MATHEMATICAL MODEL OF HIGHLY EFFICIENT AIR FILTRATION PROCESS FOR NONWOVEN FABRICS MANUFACTURED BY PAPER-MAKING METHOD

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ABSTRACT

The necessity to provide and maintain high cleanness of air in the rooms of the highest cleanliness classes requires a proper adaptation of selection and designing methods for air filters. The level of air cleanliness for such rooms is defined numerically by the determination of the permissible number of dust particles whose diameters are equal or higher than the given limit values. Thus, in order to determine in reliable way the level of pollution in the air prepared and supplied to the cleanrooms it is essential to be able to predict the numerical fractional filtration efficiency for every stage of filtration. Such an analytical method for the determination of the filtration efficiency carried out at the stage of designing of an air cleaning system and leading to the quantitative assessment of dust concentration in the air behind the successive filters, will permit a reliable analysis of the possibility of application of the specific filtration materials. For this purpose previously developed mathematical models for the process of air filtration should be applied.

This article presents a probabilistic model of air filtration process elaborated for filter papers made of glass fibre. The applied method of modelling allowed to select the most important parameters of fibres and nonwoven fabrics that (apart from the sizes of dust particles), have an essential influence on the variability of the numerical filtration efficiency. The article also focuses on the area of application of the proposed model and the reliability of quantitative assessment of numerical concentration of dust behind the air filter.

INTRODUCTION

The highly effective air filters, which stop the finest fractions of dust, are one of the most important elements in a system enabling to keep a required cleanness of air in cleanrooms.
The requirements concerning the quantitative concentration of particles in definite sizes are known on the basis of classification of cleanrooms presented in standards [2], [5]. To meet these requirements and to be able to compare the obtained concentration of pollutants behind the filters with permissible number of particles in indoor air it is necessary to define the numerical fractional filtration efficiency not only for HEPA or ULPA filters, but also for lower class filters. This approach to the problem under consideration may change the method of filter selections applied to date sometimes simply by routine (based on the total effectiveness) and force designers to take an integral outlook on the problem of filter system selection with special attention given to quantity of numerical concentration, in every step of filtration.

It is possible to carry out such an analysis of filtration efficiency thanks to anticipation of the course of filtration processes made on a basis of earlier elaborated mathematical models. These models, as given in the present article, should allow to predict the quantity of numerical concentration of particles behind the filter, being the answer of the system to assumed or known input parameters (distribution of dust before the filter and structural parameters of materials). On this basis it should be possible, with imposed permissible maximum quantity of particles in air blown to room, to look for optimum structural parameters of nonwoven fabrics that will guarantee the correct running of the air cleaning process or the determination of such composition of particle dust before the filter, which by an application of a specific air filter can assure the maintenance of the admissible values of numerical concentration of dust at the air intake to the room.

MATHEMATICAL MODELS OF THE AIR FILTRATION PROCESS

The present state of the theory of aerosol filtration does not permit to design correctly the real filtration structures owing to often occurring divergences between theory and experiment and also the differences between mathematical models elaborated and proposed by various authors. The elaboration of a satisfying theoretical model, even for an unary material and for a determined filtration, meets serious difficulties. This is the result of the fact that real fibrous filtration materials and conditions of aerosol flow differ from assumed theoretical foundations of mathematical models and do not comply with simplifications assumed for them [3].
In this situation, with increasing disordered state of the filtration material structure, the trials for a further development of the deterministic theoretical models may not give the correct solution for the description of the filtration process.

Besides the complicated structure of the highly efficient filter papers and differentiated particle composition of aerosols, an additional problem, causing the divergences between measurement and theoretical results, makes the correct assessment of occurring phenomena and also correct description of them. Although tests have been carried out for a long time, among others on the course of the filtration mechanisms, a full consensus among scientists as regards the method of their mathematical description has not been achieved as yet. Also the fact that in the classical models of the filtration process such phenomena as for example the deposition of particles under the influence of electrostatic forces or forces of intermolecular reaction have not been taken into account involves differences between the value of efficiency obtained on the basis of theoretical deliberations and the real value.

All the above-mentioned problems forced to search for the method for a description of the filtration process other than the deterministic one, in which not only the knowledge of the phenomenon alone will be used, but which will extend also the approach to the problem of modelling by using the measurement data and their statistical analysis.

CHARACTERISTICS OF THE PROPOSED MODEL OF AIR FILTRATION

One of the main classification criterions of the mathematical models, depending on the method of representation of the phenomena, is the division into:

- nonphysical models (statistical, empirical),
- physical models (deterministic),
- hybrid models.

During the modeling of the filtration process the hybrid model had been used, bonding the fundamental knowledge of the filtration process with the results of the carried out measurements of the filtration efficiency. To describe the air filtration process through the micro-fibrous filter materials one of the methods of hybrid modelling, i.e., the multi-parameter regression, was applied.

As a result of the analysis done using the method of a stepwise linear multi-parameter regression (1) the following dependence had been obtained [1]:

$$\eta = -15.11\,D_F - 1227\ln(\rho_F) - 19.76 D_P + 291.2\,M_S + 9591 \quad [\%] \qquad ....(1)$$

where η is the numerical efficiency of the filtration (%), D_F is the diameter of the glass fibres, ρ_F is the density of fibres (kg/m^3), D_P is the diameter of the particles (μm), M_S is the substance of the nonwoven fabric (kg/m^2).

The obtained equation describes the numerical fractional efficiency of the fibrous filter materials with highly disordered structure, manufactured by paper-making method from the glass microfibres with the air inflow speed 3 cm/s. The dependence concerns the process of a fixed filtration. It is true for the range of value of the structural parameters for the nonwoven fabric and the diameters of particles given in Table 1.
The coefficient of multiple regression for this equation was equal to R=0,91.

Table 1. Limit values of the independent variables contained in the regression equation.

No.	Parameter	Unit of measure	Minimum value	Maximum value
1	D_F	μm	1.142	4.107
2	ρ_F	kg/m^3	2250	2290
3	D_P	μm	0.0316	1.0
4	M_S	kg/m^2	0.0562	0.0877

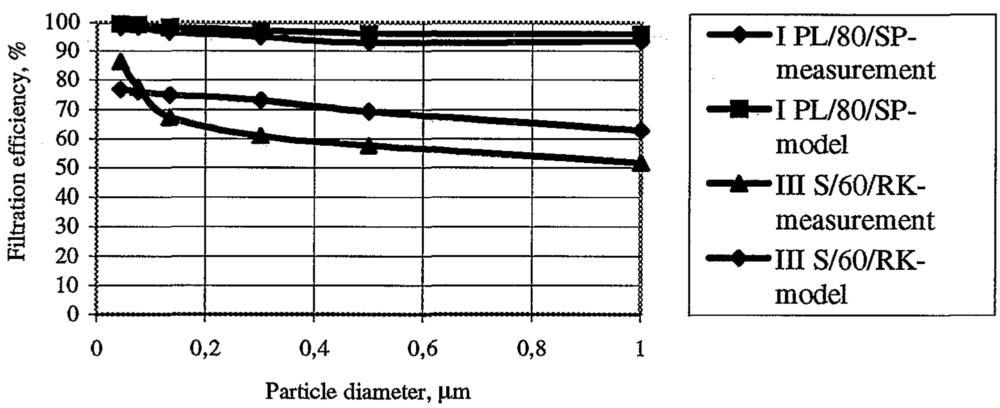

Figure 1. The comparison of the characteristic of the filter obtained on the basis of the proposed model of the filtration process and real for the non-wovens I PL/80/SP and III S/60/RK.

On the Figure 1 the following characteristics of the filter have been compared: obtained on the basis of the proposed model of the filtration process and real, determined for the exemplified non-wovens: I PL/80/SP and III S/60/RK. The close position of both lines (especially for the filter of a higher efficiency) on the diagram confirms that the undertaken trial to describe the filtration process represents the correct approach to the problem under consideration and a good starting point to further research, e.g., on the basis of the developed model of the optimum structural parameters for the nonwoven fabric.

RELIABILITY OF THE ASSESSMENT OF THE QUANTITY OF NUMERICAL CONCENTRATION OF DUST IN THE AIR OUTFLOW FROM THE FILTER

The assessment of the adherence to a numerical concentration of pollutants in cleanrooms is carried out on the basis of the measurement results of control tests with the 95% confidence threshold imposed by standards [2], [5]. Therefore, there is a small acceptable range of variations in the conditions occurring in the controlled environment. It comes from the nature of things that in the course of their operation the air filters by the interception of more and more particles change their characteristics as a result of increased layer of dust. The worst conditions as regards the filtration efficiency appear in the beginning of their work; in so-called fixed conditions of the air cleaning process. These worst conditions just had been the subject of considerations.
By turns the uncertainty of the model itself (with assumed confidence intervals determined with 95% probability of the adhering to the parameter values) requires to take into account some safety margin. To assure that the required quantity of particles behind the filter will be kept, the particle composition of the dust appearing before the filter should be taken into consideration with a big caution and reserve so that even in the worst conditions the admissible value of its concentration is not exceeded.
Simultaneously taking into consideration the worst conditions from the point of view of the assurance of the best air purification, the selectivity phenomenon that appears during the process of filtration and causes the occurrence of the minimum efficiency value of filtration has to be taken also into account. From this results the necessity of a strict control of the aerosol concentration before the filter, particularly in the range of particle diameters 0,1÷1 μm, being according to the data from the literature the area of the appearance of the phenomenon of the greatest particle permeability.

THE RANGE OF THE APPLICATION OF THE ELABORATED MODEL OF THE AIR FILTRATION PROCESS

We can expect from the mathematical models which conduct to the determination of the numerical fractional filtration efficiency that they will ensure a reliable assessment of the computed quantity and not so troublesome calculation procedure. The deterministic models used to date, in which the particular filtration mechanisms are considered in detail, describe the air filtration process in a very complicated manner, which does not encourage making use of them. They require not only the knowledge of the parameters and the properties of the material and dust, but also of many similarity numbers and parameters, which characterize the air. At the same time many of them cannot provide a sufficiently precise basis for the quantitative assessment of the filtration efficiency [1]. On the other hand the available hybrid models do not comprise the problems connected with the filtration of the submicron size particles through the structurally- complicated non-wovens.
In order to assess the numerical fractional efficiency it was decided to make for the needs of the planned experiments the nonwoven fabrics from ultrathin and thin glass fibres. Their choice was based on the information obtained from manufacturers concerning the diameters of the fibres. The diameter had to be equal to 1 μm in the case of the fibres marked with the symbol PL and to.1.15 μm for fibres marked with the symbol S. It was expected that the decision to produce the non-woven fabrics from such thin fibres by paper-making method, would bring about very high values of filtration efficiency. But the measurements proved that the purpose was not fully achieved because of the non-homogeneous structure of fibres leading to production of structures with non-uniform density (Figure 2, Figure 3).

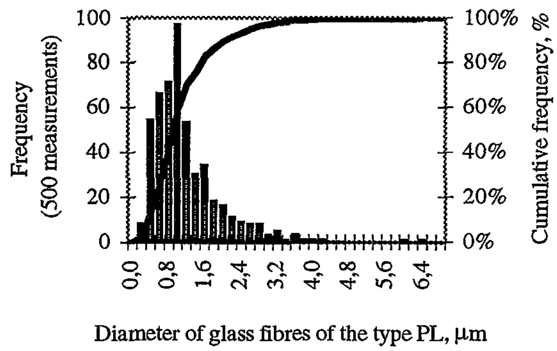

Figure 2. The distribution of cumulative frequency and frequency of occurrence of the given diameter of glass fibres - type PL.

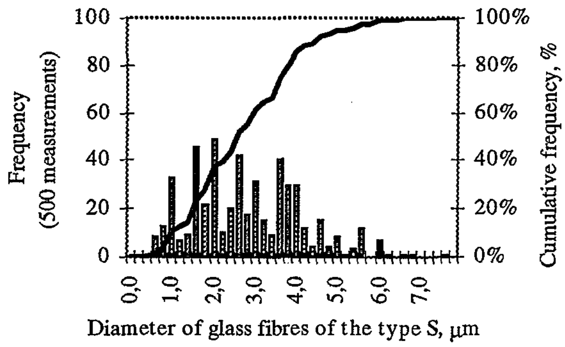

Figure 3. The distribution of cumulative frequency and frequency of occurrence of the given diameter of glass fibres - type S.

To start the planning of experiments and having as a goal (apart from the assessment of the fractional filtration efficiency) a closer localization of the area of the highest permeability for non-wovens made by paper-making method from the ultrathin glass fibres, the reference data [3] that indicated the appearance of such an area in the range of particle diameters from 0,1µm to 1µm were taken as a basis. Unfortunately the research has not confirmed the occurrence of such defined limits of the range. The dislocation of this area in the direction of greater particle diameters (1 µm) was observed, what gave in the analyzed dimensional area the linear dependence characterized by the decline in the filtration efficiency value together with an increase in the particle sizes (Figure 1). Thus for the univocal identification of the localization of the area of the minimum filtration efficiency it would be necessary to make in future a research that would extend the range of the particle diameter to 2 µm. The obtained dependence offers, however, essential information about the direction of changes in values of the filtration efficiency in the area of the submicron size particles and within this scope it serves its purpose. The applied method of modelling the air filtration process (which makes use of the multi-parameter linear regression) allowed selecting the most essential parameters of fibres and non-wovens that exert an influence on the variability of the filtration efficiency. Simultaneously this method created the possibility of a synthetic approach to the influence of the most important parameters for the range of considered data, on the run of the filtration process, without the necessity to look deeper in the complicated nature of the filtration mechanisms taking place during the air cleaning.

The equation, created on the basis of the model of a multi-parameter regression, that describes the air filtration process, may become the foundation for optimization of structural parameters of the nonwoven filter fabric and lead to designing filters with the highest efficiency of filtration. This equation may be applied especially in the case of materials having a very complicated structure that cannot be described analytically (e.g., non-wovens produced by the paper-making method). The determination on the basis of this model of such parameters as the fibre diameter and density or the substance (grammage) of the nonwoven fabrics, could facilitate the better adaptation of the material to the specific needs.
The obtained dependence does not exhaust all problems connected with designing and production of filtration materials. However, because to date there has been a lack of considerations concerning the modeling of the filtration process for the submicron size particles through the nonwoven filter fabrics produced by the paper-making method and the assessment of the numerical fractional efficiency occurring in such conditions, this model complements the knowledge on the subject of the air filtration process.

CONCLUSIONS

The main aim in the search of filtration materials for the needs of the cleanroom technology consists in obtaining such materials that in a reliable way will allow realizing the accomplishment of the requirements concerning the high purity of air behind the filter. This is particularly important in the case of technological premises, e.g., in the microelectronics industry, where the priority requirement comprises the assurance of a strictly controlled, very low and determined in a numerical way concentration of the submicron size particles in the room. Thus it cannot be allowed that an application of filter materials having a complicated, disordered structure exert an influence on the accidental character of their work and worsen, even temporary, the level of purity of air, blown into a room. It requires a continuous improvement in the mathematical description of filtration process, enabling to foreseen the air purification efficiency or facilitating the decisions making relative to the selection of parameters of the nonwoven fabrics.
The experimental tests that have been carried out simultaneously confirmed the existence of the area of the maximum permeability of particles. Yet the dislocation of this area in the direction of the particles of a higher diameter (1 μm) in comparison with the results obtained on the basis of the existing mathematical models, as well as the range given in the literature (0,1÷1 μm) has been observed. The developed model permits to forecast in an easy and clear manner by an analytical way the efficiency of filtration and to localize the most sensitive areas with the lowest efficiency of filtration.

REFERENCES

1. Charkowska, A. 1997. Probabilistic evaluation of numerical efficiency of aerosol filtration within microfibrous materials with poorly determined structure, Ph.D. thesis (in Polish), Warsaw University of Technology, Faculty of Environmental Engineering, Warsaw.
2. Federal Standard 209E. 1992. Airborne Particulate Cleanliness Classes in Cleanrooms and Clean Zones.
3. Filter Engineering, Camfil, Technical reference book.
4. Furs, S. 1977. Theoretical and empirical analysis of pressure drop of fibre materials and dust filters, Ph.D. thesis (in Polish), Lodz University of Technology, Institute of Textile Machinery and Equipment, Central Institute of Labour Protection, Lodz.
5. ISO/DIS 14644-1. 1996. Cleanrooms and Associated Controlled Environments, Part 1: Classification of Airborne Particulates.