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# Transmitted-light microscopy – a new method for surface structure analysis of cleanable non-woven dust filter media

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**Abstract**

With regard to the more stringent legislation in environmental protection strong efforts have been made to reduce fine dust emissions. As a result filter devices equipped with dry operating cleanable textile filter media have become one of the most favoured separation techniques for fine dust. For improvement of cleanable filter media it is necessary to understand the influence of their structure on their filtration behaviour and to develop parameters for characterising their clogging and penetration behaviour.

The aim of the research work presented in this paper was to improve the already developed reflected-light method [W. Koschutnig, G. Mauschitz, W. Höflinger, Charakterisierung der Oberflächenbehandlung und des Verstopfungsverhaltens von abreinigbaren Staubfiltermedien mittels Bildanalyse, CIT 76, 2004, 10, 5 pp.] to get a structure parameter of cleanable non-woven dust filter media, which can give information about the particle penetration. To reach this goal transmitted-light is used instead of reflected-light. By that way images with higher contrast will be achieved which enable to define a mean hydraulic diameter for the pores near the outer surface of cleanable non-woven dust filter media.

Experimental measurements were carried out which prove that the mean hydraulic pore diameter can be a measure for the particle penetration of a filter medium. The pore volume equivalent, which can be used as a measure of the dust storage capacity of the filter medium can also be detected by the transmitted-light method.


*Keywords:* Baghouse filter; Filter clogging; Filter test; Image analysis; Non-wovens; Pore structure characterisation

## 1. Introduction and problem description

For the separation of fine dust from gases, cleanable filter media are used. To face the specific requirements of a filtration process, a wide range of different filter media are applied. Several characteristic values of filter media are available and can be used for the pre-selection of filter media. In particular material-specific parameters (e.g. fibre diameter, thickness of filter medium, weight per unit area, etc.) are applied, but structural parameters are missing although they could give information about the clogging and separation behaviour of textile filter media.

During the research project *“Structural Analysis of Thermally Finished Non-wovens for the Description of their Filtration Behaviour in Cleanable Filters”* – financially supported by the Austrian Research Fund (FWF) – two structural parameters [1] were created to describe the porosity of the surface and the fibre layers near the surface of non-wovens respectively.

- The two-dimensional top-layer porosity (surface porosity).
- The pore depth distribution of the partial fibre layer below the surface (PF-layer).

The porosity situation near the surface of the non-woven cleanable filter media is essential for particle clogging. An optical method based on computer aided image analysis was developed for the measurement of this parameter.

The initial method (Fig. 1a) [2] works with direct illumination of the specimen. The reflected-light is detected. Fibres on the surface are directly illuminated and appear brighter than the dark coloured pores in the specimen. It is thus possible to differ between the surface and the pores of a filter medium.

The new method uses a light source underneath the specimen (Fig. 1b), thus detecting the transmitted-light. The surface

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**Nomenclature**

| | |
|---|---|
| $A_i$ | area of pore $i$ (μm$^2$) |
| $A_{p,tot}$ | total area of analysed pores (μm$^2$) |
| $d_h$ | mean hydraulic pore diameter (μm) |
| $E_0$ | surface porosity (−) |
| $h_p$ | pore depth (μm) |
| $h_{p50,0}$ | median pore depth (μm) |
| $H$ | pore volume equivalent (μm) |
| $k_{acc}$ | accumulation factor (g/(m$^2$ μm)) |
| $m_{attached}$ | dust mass attached on the surface of the filter medium (g/m$^2$) |
| $m_{res}$ | residual dust mass (g/m$^2$) |
| $m_{within}$ | dust mass stored inside the filter medium (g/m$^2$) |
| $N_{tot}$ | total number of analysed pores (−) |
| $O_i$ | circumference of pore $i$ (μm) |
| $O_{p,tot}$ | sum of the circumferences of all analysed pores (μm) |
| $Q_0(h_p)$ | cumulative pore depth distribution (−) |

thereby appears dark coloured and the pores light and bright. The advantage of the method is to get pictures with a higher contrast compared with the reflected-light method. So it is easier to differ between pores and the surface. Because of the better contrast of the images it is also possible to calculate another structural parameter, i.e. the mean hydraulic diameter of the pores near the surface of the filter medium.

The aim of the research work is the demonstration of the transmitted-light method for evaluating the pore situation near the surface of a filter medium and to find out if the determined porosity parameters can be a measure for the dust storage capacity and particle penetration of the filter media.

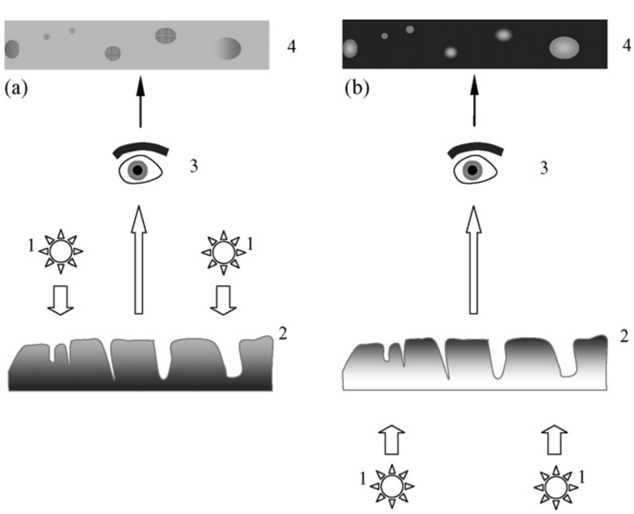


Fig. 1. Reflected-light microscopy (a) vs. transmitted-light microscopy (b) for surface structure analysis of cleanable non-woven dust filter media. (1) Light source; (2) specimen; (3) optical detection device; (4) image of the surface of the specimen.

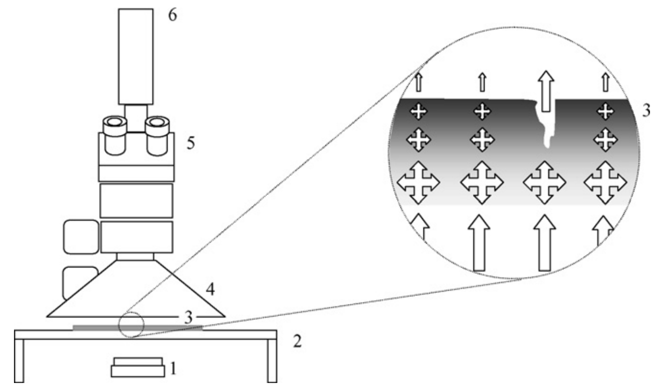


Fig. 2. Experimental set up: (1) cold-light source; (2) optical desk; (3) specimen; (4) cover shield; (5) microscope; (6) camera.

## 2. Experimental set up

The main parts of the experimental set up are a bi-ocular light microscope (LEICA MZ8) equipped with a cold-light source and a CCD camera (SONY XC-003P). The specimen is placed on an optical desk. The light source is mounted in a holder underneath the desk. By passing the specimen, light is scattered and absorbed (Fig. 2). The light intensity decreases across the specimen. To minimize the influence of daylight a shield is mounted around the objective of the microscope. The surface of the filter medium appears dark coloured. The pores in the surface layer through which the particle/air fluid can penetrate into the depth of the textile filter medium appear with different brightness contrary to the dark coloured surface.

From each circular filter sample (diameter 165 mm) 20 pictures (each 2390 μm × 1860 μm, 80-times magnified) are recorded by the observation system. The observed areas of the specimen are randomly distributed. The different colours, brightness and contrast ratios of the image are analysed by a special computer algorithm to convert the colour image in an image with different grey values and finally the picture is transformed in a binary image. The black coloured areas in the binary image are equivalent to the surface. The white-coloured areas in the picture correspond to the pores, which are opened towards the surface of the filter medium. The surface porosity $E_0$ is by definition the ratio of the area of the pores (white coloured parts of the binary image) to the total area of the recorded image of the filter medium. Due to the inhomogeneity of the surface of the needle felt the results from the analysed detail images vary. Therefore an average value for the surface porosity is calculated from all 20 individual results of determination.

For the pore depth distribution $Q_0(h_p)$ of the partial fibre layer (PF-layer) below the surface the depths of single pores at 100 representative measuring positions on each filter sample were optically measured like it is also made by the reflected-light method [3]. At first the bottom layer of the pore opened to the surface of the filter sample is focussed. The bottom of the pore is formed by textile fibres of deeper layers of the filter medium. Then the upper margin of the same pore at the surface of the textile filter medium is focused. The indicated value on the scale of the focussing drive of the microscope makes it possible to accu-

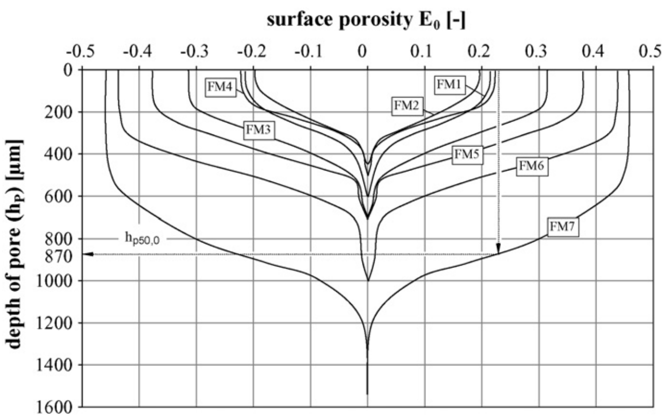


Fig. 3. Structural analysis of different non-dusted filter media (characterised in Table 1), which are used for the following filter tests.

rately determine the vertical distance in micrometer between the bottom and the entrance of the analysed pore. The evaluation of the pores according to their depths and their numbers gives a pore depth distribution of the PF-layer. The function of the pore depth distribution can be used to calculate a median pore depth $h_{p50,0}$. This value indicates that 50% of all optically detected pores of the PF-layer have a pore depth below the pore depth $h_{p50,0}$.

The total curve of pore depth distribution is used to formulate a model pore, which approximately characterises the porous structure of the surface fibre layer. The geometry of this pore can be derived from the surface porosity ($E_0$) and the pore depth distribution $Q_0(h_p)$. Finally a pore volume equivalent ($H$) is defined as the product of the surface porosity $E_0$ and the median pore depth $h_{p50,0}$ (µm)

$$H = E_0 \times h_{p50,0} \quad (1)$$

In the following it will be investigated whether it is possible to evaluate the ability of the investigated non-wovens to store particles in their PF-layers, using their pore volume equivalents $H$.

The graphs shown in Fig. 3 are examples of model pores (related to $E_0$) representing the porous surface structures of the PF-layers of different tested filter samples. The results of the calculated porosity data are summarized in Table 1.

Table 2
Experimental parameters for the filter tests

| Test filter medium | PI, PPS and PET needle felts |
|---|---|
| Effective surface area of a filter sample | 176 $cm^2$ |
| Test dust | $Al_2O_3$ ($d_{50,3}$ = 4.10 µm) (Sasol Pural) |
| Dispersing fluid | Ambient air |
| Filter face velocity | 0.05 $m\,s^{-1}$ |
| Dust concentration at the filter | 5.0 $g\,m^{-3}$ |
| Pressure loss before cleaning | 1000 Pa |
| Valve opening time | 150 ms |
| Tank pressure (filter cleaning) | 0.4 MPa |

The experimental investigations of the filtration and cleaning behaviour of the surface- analysed non-wovens were carried out by using a test apparatus for textile filter media with horizontal test channel (type 2) as recommended by VDI 3926. As a result of these tests the residual dust masses of filter samples and the mean clean gas concentrations are recorded.

Table 2 summarizes the experimental parameter set-up for the tests of the textile filter media.

The dust loaded raw gas stream was generated by drawing ambient air into a horizontal raw gas channel where test dust in exactly known amounts was added by using a brush feeder. The dust-loaded raw gas stream then passes through the filter sample. The circular filter sample (diameter 165 mm) to be investigated is mounted flat in a filter fixture and separation of the dust particles by the filter sample causes the formation of a test dust filter cake.

The pressure loss across the filter sample is continuously monitored. When the pre-determined maximum pressure loss across the dust loaded filter sample is achieved the filter cake is removed by pulse jet cleaning, using a pulse of compressed air coming from the clean gas side of the apparatus. After regeneration of the filter medium the next filtration cycle starts. A complete test series includes 100 filtration/cleaning cycles.

After 100 cycles the total dust mass stored inside the filter media is measured by differential weighing. This mass is a measure how much dust can be stored inside the compared filter media.

Secondly an absolute filter is situated behind the tested filter medium, which collects most of the dust, which is going through the investigated filter sample during 100 cycles.

Table 1
Porosity data of tested polyimide (PI), polyphenylene sulphide (PPS) and polyester (PET) filter media

| Sample | Filter medium | Finishing | Surface porosity, $E_0$ (−) | Mean pore depth, $h_{p50,0}$ (µm) | Pore volume equivalent, $H = E_0 \times h_{p50,0}$ (µm) | Mean hydraulic pore diameter $d_h$ (µm) |
|---|---|---|---|---|---|---|
| FM1 | Spun lace PI/glass | Singed | 0.21 | 271 | 57 | 40 |
| FM2 | Spun lace PPS/glass | Singed | 0.20 | 224 | 45 | 43 |
| FM3 | Needle punched PI | Singed | 0.31 | 376 | 117 | 57 |
| FM4 | Needle punched PPS | Singed | 0.22 | 229 | 50 | 45 |
| FM5 | Needle punched PET | Singed | 0.37 | 376 | 139 | 61 |
| FM6 | Needle punched PPS | Not surface treated | 0.43 | 487 | 209 | 70 |
| FM7 | Needle punched PI | Not surface treated | 0.46 | 870 | 400 | 79 |

In order to find out if the pore volume equivalent $H$ can be a measure for the dust holding capacity of a filter medium, H was calculated for different filter media shown in Fig. 3. Finally the measured total dust mass is related to pore volume equivalent.

## 3. Results and discussion

The test results show a nearly linear correlation [4] between pore volume equivalent ($H$) and the dust mass stored inside the filter medium, as illustrated in Fig. 4. Thereby the needle felts with small pore volume equivalents (FM1, FM2, FM4) store less dust inside than filter media with a larger pore volume equivalent (FM6, FM7) and therefore $H$ can be seen as a measure for the dust holding capacity of a filter medium.

It can also be seen that the residual dust mass for given test conditions is a linear function of the pore volume equivalent, which cuts the $y$-axis at a positive value $m_{\text{attached}}$. $m_{\text{attached}}$ symbolizes the residual dust mass which is attached on the surface of the filter media and will not be directly affected by the porosity of the filter media. Consequently the whole measured residual dust mass $m_{\text{res}}$ is a sum of the dust mass stored inside the filter medium $m_{\text{within}}$ and $m_{\text{attached}}$

$$m_{\text{res}} = m_{\text{within}} + m_{\text{attached}} = k_{\text{acc}} \times H + m_{\text{attached}} \quad (2)$$

The accumulation factor $k_{\text{acc}}$ is an experimental value which relates the residual dust mass to the pore volume equivalent $H$. $k_{\text{acc}}$ is only dependent on the kind of dust and the operation conditions and not on the kind of filter media, because different kinds of filter media follow the same linear relationship.

It is furthermore possible to calculate a mean hydraulic pore diameter from the images. Therefore the equation for the hydraulic diameter ($d_{\text{h}}$) is used

$$d_{\text{h}} = \frac{4A_{\text{p,tot}}}{O_{\text{p,tot}}} = \frac{4\sum_{i=1}^{N_{\text{tot}}} A_i}{\sum_{i=1}^{N_{\text{tot}}} O_i} \quad (3)$$

In this equation $A_{\text{p,tot}}$ represents the whole surface pore area and $O_{\text{p,tot}}$ represents the sum of all circumferences of the detected surface pores.

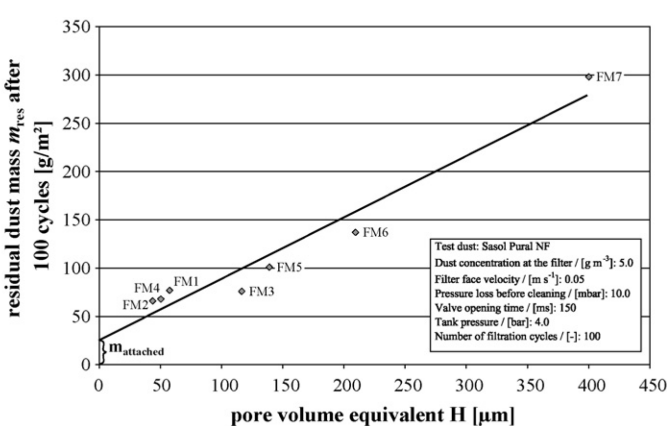


Fig. 4. Residual dust mass after 100 cycles as function of pore volume equivalent ($H$) of tested needle felts.

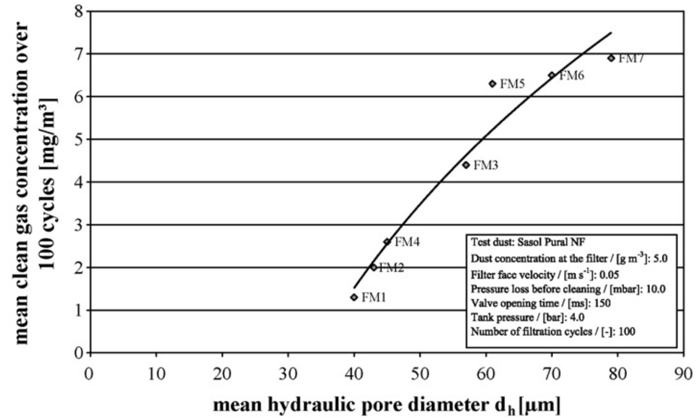


Fig. 5. Mean clean gas concentration over 100 cycles as a function of the mean hydraulic pore diameter of the non-dusted PI-, PPS-, PET-needle felts.

Fig. 5 shows an interesting correlation between the mean clean gas concentration over 100 cycles which was measured with the absolute filter and the calculated mean hydraulic diameters for the tested filter media. Obviously there is also a relationship between these values which indicates that the mean hydraulic pore diameter can be a measure for the particle penetration through filter media. The needle felts with a larger mean hydraulic diameter (FM6, FM7) show a higher clean gas concentration than the filter media with a smaller value for the mean hydraulic pore diameter (FM1, FM2, FM4).

A reason for curve progression can be the different formation of dust bridges above the pores during a filtration cycle. Thereby dust bridges above small pores are generated earlier which cause lower penetration in comparison to greater pores. Further investigations of this matter are ongoing.

## 4. Summary

For improvement of cleanable filter media it is necessary to understand the influence of their structure on their filtration behaviour. Using transmitted-light microscopy instead of reflected-light microscopy it is possible to make the pore structure near the outer surface of cleanable non-woven filter media with a higher contrast visible.

From the high contrast images it is possible to calculate a mean hydraulic diameter for the pores near the surface of filter media. Experimental results show that there is a correlation between calculated mean hydraulic pore diameter and mean clean gas concentration. Thereby tested filter media with smaller mean hydraulic pore diameter show a lower mean clean gas concentration than filter media with larger mean hydraulic pore diameter.

The investigations show that surface porosity and pore depth distribution can also be detected by the transmitted-light method. These structural parameters are used to calculate a pore volume equivalent, which is a measure for the dust storage capacity of filter media. Together with the accumulation factor, which is a storage factor for given test conditions, the clogging behaviour of cleanable non-woven filter media can be estimated.

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