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Consecutive filtration of solid particles and droplets in fibrous filters

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ABSTRACT

The dynamics of filtration efficiency during consecutive solid-liquid and liquid-solid aerosol filtration was investigated. Presence of solid particles deposited inside a filter affects the efficiency of liquid aerosol filtration on this filter. Similarly, liquid droplets deposited on filtration fibers inside the filter influence the removal efficiency of solid particles. It is caused by the different character of interactions between solid particles in the presence and absence of liquid. In this work these effects were identified in experimental results and their phenomenological explanation was presented.

1. Introduction

Filtration of aerosols on fibrous filters is one of the most popular separation methods of micrometer and sub-micrometer particles from a gas. It is utilized in many branches of industry to obtain a pure gas for various applications as well as in environment protection processes to remove solid or liquid impurities from an exhausted gas. Thus, the mechanism of this process has been a subject of numerous experimental and numerical investigations recently [1–9].

Early works on filtration attempted to identify the capture mechanisms of solid or liquid particles: direct interception of particles on fibers, inertial impaction and diffusion. Additional mechanisms can also be considered e.g. electrostatic one. The significance of particular mechanisms depends on various factors characterizing an aerosol. First of all it is particle diameter and gas velocity. Different formulae for single fiber efficiency in respect to these mechanisms have been elaborated e.g. in papers [1,2]. On their basis it is possible to compute the total initial efficiency of a filter. On the other hand it is also possible to determine the initial pressure drop of a filter if its parameters i.e. fiber mean diameter or filter porosity are known [3].

Another important issue concerning filtration is the dynamics of efficiency and pressure drop during the process. In solid aerosol filtration deposited particles form dendrite-like structures on fibers inside the filter (so-called deep filtration). Those structures increase fractional efficiency and pressure drop. After a certain time particles fill empty spaces between fibers and start to deposit on the inlet surface of the filter - surface or cake filtration begins. These processes have been intensively explored experimentally and theoretically. Jackiewicz et al. [10] studied the distribution and reorganization of deposits inside a fibrous filter at subsequent stages of filtration using computed tomography. Kasper et al. [11] investigated the dependence of single fiber efficiency as a function of the mass of particles deposited on the fiber per length unit. They proposed the formula:

$$\frac{\eta(M)}{\eta_0} = 1 + b \cdot M^c \qquad (1)$$

where η_0 denotes the initial single fiber efficiency, $\eta(M)$ - single fiber efficiency after deposition of particle mass M (per a unit of length in the fiber) and b and c are parameters of the model. The same formula with different parameter values appears to be valid for a single fiber efficiency of a fiber placed in an array of parallel fibers. It is expected that a similar expression may be used for fibers inside a porous medium. This approach has been then extended in paper [12] to obtain a qualitative description of a penetration change during filter clogging through a fibrous filter. Thomas et al. [13] built a numerical model of deep filtration assuming that dendrites growing during the process may be treated as additive fibers because of their nearly linear structure. According to this assumption, particle deposition inside a filter is treated as an appearance and growth of fibers with a diameter equal to that of particles. Following that, during the filtration process the packing density grows and the mean fiber diameter usually falls down.

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The last effect is due to the fact that particles which build "new fibers" (dendrites) have a smaller mean diameter than original filtration fibers. Both the effects cause changes in the pressure drop and the efficiency of the filter. Although such an assumption is open to criticism, while deposits have the morphology of fractals rather than straight fibers, results provided by the model are consistent with experimental data.

Research into fibrous filter efficiency is also based on computational fluid dynamics (CFD), e.g. using Ansys-FLUENT software [14,15]. However, these methods appear to be very memory- and time consuming and thus their practical significance is rather low.

In the case of liquid aerosols, their dynamic behavior during filtration is different compared to solid particle filtration dynamics while liquid deposits differ from solid ones. In papers [16–19] results of experimental investigations of this process are presented. According to these findings, filtration of liquid aerosols may be divided into three stages. During the first one, the pressure drop as well as the filtration efficiency remain approximately at a constant level while deposited droplets spread on fibers and thus do not change the inner structure of the filter very much. In the second stage liquid bridges are formed between fibers which leads to increase of the pressure drop on the filter and the efficiency of droplet removal. Finally, the last stage starts when the system reaches an equilibrium state between the amount of the fluid drained and deposited. Then the pressure drop is nearly constant in time again but its value is a few times greater than that during the first stage of the process.

In practical applications of gas filtration processes there usually appear both solid particles and fluid droplets upstream. One may expect that the presence of droplets deposited on filtration fibers influences the efficiency of solid particle removal and vice versa. However, there exists a limited body of literature on consecutive solid and liquid filtration on the same filter. Filtration of solid and liquid aerosol mixtures was investigated by Sun and Chen [20] and Frising et al. [16]. They analyzed mainly the evolution of pressure drop rather than filtration efficiency. Frising et al. [16] showed that the pressure drop during the filtration of mixed aerosols behaves like that of liquid aerosol only. The main difference is the additive filtration stage before the stationary one when a filtration cake is formed parallel to droplet deposition. However, changes of filtration efficiency were not investigated by these authors. Mead-Hunter et al. [21] analyzed the filtration of soot-in-oil colloid aerosols. They found that the equilibrium (final) pressure drop during that process was higher than the pressure drop during the filtration of pure oil droplets. It has been explained as an effect of the increase in effective oil viscosity caused by the presence of soot particles. This issue was also investigated by Bredin et al. [22] who focused on the impact of different oil aging mechanisms and their influence on filtration by fibrous filters. Another work on consecutive droplet-particle efficiency was done by Müller et al. [23]. They showed experimentally that pretreatment of filtration fibers with oil leads to the decrease of pressure drop. Consequently, the efficiency of consecutive filtration differs strongly from sole solid or liquid aerosol filtration. Finally, Mullins et al. [24] analyzed the capture of solid and liquid aerosols on fibrous filters which were previously wetted with water. They have found that wet fibers are more efficient in capturing of dust particles. Moreover, they observed the difference in interactions between particles directly deposited on fibers and particles deposited as evaporated droplets with newly deposited droplets.

The main goal of this paper is to investigate changes of filtration efficiency and pressure drop in time during consecutive solid-liquid and liquid-solid aerosol filtration. The paper is organized as follows: in Section 2 investigated filters – their structure and properties – and the experimental set-up are described. The results of experiments together with their interpretation are presented in Section 3. Finally, Section 4 provides the conclusions of investigations performed.

2. Materials and methods

In this work three types of fibrous polypropylene filters were studied. They were obtained by means of melt-blown technique, described in detail elsewhere [25,26]. This method of production allowed us to obtain filters with repeatable structure. Main parameters of these filters are listed in Table 1. The mean fiber diameter was obtained by means of statistical analysis of scanning electron microscope (SEM) pictures. This diameter was computed as an arithmetic mean of a large number (about 500) of diameters measured directly in the picture. These measurements allowed us also to compute the standard deviation of fiber diameter.

The filter thickness was measured using calipers. The porosity was calculated according to the following expression:

$$\varepsilon = 1 - \frac{m}{\rho F h} \tag{2}$$

where m denotes the mass of the filter, F – its cross-sectional area, h – filter thickness and ρ - the density of polypropylene.

As can be seen, the main difference between the filters was the mean fiber diameter while the other parameters (packing density and filter thickness) were similar.

The experimental set-up for investigation of the dynamics of an overall filters efficiency (only such an efficiency is measured in current work) and pressure drop during the gas flow thru the filter is presented in Fig. 1. It was based on HFP 2000 filter test system designed by PALAS GmbH, Germany. The main element of this test-bench was a horizontal channel with a holder where the investigated filter is placed. The gas (air) flow rate in the channel

Table 1
Properties of the fibrous filters used in experiments.

Filter	Mean fiber diameter [μm]	Porosity [–]	Filter thickness [mm]
f10	10.0 ± 4.0	0.880	2.26 ± 0.13
f5	5.0 ± 2.3	0.941	2.55 ± 0.22
nano	0.5 ± 0.3	0.979	1.88 ± 0.15

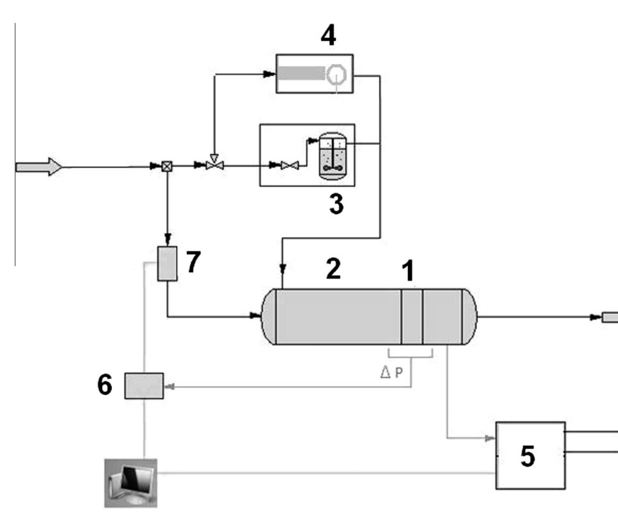

Fig. 1. Experimental set-up for investigation of the dynamics of filter efficiency and pressure drop. 1 – filter holder, 2 – horizontal channel, 3 – nebulizer PLG 2000, 4 – solid aerosol generator RBG 1000, 5 – particle counter, 6 – control unit, 7 – pump.