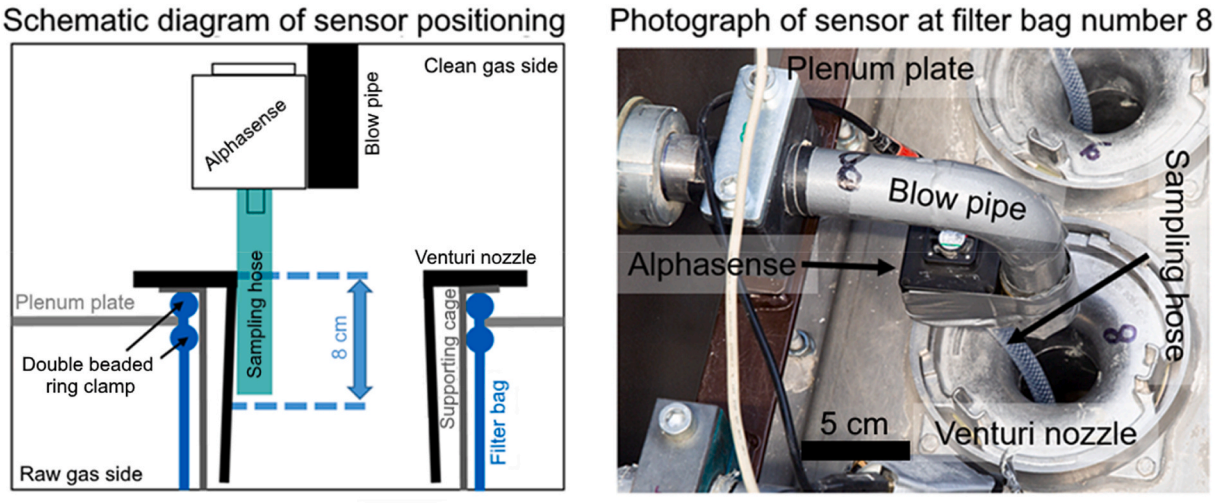

Fig. 2. Schematic diagram and photograph of sensor positioning.

be able to easily allocate filter regeneration events to the corresponding emission data, a Δt-controlled operation with a bag-by-bag cleaning rhythm (Fig. 3 - left) was selected for the experiments. The cleaning interval was set to 120 s to enable sufficient cake build up between the different filter regenerations, thus avoiding emission contribution of multiple bags due to insufficient cake build up. The differential pressure range during steady state operation was between 2 and 3 kPa. Before starting the experiments, a leakage test using fluorescent dust was performed to ensure that no significant leaks on the plenum plate exist and that the filter bags have been installed correctly.

2.2. Aerosol measurement technology

A Promo® 2000 aerosol spectrometer in combination with a welas® 2100 sensor from the manufacturer Palas® serves as the reference instrument, due to its high maximum concentration and accurate size categorization (https://www.palas.de/prod). As state of the art aerosol measurement technology, the Promo® 2000 corrects for coincidence and border zone errors. Particles that pass the measurement volume are assigned to a certain optical particle size dependent on intensity of the light that is scattered by particles. Based on the measured particle number and particle size, PM_x concentrations are subsequently calculated assuming spherical shape, a given particle density and index of refraction of the particle. The Palas® reference has been deployed both for the emission measurement of the clean gas via the extraction of a sample flow with an isokinetic probe and to investigate the local emission of an individual filter bag after regeneration to compare to PM measurements of distributed low-cost sensors.

To simultaneously investigate the local emission behavior of all filter bags of the pilot plant scale baghouse, nine low-cost PM sensors were spatially deployed. From a variety of commercially available sensors, the sensor OPC-N3 from the manufacturer Alphasense has been selected for the investigation (http://www.alphasense.com). In a previous publication, the low-cost PM-sensor SPS30 from the manufacturer Sensirion has been investigated regarding its performance for the characterization of the emission behavior of surface filters in a test rig according to ISO11057 (Bächler et al., 2019a). The Alphasense sensor showed similar results to the Sensirion sensor regarding the identification of different emission levels (Bächler et al., 2019b). Yet, the advantage of the Alphasense sensor compared over other low-cost PM-sensors is the improved size categorization of detected particles. In addition to PM_x-weighted mass concentrations, the sensor classifies particle counts in one of 24 size intervals across its measurement range. Additionally, the maximum concentration of the sensor is comparatively high at a specified mass concentration of 2000 $\mu g/m^3$. A maximum number concentration is not stated; however, a coincidence probability of 0.84% can be expected at a particle number concentration of 10^3 $\#/cm^3$ according to the manufacturer (https://www.palas.de/prod).

The low-cost sensor allows for the consideration of aerosol properties through a coefficient called “bin-weighting index”. In its default setting, the bin weighting index is set at 1.65 (−) corresponding to a particle density of 1650 kg/m^3. A higher bin-weighting index thus causes a higher particle mass concentration due to an increased particle mass from the individual counting event (Crilley et al., 2020). The index of refraction of the dust, applied by the sensor, is 1.5 (−). As only the bin-weighting can be changed, only the particle density of the aerosol can be considered in the configuration of the Alphasense sensor.

Table 1 summarizes several key specifications of the two optical particle counters applied. The selected measurement range for the Palas® system was 0.2–10 μm to be close to the most penetrating particle size of surface filters and to obtain the most accurate $PM_{2.5}$ mass concentration (Binnig et al., 2009; Kurtz et al., 2017). The Alphasense sensor has by default a wider measurement range, due to its focus on immission measurement and the requirement to detect larger particles present in outdoor aerosols (e.g. pollen) (https://www.palas.de/prod). A low response time is crucial for emission measurement including a clear detection of the emission peak. The sensors have not been calibrated against each other or against the reference particle counter.

In the result section, the main value for characterization of the emission will be $PM_{2.5}$, as it has high relevance regarding human health and international immission law (German National Academy o, 2019). Furthermore, the $PM_{2.5}$ mass concentration is not as easily influenced by singular bigger particles compared to PM_{10}.

2.3. Test dust

The employed test dust was PURAL® SB from the manufacturer Sasol. It has a solid density of 2800 kg/m^3, a mass median diameter $x_{50,3}$ of 45 μm and an index of refraction of 1.64 (−) according to the manufacturer. The dust is non agglomerating and has good

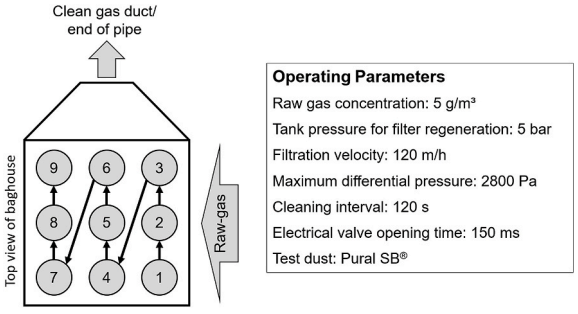

Fig. 3. Bag by bag cleaning rhythm and summary of operating parameters.

Table 1
List of several key sensor specifications (https://www.palas.de/prod; http://www.alphasense.com).

Device	OPC-N3	Promo® 2000 with welas® 2100
Manufacturer	**Alphasense**	**Palas®**
Measurements	Mass based concentration PM_1, $PM_{2.5}$, PM_{10} Count rate and size resolved particle counts	Mass and number based total concentration and size distributions with size resolved PM conversion
Detectable size range	0.35–40 µm	0.2–10 µm; 0.3–17 µm; 0.6–40 µm (user selectable)
Size categorization	24 bins	64 bins per decade
Maximum concentration	Mass based: 2000 µg/m^3 0.84% coincidence probability at 1000 #/cm^3	$5 \cdot 10^5$ #/cm^3
Approximate cost (including required cables & connectors)	400 €	>30.000 €
Length x Width x Height	75 mm × 45 mm x 63.5 mm	245 mm × 100 mm x 80 mm (welas® sensor only)
Response time	≈ 1 s	≈ 1 s
Configuration	$\rho_{particle} = 2800$ kg/m^3 $n_{aerosol} = 1.5$ (−) Spherical particles	$\rho_{particle} = 2800$ kg/m^3 $n_{aerosol} = 1.59$ (−) Spherical particles

dispersion properties, therefore the emission of the test dust in filter tests is higher compared to agglomerating dusts (Kurtz et al., 2017). The density of the test dust has been considered in the configuration of both, the low-cost sensors and the Palas® reference.

2.4. Filter media

The selected filter medium for the investigation is a polyphenylene sulfide medium with an ePTFE membrane layer laminated on the upstream side (area weight: 500 g m^{-2}; air permeability (200 Pa): 30 l dm^{-2} min^{-1}). This medium was also investigated in a previous publication and showed a lower emission compared to two filter media without a membrane (Bächler et al., 2019a). The filter medium was not aged significantly, however due to the membrane layer the storage of particles inside the medium is relatively low, so that filter aging has a reduced effect. A main source of emissions in baghouses are the seams of the filter medium (Kurtz et al., 2017). To provide a low emission level and defined conditions for the first evaluation of spatial emission measurement, the seams of the employed filter medium have been sealed with sealing compound. Fig. 4 shows SEM images of the filter medium before and after sealing the seams. The membrane layer can be clearly distinguished from the area around the seams, where regular fibers are visible.

3. Results and discussion

3.1. Reference measurement of emissions from individual filter bags using a Palas® Promo® 2000 aerosol spectrometer with welas® 2100 sensor

As a first step, measurements employing the Palas® reference system have been performed at each individual filter bag in order to evaluate the performance of the low-cost sensors afterwards. The data for each filter bag had to be taken from an individual experiment, as parallel deployment of multiple welas® 2100 sensors is not possible from an economic point of view, due to the comparatively high cost of the measurement instrument compared to low-cost PM-sensors. The whole Palas® system was located outside of

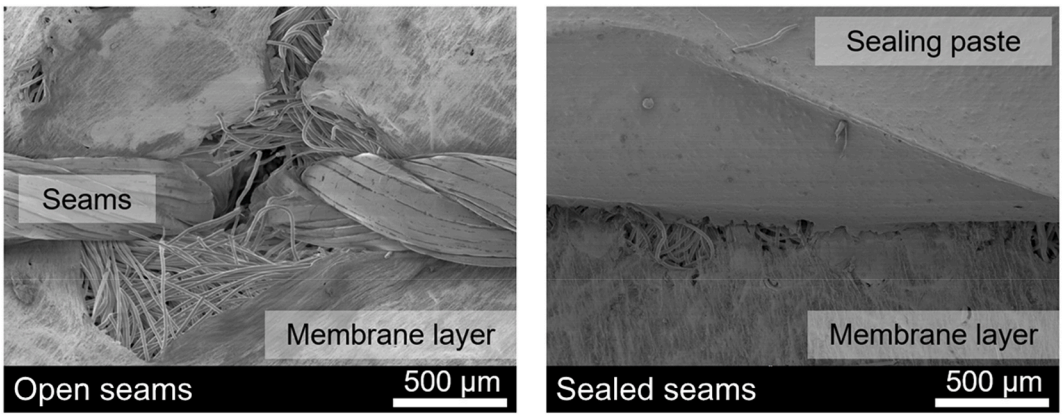

Fig. 4. SEM images of the membrane filter medium with open (left) and with sealed (right) seams.

the filter house, while the inlet tube for the welas® 2100 sensor was connected to the interior of the clean gas side of the baghouse. A sampling hose was then led from the inlet tube to the respective filter bag to measure the local PM emission similarly to the deployment of the low-cost sensor (see appendix for detailed figure of setup).

The time dependent PM-series of a complete filtration cycle (consisting of a time controlled regeneration series of all of the nine filter bags individually) is shown for the central filter bag (bag 5) in Fig. 5. The differential pressure curve serves as an indication for the cleaning pulses for a single bag occurring every 120 s. After each jet pulse, the differential pressure decreases rapidly due to the detachment of the filter cake.

The results show a single distinct $PM_{2.5}$ emission peak with high intensity during each complete filtration cycle (one filter regeneration of each bag). This emission peak can be allocated to the jet-pulse cleaning of the corresponding filter bag. The dust cake that is formed on the surface of the filter medium during operation has a high separation efficiency. Cake removal via jet pulse enables particle penetration through the filter medium at the respective measurement position, what causes the characteristic PM emission peak in surface filtration (Binnig et al., 2009). Almost no continuous emission flux between the respective peaks is detected mainly due to the sealing of the seams of the filter bag (Kurtz et al., 2017). Hence, the emission behavior is similar to the ideal emission behavior typical for filter coupon test rigs (Bächler et al., 2019a). The measurement is slightly influenced by the consecutive regeneration of the next filter bag, however the intensity of this peak is much lower compared to the actual cleaning. Other runs at different filter bags show qualitatively similar results, where the emission peaks with the highest intensity can be clearly designated to the regeneration of the corresponding filter bag and regenerations of the adjacent filter bags are detected with lower intensity, if at all.

This low emission level should create unproblematic conditions regarding sensor lifetime, as during the filtration phase, almost no contamination of the sensor optics can occur. More realistic testing conditions at a higher emission level, where filter bags with open seams are employed might be a challenge for the lifetime of low-cost PM-sensors.

For better assessment of sensor accuracy during the cleaning event, the particle number concentration detected by the Palas® reference during individual measurements at each single filter bag is shown in Fig. 6.

Note that a direct comparison between each measurement is not possible, as the reference could only be employed at a single bag, nonetheless the data gives an overview of the approximate number concentration after cleaning. As the number concentration right after cleaning often exceeds the concentration limit of 1000 #/cm^3 of the Alphasense sensor, a coincidence free measurement with the low-cost sensor at all times is unlikely.

3.2. Results of simultaneous local emission measurement at individual filter bags

For the simultaneous measurement of the local $PM_{2.5}$ concentration on the clean gas side of the baghouse, one Alphasense sensor has been installed at each of the nine filter bags according to Fig. 2. The Palas® reference has been set up for measurement of the global PM emission downstream on the clean gas side (Fig. 1).

Fig. 7 shows the time resolved local $PM_{2.5}$ concentration measured simultaneously by the low-cost sensors at each filter bag compared to the global end of pipe emission detected on the clean gas side by the Palas® reference.

The detected PM emission contribution of the individual filter bag is qualitatively similar to the reference measurement discussed in the previous chapter (Fig. 6). Every low-cost sensor detects a clearly assignable emission peak after the regeneration of the corresponding filter bag. Local differences between the individual filter bags exist. When comparing the $PM_{2.5}$ concentrations of all low-cost sensors with the reference measurement at the end of the pipe, the emission peaks detected by the low-cost sensors at each individual filter bag correspond predominantly to an emission peak detected by the Palas® reference further down the clean gas duct. The global emission consists qualitatively of the overlay of the individual PM measurements of the low-cost sensors.

Differences regarding peak intensity and the overall detected particulate matter concentration between the two measurement devices are to be expected (e.g. different detectable size ranges) (Asbach et al., 2018; Bächler et al., 2019b). Additionally, the concentration detected at the filter bag as an emission hotspot can deviate from the concentration detected in the downflow pipe due to several reasons. Firstly, dilution effects due to a higher cross section of the downflow pipe on the clean gas side could lower the detected concentration compared to the emission hotspot. Though the majority of the total volume flow passes the newly regenerated bag, the emitted particle mass gets further diluted by the volume flow through the other eight filter bags, lowering the concentration of

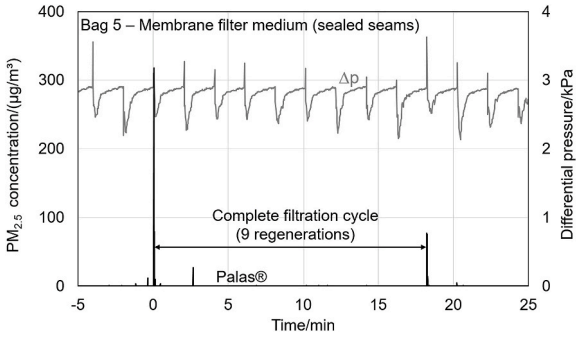

Fig. 5. Time dependent $PM_{2.5}$ concentration detected by the Palas® reference at the central filter bag (bag 5) and differential pressure curve.

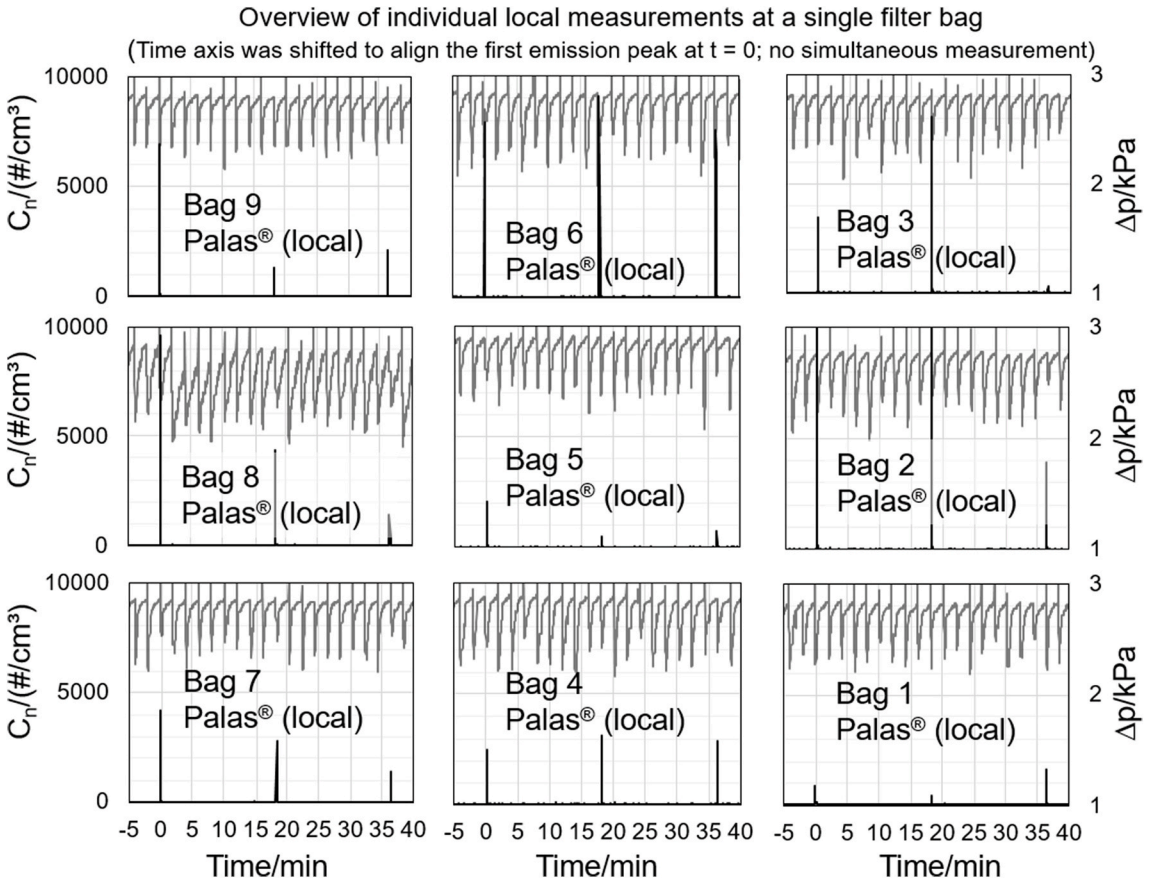

Fig. 6. Overview of time dependent particle number concentrations detected by the Palas® reference at each filter bag (no simultaneous measurement) and differential pressure curve.

the emitted particle mass. Secondly, spatial inhomogeneity of the particle concentration inside the filter bag could cause differences between the actual emitted particle mass that affects the global PM emission and the resident concentration that is detected at the sampling position of the sensor.

Finally, signal smoothing (unspecified for the low-cost sensor) and the response time regarding swift concentration variations in the case of a cleaning event affect the output signal peak height.

For further evaluation of the individual PM emission peaks, Fig. 8 displays a comparison between the peak detected locally at the recently cleaned filter bag with the emission peak detected at the end of the pipe by the Palas® reference.

Note that the overall emission level is low due to the high separation efficiency of the membrane filter medium and the sealed seams. Thus, the emission itself only occurs over a time period of several seconds, where the peak intensity is often defined by only one or two datapoints, making an in depth quantitative evaluation difficult. Additionally, the measuring conditions at the end of the pipe and the local measurement are different (e.g. different volume flow/dilution of emitted particle mass), so that for a better quantification of the PM emission, not the concentration but the emitted dust mass would have to be considered.

Furthermore, as these results describe the very first stages of filter life, fluctuations between individual cleaning events regarding peak intensity are to be expected. Coincidence errors caused by high particle number concentrations after jet-pulse cleaning could potentially affect the measurement result of the low-cost sensors, as was shown by the particle number concentrations detected by the Palas® reference in Fig. 6. Another factor that has to be considered regarding sensor accuracy is the flow through the sensor. The pressure pulse and the varying flow conditions on the clean gas side influence the sensor's sampling flow and could potentially affect the detected PM concentrations. To be able to create more defined measurement conditions, a sensor housing will be employed in future investigations to be able to draw a defined volume flow and improve sensor accuracy.

Summarizing, the low-cost sensors can qualitatively characterize the spatial PM emission behavior of baghouse filters under the applied defined conditions (sealed seams, low emission level). This demonstrates the potential for improved process monitoring by the application of distributed sensors. Deviations to the steady state PM emission behavior could be detected and alarm plant operators. The following chapter presents results regarding the identification of a local emission hotspot.

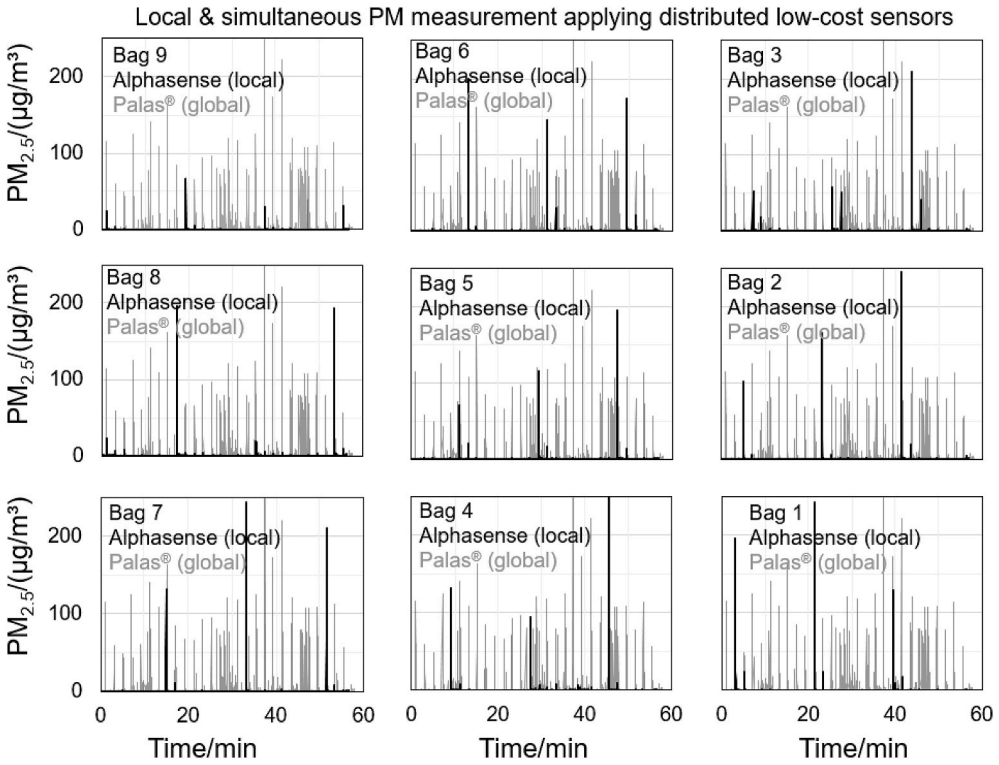

Fig. 7. Simultaneous $PM_{2.5}$ measurement employing nine low-cost sensors (one at each individual filter bag) and comparison with the detected global emission by the Palas® reference on the clean gas side. All bags made from membrane medium with sealed seams.

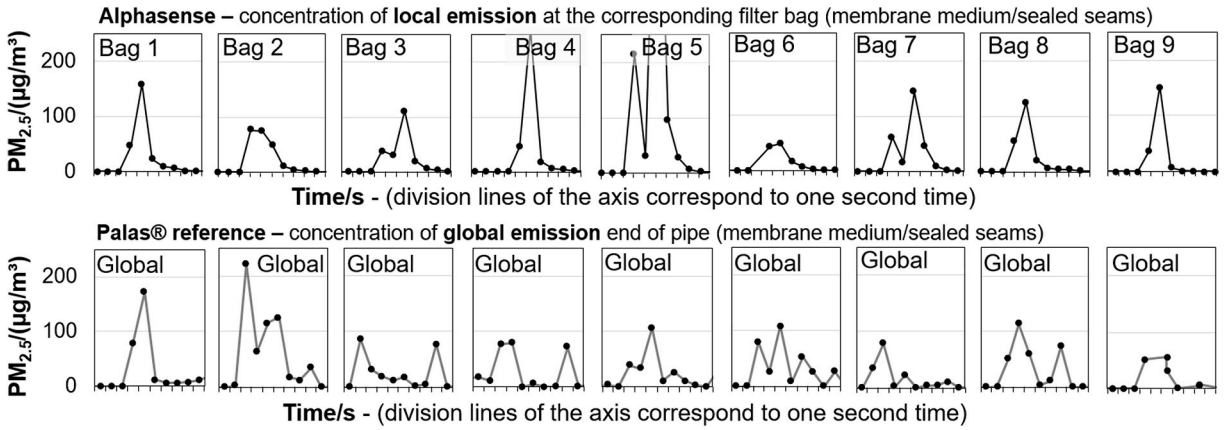

Fig. 8. PM Emission peak of recently cleaned filter bag detected by a locally deployed Alphasense sensor and the Palas® reference measuring the global emission (Time axis always represents the 10 s time period where the corresponding PM emission peak is detected).

3.3. Impact of a different filter media on local and global PM emission level

To investigate the contribution of locally increased emission levels, one of the bags made from the membrane medium with sealed seams has been exchanged by a filter bag made from a non membrane medium (area weight of 240 g m^{-2}; no membrane; air permeability at 200 Pa of 100 l dm^{-2} min^{-1}) and with open seams. The emission of the replacement filter bag is expected to be higher, as the seams contribute to the emission and the efficiency of the more open base felt is not boosted by a membrane layer. The filter medium has been evaluated in a filter test rig and showed a higher emission level compared to the membrane filter medium (Bächler et al., 2019a).

The time resolved $PM_{2.5}$ measurements are shown in Fig. 9. The regular filter bag has been installed at position nine for this experiment. The Palas® reference detects a strong increase in the continuous particle emission in the clean gas duct.

The difference in particle emissions from the two different types of filter bags can be clearly identified in the local $PM_{2.5}$ concentration measured by the low-cost sensors. While the sealed membrane medium only shows an emission peak directly after jet pulse cleaning of the corresponding filter bag, the particle emission of the exchanged bag is vastly different. Instead of clearly assignable emission peaks, a permanent particle emission flux is detected. This steady flux coming from bag number nine does not influence the measurements at adjacent filter bags, which still show an ideal emission behavior.

For the validation of the spatially resolved data, reference measurements employing the Palas® system have been performed at filter bag number nine and the adjacent bag number six in two consecutive test runs (Fig. 10).

The reference measurement qualitatively validates the spatially resolved data. While the PM emission of the membrane medium with sealed seams only consists of the peaks right after cleaning of bag 6, the PM emission of the non-membrane medium without sealed seams at bag nine has a permanent PM emission and emission peaks with high intensity after jet-pulse cleaning. The peak concentrations detected by the Palas® reference at these two bags are higher compared to the PM emission detected by the low-cost sensors, exceeding the maximum mass concentration specified in the datasheet of the low-cost sensor (Fig. 10) (http://www.alphasense.com). This is another indication, that the measurements of the low-cost sensors could potentially be affected by coincidence errors or signal smoothing, limiting their potential for quantitative information. The permanent emission is increasing over the course of each complete filtration cycle and decreases after the PM emission peak due to jet-pulse cleaning. The global emission presented in Fig. 9 does not show the same trend and does not change significantly over time. This could potentially be an indication that the seams are not clogged by the dust cake and serve as a constant PM emission source. A possible explanation for the rising continuous particle emission detected at filter bag number nine can be given by evaluation of the flow conditions inside the baghouse.

Several Schmidt® SS.20.250 flow sensors have been employed to determine the local flow-velocity at the outlet of each filter bag (see appendix for detailed figure of setup).

A qualitatively similar velocity profile was obtained at all nine measurement locations. Due to the limited space available on the clean gas side not all flow sensors could be installed exactly the same way, so that slight variations are to be expected. Fig. 11 shows the flow velocity for filter bag number nine measured with the flow sensor and the PM emission of the non-membrane medium without membrane and sealed seams.

Directly after regeneration, the velocity through the filter bag increases, as the flow resistance of the filter bag is lowered due to the removal of the dust cake. With increasing thickness of the dust cake during operation, the volume flow through the filter bag, respectively the flow velocity, decreases at the newly regenerated bag. The regeneration of consecutive filter bags abruptly decreases the flow of the other bags, as a higher fraction of the total flow passes the newly regenerated bag. Over the course of the cake formation of the regenerated bag, the flow through all other bags increases slightly. The results correspond to the findings of Simon et al., who investigated the flow through individual filter bags. They already demonstrated that the flow through recently cleaned bags is higher

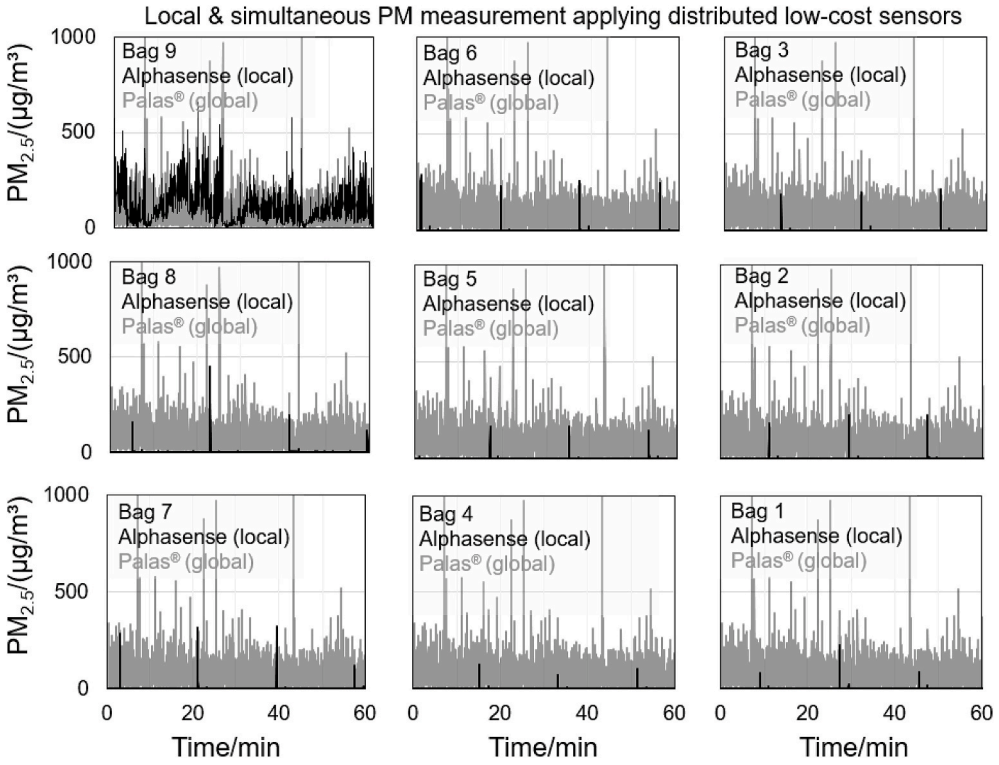

Fig. 9. Simultaneous $PM_{2.5}$ measurement employing nine low-cost sensors (one at each individual filter bag) and comparison with the detected global emission by the Palas® reference on the clean gas side. Bags 1–8: membrane medium. Bag 9: non-membrane medium with open seams.

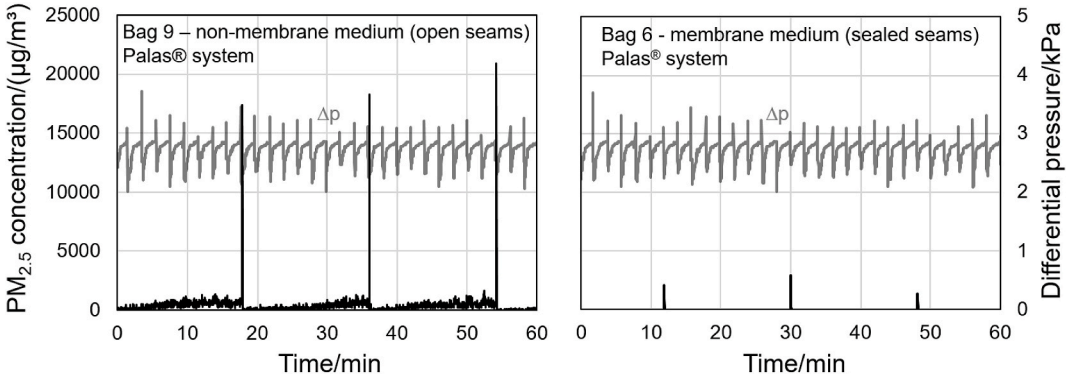

Fig. 10. Reference measurement employing the Palas® system at bag nine with the non-membrane medium and bag 6 with the filter bag made from a membrane medium with sealed seams.

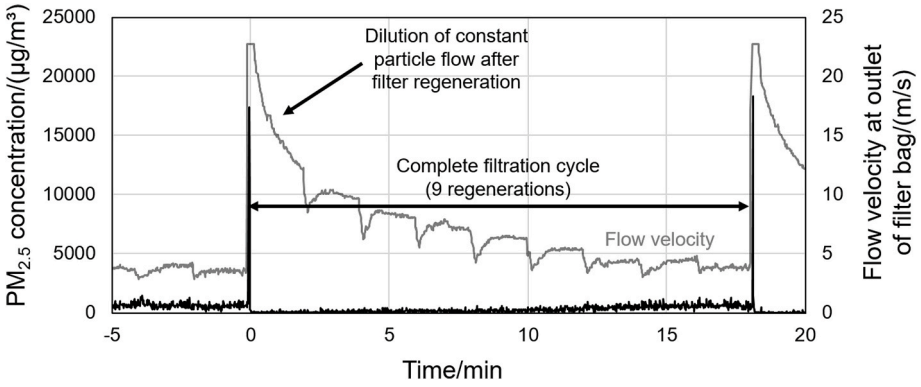

Fig. 11. Reference measurement employing the Palas® system at bag nine with the non-membrane medium and flow-velocity measured with a Schmidt® SS 20.250 flow sensor.

compared to clogged bags with an established dust cake (Simon et al., 2010). The absolute velocities right after jet-pulse cleaning are likely to be influenced by the pressure pulse and the sensor reaches its maximum value.

Since the passage of particles through the seams is likely not significantly affected by the cake formation on the filter medium, as shown by the permanent PM emission in Fig. 8, dilution effects can explain the rising particle concentration detected by the Palas® reference. Assuming a constant particle flow through the seams of the filter bag, a high total flow through the bag after jet pulse cleaning dilutes the local particle concentration at the outlet of the filter bag. With increasing cake thickness the flow through the medium decreases, thus the local concentration of the continuous PM emission is higher by comparison.

In addition to different particle concentration levels, the local particle size distribution is also affected by the exchanged filter bag (Fig. 12). The size distribution for the low-cost sensors has been calculated from the sampling flow rate, time interval and the number of particles for the corresponding size interval.

The number concentration varies and is about an order of magnitude lower for bag number six, where bigger particles with a diameter higher than 1 µm are only rarely detected (single counting events) due to the membrane and sealing of the seams. The highest number of particles is detected close to the most penetrating particle size of surface filters at about 0.3 µm. The respective size distributions of reference and low-cost sensor deviate, which can be attributed to sensor limitations (e.g. sampling conditions, coincidence effects, etc.). Due to the limited use of the detected particle size distributions, cheaper PM sensors with limited sizing might also be suitable for simple PM monitoring (Bächler et al., 2019a). Improved sampling conditions might improve the potential for size resolved information and will be investigated further.

The results demonstrate potential applications for the implementation of spatially resolved particle emission level measurements. The emission hotspot can be easily identified by the $PM_{2.5}$ concentration measured by one of the low-cost sensors. This could potentially help operators detect damaged filter media or leaks. It remains to be seen how well the qualitative information of the low-cost PM-sensors follows similar trends in comparison to the reference measurements for different process conditions and emission levels.

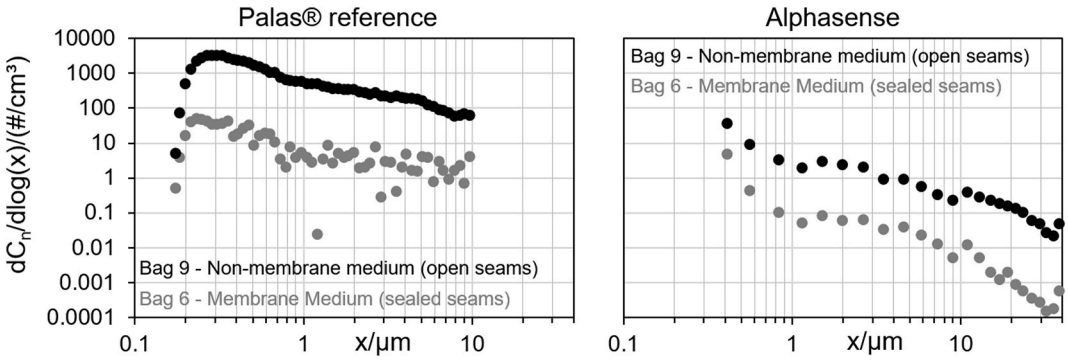

Fig. 12. Particle size distributions detected by the Palas® system and the low cost sensor at bag nine with the non-membrane medium and bag 6 with the filter bag made from a membrane medium with sealed seams.

4. Summary and outlook

The local PM emission contributions of individual bags to the overall PM emission of a pilot plant scale baghouse filter was evaluated under defined conditions by equipping each filter bag with a low-cost PM-sensor. Contrary to typical emission measurement, where only a global emission in the clean gas duct is evaluated, the novel approach of utilizing distributed sensors in baghouse filters allows for the detection of spatially resolved PM-emission data with high temporal resolution.

The baghouse filter was equipped with nine filter bags that were made from an e-PTFE laminated needle felt and all seams were sealed to provide a low emission level on the clean gas side. The filter regeneration was time-controlled with intervals set at 120 s to enable a sufficient cake formation after each cleaning pulse to lower potential interferences and dispersion effects. The selected low-cost PM-sensor for this investigation was the sensor OPC-N3 from the manufacturer Alphasense.

A reference measurement employing a Palas® Promo® 2000 in combination with a welas® 2100 sensor showed clear emission peaks after the regeneration of each filter bag when measuring in the collector line of the clean gas, and a distinct single peak associated with the respective regeneration pulse when measuring at the exit of a single bag. A permanent emission flux typical for baghouses at real conditions was prevented due to sealing of the seams of the filter bag, and regenerations of adjacent bags were either not detected or had small peak heights compared to peaks caused by the regeneration of the corresponding bag.

One low-cost sensor was mounted above the outlet of the venturi nozzle of each filter bag, thus enabling the simultaneous measurement of the spatial particulate matter concentration during operation of the baghouse filter. The detected PM-emission was qualitatively similar to results of the reference measurement (distinct PM emission peaks after jet-pulse cleaning).

Differences in the local emission levels were provided by exchanging one of the filter bags with membrane layer and sealed seams with a filter bag without membrane and with open seams. A constant emission flux and a higher emission level with less pronounced emission peaks was detected at the measurement position of the exchanged bag. The detected particle emission level of the original bags was not affected by the exchanged bag, and pronounced emission peaks, which can be assigned to the regeneration of the respective filter bag, were still detected. This demonstrates the potential for the detection of damaged filter media or filter media with different properties in real applications, provided the emission level on the clean gas side is low enough.

In further investigations, the applicability of the low-cost sensors under different conditions (e.g. different filter media, tank pressures, cleaning intervals, raw-gas concentrations) will be tested. The applied process parameters in this study aimed to generate a low emission level with clearly assignable events (e.g. filter regenerations). Additionally, the local particle size distribution of the emission will be evaluated to potentially gain further information on filter aging, leaks and damaged filter media from the size distribution.

Further challenges regarding the industrial application of low-cost PM-sensors include the lifetime and functionality of these sensors under real process conditions over a larger period of time. Exposure to increased temperatures, corrosive gases, or higher dust concentrations that might cause soiling of sensor optics are limitations to the current state of technology of low-cost PM-sensors. This study showed first results of spatial and simultaneous PM emission monitoring in a baghouse filter and the potential to characterize the local emission behavior at a low emission level applying highly efficient membrane filter media with sealed seams as well as to show potential for further applications regarding identification of different emission levels on the clean gas side.

The goal of this research is to transfer the conclusions from spatially resolved measurements to optimization strategies to improve the operating behavior of baghouse filters regarding energy demand and their particle emission, as well as employing aspects of digitalization like predictive maintenance and online process monitoring.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

We acknowledge the financial support and close cooperation of Filterkonsortium at KIT. Filterkonsortium at KIT unites leading companies in the fields of fiber and media production, assembly, plant engineering and measurement technology with the research activities of the working group Gas-Particle-Systems of the Institute of Mechanical Process Engineering and Mechanics (MVM). The members of Filterkonsortium at KIT are as follows: BWF Tec GmbH & Co. KG, ESTA Apparatebau GmbH & Co. KG, Evonik Fibres GmbH, Freudenberg Filtration Technologies SE & Co. KG, Junker-Filter GmbH, KAYSER FILTERTECH GmbH, MANN + HUMMEL GmbH, PALAS GmbH, Sick AG.

We acknowledge the collaboration of Grigor Vrhovac for his help in conducting the experiments.

Appendix A. Supplementary Figures

Supplementary figures to this article can be found online at https://doi.org/10.1016/j.jaerosci.2020.105644.

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