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Numerical modeling of solid deposits reorganization during consecutive solid-liquid aerosol filtration: Influence on the dynamics of filtration efficiency

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ABSTRACT

Formation and dynamics of solid deposits during consecutive solid-liquid or liquid-solid aerosol filtration is analyzed by means of numerical modeling. A new numerical model has been proposed which enables taking into account changes of morphology of deposits and an influence of these changes on single fiber efficiency. This model investigates the displacements of solid particles inside the deposit. Forces which cause these displacements arise from the presence of small amount of liquid inside the deposit. Knowledge of the dynamics of such deposits allows us to compute the dynamics of single fiber efficiency at different process conditions. Results of numerical modeling has been compared with experimental results available in literature.

1. Introduction

One of the most popular methods of removal of micrometer or submicrometer particles from gas is filtration on fibrous filters. These nonvoven filters have found their application in many branches of industry for cleaning gaseous products of industrial processes as well as in environment protection processes to remove particulate impurities from an exhausted gas (Baker & Lookhandwala, 2008; Davies, 1973). Thus, the process of filtration has been a subject of numerous investigations for many decades. First papers has been devoted to the main mechanism of particles deposition mechanisms (Davies, 1973; Lee & Liu, 1982). Later on, there have appeared the works which introduced the numerical models of filtration process (Jaganathan, Tafreshi, & Pourdeyhimi, 2008; Mead-Hunter, King, & Mullins, 2014).

Most of these investigations have concern themselves on analyzing of initial filtration efficiency and pressure drop for filters with various characteristics and structure (Davies, 1973). Later on, more attention has been paid for late stages of filtration when the filtration fibers have been loaded with relatively big amount of aerosol particles. First, most of investigations on dynamic filtration have been subjected to filtration of solid aerosols. There has been described the influence of solid deposits which appeared as a result of particles deposition, on efficiency and pressure drop dynamics during the filtration (Bhutra & Payatakes, 1979; Payatakes & Tien, 1976; Przekop, Moskal, & Gradoń, 2003; Thomas, Penicot, Contal, Leclerc, & Vendel, 2001). Many of authors analyzed the formation of solid deposits as a main effect causing the changes of filtration efficiency and flow resistance. These deposits has been recognized as having dendrite-like shape (Payatakes & Gradon, 1980). There has been investigated a density and porosity such deposits (Kasper, Schollmeier, & Mayer, 2010; Rembor & Kasper, 1999) and its influence on filtration process (Kasper, Schollmeier, Mayer, & Hoferer, 2009).

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Since 1990s there have appeared the results of researches on dynamic filtration of liquid aerosols (Charvet, Gonthier, Gonze, & Bernis, 2010; Frising, Thomas, Bémer, & Contal, 2005). Again, these were initially experimental results, but last time the dynamics of mist filtration has been also described analytically and numerically (Gac & Gradoń, 2012; Gac, 2015). The less attention has been paid to a filtration of mixed aerosols i.e. removal of both solid particles and liquid droplets in the same filter. One of a few works devoted to that problem is a work by Frising et al. (2004) who have shown the dynamics of pressure drop during such a process. They, however, did not analyzed the dynamics of filtration efficiency. The dynamics of filtration efficiency during a consecutive filtration (i.e. when the filter is exposed first on solid particles only and then on liquid droplets only or vice versa) has been a subject of our last paper. We have observed experimentally some tendencies which has appeared for filters with various structural properties (e.g. mean fiber diameter). These tendencies are: rapid decrease of filtration efficiency when switching from solid to liquid aerosol filtration or slower increase of the efficiency of solid aerosol filtration after previous period of droplet filtration. We have given qualitative explanation of both of those phenomena as an effect of an influence of thin liquid film on solid deposits structure and a dynamics of their growth. Besides of those works, there may be found some papers reporting the analysis of filtration efficiency of filters (or, sometimes, single filtration fibers) in respect to solid particles filtration after the initial pre-coating of fibers with thin film of oil (Boskovic, Agranovski, & Braddock, 2007; Müller, Meyer, Thébault, & Kasper, 2014; Mullins, Agranovski, & Braddock, 2003). Probably, the most full description of this problem may be found in paper by Müller et al. (2014). Their results confirm our observations that after pre-treatment of fibers with oil the increase of the efficiency of solid aerosol filtration is slower than in a case of the absence of such a pre-treatment. Though the authors of that paper suggested that the reason of observed tendency is a reorganization (collapse) of deposits, they did not give the qualitative explanation of the influence of this reorganization on the dynamics of filtration efficiency. This paper is devoted to numerical modeling of dynamics of solid deposits containing some amount of liquid. Basing of the results of computation, we present how this dynamics influences the changes of single fiber efficiency during initial and later stages of filtration. The paper is organized as follows. In Section 2 the numerical model of deposits dynamics is formulated. Section 3 contains the results of numerical modeling. We present both the dynamics of reorganization of deposits as well as the dynamics of single fiber efficiency. These last results have been compared with experimental ones. Finally, in Section 4 we conclude the results and suggest the possible further directions of investigations

2. Numerical model of deposits reorganization

To explain changes of filtration efficiency during consecutive filtration, a numerical model has been developed. The model describes dynamics of aerosol particles (both free and deposited on fiber surface) in the vicinity of a single fiber. A scheme of a computational domain is presented in Fig. 1. Its shape is cylindrical with fiber placed coaxially – similarly to the Kuwabara cell (Kuwabara, 1959). The radius of the domain is chosen to ensure a proper porosity of the system.

The numerical model designed for investigations of evolution of solid deposits (in the absence or presence of deposited liquid) takes into account the following issues: (i) gas flow field and, eventually, its change during the deposit growth; (ii) dynamics of free particles in gas flow and their deposition on a fiber (or on already deposited particles); (iii) dynamics of particles inside the deposit powered by forces arising from the presence of deposited liquid.

Initial gas flow field (around a bare fiber) is described by means of the kuwabara formula (Kuwabara, 1959). Indeed, while the reynolds number, defined as:

$$Re = \frac{ud_f}{\nu} \tag{1}$$

where u denotes linear gas velocity, d_f – fiber diameter and ν - kinematic viscosity, is low, all the assumptions on which the Kuwabara formula is based are fulfilled. Later on, when solid deposits on the fiber surface start to appear, the Kuwabara solution may not be

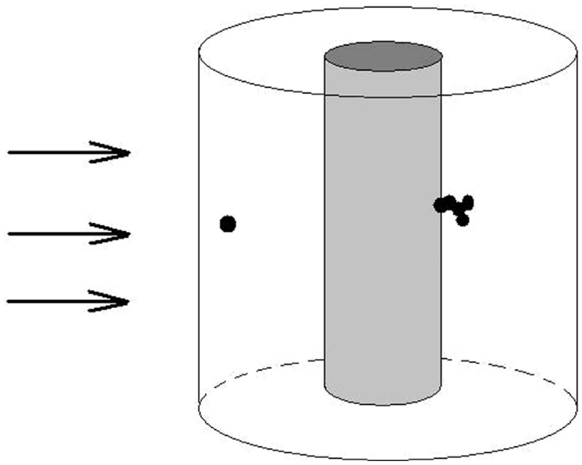

Fig. 1. Scheme of computational domain.