Dust capacity increase of air filters by oil pre-treatment

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Keywords: Dust filter, fibrous media, oil pre-treatment, dust holding capacity

Pre-treatment of fibrous intake air filters with oil has a huge impact on their pressure drop evolution and dust holding capacity. Surprisingly, the interactions between solid particles and the oil film responsible for this effect are not well understood today. The first part of the present work was to clarify those mechanisms by experiments on the micro-scale. The second part covers experiments performed with oil-treated flat filter sheets.

Based on experimental observations and data, we present a two-stage model to describe the evolution of deposit morphology on oil-treated fibers under predominantly inertial conditions and discuss its implications for practical filter operation with respect to pressure drop evolution, dust holding capacity and filter efficiency.

In the film loading stage particles get immersed inside the oil film. Hence, particle deposition only leads to a marginally small increase in both, single fiber efficiency and fiber drag. Consequently, filter efficiency and pressure-drop will stay almost constant over long periods of the loading process, which eventually leads to a delayed (and steeper) upswing of the respective curves. By increasing the amount of oil on the fibers, the film loading stage and its associated benefits can be prolonged.

Figure 2. Pressure drop curves of flat filter sheets treated with various amounts of engine oil and loaded with ISO-12103-1 A2 filter test dust. (Müller, 2014)

Hence, an advantageous pressure drop evolution can be achieved by oil-treatment, but at the cost of higher particle penetration. However, if the initial filtration efficiency is sufficient for the respective filtration task (i.e. no improvement is required during the filtration process), oil-treatment can be utilized to increase the dust holding capacity and hence filter life-time.

Dynamical filtration of liquid aerosols on vertical fibrous filters

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Keywords: filtration, fibrous filters, liquid aerosols, numerical modelling

The aerosol filtration is a key process in various industrial plants. Indeed, the removal of solid particles or liquid droplets from gas stream is important to fulfill the environmental protection requirement as well as for obtaining the pure and uniform products of reaction.

Contrary to the filtration of solid aerosols, the mist filtration is still poorly understood, although it has been a subject of some experimental and theoretical investigations (Charvet et al., 2008; Charvet et al., 2010; Frising et al., 2005; Gac & Gradoń, 2013). The results of these papers show that the initial efficiency of fibrous filters for mist filtration may be computed in the same manner as the efficiency of the filter during solid particles filtration. Indeed, when we consider small droplets (with a diameter below 10 μm) the surface tension forces are dominant. Thus the droplet remains its spherical shape and does not exhibit any deformation, internal circulation or breakup. The coalescence between two droplets in gas stream is also rather seldom.

As a result of the loading of filtration fiber, the efficiency of the removal of large droplets (above 1 μm) increases while the efficiency of removal of small droplets decreases. This tendency is thus similar as for the solid aerosol filtration. However, the quantitative description of the filtration efficiency during the mist filtration is significantly different as that during solid aerosol filtration. The reason of these differences is the difference between the morphology of loaded fibers in both cases. For solid aerosols the dendrite-like structures of deposited particles are formed on fibers. In the case of liquid aerosols, on the other side, the liquid film or droplet appear on the surface of the fiber. There is not satisfactory theoretical description of the morphology of such a liquid-loaded fiber. The early models assumed that the deposited droplets form a cylindrical liquid film around the fiber (Frising et al., 2005). This is however invalid assumption while such a film would break into the droplet deposited because of Raileigh-Plateau instability (Mullins & Kasper, 2006). Further models tried to take this property of liquid into account but their results still did not exhibit a satisfactory agreement with the experimental results.

Another problem which has not been investigated yet is the change of the morphology of the filter working in vertical position during its loading. Almost all of the results of former investigations have been obtained for the filtration in horizontal configuration with the gas flow from upstairs to downstairs. Such a system is easier for theoretical description because of avoiding of gravimetric effects and thus limitation of the system to the axial symmetry (Charvet et al., 2008). However, in the case of the system with vertical filter there appear the difference between the loading of up and down half of the filter as an effect of drainage of the fibers. This circumstance is important while in industrial practice the liquid aerosol filters work usually in vertical position.

The aim of our work is to investigate the behaviour of the vertical filter for liquid aerosols. The experimental investigation has been done by use of the filter test system FHP 2000 (PALAS, Germany). After that, we build the theoretical model of filtration of liquid aerosol on vertical fibrous filter. The model is an extension of the model presented in (Charvet et al., 2010). The main difference is that we take into account the nonuniform decrease of the porosity of the filter as an effect of drainage and thus the breaking of symmetry of the system. To describe the gas flow through such an asymmetrically porous filter we apply the simple hydrodynamic model.

The main result of our investigations is that after the certain time there appear the steady state filtration. During this stage the mass of droplets deposited in the filter is balanced by the mass of droplets removed. However, contrary to the commonly investigated horizontal systems, in present system the droplets are removed from the filter rather by means of the reentrainment than by means of the drainage.

Droplet entrainment mechanisms from oil-mist filters

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Keywords: mist filtration, coalescence filter, blow-off, optical size analysis.

Oil-mist, consisting of fine droplets in the order of 300 nm is generated in large amount by various industrial processes, such as engine crankcase ventilation, by oil lubricated compressors or metal cutting tools. The most common method for removing such particles from an air stream is the use of fibrous filters. As a result of gas flow through the partially saturated filter media, previously collected liquid is entrained further downstream. The effectiveness of the filter may decrease significantly by such common phenomenon.

The scientific literature on oil entrainment from fibrous filters media is very sparse (Payet, 1992; Raynor, 2000; Contal, 2004). Drop formation mechanisms are not well understood on microscale, and there are no macroscale models to express dependence of entrainment on operating conditions, oil properties or filter structure parameters. Some work on oil-mist filtration has concerned mainly on macroscale phenomena on internal transport of oil which is critical for determination of pressure drop (Walsh, 1996; Charvet, 2008; Kampa, 2014) and thus of primary interest for filter design. From studies on internal oil transport it is known, that the oil arrives at the back of filter face either in form of isolated drops (in the case of non-wetting filter media, shown in Fig.1, lhs) or in form of small contiguous regions of oil resembling oil films (in the case of wetting filter media, shown in Fig.1, rhs).

Entrainment drop sizes range several magnitude orders. At the coarse end, which contains most of the mass, large blown off drops from several hundred microns up to a millimeter are observed. To detect these drops a light-sheet device was developed. A laser beam is expanded to form a plane directly after the filter. The scattered light of individual drops, which are blown off the filter and hence passing through this light-sheet, is detected via a photomultiplier. The signal height corresponds to the drop’s size. At the fine end, which contributes to most of number emission, conventional particle counters are in use.

In addition to the introduction in entrainment mechanisms, size distributions of large drops as well as their rates, blown off the filter, are discussed as a function of filtration velocity and loading rate for oil-mist filters at steady-state conditions. Some results of the optical measurements of entrainment sizes or rates are compared with visual oil patterns from the back of filter media.

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Figure 1: Visualization of drainage at back of filter from non-wetting (left) and wetting filter media (right).

Oil patterns on the back of filter media yield presumptions of entrainment mechanisms. So in the case of non-wetting filter media entire millimeter-size drops or fragments of them might be blown off by the air flow, while in the case of wetting filter media fragment drops are released by bubble bursting. Aerosols generated by bursting air bubbles have been investigated extensively for water and it is well known that this mechanism can lead to the formation of multimodal spectra. Results, mainly from visual observations, of dominating entrainment mechanisms from non-wetting and wetting filter media are discussed in detail.
Filtration properties of coalescence filters at different temperatures: a preliminary study on compressed air filters

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Keywords: coalescence filters, compressed air filters, reentrainment, viscosity, surface tension.

Compressed air filtration is based on the well known principle of the coalescence filtration and can be regarded as a highly complex process which consists of several subtasks like droplet separation, coalescence, transport and drainage of liquids inside porous filter media and reentrainment (Raynor, 2000, Kampa, 2009). In steady state operation the same liquid mass of droplets introduced as upstream aerosol is simultaneously drained from the filter such that the liquid oil mass inside the filter medium (i.e. the degree of saturation) remains constant. This degree of saturation determines the pressure drop of a filter cartridge.

The clean gas quality is determined by the penetration of primary droplets which penetrate directly the filter media and by reentrainment, i.e. redispersion of already coalesced liquid, which has to be taken in consideration when the filter medium is wetted.

Due to changing ambient conditions the temperature increase during gas compression, operational temperatures between 10°C and 60°C or sometimes even higher are possible.

In this preliminary study the influence of loading and temperature on pressure drop and clean gas quality of compressed air filters have been investigated. In a first experiment the dependency of clean gas particle concentration and pressure drop from loading at constant temperature was measured.

Fig. 1: Pressure drop and number distribution vs. loading

To measure the pressure drop and clean gas quality, a novel test rig for compressed air filters was used (Mölter-Siemens, 2011). In Fig. 1 the pressure drop and particle number size distribution are shown during a time of constant filter loading. The constant loading is realized by generating an oil droplet aerosol with mean particle size of about 0.2 – 0.4 µm. The slope of pressure drop curve initially remains constant but then changes after a loading time of about 6 hours. This is presumably caused by internal rearrangement of the liquid oil inside the filter media. During the initial 6 h period, penetration of primary droplets decreases, but then instantaneously increases drastically when the rearrangement occurs. A second rise of primary particle penetration can be seen after nearly 9h of loading when the filter approaches saturation and the pressure drop remains constant. At this point reentrainment of droplets larger than 0.5 µm appears.

Fig. 2: Pressure drop and clean gas number concentration at unsteady temperature.

In a second experiment the dependency of filtration properties on temperature was investigated. A dipped saturated cartridge was mounted in the test rig and flowed through by clean gas. An unsteady temperature profile (22°C – 32°C) was applied and the decline of pressure drop and the clean gas particle concentration were measured simultaneously (see fig. 2).

The pressure drop does not depend on temperature (the small variations are caused by changing of gas density), where as the concentration of reentrained particles is strongly temperature dependant, caused by the temperature dependency of the oil viscosity and surface tension.

Kampa, D. et al. (2009), A Model for Steady-State Oil Transport and Saturation in a Mist Filter. 18th World IMACS Congress, Cairns, Australia
Separation and agglomeration kinetics of airborne nanoparticles in bubble columns

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Keywords: pharmaceutical nanoparticles, bubble column, separation, agglomeration.

The separation of airborne nanoparticles in bubble columns represents an innovative and easy technique to produce stable nanosuspensions. This technique is used for instance in the micronisation and stabilisation of pharmaceutical agent particles as Rapid Expansion of Supercritical Solution in Aqueous Solutions (RESSAS). So far the investigations of the process aimed mostly at the experimental quantification and at the development of the descriptive models of the separation efficiency (1) (2).

However at high number concentrations as they are encountered in industrial processes the aerosol particles may undergo substantial agglomeration in the bubbles influencing the particle size and hence the separation process itself. Therefore, in the present studies the simultaneous agglomeration and deposition of airborne particle in rising bubbles were investigated. To achieve high number concentrations of small particles as they are typical for pharmaceutical agent particles generated by nucleation in RESSAS Ni-nanoparticles were produced with a dielectric barrier-discharge (DBD) generator. This aerosol was introduced into a bubble column through a nozzle. The properties of the resulting bubbles such as size, shape and rising velocity were measured with a high speed camera. In Fig. 1 the correlation of the bubble rise velocity with the bubble diameter is shown for bubbles rising in pure water.

In addition, to employ the models for the separation efficiency the relative velocity between bubbles and surrounding fluid was measured with tracer particles made of polystyrene. This is important since the relative velocity determines the internal circulation in the bubbles and influences the deposition efficiency as captured by the Fuchs model (1). While this is true for pure water the addition of surfactants may immobilise the bubble-liquid interface. This situation is described by the Friedlander model (1). The comparison between model predictions of the separation efficiency and experimental results for phytosterol particles is shown in Fig. 2. It becomes obvious that the suppression of the internal circulation greatly reduces the separation efficiency.

Finally, the Fuchs and Friedlander models were extended to include an agglomeration term. On the basis of the experimental results, the validity of the extended models was verified for the metal nanoparticles produced with the DBD generator. In this way, the complete fate of airborne nanoparticles in rising bubbles is described correctly for the first time taking into account separation and agglomeration processes.


(2) Charvet A.; Bardin-Monnier N.; Thomas D.: "Can bubble columns be an alternative to fibrous filters for nanoparticle collection?", in J Hazer Mater, Volume 195, 2011
Enlargement of submicron particles by heterogeneous condensation
for efficient aerosol separation

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Keywords: gas cleaning, wet scrubber, heterogeneous condensation, aerosol growing

Due to the trend of the reducing emission limit values and the increasing energy costs in Europe, it will be essential to have a smart combination of economic and efficient wet scrubber processes, to abate the last fine particular aerosol fractions with a diameter of smaller than 1µm. Usually for a fine aerosol fraction, a high energy consumption is necessary.

Figure 1: Simplified Holzer diagram of wet scrubbers

In a joint project with industry and university, our focus is lying on the heterogeneous condensation and the growing of aerosol particles to generate a separable aerosol diameter for the wet scrubbers. From the last 10-15 years a lot of knowledge is available about the heterogeneous condensation, about saturation and the growing of the aerosols, according to Gretschler et al. (1999) and Heidenreich et al. (2000,2005). Our goal of this R&D project is beyond the limits of inertial separation <1.5µm, what means: High raw gas particle concentrations, low saturated and the particle diameter before growing is in a range of 100nm till 300nm.

For the better understanding of efficient separation of submicron aerosols it is necessary to have more knowledge about the wetting kinetics that will be influenced from the particle shape, kind of surface, surface morphology or agglomeration. The evaluation in lab scale experiments is also important for an industrial scale implementation.

So the project is divided in to three main tasks: First the understanding for the growing in lab experiments through mixing of warm and cold particle loaded gas flows, the cooling or warming of particle loaded gas flows and the expansion of the particle loaded gas flow. The second part is to find a correct and economic energy concept for the wet scrubbing process. The third part of the R&D project is the industrial scale implementation and testing the concept in an efficient way.

In this contribution the lab experiments are introduced for the experimental determination of the characteristics of different methods for obtaining an supersaturated gas-phase. Furthermore, results are shown with different aerosols. The activation efficiency is one of the main influence values. In a second step, the transfer to an industrial process is shown. Here are high particle concentrations from more than >1·10⁶1/cm³ focused.

Figure 2: State of the Art: Influence of the particle concentration about the separation efficiency

A Multiscale Approach for Filter Simulations

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Keywords: Multiscale Modelling, Filtration Simulation, Micro-Macro-Coupling, CFD

For more than a decade, modelling and simulation of filtration processes has been one of the main research and development topics of the Fraunhofer Institute for Industrial Mathematics. Historically, micro and macro simulations have been separate approaches capable to investigate questions related to filtering media and filter elements, respectively. Simulations of fully resolved filtering media on the microscale give detailed information of flow, particle transport and deposition. However, such a direct numerical simulation approach becomes still impractical when simulating entire filter elements due the required computer power, i.e. memory consumption and run-time.

We pursue the following approach to avoid the computational complexity and while keeping a reasonable amount of microscale information in the simulation: Let us consider the filter element in Fig. 1.: There is an inlet and an outlet on the bottom and on the top, respectively. The filtering medium is drawn in dark grey and the arrows indicate some streamlines. We consider the filtering medium as a porous medium possessing effective properties like permeability and particle deposition rates for instance. Up-to-now, the model is purely macroscopic. To determine the effective properties of the filtering medium, which are by the way time dependent in general, we employ fully resolved virtual microstructure models being representative for a certain number of locations (indexed by $\alpha$ and $\beta$ in Fig. 1) in the filtering medium. To simulate the filtration process in time, permeabilities and particle deposition rates are computed on the microscale. These data are used as input parameters for the macroscopic filter element simulation, together with an interpolation step onto each discretization cell. The macro simulation in-turn provides local flow velocities and particle concentrations after a certain time interval and the micro simulations are restarted with updated boundary conditions.

In the presentation, we will focus on the aforementioned iterative multiscale approach, show simulation examples and discuss the software realisation by coupling of the tools GeoDict and FiltEST by Math2Market GmbH and Fraunhofer ITWM, respectively.
Influence of filter structure on the filtration efficiency and pressure drop – non-steady state loading

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Keywords: aerosol filtration, fibrous filter, melt-blown, modelling.

Three polypropylene melt-blown fibrous filters having various morphology were tested. Their precise structural analyzes and their behavior during the initial stage of filtration were presented in the previous abstract (Influence of filter structure on the filtration efficiency and pressure drop – initial stage). In this work it was checked how the main parameters characterizing fibrous filters, i.e., pressure drop across the filter and filter efficiency, change during continuous loading with polydisperse solid silica particles (see photos of the loaded filters in Figure 1). The figures 2-3 show changes in pressure drop and overall numerical efficiency in time.

As it was shown in the previous abstract (Influence of filter structure on the filtration efficiency and pressure drop – initial stage) on the basis of our experimental results, the initial character of filtration process depends on the filter structure. Therefore, depending on the filter morphology its operation parameters, i.e., the pressure drop and filtration efficiency, change with the duration of the process.

The models of hydrodynamic and aerosol movement described in previous abstract were used to calculate the time evolution of filter performance. Four different structure models, regarding to fiber size distribution and regularity of the structure, were proposed: a) Basic model (regular structure, monodisperse fibers), b) Regular structure, log – normal fiber size distribution, c) Randomized structure, monodisperse fibers, d) Randomized structure, log – normal fiber size distribution. As one can see, the theoretical results underestimate the filtration efficiency. Assumption of polydispersity of fiber sizes increases the predicted values of filtration efficiency. It is probably related to presence of small fibers in the filter structure. On the other hand the randomization of filter structure causes the decrease of predicted filtration efficiency, what may be explained by the fact of channelling of the aerosol stream through the filter regions of higher porosity.

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Influence of filter structure on the filtration efficiency and pressure drop - initial stage

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Keywords: aerosol filtration, fibrous filter, melt-blown, lattice-Boltzmann, Brownian dynamics.

Filtration is one of the most effective methods of particle removal from an aerosol stream. New fibrous structures may be conducive to the development of highly efficient filters for the capture of aerosol particles. Its effectiveness depends on the particle and fiber size, filter porosity and material properties of particle and filter media. Performance of a filter can be defined by its efficiency, pressure drop and lifetime.

This work includes both experimental data on the filtration process as well as their theoretical description. Three various filters (see photos in Figure 1) made by us using the melt-blown technique were tested (Jackiewicz et. al, 2013). Utilizing this the most promising technique, through selection of the appropriate process conditions, the filters of desired structures for a certain application may be obtained.

The analyzed filters’ structures were characterized and results (filter thickness, \(L\), solidity, \(\alpha\), basis weight, \(q_s\), arithmetic mean fiber diameter, \(d_{fa}\), together with arithmetic standard deviation, \(\sigma_{adF}\)) are summarized in Table 1.

<table>
<thead>
<tr>
<th>Filter</th>
<th>(L) [mm]</th>
<th>(\alpha) [-]</th>
<th>(q_s) [g/m²]</th>
<th>(d_{fa}) [μm]</th>
<th>(\sigma_{adF}) [μm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>F10</td>
<td>2.98</td>
<td>0.105</td>
<td>282.9</td>
<td>8.99</td>
<td>0.76</td>
</tr>
<tr>
<td>F5</td>
<td>1.81</td>
<td>0.072</td>
<td>117.1</td>
<td>5.60</td>
<td>0.99</td>
</tr>
<tr>
<td>Fnano</td>
<td>1.75</td>
<td>0.029</td>
<td>54.9</td>
<td>0.47</td>
<td>0.83</td>
</tr>
</tbody>
</table>

In the next stage of work filtering media were examined with Palas MFP 2000 test bench for determination the initial pressure drop across the filters and their initial filtration efficiency. As the standard test particles in the size range of submicrometers and micrometers the Arizona Fine Test Dust ISO 12103-1 (Power Technology Incorporated, USA) was used. The experiments were performed for the air velocity of 0.2 m/s.

The obtained experimental results were compared with predictions of the theoretical model. The model combines lattice-Boltzmann hydrodynamics (Qian et al., 1992) with Brownian dynamics model for aerosol particle motion (Podgórski, 2001). The use of lattice-Boltzmann model enables to easily change boundary condition of fluid flow due to the deposition of particles, while Brownian dynamics method allows to take into account all forces acting on the moving particle. The good accuracy between experimental data and theoretical predictions was found.

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Numerical study of air flow at the vicinity of a fibrous pleated filter

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Keywords: porous media, filtration, CFD simulation.

This study deals with the implementation of numerical simulations of air flow at the vicinity of a fibrous pleated filter typically used in HVAC systems of buildings for urban aerosol collection. The main aim is to use the CFD calculations to analyse the influence of the pleated geometry on the local performances of the filter which is also tested experimentally.

The filtering media studied is a G4 prototype pleated filter, according to European standard EN779, with a filtration surface of 615 ± 109 cm². The porous media is constituted from cotton and polyester fibers. The main structural parameters of the media are presented in Table 1. The height H and the width W of the pleat are respectively 40 mm and 23 mm.

Table 1. Main structural parameters of the media.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thickness t (mm)</td>
<td>2.8 ± 0.7</td>
</tr>
<tr>
<td>Fiber diameter (µm)</td>
<td>13.8 ± 4.4</td>
</tr>
<tr>
<td>Porosity (-)</td>
<td>0.92</td>
</tr>
<tr>
<td>Media weight (g/m²)</td>
<td>85 ± 5</td>
</tr>
</tbody>
</table>

The computational domain used to implement the simulations is two-dimensional, and it is constituted by a half pleat included between two symmetry planes (Figure 1). The turbulence model chosen is k-ε. A constant velocity is imposed at the inlet of the geometry, where the turbulent intensity and the hydraulic diameter are respectively 5% and 0.115m (half pleat height). At the outlet the pressure is imposed, and the reference value chosen is 101325 Pa.

The governing equations for the air flow are the Navier-Stokes equations which are solved at steady-state. The pressure drop generated by the porous media is calculated by the Darcy Forchheimer equation (Equation 1) which takes into account the viscous as well as the inertial resistances to the flow. The viscous and inertial resistances involve respectively the permeability B and an inertial coefficient C. These physical parameters are determined from pressure drop measurements in flat filter configuration perpendicular to the flow, and the values obtained are 2.02x10⁻⁹ m² for the permeability and 8.7x10⁻² m⁻¹ for the inertial coefficient.

\[ \nabla P = \frac{\mu}{B} v + C \left( \frac{1}{2} \rho \left( \frac{v}{\nu} \right)^{1.8} \right) \]

For the numerical simulations in the pleated filter we consider that the previous permeability value represents the through-plane permeability of the fibrous media. We estimate the in-plane permeability by considering a 1.8 ratio between the in-plane and the through plane permeability obtained by Fotovati et al. (2011) for similar fibrous media. The same hypothesis is made for the inertial coefficient.

In order to validate the numerical simulations the pressure drop across the pleated media is compared to the experimental data (Figure 2), for inlet velocities ranging from 0.8 to 3.1 m.s⁻¹, corresponding to filtration velocities (which is the inlet velocity multiplied by the ratio of the air duct area and the filtration area) ranging from 0.18 to 0.72 m.s⁻¹.

Figure 2: Comparison between experimental and simulated pressure drop across the pleated filter

The Figure 2 shows that the pressure drop predicted by the simulations well agree with the experimental data. The CFD calculations are thus used to analyse the local velocity gradients resulting from the filter geometry which can be responsible for local variations of the filter particle collection efficiency.