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A MODEL FOR SIMULATION OF PARTICLE COLLECTION IN FILTER MATS

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Abstract. The most important parameters of fibrous filters: the separation efficiency and pressure drop change during the operation. Theoretical and experimental investigations have been carried out to develop an adequate model for numerical simulation of the clogging process. The model and some results of numerical simulations are presented in this paper. Also basic considerations on the combination of the particle deposition, on fibres inside the filter, and the formation of dust cake are suggested.

Keywords: Filtration, dust, clogging, numerical simulation, flow field

1. Introduction

Fibrous filter mats play a significant role in the separation of solid particles and drops suspended in gas. Their wide application in air pollution control and in different technologies is justified by their reliability of service and relatively low overall cost. The porous layers are produced either as woven fabrics or as felts. The most significant disadvantage of filters is the time dependence of their operation parameters. The temporal change is the consequence of the way of separation of particles in filters: the particles deposit on the fibres, increasing both the filtration efficiency and the pressure drop (at constant flow rate). This characteristic makes the design and in some cases also the operation of filters difficult. The objective of the research presented here is the investigation on the mechanism of particle deposition with special regard to the effect of the previously separated particles and the inhomogeneity of filter structure as well as the development of a model for simulation of the clogging process in fibrous filters.

2. Dust separation by filter mats

Industrial gases of usual concentrations, cleaned by fibrous filters, are very thin mixtures of gas and solid particles. Even in case of relatively high concentration, $c = 10\frac{g}{\mathrm{m}^3}$, the average distance between particles is about 50 particle diameters which is in most cases in the range $10^{-1} < d_p[\mu\mathrm{m}] < 10$. Fibrous filters consist of cylindrical fibres of $d_f = 5 - 30\mu\mathrm{m}$ diameter, the average distance between fibres is about $2 - 10$ fibre diameters. Since the distance between fibres is in general much bigger than the particle diameter, the particles should be displaced relative to the gas in order to put them in contact with the fibres. This transport is caused by inertia of particles, by gravity and at smaller particles by diffusion. In case of charged particles and/or fibres the electrostatic attraction plays a role. Particles can contact the fibres also without displacement if they move along streamlines approaching the surface of the fibres at most at one particle radius distance (interception). The displacement of particles is hindered by viscous forces arising when particles move relative to the gas.

The influence of the deposited particle on the separation of further particles and on pressure drop was investigated and described by [1] - [3], but because of the neglect of significant influencing factors the results obtained are only qualitatively correct. Deposited particles form dendrites under certain condition , which act as thin fibres influencing both the filtration efficiency and the pressure drop [3] - [5]. The description of the very complicated processes of particle deposition has been simplified by using the isolated fibre approach. In [3], [5], [6] the effect of dust load on filter has been considered by modification of single fibre efficiency. Most of the authors suggested a linear relation between the concentration of deposited particles and the increase of single fibre efficiency:

$$\eta_{\mathrm{l}}/\eta_{\mathrm{f}} = 1 + \lambda c_{\mathrm{d}}, \tag{2.1}$$

where η_{l} and η_{f} is the single fibre efficiency of loaded and clean fibres, respectively, $c_{\mathrm{d}}[\frac{\mathrm{kg}}{\mathrm{m}^3}]$ is the concentration of deposited particles, γ is a factor depending mainly on the characteristics of fibres. The value of single fibre efficiency expresses the ratio of the number of particles deposited on a given fibre and that of approaching the fibre in a layer of thickness equal to the fibre diameter d_{f}.

As a result of the first phase of research reported here, the author suggested a method for calculating 3D flow field in inhomogeneous filter mats [7], and a simplified 1D model for describing the clogging process in filters [8]. A 3D model for calculation of dust deposition in real filter mats was published [9] but it doesn't take the particle deposition into consideration. In the second phase of research, 3D calculation of flow in filter mats and the extended dust deposition model have been combined [10], [11]. At high filter load at first continuous layer of dust particles, later a dust cake arises at the inlet of the filter mat. A model and numerical simulation have been developed [12] to predict the process of cake formation. Recently measurement results have been published [14] on the size of dendrites of deposited particles. On the basis of these results development of a comprehensive model combining the dust deposition inside the filter mat and the formation of a dust cake in the final period of the lifecycle of the filter seems to be realistic.

3. Model for dust deposition inside filter mats

3.1. Simulation of particle deposition in filter mat. Because of the complexity of flow in real filter mats due to complex fibre structure and because of the large number of dust particles (in case of $d_{\mathrm{p}} = 3\mathrm{mm}$ particle size and $10\frac{\mathrm{g}}{\mathrm{m}^3}$ concentration the number of particles in $1\mathrm{cm}^3$ is $3.5 \cdot 10^5$) the direct simulation of dust separation process still seems to be impossible. That is why a simplified model has to be developed relying on basic laws of fluid mechanics as well as on assumptions based on experimental investigations. So since the dominant position of the fibres is parallel to the surface of the mat and the dominant direction of filtration velocity is perpendicular to it, the fibres are supposed to be perpendicular to filtration velocity. From the point of view of the flow field the individual fibres are disregarded: the filter mat is considered as a porous layer of spatially and temporally changing permeability. The model for calculation of the clogging process can be divided into two interconnected parts: simulation of particle deposition and calculation of flow field in filter mat. The model described here is elaborated for monodisperse ($d_p = \text{const.}$) dust particles.

As a result of considerable efforts made in this field a number of expressions have been published for the calculation of the collection efficiency of clean single fibres. The expressions proposed in [9] have been used by the author to calculate the single fibre efficiency in case of no dust deposition.

The suggested model takes the effect of collected particles in the following way into consideration. The deposited particles take part in the collection of subsequent particles by increasing the collecting surface of the filter mat. Not the whole surface area of the deposited particles should be regarded as additional collecting area, because the particles and fibres "shadow" each other (see Figure 1). This effect is considered by the shadowing factor $k = 0.5$, i.e. on the basis of simple geometrical considerations about half of the surface area of deposited particles (which are regarded as spheres) increases the collecting area of the filter mat.

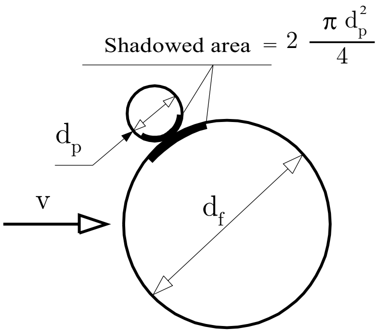


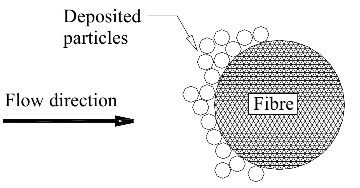
Figure 1. Shadowing effect

On the basis of experimental observations three different models of particle deposition have been suggested. In case of low filter loading, at the beginning of the filtration process, the majority of the deposited particles cover the surface of the fibres, which can be taken into consideration as increase of fibre diameter: thickening model, see Figure 2.

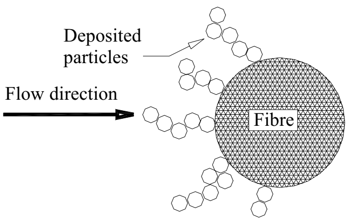
At higher filter load the ratio of particles collected by the deposited particles is increasing, so more and more model. During the filtration process the combination of these two models occurs, called combined model (Figure 2).

Since the particles deposited according to the thickening model and the dendrite model influence the separation and pressure drop differently, the share factor b is suggested expressing the ratio of amount of particles forming dendrites to the amount of all deposited particles. On the basis of the published evaluation of experimental results and our own measurements, linear correlation has been found between the share factor and the concentration of particles collected previously

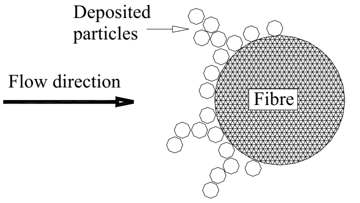
$$b = 0.024 c_d\,. \tag{3.1}$$



a. Thickening model



b. Dendrite model



c. Combined model

Figure 2. Deposition models

The efficiency (E) of filter mat of Δx width can be expressed:

$$E = 1 - \frac{c_0}{c_\mathrm{i}} = 1 - exp\left(-\frac{a_\mathrm{f}\eta_\mathrm{l}}{\pi}\Delta x\right), \tag{3.2}$$

where c_0 and c_i $[\frac{\mathrm{kg}}{\mathrm{m}^3}]$ is dust concentration at the inlet and outlet of filter layer, respectively, and a_f $[\frac{\mathrm{m}^2}{\mathrm{m}^3}]$ is the specific area of fibres.

In equation (3.2) the single fibre efficiency of loaded filter ηl includes the effect of collected particles. According to the suggested model it can be expressed in the following way [11]:

$$\eta_\mathrm{l} = \eta_\mathrm{f} + \frac{\eta_\mathrm{f} c_\mathrm{d}}{\rho_\mathrm{p} d_\mathrm{p} a_\mathrm{f}}\left[3\left(1-b\right) + \right.$$
$$\left. +4b\left(\frac{\eta_\mathrm{dend}}{\eta_\mathrm{f}} - k\right)\right], \tag{3.3}$$

where ρ_p $[\frac{\mathrm{kg}}{\mathrm{m}^3}]$ is the density of dust particle and η_dend is the single fibre efficiency of the dendrites. The comparison of equation (3.3) and equation (2.1) with experimental results shows that equation (3.3) based on model considerations describes much more accurately the influence of deposited particles on particle collection than equation (2.1) suggested previously [10].

3.2. Calculation of 3D flow field in filter mats. Because of the small size of particles and fibres and the relatively low filtration velocity the particle or fibre Reynolds number is small, so the flow in porous filter mats is laminar. The pressure drop Δp [Pa] across the filter mat, needed to reach a given filtration velocity v_f $[\frac{\mathrm{m}}{\mathrm{s}}]$ through the filter mat can be determined as the aerodynamic force acting on fibres in filter mat of $1\mathrm{m}^2$ area:

$$\Delta p = \frac{4\pi}{Ku}\mu L v_\mathrm{f}, \tag{3.4}$$

where μ $[\frac{kg}{\mathrm{ms}}]$ is the dynamic viscosity, Ku is the Kuwabara coefficient [13]:

$$Ku = -0.5\ln\alpha - 0.75 + \alpha - 0.25\alpha^2, \tag{3.5}$$

depending on the packing density $\alpha = \frac{V_\mathrm{f}}{Vm}$ of the filter mat (V_f and V_m is the volume of fibres and filter mat, respectively), and L [m] the overall length of fibres in filter mat of $1\mathrm{m}^2$ area and h [m] thickness:

$$L = 4\alpha s/{d_\mathrm{f}}^2\pi\ . \tag{3.6}$$

Inserting equation (3.6) in equation (3.5) and substituting the thickness of the layer h [m] by Δx (x co-ordinate is perpendicular to the surface of the filter mat and pointing in the direction of the flow) and considering that the gas is flowing in the direction of pressure decrease, the x component of the filtration velocity can be expressed:

$$v_{\mathrm{fx}} = -\frac{Ku{d_{\mathrm{f}}}^2}{16\mu\alpha}\frac{\Delta p}{\Delta x} \ . \tag{3.7}$$

Equation (3.7) shows that by neglecting the inertia of fluid and particles in comparison with viscous forces and effect of pressure gradient, the generalised form of Darcy equation can be formulated:

$$\mathbf{v} = -C\nabla p \tag{3.8}$$

where C $[\frac{\mathrm{m}^3\mathrm{s}}{\mathrm{kg}}]$ is the permeability coefficient which can be expressed in case of loaded filters as

$$C = \frac{Ku}{16\mu}\frac{1}{\dfrac{\alpha}{d_{\mathrm{f}}^2} + \dfrac{bc_{\mathrm{d}}}{\rho_{\mathrm{p}}d_{\mathrm{p}}^2}} \ . \tag{3.9}$$

Equation (3.9) takes both the thickened fibres and the dendrites into consideration.

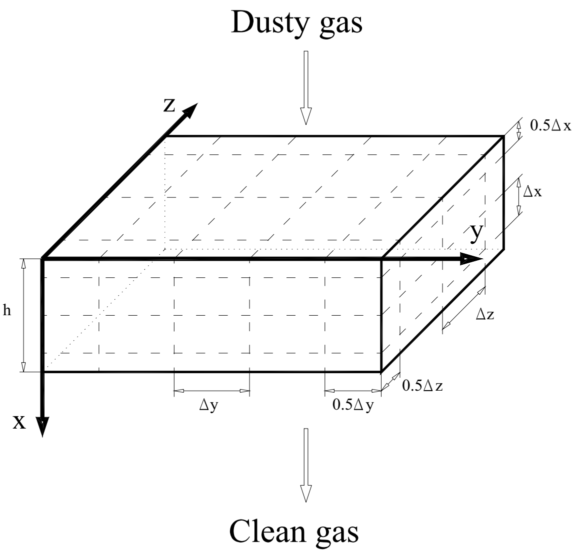


Figure 3. Co-ordinate system and division of filter mat

By neglecting the volume of fibres and particles and the compressibility of gas the continuity equation ($\nabla \cdot \mathbf{v} = 0$) can be transformed by using equation (3.8):

$$\nabla \cdot (C\nabla p) = 0 \ . \tag{3.10}$$

Knowing the actual 3D permeability distribution in filter mat and the boundary conditions: $x = 0$ $p = p_{\mathrm{in}}$, $x = h$ $p = p_{\mathrm{in}} - \Delta p_{\mathrm{f}}$, on the periphery (see Figure 3), the flow field can be calculated.

3.3. Simulation of particle collection process. The filter mat is divided into a number of elements (Figure 3) and the initial characteristics of the clean filter elements (packing density and fibre diameter) are given. Also particle diameter, inlet dust concentration, pressure drop across the mat (or filtration velocity), gas viscosity and particle density should be known. After calculating the permeability coefficient distribution by using equation (3.9), the pressure distribution can be determined by solving equation (3.10). The inlet and outlet velocities at all faces of volume elements can be determined from p distribution. Also the single fibre efficiency for clean fibres can be calculated for all filter elements as well as that of loaded fibres by using equation (3.3). Using these variables and the dust concentration at the inlet of the filter mat, a mass balance equation can be formulated for all filter elements: the difference of particle mass entering and leaving the filter element in a given time interval Δt [s] is equal to the increase of the quantity of collected particles. Summarising the mass of collected particles the filtration efficiency of the filter mat (E) can be calculated. At the end of the time interval the collected mass of dust and by using equation (3.9) a new distribution of permeability coefficient can be determined, so the next cycle of calculation for the next time interval can be started.

4. Considerations on the formation of dust cake

The lifecycle of a filter mat can be divided into two parts: in the first period of filtration the dust particles are collected by the fibres and already deposited particles

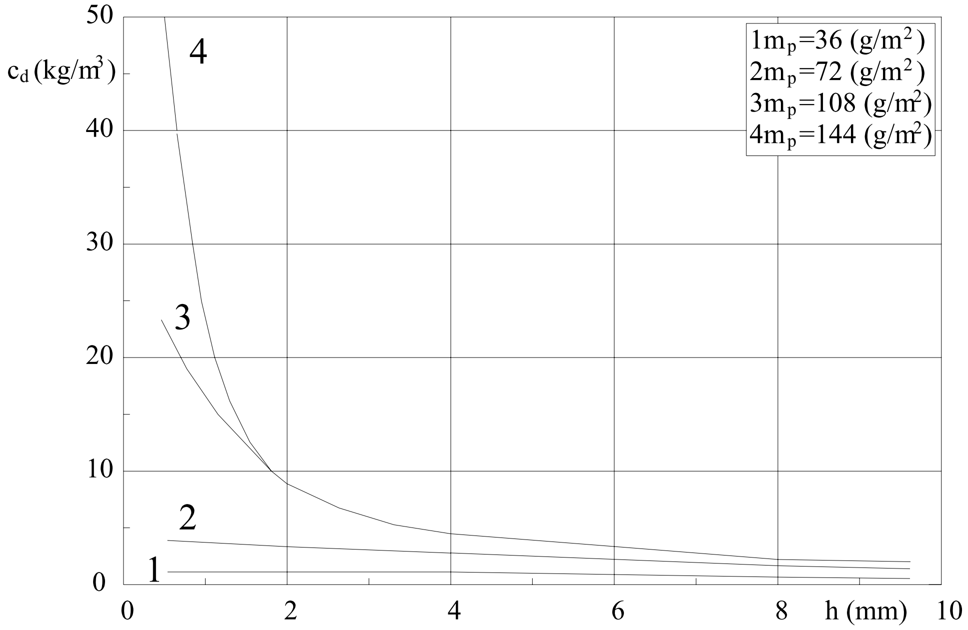


Figure 4. Variation of concentration of deposited particles across filter mats ($d_p = 1\mu\text{m}, \mathrm{d_f} = 20\mu\text{m}, \mathrm{h} = 10\text{mm}, \mathrm{v_m} = 0.1\frac{\mathrm{m}}{\mathrm{s}}$)

are situated in the depth of filter mat (depth filtration). Since the particle concentration is the highest at the inlet of the filter mat, and the deposition of particles increases the subsequent collection, the concentration of the deposited particles increases very rapidly in the vicinity of inlet surface of the mat. Figure 4 shows the result of a 1D calculation of distribution of deposited particle concentration (c_{d}) across the filter mats at four different dust loads. If the dendrites created by the deposited particles near the inlet of the filter mat bridge the distance between fibres, the second period of the lifecycle of filter mat starts. A continuous and gradually thickening dust layer (dust cake) arises, assuming the task of collection of subsequent particles (surface filtration). While the regular removal of individual dust particles from the surface of the fibres situated inside of the mat is practically impossible because of the very strong attraction forces, the dust cake on the inlet surface of filter mat can be removed relatively easily by shaking the filter bags or by using reverse flow. Therefore those filter mats where the surface filtration dominates can be regenerated periodically, consequently they are widely used for cleaning gas of relatively high dust concentration.

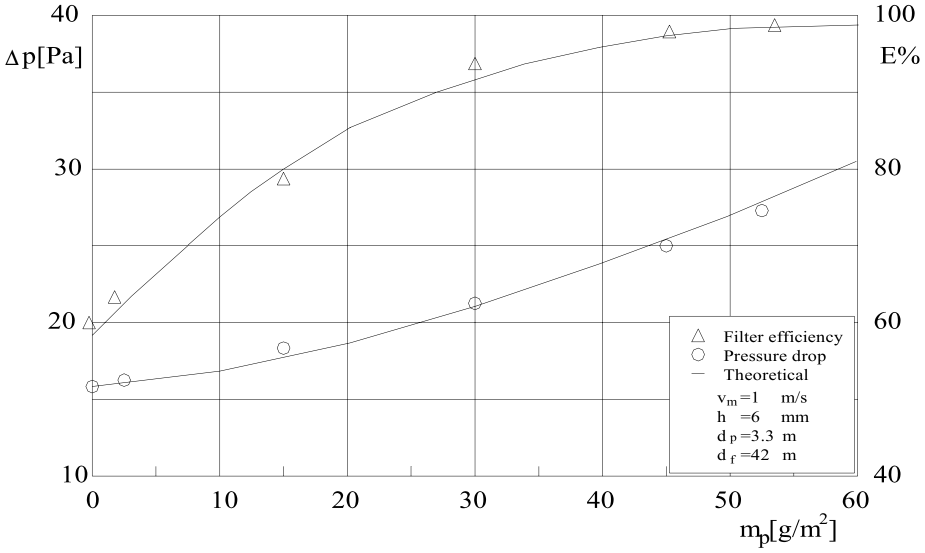
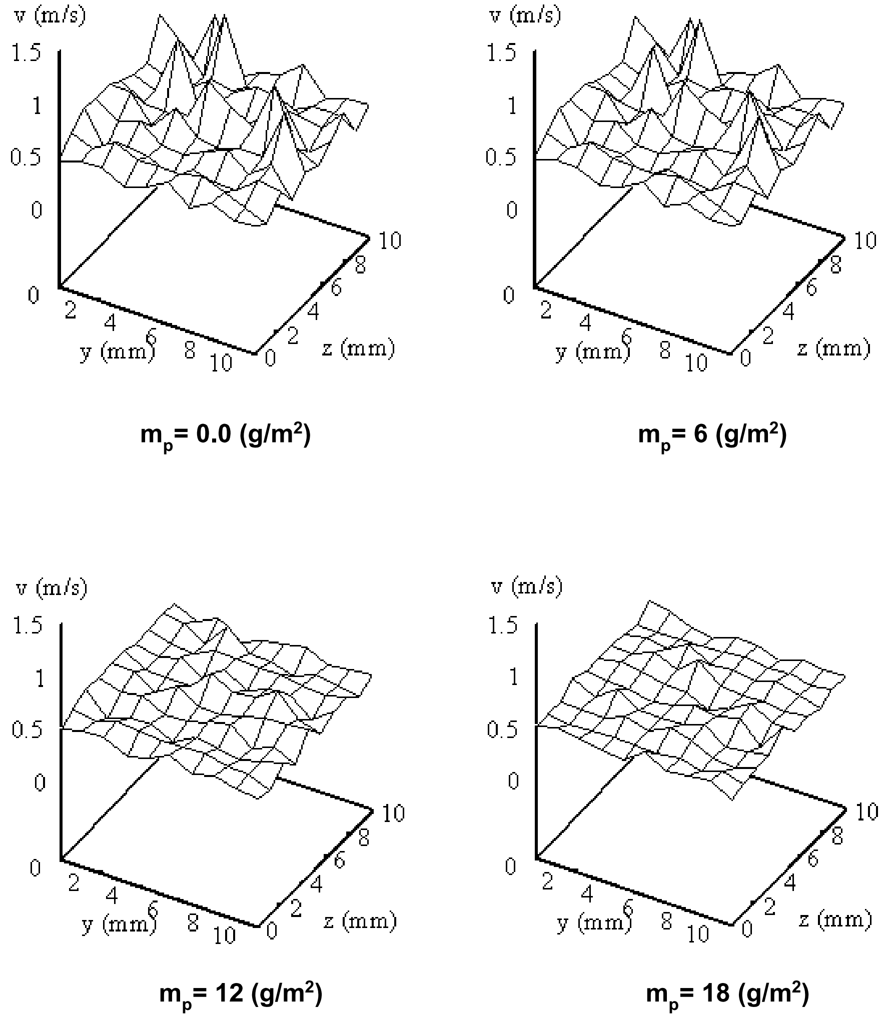


Figure 5. Change of filtration characteristics as function of dust load

The final objective of the research presented here is the combination of the simulation of filtration process in both periods of the lifecycle of the filter mat. The simulation of the first filtration period is outlined in this paper, and methods for calculation of the development of dust cake is also available [12]. The combination of the two simulation methods necessitates the correct description of the formation of continuous dust layer on the inlet surface of the filter mat, which is the starting point of the formation of a dust cake. Recent experimental investigations on the lateral size



m_p= 0.0 (g/m^2)

m_p= 6 (g/m^2)

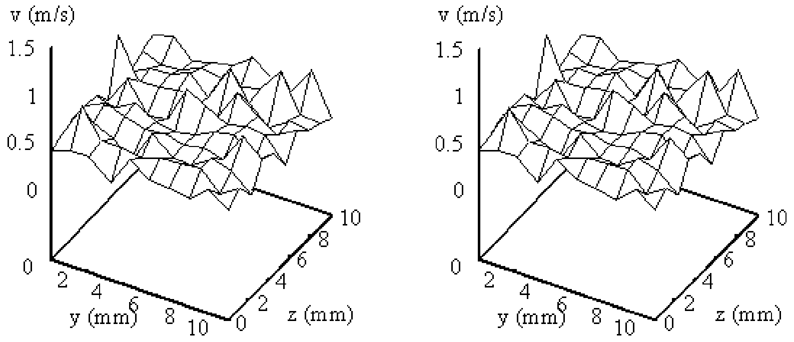
m_p= 12 (g/m^2)

m_p= 18 (g/m^2)

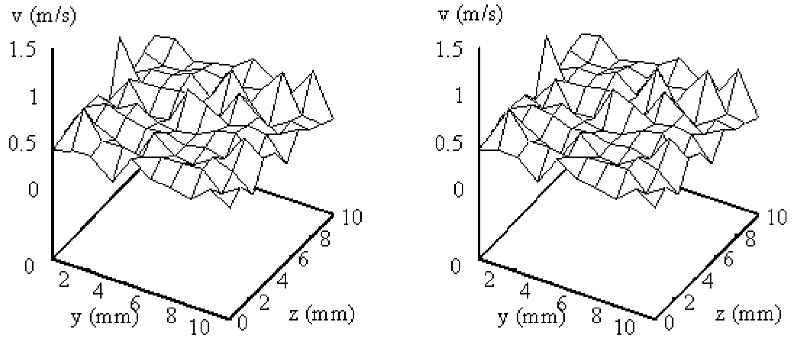
Figure 6. Computed velocity at filter inlet at different values of m_{p}

statements: the lateral size of the dendrite is much smaller than the average distance between the fibres. Consequently if the fibres are homogeneously distributed the formation of a continuous dust layer can arise only at a very high concentration of deposited mass.

The author suggests explaining the formation of a dust cake at a relatively low dust load by the inhomogeneity of fibre distribution. In this case first the relatively small distances between the fibres will be bridged and so "fibres" of much higher diameter



m_p= 0.0 (g/m^2) **m_p= 6 (g/m^2)**



m_p= 12 (g/m^2) **m_p= 18 (g/m^2)**

Figure 7. Computed velocity at filter outlet at different values of m_{p}

occur. The dendrites developing on these thicker formations can bridge much larger distances. The simulation of this phenomenon is in progress.

5. Simulation results

3D numerical simulation of flow field has been performed for filter mats of different inhomogeneity of fibre packing density. The model filters have been put together from filter elements selected randomly from a set of filter elements, the permeability coefficient of which corresponded to the Gaussian normal distribution of given standard deviation. The calculated increase of the overall permeability of the filter mat with increasing the inhomogeneity has shown good agreement with experimental result [7].

The results of numerical simulation of the clogging process show acceptable agreement with results published in the literature. Figure 5 shows the calculated and measured change of pressure drop and filtration efficiency of filter mat as the function of a specific dust load (which is proportional to the filtration time).

The dust deposition decreases the inhomogeneity of overall packing density in y and z directions and increases in x direction (Figure 3). The decrease of inhomogeneity in $y - z$ planes depends also on the amount of collected particles: it is considerable close to the inlet plane and much less at the outlet. This is clearly demonstrated by the calculated velocity distributions at inlet and outlet of clean and loaded filter mats shown in Figures 6 and 7.

6. Conclusions

A model of dust particle collection relying on experimental investigations has been developed. It regards a part of surface of the deposited particles as additional collecting surface. The shadowing effect and the share factor have been suggested to simulate the real processes more accurately. A numerical method has been developed for calculation of 3D flow field in filter mat based on the generalized form of Darcy equation and continuity equation. The results of simulation of the filtration process show acceptable agreement with experiments. The numerical simulation of combination of the two phases of lifecycle of a filter mat needs further investigations concerning the formation of continuous dust layer on the surface of the filter mat. A significant influence of inhomogeneity of fibre structure on the formation of the dust cake is suggested.

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