



Effect of absolute pressure on the fractional separation efficiency of surface filters for particle removal from gases

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ABSTRACT

Surface filters are widely used in industrial gas cleaning to separate particles from dust laden gas flows. During vacuum drying, filtration is performed at reduced absolute pressure, yet systematic data on the effect of absolute pressure on separation performance remain limited. This study investigates the influence of absolute pressure on the separation behavior of two surface filter media operated at $p_{\text{abs}} = 900$, 100, and 25 hPa. A polydisperse test aerosol was applied, and total concentrations in the raw gas and clean gas as well as size-resolved number concentrations ($x \geq 0.3 \mu\text{m}$) were measured continuously. The total separation efficiency E_m was evaluated as a function of the mass loading W_{dep} . The emitted mass per filtration cycle per area was quantified from downstream measurements. In addition, the fractional separation efficiency $T(x)$ was determined at defined loading states. The results show that, for both media, E_m increases with W_{dep} and improves systematically with decreasing absolute pressure. The fractional separation efficiency $T(x)$ likewise increases across all measured size classes as p_{abs} is reduced. These findings show that the reduced absolute pressure can substantially enhance separation performance in vacuum drying and related low pressure applications compared to filter operation at near-ambient conditions ($p_{\text{abs}} = 900 \text{ hPa}$).

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1. Introduction

In many industrial processes, particulate matter is present in gas streams and must be separated before the gas can be discharged, recycled, or conveyed to downstream unit operations [1–3]. Depending on the process objective, filtration is required either to protect downstream equipment such as blowers, condensers, and vacuum pumps, or to retain and recover the particulate phase as the valuable product. Both aspects are particularly relevant in vacuum drying. During drying, fine particulate material can be entrained by the vapor flow and emitted from the product bed. Filtration is therefore required to prevent product losses, to avoid contamination of downstream components, and to ensure stable dryer operation [4–7]. A characteristic feature of this application is that filtration takes place in integrated filters inside the dryer at reduced process pressure rather than at ambient conditions [8,9].

Operating at reduced absolute pressure introduces fundamentally different boundary conditions for filtration. As the absolute pressure decreases, the molecular mean free path λ increases, so that rarefaction effects become more relevant and the continuum assumption may be questioned, depending on the characteristic length scales of the system such as particle size, fiber diameter, or pore size [10,11]. Rarefaction is commonly quantified by the Knudsen number

$$\text{Kn} = \frac{\lambda}{a}, \quad (1)$$

where a denotes the characteristic length scale. In the context of filtration, a is typically related to a geometric scale of the collector or the porous structure, for example a representative fiber diameter or a pore diameter. In addition, the gas density decreases with pressure, which reduces the Reynolds number and changes the flow regime around collectors and within porous structures. Altogether, reduced absolute pressure can alter particle transport and deposition mechanisms and therefore the separation performance of filters.

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A key parameter for the design and assessment of filters is the separation efficiency, both as an overall value and in a particle-size-resolved form [12,13]. A commonly used definition is the mass-based overall separation efficiency

$$E_m = \frac{C_{m,Raw} - C_{m,Clean}}{C_{m,Raw}}, \quad (2)$$

where $C_{m,Raw}$ is the mass concentration upstream on the raw gas side and $C_{m,Clean}$ is the mass concentration downstream on the clean gas side of the filter. Analogously, the fractional separation efficiency for a particle size x can be written based on mass concentrations as

$$T(x) = \frac{C_{m,Raw}(x) - C_{m,Clean}(x)}{C_{m,Raw}(x)}. \quad (3)$$

For surface filters, the separation efficiency is not constant in time. Starting from a clean medium, penetration can be comparatively high until a dust layer develops and cake filtration begins to dominate. In practical operation, surface filters are regenerated periodically, for example by pulse-jet cleaning, which removes the cake and exposes the filter medium again. Immediately after cake detachment, penetration increases and then decreases again as a new cake builds up. Consequently, a substantial fraction of emitted mass is typically associated with the initial filtration phase after installing a new medium or directly after effective regeneration [12]. The present work focuses on this initial, cake free to early cake formation phase and does not address regeneration induced emissions.

Only few studies have investigated the influence of reduced absolute pressure on filtration performance, and the available literature predominantly focuses on depth filters, meaning highly porous fibrous media with low packing density [14–18]. These works typically consider comparatively high face velocities, negligible mass loading, deposition in the filter medium structure, and aerosols in the submicrometer range, often generated from nebulized solutions such as NaCl or sucrose followed by drying, with pressures down to about 24 hPa. Across these publications, consistent trends are reported. Penetration decreases, meaning the efficiency increases, as the absolute pressure is reduced. In addition, the most penetrating particle size shifts toward larger particle sizes. The improvement is observed across the investigated size range, indicating that both diffusion related and inertia related collection can be enhanced at reduced pressure.

These trends can be rationalized by considering how pressure affects transport parameters through slip and rarefaction effects. In the diffusion dominated regime, the Brownian diffusion coefficient of a spherical particle is

$$D = \frac{k_B T}{3\pi\eta x} C_c, \quad (4)$$

where k_B is the Boltzmann constant, T the gas temperature, η the dynamic viscosity of the gas, x the particle size, and C_c the Slip correction factor.

In the inertia dominated regime, the absolute pressure effect can be expressed by the inertial parameter ψ as used in this work. With a characteristic collector length d_F , ψ is identical to the Stokes number $Stk = \tau_p v_F / d_F$ that is frequently used in filtration theory. Thus, $\psi \equiv Stk$ under the present definition

$$\psi = \frac{C_c \rho_p v_F x^2}{18\eta d_F}, \quad (5)$$

where ρ_p is the particle material density, v_F the filter face velocity, and d_F a characteristic collector length scale such as a representative fiber diameter or a structure related scale.

A widely used correlation for the Slip correction factor is [19]

$$C_c = 1 + \frac{2\lambda}{x} \left[1.23 + 0.41 \exp \left(-0.44 \frac{x}{\lambda} \right) \right], \quad \text{for } 0.1 < \frac{2\lambda}{x} < 134, \quad (6)$$

where λ is the molecular mean free path and x is the particle size. The ratio $2\lambda/x$ corresponds to a particle scale Knudsen number and quantifies rarefaction in the drag law. Since λ increases as the absolute pressure decreases, C_c increases at reduced pressure. As a consequence, both the diffusion coefficient D in Eq. 4 and the inertial parameter ψ in Eq. 5 increase for otherwise identical operating conditions, providing a mechanistic basis for enhanced diffusion related and inertia related deposition at reduced p_{abs} . In addition to the parameter level effect through C_c , reduced pressure can also modify the local flow field around collectors through aerodynamic slip, which may further affect interception and inertia related deposition [20,21]. Pich [22] and several later studies employ single fiber theory and Knudsen number dependent correlations to analyze pressure effects in depth filtration [23,16,18]. However, these derivations are strictly based on isolated unloaded collectors and are therefore most directly applicable to the initial depositions phase of highly porous depth filters.

In contrast, surface filters exhibit substantially different morphologies and deposition patterns. In depth filters, particles deposit within the porous structure, which gradually changes the internal flow distribution and can lead to clogging as loading progresses [24]. Depending on the operating conditions and the deposited material, the deposition pattern may eventually shift toward more pronounced upstream deposition and the onset of a surface layer in late filtration stages. In surface filters, on the other hand, deposition is intended to occur predominantly at or near the upstream surface, and cake filtration becomes dominant comparatively early. During the initial, cake free phase, separation is governed by the structure of the filter medium itself, while during cake filtration the properties of the deposited layer control both pressure drop and penetration. Because of these fundamental differences, pressure dependent separation characteristics of surface filters cannot be inferred quantitatively from depth filter literature alone and require systematic experimental validation.

To the authors' knowledge, systematic investigations of the separation efficiency of surface filters as a function of absolute pressure are still largely missing. In the present work, two surface filter media with non-negligible penetration at ambient conditions are investigated. To represent the critical initial phase of a filtration cycle, only new or thoroughly cleaned media are used, effectively simulating the first filtration cycle after installation. All experiments are conducted at a constant filter face velocity of $v_F = 5.5 \text{ cm s}^{-1}$. Particle concentrations upstream and downstream are measured using optical particle counters, providing size resolved information down to $x = 0.3 \text{ }\mu\text{m}$. Based on these measurements, total mass concentrations are determined from size and number-based concentrations each second and, the time resolved mass-based total separation efficiency is evaluated. A cycle-integrated emitted mass per filter area is used as a compact performance metric, and the fractional separation efficiency $T(x)$ is determined as a function of absolute pressure for a series of loading states. The pressure levels were selected to cover a wide range of absolute pressures relevant to vacuum drying applications. The pressure level of $p_{abs} = 900 \text{ hPa}$ serves as a near-ambient reference, as higher absolute pressures cannot be achieved with the present experimental setup (cf. Section 2.4.2). The lower limit of $p_{abs} = 25 \text{ hPa}$ was chosen based on previous work [25], which showed that at substantially lower absolute pressures, a non-negligible shift in raw gas concentration conditions between the measurement position and the filter medium occurs. Overall, the objective of this study is to systematically quantify the filtration behavior of surface filters within the first filtration cycle at reduced

absolute pressure and thereby provide a basis for pressure adapted filter design in vacuum drying applications.

2. Materials and methods

2.1. Experimental set-up

A schematic overview of the experimental set-up is shown in Fig. 1. The set-up comprises a low absolute pressure filtration system, an aerosol generation and neutralization unit, and an aerosol measurement section. In Fig. 1, these subsystems are highlighted in red, green, and blue, respectively. The individual components and operating principles are described in the following.

2.1.1. Low absolute pressure filtration system

The aerosol volumetric flow rate supplied to the filtration system, $\dot{V}_{\text{Aerosol}}$, enters the raw gas side of the set-up via the inlet section on the right side of the filtration system. Depending on the targeted operating conditions, the inlet section consists of either an interchangeable inlet nozzle (coarse flow pre-adjustment) followed by a pinch valve (fine control), or the pinch valve alone for operation at ambient pressure. For reduced absolute pressure operation, two inlet nozzles are available: a nozzle with diameter $d_{\text{IN},1} = 2.94 \text{ mm}$ for operating volumetric flow rates up to 46 Lmin^{-1} , and a nozzle with $d_{\text{IN},2} = 1.36 \text{ mm}$ for low flow operation below 10 Lmin^{-1} . The pinch valve (KVT GmbH, DN 6) provides fine adjustment of $\dot{V}_{\text{Aerosol}}$ controlled via the measured outlet flow rate.

Downstream of the inlet section, the aerosol passes an aerosol distribution section. This volume promotes flow homogenization and houses the raw gas sampling nozzle. The aerosol is then guided to the raw gas chamber through four hoses evenly distributed over the cross-section to obtain a spatially uniform inflow distribution on the upstream side of the filter sample.

The filter medium is installed 53 cm downstream of the distribution section. The effective filtration area is $A_F = 154 \text{ cm}^2$. On the clean gas side, a second sampling nozzle is installed for measuring the clean gas particle concentration. Downstream of this position, a HEPA filter is placed to protect the downstream components and to prevent particle release to the environment.

Absolute pressure control is implemented on the clean gas side by two valves in series: a gas control valve (EVR 116, Pfeiffer

Vacuum GmbH, ISO KF DN 16) for coarse adjustment and a butterfly valve (VAT Group AG, ISO KF DN 25) for fine pressure control. The flow through the entire system is driven by a downstream compressor. The volumetric flow rate is measured downstream of the pump at ambient conditions using thermal mass flow meters (MKS Instruments Deutschland GmbH). Two MFMs with full-scale ranges of 50 Lmin^{-1} and 2 Lmin^{-1} (specified at normal temperature and pressure, NTP) are used, each with a resolution of 0.1% of full scale. Together with the prevailing operating pressure and temperature on the raw gas side, these measurements are used to determine the volumetric flow rate at operating conditions and thus the filter face velocity v_F .

The raw gas temperature is measured using a Pt100 sensor. The raw gas absolute pressure is monitored with a Pirani vacuum transmitter (Thyracont Vacuum Instruments GmbH) covering $5 \times 10^{-5} \text{ hPa}$ to 2000 hPa . The specified accuracy is $< 2\%$ of reading for 200 hPa to 2000 hPa , $< 5\%$ of reading for 40 hPa to 200 hPa , and $< 10\%$ of reading for $2 \times 10^{-3} \text{ hPa}$ to 40 hPa . The differential pressure across the filter is recorded continuously using two differential pressure transmitters (IPD 40, ICS Schneider Messtechnik GmbH) with ranges 0 hPa to 50 hPa and 0 hPa to 200 hPa , respectively. Both signals are acquired with a temporal resolution of 1 s , the specified accuracy is $\leq \pm 0.2\%$ of full scale.

The facility enables largely independent adjustment of absolute pressure and volumetric flow rate (and thus v_F). In this study, $\dot{V}_{\text{Aerosol}}$ is set such that a constant face velocity of $v_F = 5.5 \text{ cm s}^{-1}$ is maintained at all investigated pressure levels. For operation close to ambient pressure it should be noted that, at the applied face velocity, a raw gas side pressure of 1013 hPa cannot be reached due to pressure losses across the inlet section and the pinch valve. Moreover, the achievable raw gas absolute pressure depends on the atmospheric pressure on the day of measurement. Averaging over measurements performed on different days yielded a mean raw gas side absolute pressure of approximately 900 hPa . Accordingly, $p_{\text{abs}} = 900 \text{ hPa}$ is used throughout this work to represent ambient absolute pressure.

2.1.2. Aerosol generation and neutralization

The test aerosol is generated using a rotating brush generator (RBG 1000, Palas GmbH). The generator is operated at a constant inlet pressure of 1.4 bar , corresponding to a volumetric flow rate of $\dot{V}_{\text{RBG}} = 53 \text{ Lmin}^{-1}$.

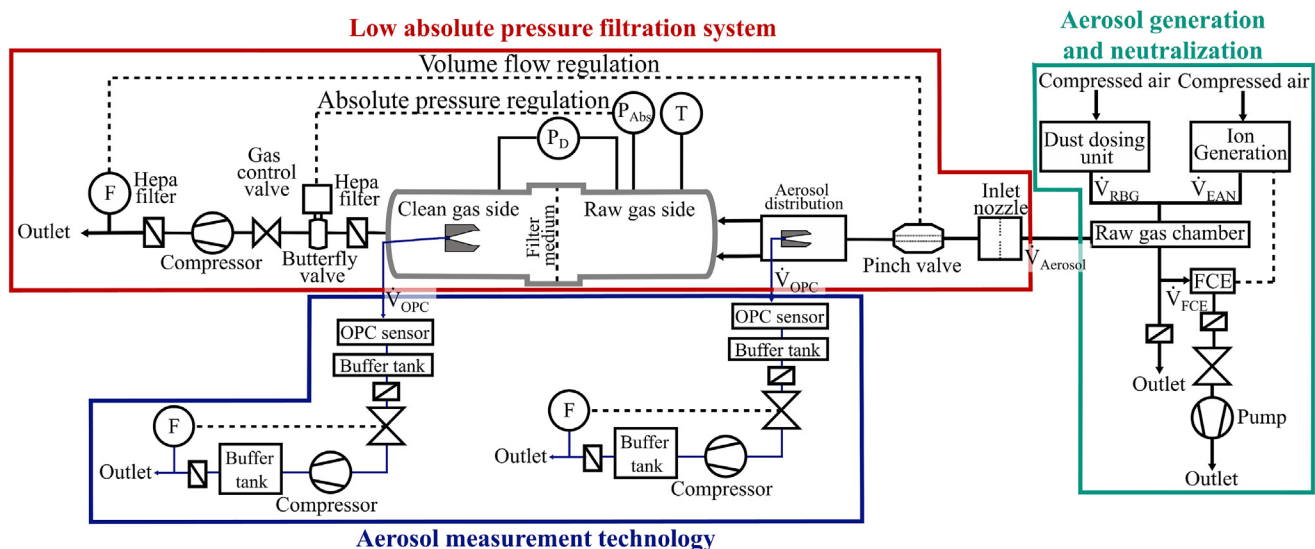


Fig. 1. Schematic overview of the experimental set-up.

Downstream of the aerosol generator, the aerosol is passed through a charge neutralizer (EAN 581, Topas GmbH). The neutralizer produces ions by corona discharge and introduces them into the aerosol stream by mixing ionized carrier gas with the aerosol flow inside the neutralizer head. The particle charge state after neutralization is quantified using a Faraday cup electrometer (FCE; ACD 331, Topas GmbH).

The aerosol produced by the rotating brush generator is predominantly positively charged. Therefore, only negative ions are required for neutralization. In the present configuration, only the negative ion neutralizer head is purged, while the second head is closed by a shut-off valve. This reduces aerosol dilution by the neutralizer carrier gas. The negative ion head is supplied with $\dot{V}_{\text{EAN}} = 45 \text{ Lmin}^{-1}$, yielding a total aerosol flow rate of $\dot{V}_{\text{Aerosol}} = 98 \text{ Lmin}^{-1}$.

For separation efficiency measurements, a near neutral aerosol is essential because particle charge can significantly affect deposition and penetration [26–28]. Fig. 2 summarizes the particle charge characterization as a function of aerosol generator feed rate.

The mean particle charge per particle, expressed in elementary charges per particle, was calculated from the current measured by the FCE and the particle number concentration according to

$$\bar{n}_p = \frac{I_{\text{FCE}}}{e C_{N,\text{raw}} \dot{V}_{\text{FCE}}} \quad (7)$$

where I_{FCE} is the electric current measured by the FCE, e is the elementary charge, $C_{N,\text{raw}}$ is the particle number concentration in the raw gas, and $\dot{V}_{\text{FCE}}$ is the sampling flow rate through the FCE.

While I_{FCE} is measured directly at the FCE, the particle number concentration $C_{N,\text{raw}}$ is obtained from the OPC at the raw gas measurement position. Hence, the two quantities used to calculate the mean particle charge are not measured at the same location. Possible particle losses between the OPC measurement position and the FCE may therefore affect the calculated value and can lead to an overestimation of the mean particle charge.

At near-ambient conditions, the raw gas particle number concentration could be measured reliably only for a generator feed rate of 5 mmh^{-1} , resulting in $C_{N,\text{raw}} \approx 4.4 \cdot 10^5 \text{ cm}^{-3}$. For feed rates of 10 mmh^{-1} and 20 mmh^{-1} , the concentration exceeded the detection limit of the OPC. The corresponding values were therefore estimated assuming a linear dependence of particle number

concentration on generator feed rate and using the rounded value at 5 mmh^{-1} as reference. This yields $C_{N,\text{raw}} \approx 8.8 \cdot 10^5 \text{ cm}^{-3}$ for 10 mmh^{-1} and $C_{N,\text{raw}} \approx 1.76 \cdot 10^6 \text{ cm}^{-3}$ for 20 mmh^{-1} . These estimates apply to the generator configuration with a solids container diameter of 28 mm and a constant upstream pressure of 1.4 bar at the RBG.

Based on these results, experiments were conducted only under generator settings that yield an approximately neutral mean particle charge, cf. Table 2. In particular, for feed rates up to 10 mmh^{-1} , the aerosol is close to neutral on average, whereas at 20 mmh^{-1} the charge can only be reduced to about half of its initial magnitude.

After neutralization, the aerosol enters a raw gas mixing chamber to increase the residence time for aerosol discharge processes and to stabilize the raw gas concentration. Depending on the selected absolute pressure and face velocity, only a fraction of the generated aerosol flow is directed to the filter chamber, while the remaining excess flow is discharged to the environment via exhaust filters. From this excess stream, a defined sampling flow of $\dot{V}_{\text{FCE}} = 3.33 \text{ Lmin}^{-1}$ is extracted upstream of the exhaust filter and directed to the FCE.

2.1.3. Aerosol measurement technology

Particle number concentrations and particle size distributions are measured simultaneously upstream and downstream of the filter medium using optical particle counters (OPCs). Two OPC systems (Promo[®] 3000 and Promo[®] 2000, Palas GmbH) are employed to enable synchronized raw gas and clean gas measurements. For the separation efficiency measurements reported here, Welas[®] 2070 sensors are installed on both sides of the filter medium (maximum concentration $1 \cdot 10^6 \text{ cm}^{-3}$). The size channels cover a range of $d_p = 0.2 \mu\text{m}$ to $10 \mu\text{m}$ (PSL-equivalent). Since the counting efficiency of the OPC decreases at very small particle sizes, only the particle size range from $0.3 \mu\text{m}$ to $10 \mu\text{m}$ is considered in the present study.

To obtain reproducible sampling conditions at all investigated pressures, dedicated sampling nozzles are implemented on the raw gas and clean gas side. The nozzle diameters are selected to account for the different local flow velocities. The raw gas nozzle has a diameter of 2.3 cm, while the clean gas nozzle has a diameter of 6 cm. The raw gas sampling position is located in the upstream

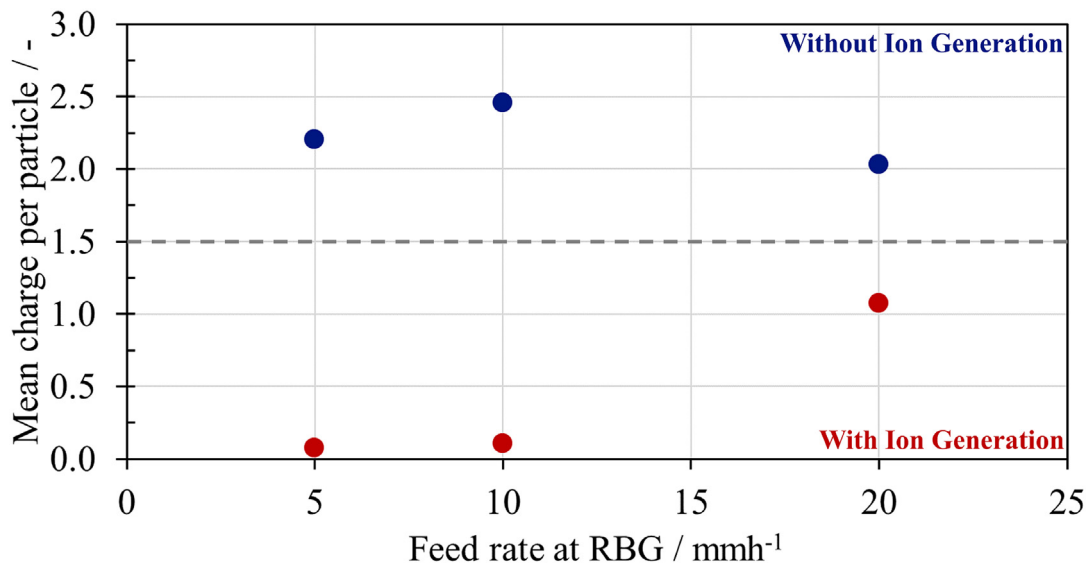


Fig. 2. Particle charge after neutralization as a function of generator feed rate.

aerosol distribution section (rather than inside the raw-gas chamber) to avoid obstructing the optical access window of the filter chamber.

Particle losses between the raw gas sampling position and the filter medium were quantified previously [29]. Based on these investigations, absolute-pressure-specific correction factors are applied to the measured raw gas concentration for the investigated absolute pressure levels.

At reduced absolute pressure, the internal pump of the Promo® 3000 and 2000 system cannot maintain the nominal sensor flow rate. Therefore, external pumps (Duo 10 M, Pfeiffer Vacuum GmbH) are used to ensure a constant sampling volumetric flow rate through each Welas® sensor of $\dot{V}_{\text{OPC}} = 5 \text{ L min}^{-1}$ at operating conditions. The sampling flow rate is measured downstream of each pump at near-ambient conditions using thermal mass flow meters. To keep $\dot{V}_{\text{OPC}}$ constant across the investigated pressure levels, each pump is throttled on the low pressure side using a gas control valve installed upstream of the pump.

In addition, buffer tanks are installed at two positions, one upstream of the pump between Welas sensor and gas control valve, and one downstream of the pump between pump outlet and exit filter/flow measurement. These buffer volumes dampen both, pump induced and control related fluctuations and thereby improve the stability of the sampling flow regulation.

Sensor cleaning procedures and calibration checks are described in detail in [29]. In brief, the calibration check is performed after cleaning at $p_{\text{abs}} \approx 900 \text{ hPa}$. The results showed that, for the operating conditions considered here, absolute pressure-specific re-calibration at each investigated pressure level is not required.

2.2. Filter medium

Two different surface filter media are investigated in this work. The first is a spunbond filter medium made of polyester and polyamide fibers with a hydroentangled microfilament surface (SB). The second is a woven metal fiber medium (WMF). Fig. 3 shows scanning electron microscope (SEM) images (top view) of the upstream side of both media. The SB medium is shown in Fig. 3 (a), and the WMF medium in Fig. 3 (b).

The key filter medium parameters are summarized in Table 1. The media were selected intentionally to exhibit measurable penetration during the initial filtration phase. This is essential for resolving absolute pressure dependent trends in separation performance.

For experiments with the SB medium, a new sample is used for each test to ensure reproducible initial conditions. Prior to the experiments, SB samples are pre-screened with respect to initial differential pressure and mass of clean filter medium. Only samples within $\pm 10\%$ of a defined reference value are included.

For the WMF medium, only a limited number of samples were available. Therefore, the samples are cleaned and reused between tests. Cleaning is performed by immersing the sample in distilled water in an ultrasonic bath for $2 \times 30 \text{ min}$. Afterwards, the sample is dried overnight in a drying oven. The SEM image shown in Fig. 3 (b) was taken from such a cleaned WMF sample. Only a few isolated residual particles are visible locally. Their amount is small, thus, contamination is assumed to have a negligible influence on the measured separation efficiency.

2.3. Test powder

Mikhart MU 08 (Provencale) is a polydisperse limestone powder and is used as test powder in this study. The volume-based median particle diameter determined offline by laser diffraction is $x_{50,3} = 1 \mu\text{m}$, and the relative span $\left(\frac{x_{90,3} - x_{10,3}}{x_{50,3}}\right)$ is 2.03. Mikhart MU 08 is a white, fine powder with a pronounced tendency to form agglomerates. Humidity is known to affect particle cohesivity and agglomeration behavior [31–33]. In this study, all experiments were conducted using dry compressed air with a relative humidity below 6%. Humidity-induced effects on particle properties are therefore considered negligible. Owing to its high fine particle fraction, it is considered representative of particulate materials relevant to vacuum drying applications. In such processes, fine particles are expected to be preferentially entrained by the vapor flow and may therefore govern emissions during the initial filtration phase.

The normalized number-based particle size distribution density $q_0(x)$ measured in the raw gas with the OPC is shown in Fig. 4 for the three investigated absolute pressure levels. The close agreement of the curves shows that the particle size distribution was nearly identical for all conducted measurements. In addition, only a very small number of particles with diameters above approximately $2 \mu\text{m}$ to $3 \mu\text{m}$ were detected in the raw gas.

2.4. Experimental procedure, parameters and data analysis

2.4.1. Investigated parameters

An overview of the operating conditions investigated in this study is given in Table 2. In all experiments, the filter face velocity

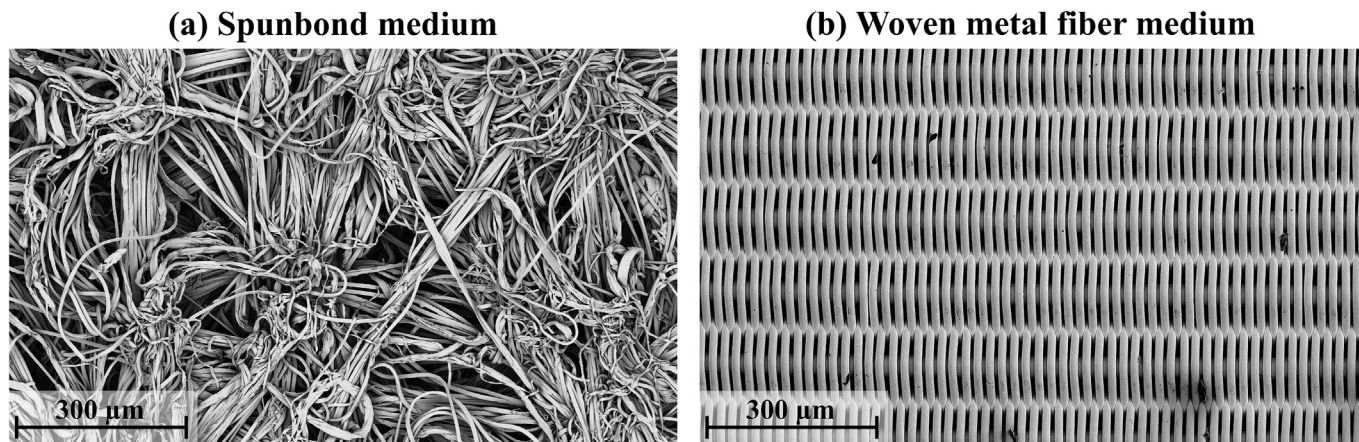
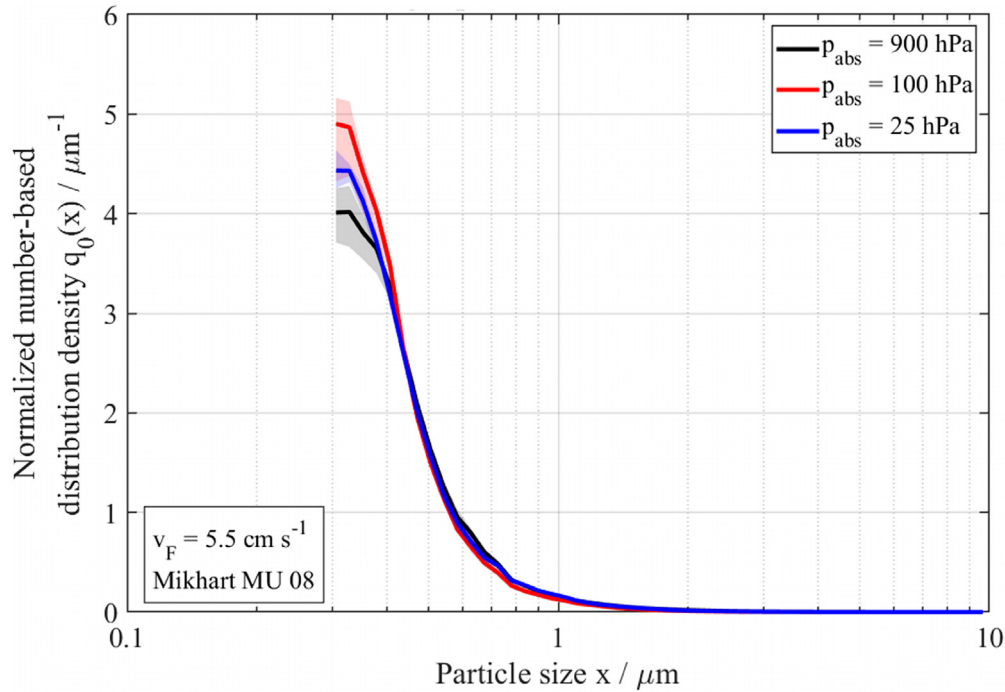


Fig. 3. SEM images (top view) of the investigated filter media. (a) SB medium. (b) WMF medium (after cleaning).

Table 1

Overview of filter media parameter.

Name	Label	Thickness L/mm	Basis weight $W/\text{g m}^{-2}$	Mean porosity $\varepsilon/-$	Mean pore size $d_p/\mu\text{m}$
Spunbond medium	SB	1 ^a	240 ^a	0.82 ^b	14 ^c
Woven metal fiber medium	WMF	0.07 ^a	230 ^a	0.68 ^a	5 ^a

^a From manufacturer data sheet.^b Determined with $\varepsilon = 1 - \frac{W}{\rho_{\text{Fiber}} L}$ using an assumed effective fiber density of $\rho_{\text{Fiber}} = 1300 \text{ kg m}^{-3}$, based on typical literature values [30].^c Determined by porometry.**Fig. 4.** Normalized number-based particle size distribution density $q_0(x)$ measured in the raw gas for absolute pressures of 900, 100, and 25 hPa. The curves represent the mean values of all conducted measurements, while the shaded area indicates the minimum and maximum deviation.**Table 2**

Overview of experimental parameters.

Absolute pressure/ hPa	Brush generator powder reservoir diameter/ mm	RBG feed rate/ mm h^{-1}	Mean total number concentration in raw gas $C_{n,\text{raw}}^{\text{a}}/\text{cm}^{-3}$
900 $\pm$ (2.9%)	20	4	$(3.17 \cdot 10^5) \pm (24\%)$
100 $\pm$ (3.8%)	28	10	$(7.08 \cdot 10^4) \pm (8\%)$
25 $\pm$ (3.1%)	28	10	$(1.65 \cdot 10^4) \pm (8\%)$

^a Loss-corrected and evaluated at operating pressure.

is kept constant at $v_F = 5.5 \text{ cm s}^{-1}$, and all measurements are performed at laboratory ambient temperature. The value $v_F = 5.5 \text{ cm s}^{-1}$ was selected as a representative face velocity for industrial surface filtration, where it lies at the upper end of the commonly applied range. Operating at the upper end additionally shortens the required experimental duration. The face velocity was kept constant across all pressure levels to isolate the influence of the absolute pressure on the separation behavior. As noted in Section 2.1, the facility allows v_F to be adjusted independently of the absolute pressure, so that other face velocities can be realized [25]. A systematic variation of v_F is beyond the scope of the present work. For each absolute pressure level, three experimental runs are conducted for both filter media, SB and WMF. Aerosol generation and neutralization are carried out at near-ambient absolute pressure upstream of the filtration section. When the aerosol is

expanded to the reduced operating pressure, the number concentration in the raw gas decreases due to decompression related dilution. Consequently, lower $C_{n,\text{raw}}$ values are obtained at reduced p_{abs} . The mean total number concentration in raw gas $C_{n,\text{raw}}$ is corrected for losses between sampling point and filter medium, evaluated at operating pressure, and averaged over the full duration of the respective experiment. The values reported in Table 2 represent the mean across all experimental runs conducted at the respective absolute pressure level. The uncertainty is given as $\pm \Delta C_{n,\text{raw}}$, calculated as half the range between the minimum and maximum values observed at that pressure level. The higher variability in $C_{n,\text{raw}}$ at $p_{\text{abs}} = 900 \text{ hPa}$ is attributed to the lower RBG feed rate of 4 mm h^{-1} , which results in greater variability in powder feeding compared to the 10 mm h^{-1} feed rate applied at reduced pressure levels.

The uncertainties of the main experimental parameters comprise the instrument accuracies given in Section 2.1 and the run-to-run reproducibility, quantified as the maximum deviation from the mean across the three repeat runs. The reproducibility of the realized absolute pressure and of the mean raw gas number concentration is listed in Table 2; for the filter face velocity it remains $\leq \pm 4.1\%$, corresponding to $v_f = (5.5 \pm 0.23) \text{ cm s}^{-1}$.

Due to the absolute pressure dependent differences in raw gas number concentration (Table 2), a direct time based comparison of the separation efficiency evolution, $E_m(t)$, is misleading across different pressure levels. Instead, the filtration state is characterized by the cumulative mass loading (deposited mass on the filter medium per unit area), W_{dep} , which provides a comparable loading coordinate independent of the specific concentration level.

The mass loading up to time step k is calculated from the measured mass concentrations on the raw gas and clean gas side as

$$W_{\text{dep}}(k) = \sum_{j=1}^k (c_{m,\text{raw}}(j) - c_{m,\text{clean}}(j)) \frac{\dot{V}_{\text{op}} \Delta t}{A_f}, \quad (8)$$

where $\dot{V}_{\text{op}}$ is the volumetric flow rate at operating conditions, Δt is the time increment of the recorded signals, and A_f is the filtration area. The OPC does not directly measure mass concentrations. Instead, particle number concentrations and particle size distributions obtained from the OPC are converted into the mass concentrations $c_{m,\text{raw}}$ and $c_{m,\text{clean}}$. For the Mikhart MU 08 test powder, the conversion is based on a refractive index of 1.59 and a particle density of 2.7 g cm^{-3} .

2.4.2. Experimental procedure

For each experiment, a clean sample of the filter medium is first weighed and installed in the filter holder. The operating conditions are then set by adjusting the absolute pressure and the volumetric flow rate to reach the target filter face velocity. After the conditions have stabilized, the differential pressure of the clean filter medium is recorded.

The aerosol generator is subsequently started and operated for 15 min without connecting it to the filtration section, allowing the powder to compact in the powder reservoir and at the brush until powder feeding reaches a constant value and a stable raw gas number concentration is achieved. The start procedure for connecting the aerosol supply to the filtration section differs between near-ambient and low-pressure operation and is described separately below.

Near-ambient pressure ($p_{\text{abs}} \approx 900 \text{ hPa}$)

During aerosol conditioning, the outlet of the aerosol generation section is blocked and the generated aerosol is discarded through the excess flow filter. After aerosol conditioning, the aerosol generation and neutralization unit is connected to the filtration section, which marks the start of the loading phase. Connecting the aerosol supply causes a short transient in volumetric flow rate and, consequently, in absolute pressure and OPC sampling flow. Under near-ambient conditions, the system stabilizes rapidly, so that only the first $\sim 1 \text{ min}$ may be affected by this transient.

Low absolute pressure

At reduced absolute pressure, directly connecting the aerosol supply can lead to pronounced transients and long stabilization times, affecting absolute pressure and OPC sampling flows for several minutes. To ensure well-defined measurement conditions from the beginning of the loading phase, a barrier flow start procedure is applied.

Fig. 5 illustrates the modified inlet configuration and its two operating states. During start phase the outlet of the raw gas chamber is connected to the inlet nozzle via a tee connector and, a barrier flow of particle free compressed air is applied through the third

branch of the tee to prevent particle transport from the raw gas chamber to the filter chamber. As shown in Fig. 5 (a), the barrier flow is switched on first and adjusted using a needle valve. The barrier flow rate is set to exceed the volumetric flow rate drawn from the raw gas chamber toward the filter chamber. Consequently, the net flow direction in the inlet section is shifted away from the filter chamber, and particle laden gas does not reach the filter medium. With the barrier flow active, the neutralizer and rotating brush generator are started and operated to allow powder compaction and stabilization of the aerosol generation. At the same time, p_{abs} and the filter face velocity are adjusted and allowed to stabilize.

Once stable operating conditions are reached, the barrier flow is stopped by closing the needle valve. This marks the start of the loading phase. As shown in Fig. 5 (b), after closing the barrier flow needle valve, particle laden gas is drawn from the raw gas chamber toward the filter chamber and dust loading begins immediately. Because the transition to loading is achieved by closing the barrier flow needle valve rather than by connecting or disconnecting the aerosol supply, only minor disturbances of p_{abs} and the OPC sampling flows occur. Consequently, raw gas and clean gas particle measurements are valid from the beginning of the loading phase without requiring an extended re-stabilization period.

Common end procedure

The experiment is continued until the clean gas number concentration has decreased to 1% of its initial value. Aerosol generation is then switched off and disconnected. The operating conditions are re-stabilized and the differential pressure signal is recorded. Finally, the dust-loaded filter medium is removed and weighed.

2.4.3. Determination of emitted mass per filtration cycle

To quantify the transient total separation efficiency discussed later in Section 3.1, the emitted mass per filtration cycle per unit area is evaluated. In this work, only the initial filtration behavior of clean filter media is investigated. Accordingly, the results represent the first filtration cycle only. Regeneration is not performed, and emissions associated with filter cake detachment are not considered.

In surface filtration, the emitted mass per cycle is a common engineering metric. Here, the emitted mass is evaluated as an areal quantity, W_{emit} , obtained from the clean gas mass concentration signal measured downstream of the filter medium. For a fully measured filtration cycle, as illustrated in Fig. 6(a), the emitted mass per cycle per area would ideally be calculated as

$$W_{\text{emit}} = \int_{t=0}^{t_{\text{cycle}}} c_{m,\text{clean}} v_f dt \quad (9)$$

However, this direct evaluation is not always possible, since a complete filtration cycle was not measured in every experiment. Fig. 6 summarizes the evaluation approach and highlights three typical situations. Panel (a) shows the ideal case of a complete filtration cycle with $t_{\text{cycle}} = t_{\text{end}}$. Panel (b) illustrates an incomplete cycle, in which the measurement ends before the defined cycle end time is reached. Panel (c) shows an extended cycle, in which the measurement continues beyond t_{cycle} . The following procedure is used to obtain a comparable value of W_{emit} for all three cases.

In industrial operation, t_{cycle} is often defined by a differential pressure criterion, for example a maximum total differential pressure. However, in the present study, a differential pressure based cycle definition is not used. At reduced absolute pressure, the differential pressure decreases for the same conditions of flow and cake loading [25]. Reaching a typical Δp criterion would require substantially longer test times and would therefore lead to markedly larger deposited dust masses and much thicker filter cakes.

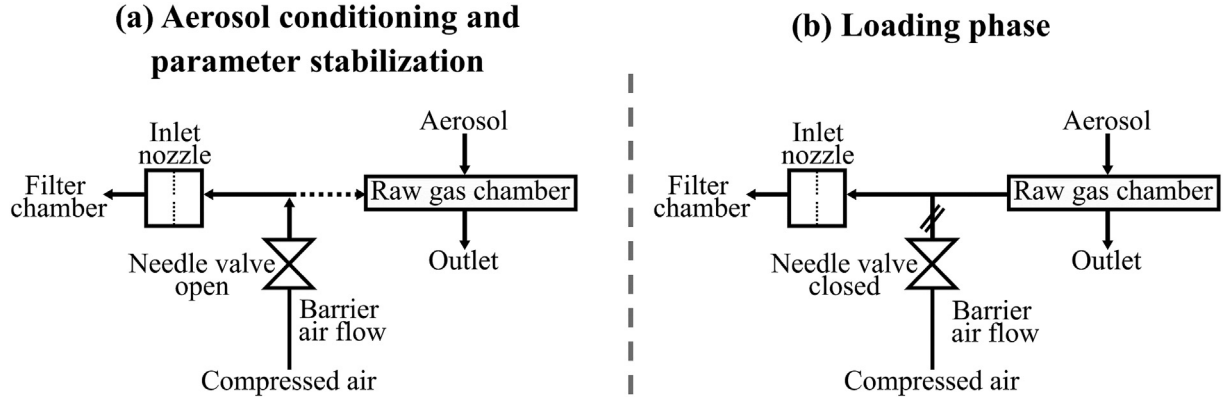


Fig. 5. Modified inlet configuration for experiments at reduced absolute pressure. (a) Start with particle free compressed air barrier flow (needle valve open), preventing particle transport to the filter chamber during aerosol conditioning and parameter stabilization. (b) Loading phase after closing the barrier flow needle valve.

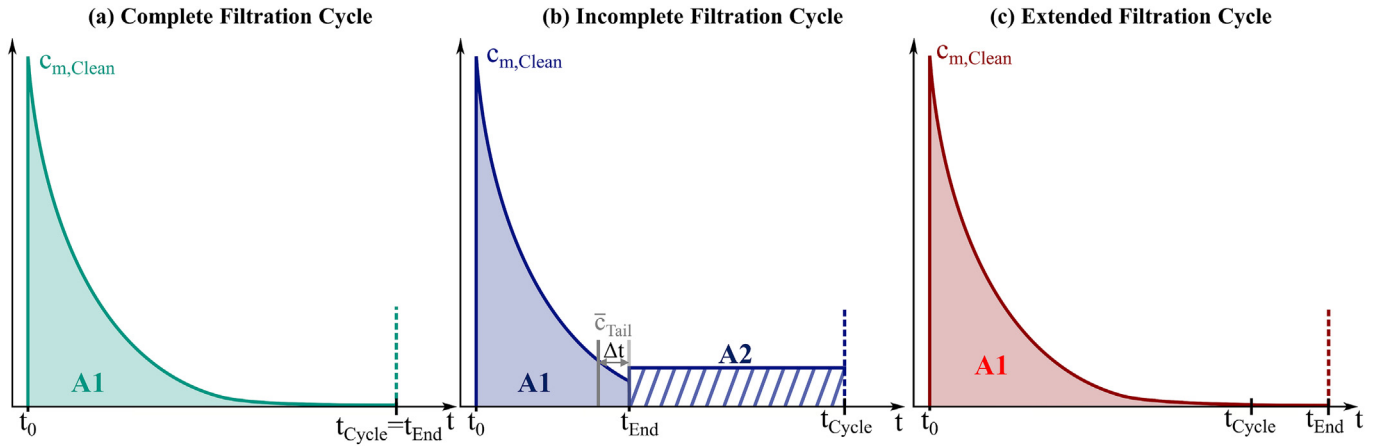


Fig. 6. Schematic illustration of the determination of the emitted mass per filtration cycle per area. (a) Idealized complete cycle with $t_{cycle} = t_{end}$. (b) Incomplete cycle with conservative tail extrapolation. (c) Extended cycle with $t_{end} > t_{cycle}$, only evaluated up to t_{cycle} .

Such heavily loaded states can introduce additional effects that are not representative of the initial filtration behavior targeted here. For comparability across pressure levels, t_{cycle} is therefore defined via a target deposited dust mass m_{cycle} , where m_{cycle} is the dust mass on the filter medium that corresponds to a differential pressure of the filter cake of 1000 Pa at near-ambient conditions. This definition of a filtration cycle is convenient for our comparison of emission levels at different levels of p_{abs} . However, a practical problem arises from this definition, as there is no online measurement of the deposited particle mass. Thus, experiments are unlikely to end exactly at the value m_{cycle} . Instead, the measurement in our case will often end before m_{cycle} is reached, as clean gas concentration drops to extremely low values well in advance. Then t_{cycle} and t_{end} do not coincide, and a hypothetical t_{cycle} has to be determined.

The cycle time is estimated from the measured test duration t_{end} and the dust mass collected on the filter medium at the end of the test, m_{end} , assuming proportionality between deposited mass and time during the loading period

$$t_{cycle} = t_{end} \frac{m_{cycle}}{m_{end}}. \quad (10)$$

Panel (b) of Fig. 6 illustrates the situation encountered for tests that were terminated after the main emission peak had decayed at t_{end} , but before t_{cycle} was reached. The measured contribution $A1$ is eval-

uated by integrating $c_{m,clean}(t)$ from the beginning of the evaluation (t_0) to the end of the measurement (t_{end}).

To obtain a comparable cycle based metric, the remaining contribution $A2$ is conservatively estimated using a constant tail concentration, $\bar{c}_{m,tail}$, determined from averaging over the final part of the measurement (grey segment in Fig. 6(b)). This tail concentration is then assumed to persist until t_{cycle} , yielding the hatched area $A2$. The sum $A1 + A2$ constitutes the worst case estimate of W_{emit} for an incomplete cycle.

Panel (c) shows an extended filtration cycle, in which the measurement continues beyond the defined cycle end time, i.e. $t_{end} > t_{cycle}$. In this case, only the part of the clean gas concentration signal up to t_{cycle} is evaluated. Accordingly, only area $A1$ contributes to W_{emit} , and no tail extrapolation is required.

The emitted mass per filtration cycle per area is computed as

$$W_{emit} = W_{A1} + W_{A2}. \quad (11)$$

If $t_{cycle} > t_{end}$, the tail contribution W_{A2} is calculated from a mean tail concentration (Fig. 6b) as

$$W_{A2} = \frac{\dot{V}_{op}}{A_F} \bar{c}_{m,tail} (t_{cycle} - t_{end}), \quad \text{for } t_{cycle} > t_{end}. \quad (12)$$

If $t_{cycle} \leq t_{end}$, $W_{A2} = 0$.

For numerical evaluation, the concentration signals are averaged over 120 s intervals prior to integration. The tail window is set to $\Delta t_{\text{tail}} = 5$ min.

3. Results and discussion

3.1. Mass-based total separation efficiency

To assess the absolute pressure dependence of the overall separation performance during the initial filtration phase, the total mass-based separation efficiency E_m is evaluated as a function of the cumulative mass loading W_{dep} (see Methods and Eqs. (8) and (2)). As discussed in Section 2.4.1, a time-based representation would be misleading due to the pressure-dependent dilution of the aerosol at reduced absolute pressure, which results in different mass accumulation rates across pressure levels. The use of W_{dep} as the independent variable therefore allows a direct comparison of the separation performance across all investigated pressure levels. The experimental run at each operating point was repeated three times per filter medium. In the figures, solid lines represent the mean of the three runs and the shaded areas indicate the minimum and maximum deviation across the runs.

Fig. 7 shows E_m as a function of W_{dep} for the WMF medium in panel (a) and the SB medium in panel (b). For both media, a clear improvement in separation efficiency is observed when reducing the absolute pressure. This trend is particularly pronounced for the WMF medium. At 900 hPa, the WMF medium exhibits a low initial separation efficiency of approximately $E_m \approx 0.5$. With increasing W_{dep} , E_m rises continuously. At 100 hPa, the initial efficiency increases to roughly $E_m \approx 0.8$, and the rise toward unity occurs at substantially lower W_{dep} than at 900 hPa. The strongest improvement is observed at 25 hPa, where the WMF medium already reaches about $E_m \approx 0.95$ at the smallest assessed mass loading.

For the SB medium, the separation efficiency is already high at 900 hPa. At the beginning of the analyzed loading range, E_m is approximately 0.94, and increases further with increasing W_{dep} . At reduced absolute pressure, the SB medium reaches near-complete separation at even smaller mass loadings. In particular, at 25 hPa, the initial efficiency increases to approximately $E_m \approx 0.9999$. These results highlight that, at reduced absolute pressure, very high efficiencies can be achieved with remarkably low mass loadings. In line with observations for surface filtration at ambient conditions, comparably high efficiencies are often associ-

ated with substantially larger mass loadings [12]. In our investigations, efficiencies close to unity are already reached at mass loadings well below 1 g m^{-2} .

It is also noticeable that the curves start at different W_{dep} values. This is mainly caused by the absolute pressure dependent raw gas concentration at operating pressure, which affects the deposited mass rate and therefore the resolved range on the W_{dep} axis. As discussed in the Methods section, the aerosol is generated and conditioned upstream close to ambient pressure. After expansion to reduced operating pressure, the number concentration in the raw gas decreases due to decompression related dilution. This leads to a slower mass accumulation on the filter medium at low p_{abs} , so that the early loading regime can be resolved at smaller W_{dep} . The confidence intervals narrow with increasing W_{dep} . As E_m approaches unity, the absolute spread between individual runs necessarily decreases. Additionally, during the early loading phase, penetration is strongly governed by the local filter medium structure and the initial particle deposition sites, leading to greater experimental scatter. As the dust cake develops and dominates the separation, conditions between repeated experiments become more uniform.

For a clearer visualization in the high efficiency range, Fig. 8 presents the corresponding mass-based penetration $P_m = 1 - E_m$.

For the WMF medium shown in Fig. 8(a), penetration at 900 hPa starts at about $P_m \approx 0.5$ and decreases with increasing W_{dep} . At 100 hPa, penetration is initially on the order of $P_m \approx 0.2$ and decreases more rapidly. At 25 hPa, penetration is already around $P_m \approx 5 \cdot 10^{-2}$ at the smallest resolved W_{dep} and approaches values close to 10^{-4} at low mass loadings. Thus, not only the initial penetration decreases with decreasing absolute pressure, but the subsequent reduction in penetration also occurs at smaller values of W_{dep} . The transition to the steep decline in penetration is shifted toward lower mass loadings as p_{abs} decreases. This indicates that the improvement in separation at reduced absolute pressure becomes apparent already at earlier stages of dust deposition. In addition, Fig. 8(a) shows that the 25 hPa and 100 hPa curves converge and can intersect at intermediate mass loadings. This crossover is observed consistently across all individual experimental runs and is therefore considered a statistically robust feature. It occurs exclusively for the WMF medium and may thus represent a filter-medium-specific phenomenon. While no definitive mechanistic explanation can be provided, this indicates that the early deposition evolution differs between these absolute pressure levels for this medium. It is hypothesized that this behavior may be

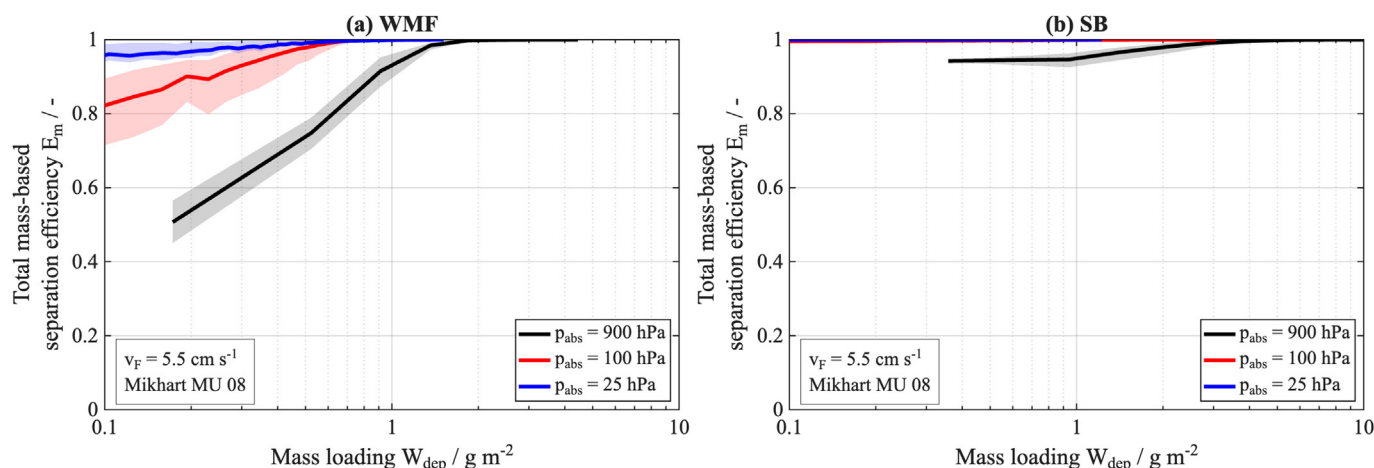


Fig. 7. Total mass-based separation efficiency E_m as a function of the mass loading W_{dep} for (a) the WMF medium and (b) the SB medium at $p_{\text{abs}} = 900 \text{ hPa}$, 100 hPa , 25 hPa and $v_F = 5.5 \text{ cm s}^{-1}$. Solid lines show the mean of three trials and shaded areas indicate the minimum and maximum deviation.

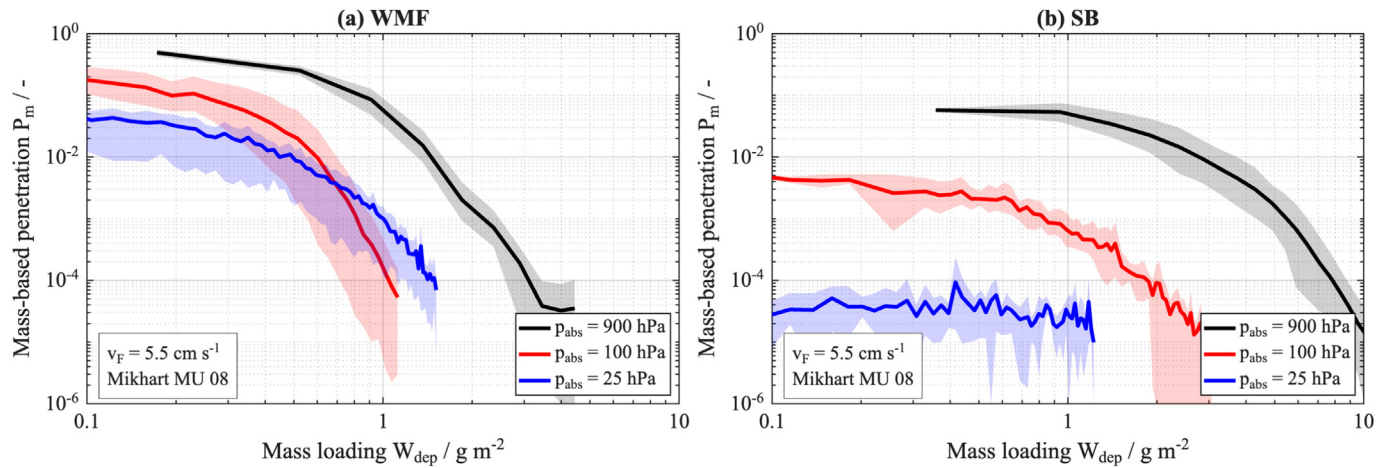


Fig. 8. Mass-based penetration $P_m = 1 - E_m$ as a function of the mass loading W_{dep} for (a) the WMF medium and (b) the SB medium under the same operating conditions as in Fig. 7. Solid lines show the mean of three trials and shaded areas indicate the minimum and maximum deviation.

related to how preferential flow paths and local deposit structures develop during pore blocking at different p_{abs} . However, this remains speculative and would require dedicated experimental or numerical investigations to substantiate.

For the SB medium shown in Fig. 8(b), the absolute pressure dependence is even more pronounced than for the WMF medium. The penetration curves are shifted much more strongly toward lower values with decreasing absolute pressure. At 900 hPa, penetration starts at about $P_m \approx 0.06$, while at 100 hPa it is already reduced to about $P_m \approx 0.005$. At 25 hPa, the initial penetration is

as low as $P_m \approx 3.3 \cdot 10^{-5}$. Thus, the effect of reduced absolute pressure on separation performance is markedly stronger for the SB medium. For SB at 25 hPa, the penetration shows hardly any further decrease with increasing W_{dep} , because it is already at a very low level from the beginning. Over most of the experiment, the signal is therefore in a range where only very few particles are counted, which limits the statistical significance of any further decrease in penetration.

SEM top views after a representative test at 25 hPa are shown in Fig. 9. For the SB medium, Fig. 9(a,c), dust is deposited on and

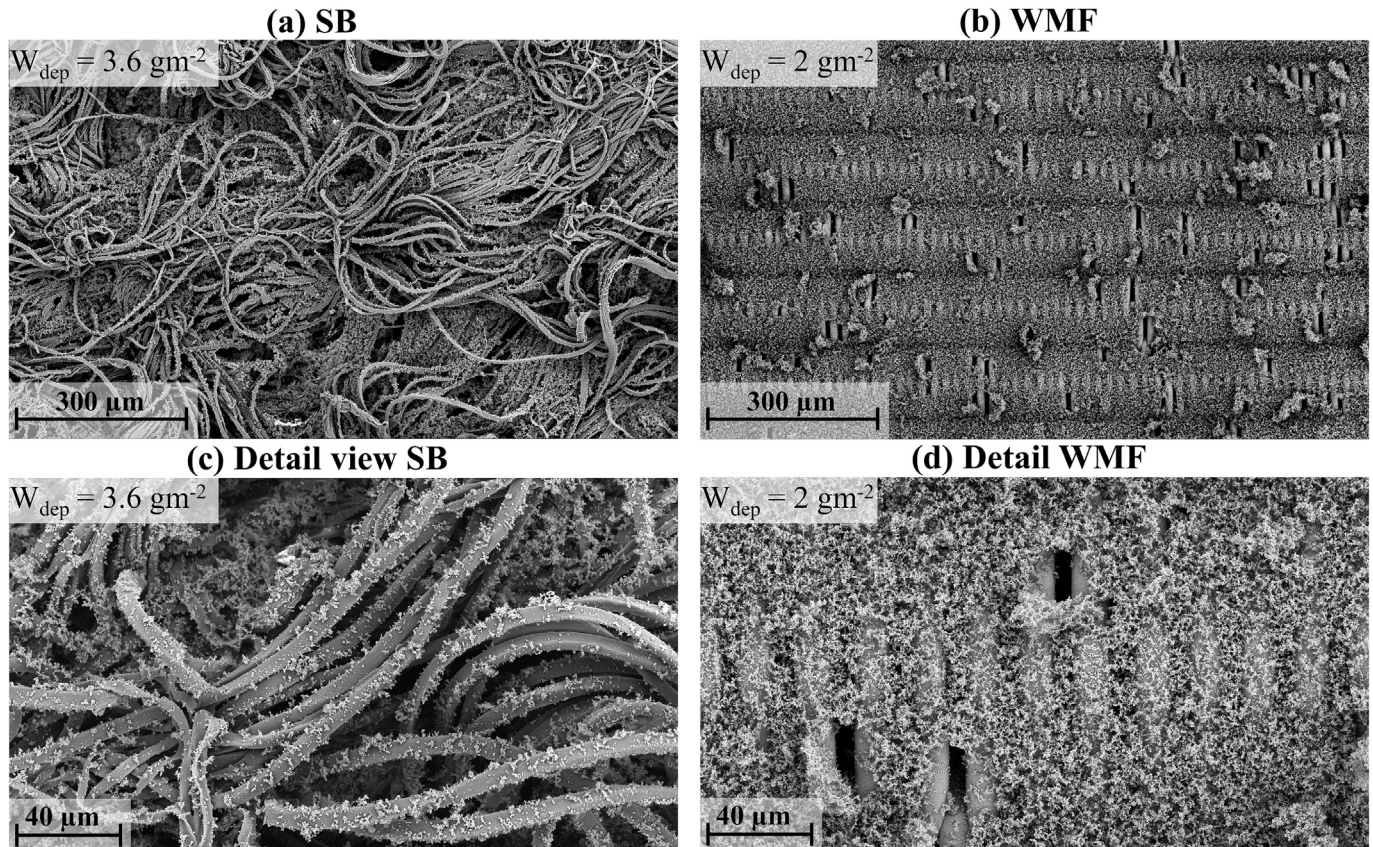


Fig. 9. SEM top views of the dust laden filter media after a representative experiment at $p_{abs} = 25\ hPa$ with a filter face velocity of $v_F = 5.5\ cm\ s^{-1}$. (a,c) SB medium at two magnifications. (b,d) WMF medium at two magnifications.

within the fibrous structure while many fibers remain exposed, indicating that a fully closed filter cake is not yet formed at the end of the test.

For the WMF medium, Fig. 9(b,d), a more continuous deposit is visible, but locally distinct pinholes and dust free spots remain. Such heterogeneities can maintain localized high permeability pathways and thereby influence the penetration evolution. Importantly, despite the presence of pinholes, the penetration at reduced pressure is already very low, demonstrating that high separation can be achieved before a uniform, fully closed surface layer develops.

Overall, Figs. 7 and 8 demonstrate that reducing p_{abs} substantially increases the separation efficiency of both investigated surface filter media during the initial filtration phase. The results further show that, at reduced absolute pressure, very high efficiencies occur at very small mass loadings.

3.2. Emitted mass per filtration cycle

To quantify the trends in separation efficiency discussed in Section 3.1 with a single performance metric, the emitted mass per filtration cycle per area, W_{emit} , is evaluated. This cycle integrated quantity is commonly used to assess emissions from surface filtration processes [34]. In the present study, W_{emit} is used as a compact measure of the overall emission severity during the first filtration cycle. The determination of W_{emit} follows the procedure described in Section 2.4.3.

For both filter media, the cycle end was defined by a target deposited dust mass of $m_{\text{cycle}} = 0.125$ g. This corresponds to a mass loading of $W_{\text{cycle}} = 8.12$ g m^{-2} . This value corresponds to the dust mass that would generate a filter cake differential pressure of 1000 Pa at near-ambient conditions and was used consistently for both media.

Fig. 10 summarizes the resulting values as a function of absolute pressure and filter medium. Error bars indicate the minimum and maximum deviation across the three repeat runs.

Fig. 10 shows that W_{emit} decreases systematically as the absolute pressure is reduced for both media. For the WMF medium, W_{emit} decreases from $5.03 \cdot 10^{-1}$ g m^{-2} at 900 hPa to $5.96 \cdot 10^{-2}$ g m^{-2} at 100 hPa and $1.65 \cdot 10^{-2}$ g m^{-2} at 25 hPa. This corresponds to reductions of 88.1% (900 $\rightarrow$ 100 hPa) and 96.7% (900 $\rightarrow$ 25 hPa). For the SB medium, W_{emit} decreases from $1.07 \cdot 10^{-1}$ g m^{-2} at 900 hPa to $2.52 \cdot 10^{-3}$ g m^{-2} at 100 hPa and

$6.20 \cdot 10^{-5}$ g m^{-2} at 25 hPa, corresponding to reductions of 97.6% and 99.94%, respectively. These results are consistent with the efficiency and penetration trends in Figs. 7 and 8, where reduced pressure yields higher separation efficiency at very small mass loadings.

At all investigated pressures, W_{emit} is higher for the WMF medium than for the SB medium. This agrees with the higher penetration of the WMF medium in the clean medium state observed in Section 3.1 and reflects the more open structure of the WMF medium. Importantly, the low pressure cases achieve very low W_{emit} values even though the SEM images in Fig. 9 indicate that a fully closed, uniform surface layer is not yet formed at the end of the tests. This shows that, at reduced absolute pressure, high separation and low emissions can be obtained already during the pore blocking and early deposition stage.

In most operating points, W_{emit} is dominated by the measured contribution W_{A1} , whereas the conservative tail extrapolation term W_{A2} contributes only marginally. Based on the mean values, W_{A2}/W_{emit} remains below 1.3% for all cases except the SB medium at 25 hPa, where W_{A2} accounts for about 23% of W_{emit} . Overall, the results demonstrate that reducing p_{abs} strongly suppresses early cycle emissions and thereby markedly lowers the emitted mass per filtration cycle.

3.3. Fractional separation efficiency

To conclude the analysis, the fractional separation efficiency $T(x)$ is evaluated. Unlike integral metrics, $T(x)$ captures how separation changes across the particle-size spectrum and how this correlation evolves with increasing particle loading of the filter medium. As outlined in the introduction, reduced absolute pressure may alter particle transport and thus the size dependence of separation, particularly in early loading stages. Therefore, $T(x)$ was determined at selected mass loading states W_{dep} that represent distinct stages of filter medium loading. For reduced absolute pressures, $W_{\text{dep}} = 0.013$ g m^{-2} was chosen as an early loading state that closely reflects the initial condition. At near-ambient pressure, this loading level could not be evaluated reliably under the present experimental constraints. Here, $W_{\text{dep}} \approx 0.4$ g m^{-2} represents the earliest comparable state. In addition, a later loading state ($W_{\text{dep}} = 3.5$ g m^{-2}) was analyzed at $p_{\text{abs}} = 900$ hPa, which was not reached in the experiments performed at reduced pressures.

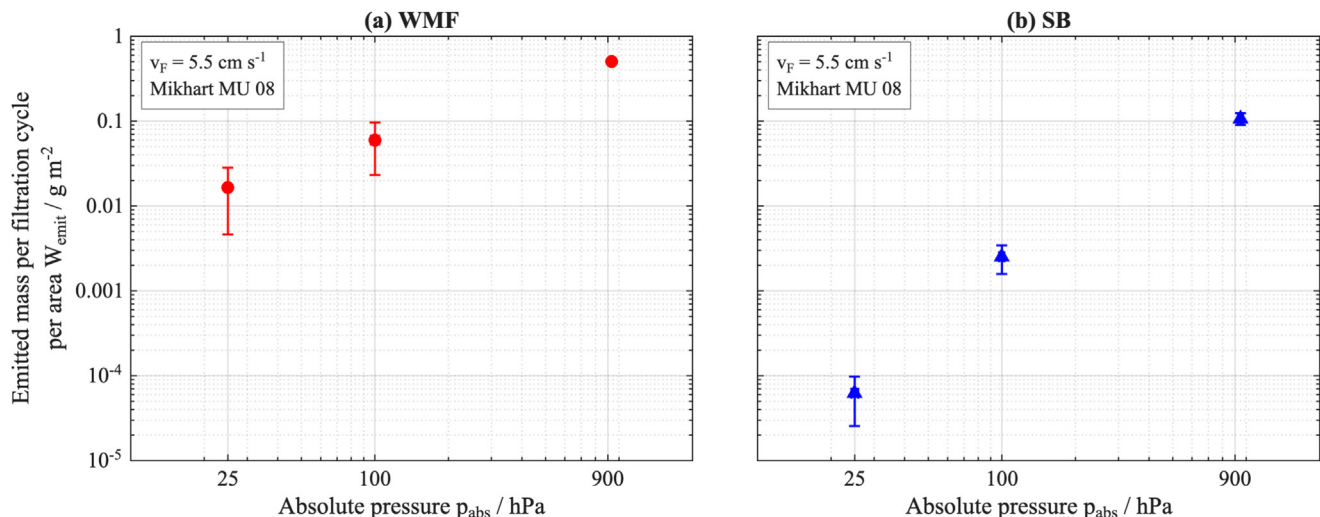


Fig. 10. Emitted mass per area per filtration cycle for WMF and SB medium for $p_{\text{abs}} = 900, 100$ and 25 hPa at a filter face velocity of $v_F = 5.5$ cm s^{-1} . Vertical error bars indicate the minimum and maximum deviation across the three repeat runs. Horizontal error bars indicate the corresponding scatter of the realized absolute pressure.

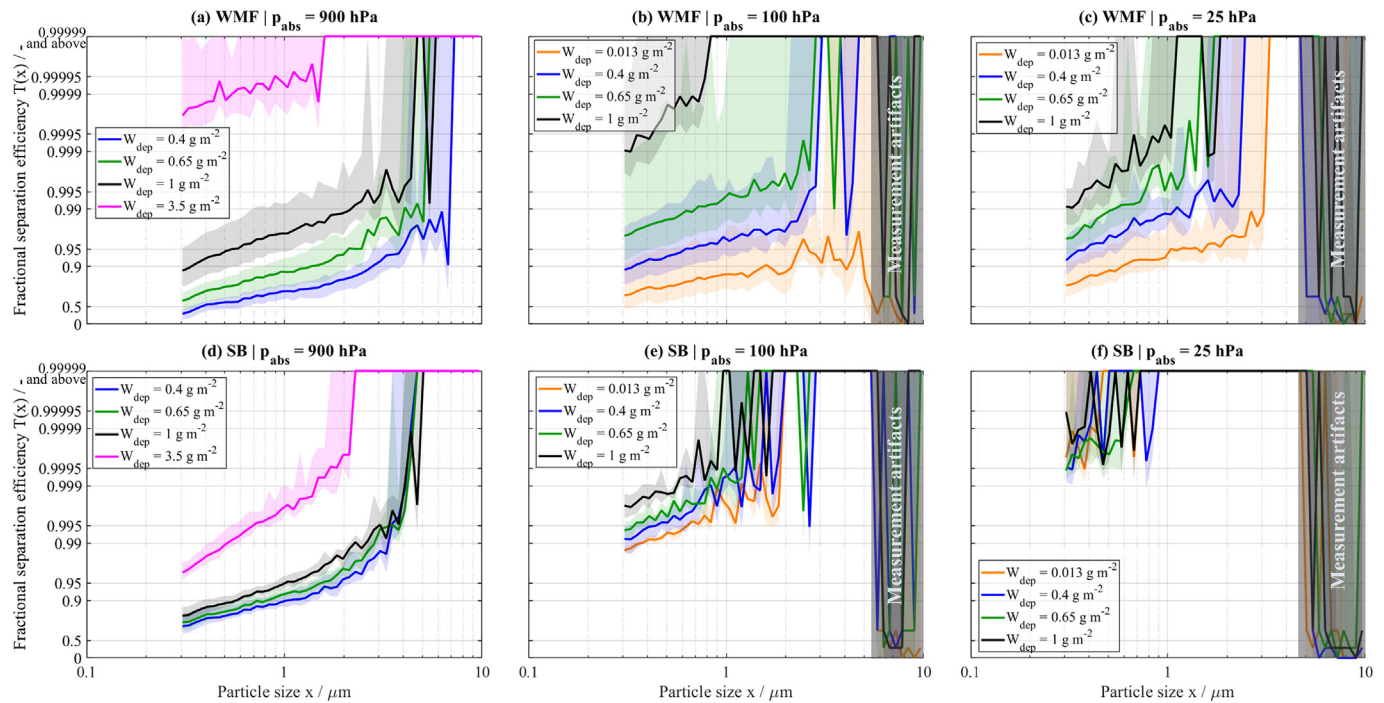


Fig. 11. Fractional separation efficiency $T(x)$ of WMF and SB at different absolute pressures and mass loadings W_{dep} . Shaded areas indicate the range (min/max) across repeated measurements. The grey region marks size classes dominated by measurement artifacts due to low counting statistics.

The fractional separation efficiency was calculated according to Eq. 3 from the size-resolved mass concentrations in the raw gas and clean gas. For each target W_{dep} , the time instant t_0 at which the corresponding deposited mass was reached was determined first. Subsequently, the concentrations were averaged over a 120 s time window. Shaded bands indicate the variability across repeated measurements.

Fig. 11 shows $T(x)$ for WMF and SB at $p_{\text{abs}} = 900, 100$, and 25 hPa. Within the accessible measurement range ($x \geq 0.3 \mu\text{m}$), the curves predominantly capture the regime of decreasing penetration, i.e., $T(x)$ increases with particle size. This behavior is consistent with the expectation discussed in the introduction that, in the micrometer regime and above, separation is primarily governed by inertial effects. A potential most penetrating particle size (MPPS) at smaller diameters is not covered due to the lower size limit of the OPC. Consequently, any pressure induced changes that would mainly manifest close or below to the MPPS cannot be resolved here.

For improved readability at high efficiencies, the y-axis is displayed using a continuous, logarithmic compression based on the penetration $P(x) = 1 - T(x)$. Tick labels are given in terms of $T(x)$.

With increasing mass loading W_{dep} , $T(x)$ shifts towards higher values over the entire size range, and the size interval in which particles still penetrate to a relevant extent shifts towards smaller particle sizes. In addition to this loading effect, a clear pressure dependence is observed. At comparable W_{dep} , $T(x)$ is systematically higher at lower absolute pressure p_{abs} . An exception is observed for the WMF medium at 100 hPa and 25 hPa at $W_{\text{dep}} = 1 \text{ g m}^{-2}$, where the trends are reverse. This behavior is consistent with the intersection of the corresponding P_m curves discussed for Fig. 11 and is therefore in line with the total mass based penetration results. The improvement of $T(x)$ is most pronounced at early loading states, where differences in $T(x)$ between the investigated pressure levels are largest, while the curves converge towards $T(x) \approx 1$ as loading progresses.

The smoothness of the $T(x)$ curves is governed by counting statistics in the clean gas signal. As long as each size class contains a sufficient number of counted particles within the 120 s averaging window, $T(x)$ varies smoothly with x . When only a small number of particles are detected (down to single-count events), the ratio used to compute $T(x)$ becomes dominated by statistical noise, leading to the strong step-like fluctuations observed at high efficiencies. This effect is particularly evident for SB at $p_{\text{abs}} = 25 \text{ hPa}$, where the remaining downstream counts are near the detection limit and the plotted curves largely reflect statistical noise rather than a resolved size dependence. The size range above $\approx 3 \mu\text{m}$ at reduced p_{abs} is even more affected by such artifacts, since in these cases the particle counts in the raw gas (see Fig. 4) are also low and prone statistical errors. The grey shaded region at large particle sizes marks size classes dominated by such low count artifacts and is excluded from the interpretation.

Overall, the results confirm the expectations introduced at the beginning of this work mainly based on depth filter investigations. A systematic and consistent pressure effect is observed, with $T(x)$ increasing as p_{abs} is reduced. This improvement is already evident on the inertial separation branch and is consistent with the anticipated change of the governing inertial parameter ψ under reduced pressure. Filter loading further enhances $T(x)$ and shifts the remaining penetration towards smaller particle sizes.

4. Conclusion and outlook

In summary, this work provides a systematic experimental assessment of the influence of reduced absolute pressure on the separation performance of surface filters in gas filtration. While improved separation at low absolute pressure has been reported primarily for depth filtration, corresponding investigations for surface filters remain scarce. To address this gap, two surface filter media, a spunbond polymer material and a woven metal fiber medium, were studied using a polydisperse test powder at a con-

stant filter face velocity of $v_F = 5.5 \text{ cm s}^{-1}$ and ambient temperature, with the absolute pressure varied between $p_{\text{abs}} = 900, 100$, and 25 hPa . The total mass-based separation efficiency E_m , the emitted mass per filtration cycle per area W_{emit} , and the fractional separation efficiency $T(x)$ were determined from continuous raw gas and clean gas measurements over $x = 0.3 \mu\text{m}$ to $10 \mu\text{m}$.

A systematic improvement in separation performance with decreasing absolute pressure was observed for both filter media. Very high efficiencies were reached already at low mass loadings, and at reduced absolute pressure less than 0.1 g m^{-2} of dust was sufficient to achieve near-complete separation. Under otherwise identical operating conditions, the SB medium exhibited a higher separation efficiency than the WMF medium. For both media, the rapid increase in efficiency occurred before a fully closed filter cake was formed, indicating that a strong improvement is already achieved during the early loading and clogging phase.

To compare the pressure effect using an integral emission metric, the emitted mass per filtration cycle per area W_{emit} was evaluated. As expected, W_{emit} decreased markedly with decreasing p_{abs} , and the WMF medium showed higher emissions than the SB medium. Reducing the pressure from 900 to 25 hPa lowered W_{emit} by 99.94% for SB and by 96.7% for WMF.

Finally, the fractional separation efficiency $T(x)$ was analyzed at defined loading states representing an early and subsequently stages of loading. At comparable W_{dep} , decreasing p_{abs} increased $T(x)$ across all measured size classes and shifted the smallest still penetrating particle sizes towards smaller diameters. Increased loading visibly enhanced $T(x)$, while at $p_{\text{abs}} = 25 \text{ hPa}$ for SB the downstream signal approached the detection limit, such that the remaining curves were dominated by single-count statistics.

Future work should extend the measurable size range towards smaller particles to capture diffusion controlled separation and to resolve the MPPS under reduced absolute pressure, including its interaction with loading effects. In addition, the influence of other filter media structures and test aerosols should be assessed. Existing filtration theories may serve as a basis for future modeling approaches, either through adaptation of established correlations or through the development of extensions for surface filtration under reduced absolute pressure. In addition, the filter face velocity could be varied, which the present experimental set up permits independently of the absolute pressure.

Declaration of generative AI and AI-assisted technologies in the manuscript preparation process

During the preparation of this work the authors used ChatGPT (OpenAI) and Claude (Anthropic) in order to improve language clarity and readability. After using this tool/service, the authors reviewed and edited the content as needed and take full responsibility for the content of the published article.

CRediT authorship contribution statement

Jörg Meyer: Writing – review & editing, Methodology, Formal analysis, Conceptualization. **Achim Dittler:** Writing – original draft, Supervision, Resources, Project administration, Funding acquisition. **Vanessa Löschner:** Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization.

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.

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References

- [1] M.W. Jorntz (Ed.), *Filtration and purification in the biopharmaceutical industry*, third edition Edition, Drugs and the pharmaceutical sciences, CRC Press, Taylor & Francis Group, Boca Raton, 2020.
- [2] A.B. Jindal (Ed.), *Pharmaceutical Process Engineering and Scale-up Principles*, Vol. 13 of AAPS Introductions in the Pharmaceutical Sciences, Springer Nature Switzerland, Cham, 2023. doi:10.1007/978-3-031-31380-6. <https://link.springer.com/10.1007/978-3-031-31380-6>.
- [3] P. Bächler, J. Meyer, R. Ligotski, P. Krug, A. Dittler, Measurement of transient nanoparticle emissions of a municipal biomass incineration plant equipped with pulse-jet cleaned filters, *Process Saf. Environ. Prot.* 184 (2024) 601–614. <https://doi.org/10.1016/j.psep.2024.02.013>, URL <https://linkinghub.elsevier.com/retrieve/pii/S0957582024001368>.
- [4] Jousten, *Handbuch Vakuumtechnik*, Springer Fachmedien Wiesbaden, 2018, oCLC: 1105115344.
- [5] W. Jorisch (Ed.), *Vakuumtechnik in der chemischen Industrie*, Wiley-VCH, Weinheim [etc.], 1999.
- [6] C.M. VanT Land, *Drying in the Process Industry*, 1st Edition,, Wiley, 2011. <https://doi.org/10.1002/9781118105818>.
- [7] J. Oess, *Vakuumtrocknung*, in: W. Jorisch (Ed.), *Vakuumtechnik in der chemischen Industrie*, Wiley-VCH, Weinheim [etc.], 1999, pp. 191–206.
- [8] A. Heindl, *Grundlagen der Trocknung*, in: *Praxisbuch Bandtrocknung*, Springer, Berlin Heidelberg, Berlin, Heidelberg, 2016, pp. 17–184. doi:10.1007/978-3-642-53905-3_2. https://link.springer.com/10.1007/978-3-642-53905-3_2.
- [9] C. Edelmann, *Vakuumphysik: Grundlagen, Vakuumherzeugung und -messung*, Anwendungen, Spektrum Akad. Vlg., Heidelberg, 1998, oCLC: 40295571.
- [10] D. Richter, *Mechanik der Gase*, Springer-Lehrbuch, Springer Berlin Heidelberg, Berlin, Heidelberg, 2010. <https://doi.org/10.1007/978-3-642-12723-6>, URL <http://link.springer.com/10.1007/978-3-642-12723-6>.
- [11] L. Wu, *Rarefied Gas Dynamics: Kinetic Modeling and Multi-Scale Simulation*, Springer Nature Singapore, Singapore, 2022. <https://doi.org/10.1007/978-981-19-2872-7>, URL <https://link.springer.com/10.1007/978-981-19-2872-7>.
- [12] F. Löffler, *Staubabscheiden*, Georg Thieme Verlag, Stuttgart [Germany], 1988, oCLC: 35461134.
- [13] E. Schmidt, *Abscheidung von Partikeln aus Gasen mit Oberflächenfiltern*, VDI Verlag, Düsseldorf, 1998, oCLC: 45561735.
- [14] S.C. Stern, H.W. Zeller, A.I. Schekman, The aerosol efficiency and pressure drop of a fibrous filter at reduced pressures, *J. Colloid Sci.* (15) (1960) 546–562.
- [15] X. Liu, H. Shen, Effect of venturi structures on the cleaning performance of a pulse jet baghouse, *Appl. Sci.* 9 (18) (2019) 3687. <https://doi.org/10.3390/app9183687>, URL <https://www.mdpi.com/2076-3417/9/18/3687>.
- [16] M. He, S. Dhaniyala, M. Wagner, Characterization of filter performance under low-pressure operation, *Aerosol Sci. Technol.* 50 (5) (2016) 417–428. <https://doi.org/10.1080/02786826.2016.1162902>, URL <http://www.tandfonline.com/doi/full/10.1080/02786826.2016.1162902>.
- [17] J.A. Hubbard, J.E. Brockmann, J. Dellinger, D.A. Lucero, A.L. Sanchez, B.L. Servantes, Fibrous filter efficiency and pressure drop in the viscous-inertial transition flow regime, *Aerosol Sci. Technol.* 46 (2) (2012) 138–147. <https://doi.org/10.1080/02786826.2011.616555>, URL <http://www.tandfonline.com/doi/abs/10.1080/02786826.2011.616555>.
- [18] Z. Zhang, B.Y.H. Liu, Experimental study of aerosol filtration in the transition flow regime, *Aerosol Sci. Technol.* 16 (4) (1992) 227–235. <https://doi.org/10.1080/02786829208959551>, URL <http://www.tandfonline.com/doi/abs/10.1080/02786829208959551>.
- [19] C. Tien, *Granular filtration of aerosols and hydrosols, Butterworths series in chemical engineering*, Butterworths, Boston London Singapore, 1989.
- [20] R.C. Brown, *Air filtration: an integrated approach to the theory and applications of fibrous filters*, 1st Edition,, Pergamon Press, Oxford; New York, 1993.
- [21] C.N. Davies, *Air filtration*, Academic Press, London, New York, 1973.
- [22] J. Pich, *The Theory of Aerosol Filtration by Fibrous and Membrane Filters*, in: C. N. Davies (Ed.), *Aerosol Science*, Academic Press, London and New York, 1966, pp. 223–285.
- [23] Z. Liu, D.-R. Chen, P. Wang, Z. Ji, Effect of filtration pressure on the particle penetration efficiency of fibrous filter media, *Sep. Purif. Technol.* 274 (2021) 119086. <https://doi.org/10.1016/j.seppur.2021.119086>, URL <https://linkinghub.elsevier.com/retrieve/pii/S1383586621007966>.
- [24] W.C. Hinds, N.P. Kadrichu, The effect of dust loading on penetration and resistance of glass fiber filters, *Aerosol Sci. Technol.* 27 (2) (1997) 162–173. <https://doi.org/10.1080/02786829708965464>, URL <http://www.tandfonline.com/doi/abs/10.1080/02786829708965464>.
- [25] V. Löschner, J. Meyer, A. Dittler, Experimental and theoretical investigation of the pressure drop across different surface filter media at low absolute

- pressures down to 100 Pa, Sep. Purif. Technol. 361 (2025) 131093. <https://doi.org/10.1016/j.seppur.2024.131093>, URL <https://linkinghub.elsevier.com/retrieve/pii/S1383586624048329>.
- [26] C. Kanaoka, H. Emi, Y. Otani, T. Iiyama, Effect of charging state of particles on electret filtration, Aerosol Sci. Technol. 7 (1) (1987) 1–13. <https://doi.org/10.1080/02786828708959142>, URL <http://www.tandfonline.com/doi/abs/10.1080/02786828708959142>.
- [27] M. Rodrigues, M. Barrozo, J. Gonçalves, J. Coury, Effect of particle electrostatic charge on aerosol filtration by a fibrous filter, Powder Technol. 313 (2017) 323–331. <https://doi.org/10.1016/j.powtec.2017.03.033>, URL <https://linkinghub.elsevier.com/retrieve/pii/S0032591017302504>.
- [28] G. Tu, Q. Song, Q. Yao, Relationship between particle charge and electrostatic enhancement of filter performance, Powder Technol. 301 (2016) 665–673. <https://doi.org/10.1016/j.powtec.2016.06.044>, URL <https://linkinghub.elsevier.com/retrieve/pii/S0032591016303825>.
- [29] V. Löschner, J. Lüttmann, J. Meyer, A. Dittler, Dust cake build-up on gas cleaning surface filters at ambient and low absolute pressure, Sep. Purif. Technol. 381 (2026) 135536. <https://doi.org/10.1016/j.seppur.2025.135536>, URL <https://linkinghub.elsevier.com/retrieve/pii/S1383586625041334>.
- [30] John Wiley & Sons, Inc. (Ed.), Encyclopedia of Polymer Science and Technology, 1st Edition, Wiley, 2002. doi:10.1002/0471440264. URL <https://onlinelibrary.wiley.com/doi/book/10.1002/0471440264>.
- [31] C. Turchiuli, A. Gianfrancesco, S. Palzer, E. Dumoulin, Evolution of particle properties during spray drying in relation with stickiness and agglomeration control, Powder Technol. 208 (2) (2011) 433–440. <https://doi.org/10.1016/j.powtec.2010.08.040>.
- [32] B. Buck, S. Heinrich, Collision dynamics of wet particles: Comparison of literature models to new experiments, Adv. Powder Technol. 30 (12) (2019) 3241–3252. <https://doi.org/10.1016/j.appt.2019.09.033>.
- [33] H.J. Sarnavi, M. Precoppe, H. Salehi, M.S. Bradley, P. García-Triñanes, Study of the evolution of drying-induced flow properties for pulverised cassava grits, J. Food Eng. 338 (2023) 111221. <https://doi.org/10.1016/j.jfoodeng.2022.111221>.
- [34] P. Bächler, J. Meyer, A. Dittler, Operating behavior of pulse jet-cleaned filters regarding energy demand and particle emissions – part 2: modeling, Chem. Eng. Technol. 47 (4) (2024) 722–731. <https://doi.org/10.1002/ceat.202300409>, URL <https://onlinelibrary.wiley.com/doi/10.1002/ceat.202300409>.