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Influence of leaks in surface filters on particulate emissions

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Abstract

Compliance with severe limit values of dust emissions is a main characteristic of surface filters. This characteristic is due to the high particle collection efficiency of surface filters. Beside regular operation it is necessary to consider phenomena such as a "pinhole" bypass through leaks in surface filters to ensure the above mentioned compliance with the limit values at all times.

Experimental research has been carried out to observe and understand the "pinhole" bypass through leaks and the behaviour of pinholes over filtration time. To work out the influence of different filtration conditions the parameters pinhole diameter, filter face velocity and dust cake thickness were varied.

The results can be explained by formulas usually used to calculate volumetric flow rates of orifice gauges. The experiments and the calculations lead to the conclusions that bigger pinholes decrease the collection efficiency and higher filter face velocities increase the collection efficiency of pinholed filter media.

Keywords: Solid/gas separation; Surface filtration; Filter efficiency

1. Introduction

Surface filters generally operate with high collection efficiency, especially for particles in the lower micrometer range. Dust-laden air is cleaned by passing from the outside to the inside of porous filter media and leaving the filter, which is normally made of bag, envelope or pleated elements, on the clean gas side. While passing the filter media, the particles firstly stick to the surface and then build up the filtration providing filter cake [1].

At the beginning of the filtration process a new, unconditioned filter medium is penetrated "straight through" by airborne particles and a high clean gas concentration peak occurs. In the course of the filtration process the filter cake has to be removed periodically from the surface of the filter medium in order to reduce the pressure drop. These periodic regenerations lead to typical clean gas concentration peaks by "seepage" penetration of previously collected particles [2–4].

In addition to these mechanisms, the dust penetration straight through a filter medium by "pinhole" bypass can be observed. Pinholes are small holes, which may be formed during cleaning or during filtrating [4–6]. Probable sites are the pores between yarns in woven fabrics, places where a synthetic felt was needle-punched in manufacture, small ruptures caused by mechanical stress or holes generated by pyrophoric particles. This bypass mechanism is of particular importance when "straight through" is not possible any more, due to the filter cake.

Regarding the risks for human health [7] and severe limit values for dust emissions [8], not only the regular operation but also phenomena such as the mentioned "pinhole" bypass through leaks should be observed and understood.

Taking this requirement into consideration, studies have been carried out to examine the behaviour of pinholes. Therefore, defined pinholes have been generated in filter media.

The present paper will report on results and conclusions obtained by experimental research.

2. Experimental

The test apparatus used corresponds in every way to the test device Type 1 described in the Guideline VDI 3926 [9]. The test parameters were: a raw gas volumetric flow rate of 5.8 m^3/h, a surface filter area of 0.0154 m^2 an average dust mass concentration upstream of the test filter of 5 g/m^3 and a pulse-jet cleaning tank pressure of 5 bar.

The other test parameters have been selected in such a way that dependencies on particle penetration on pressure drop and

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Nomenclature

a	ratio of pinhole volumetric flow rate
A_F	filter area (m^2)
d_h	pinhole diameter (m)
K'_1	specific permeability resistance of the filter medium (kg/(m^2 s))
N	particle number
Δp_0	initial pressure drop (Pa)
P	overall penetration of a pinholed filter
P_F	particle mass flow rate ratio of a faultless filter
q_0	number density distribution of particle size
Q	total volumetric flow rate (m^3/h)
Q_0	cumulative number distribution of particle size
Q_h	pinhole volumetric flow rate (m^3/h)
t	filtration time (s)
v	filter face velocity (m/h)
W	dust mass per unit area (g/m^2)
x	particle size (μm)
x_{max}	maximum particle size (μm)
x_{min}	minimum particle size (μm)
$x_{50.3}$	mass median diameter (μm)

Greek symbol

ρ_f	the density of the fluid under operational conditions (kg/m^3)

face velocity could be examined. Therefore, tests without filter regeneration have been carried out for every pinhole diameter until an additional test filter pressure drop of 750, respectively 1500 Pa has subsequently been reached. Additionally, tests with filter regeneration at a pressure drop of 1000 Pa have been carried out over 5 cycles. All tests have been run with face velocities of 60, 120 and 180 m/h.

As test dust, a cohesive limestone powder (Ulmer Weiss XMF) with a mass median $x_{50.3}$ of approximately 3 μm was chosen.

As well as the characterisation of the emissions by analytical filter (integral dust concentration over the total test phase in mg/m^3), optical measurements with a particle counter have been made. Thus, time-dependent number concentrations and size distributions of the emissions could be obtained.

Fractional grade efficiency tests have been carried out by generating $NaCl^-$ and DEHS-particles.

The first systematic tests have been run with thermally bonded nonwovens (250 g/m^2, polyester). Different areas of pinholes in these filter media were generated by the use of a CO_2-laser. The use of a laser ensures comparable areas for a range of filter media. The sizes depend on the laser energy.

In the systematic tests, filters with one pinhole (all in all four different sizes—series 1–4) and – as reference – filters without pinholes (series 0) have been investigated (Table 1).

Table 2
Integral clean gas side concentrations, *c*, for tests without regeneration, series 0–4

Concentration, *c*	Additional pressure drop					
	0–750 Pa			750–1500 Pa		
	180[a]	120[a]	60[a]	180[a]	120[a]	60[a]
Series 0 (mg/m^3)	4	2	1	0	0	0
Series 1 (mg/m^3)	6	9	3	12	16	19
Series 2 (mg/m^3)	15	22	43	34	53	76
Series 3 (mg/m^3)	27	41	39	56	79	103
Series 4 (mg/m^3)	69	96	114	122	184	218

[a] Face velocity (m/h).

3. Results and discussion

The integral clean gas dust concentrations show expectedly higher values for the pinholed filter media because more particles reaching the clean gas side. In the tests with additional pressure drops of 750, respectively 1500 Pa, the values get higher the bigger the pinhole diameters and the lower the face velocities are (Table 2).

For the filter medium without any pinhole, the clean gas concentrations rise with higher face velocities. And when once the filter cake has been built up, no more particles reach its clean gas side.

But on the contrary for the pinholed filter media, the clean gas concentrations rise with lower face velocities and are directly proportional to the pinhole areas.

Also noticeable is the fact that the integral clean gas side concentrations of the pinholed filter media reach much higher values in the second test phase up to 1500 Pa. This phenomenon seems to be governed by the flow conditions in the pinhole. The rising pressure drop of the filter caused by the filter cake leads to an increased velocity through the pinhole, which affects the results of fractional grade efficiency tests (see below).

The lower the face velocity is, the less the inertia-induced removal due to lower flow forces is. Hence, coarser particles, which mean higher masses, reach the clean gas side. Concurrently, there is a longer residence time for finer particles and the diffusion-induced removal is more developed.

Table 1
Theoretical pinhole diameter derived from the averaged pinhole areas of series 1–4

	Theoretical diameter (μm)	Max. pos./neg. deviation (%)	Average area (mm^2)	Max. pos./neg. deviation (%)
Series 1	288	+8/−9	0.065	+16/−18
Series 2	511	+5/−7	0.21	+10/−14
Series 3	680	+4/−5	0.36	+8/−10
Series 4	1041	+2/−4	0.85	+4/−8

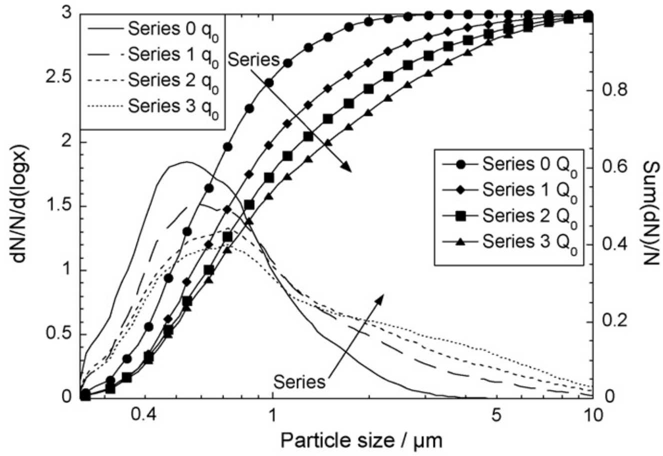


Fig. 1. Cumulative number distributions Q_0 and number density distributions q_0 in the initial filtration phase, $v = 180$ m/h.

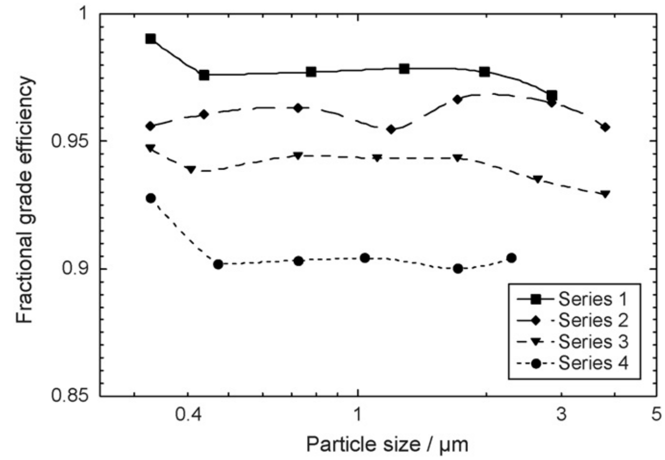


Fig. 3. Fractional grade efficiencies of virgin filter media ($\Delta p_0 + 750$ Pa), series 1–4, $v = 120$ m/h.

Because of coarser particles reaching the clean gas side already in the initial phase of the filtration, the clean gas concentrations are higher for the series with bigger pinholes. In contrast to faultless filter media, not only the "straight through" mechanism, but also the "pinhole" bypass takes place. For bigger pinholes, and therefore, lower inertial impaction near the pinholes, coarser spectra of particles at same face velocities occur (Fig. 1).

After the initial phase of the filtration, only the "pinhole" bypass can be observed. The particles get coarser in successive 180 s measurements from the beginning of the initial phase (Fig. 2). But the differences are marginal after the first 180 s.

The fractional grade efficiencies show only negligible differences for virgin filter media with or without a pinhole. Lower grades for bigger pinholes are not detectable. The resistance to flow of these filter media is quite low and only little particle-laden air passes through the pinhole first.

After reaching an additional filter respectively filter cake resistance to flow of 750 Pa, the faultless filter medium separates 100% of every particle size. But the bigger the pinhole is, the worse the particle separation gets (Fig. 3).

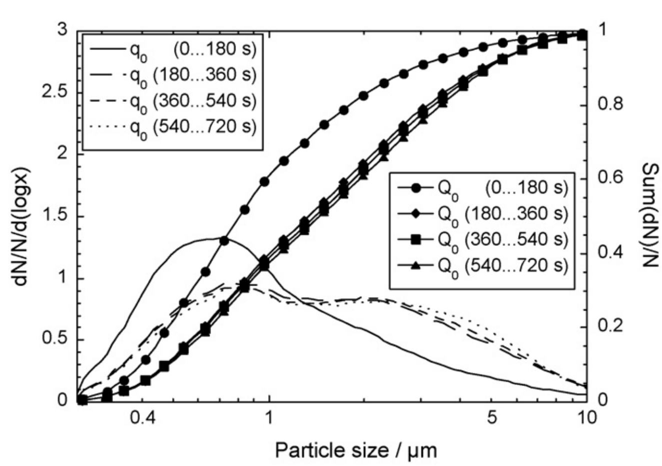


Fig. 2. Cumulative number distributions and number density distributions in four 180 s measurement periods from the initial filtration phase, series 1, $v = 120$ m/h.

After 1500 Pa of additional filter respectively filter cake resistance to flow, the fractional grade efficiencies for the smaller particles are even worse. The increase of the resistance to flow due to proceeding filter cake thickness leads to higher flow velocities through the pinholes. Thus, the bigger particles are separated more efficiently. The inertial impaction of these particles is enhanced by an exceedance of the velocities in the pinholes compared to the mean macroscopic velocities through the test filters, which is well known from the over-sampling of non-isokinetic samplers. By the formation of craters, this fact becomes apparent (Figs. 5 and 6).

To describe the phenomenon of increased clean gas concentrations caused by pinhole bypass, one has to look at the ratio of volume a, which flows through the pinhole.

$$a = \frac{Q_h}{Q} \tag{1}$$

Here Q_h is the volume flow through the pinhole and Q is the total volume flow. Thus, with a pinhole penetration of 100% an overall particle mass flow rate ratio P of the pinholed filter, assuming a particle mass flow rate ratio P_F of the intact part of

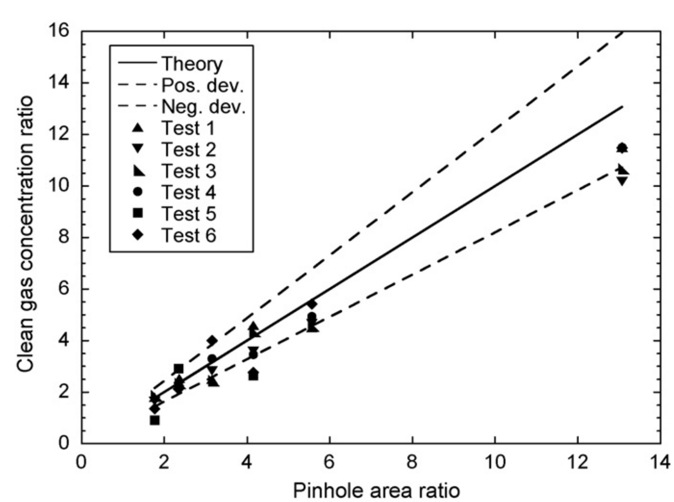
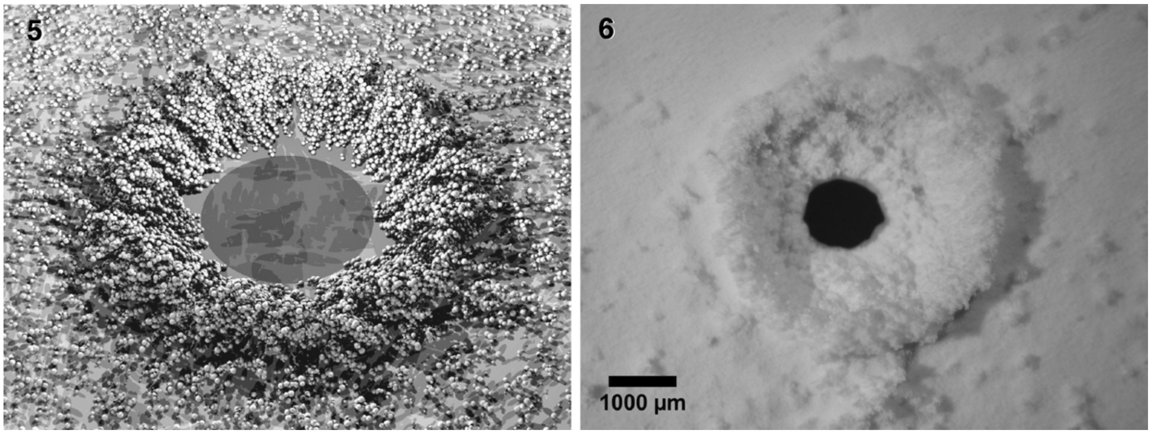


Fig. 4. Clean gas concentration ratios against pinhole area ratios.



Figs. 5 and 6. Pinhole "craters" generated by simulation and experiment.

the filter area, can be followed:

$$P = P_F - aP_F + a \tag{2}$$

The overall particle mass flow rate ratio, for example, for the beginning of the filtration process, can now be calculated by stating assumptions and using an adapted formula usually used to calculate volumetric flow rates of orifice gauges [10]:

$$P = P_F + (1 - P_F)\frac{d_h^2 \times 0.64 \times \sqrt{K_1'}}{\sqrt{v}A_F\sqrt{\rho_f}} \tag{3}$$

Here d_h is the pinhole diameter, K_1' the specific permeability resistance of the filter medium, v the filter face velocity, A_F the filter area and ρ_f is the density of the fluid under operational conditions.

The calculated results show a good agreement with experimental data of integral clean gas side concentrations (Fig. 4).

The linear dependence of the clean gas side concentrations on the increasing pinhole area at same filter face velocities is shown for the different combinations of the four pinhole diameters. The filter penetration was assumed to be 0% for these calculations and obvious measurement errors are not accounted for. The deviations of the theory can be attributed to misrepresented data due to the construction of the test apparatus.

The calculations lead to the conclusions that bigger pinholes decrease the collection efficiency and higher filter face velocities increase the collection efficiency of pinholed filters.

To represent the experimentally found dependencies, numerical flow calculations are carried out. Thereby, the aim to simulate pinhole "craters" in order to observe possible clogging effects becomes to render possible (Figs. 5 and 6).

4. Conclusions

Pinholed surface filters show a clear impact on the separation efficiencies of the test filters in experiments, such as different particle size distributions and much higher integral clean gas side concentrations than for faultless filters.

The observed pinholes in surface filters are to be rated critically concerning actual emission limit values.

The observations can be described by formulas usually used for orifice gauges. It is shown that the particulate penetration through leaks in surface filters decreases for given dust and filter medium

- the smaller the pinholes are ($\sim d_h^2$), if the filter face velocities do not vary and
- the higher the filter face velocity is ($\sim v^{-0.5}$), if the pinhole sizes do not vary.

Acknowledgement

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