Separation and Purification Technology 126 (2014) 52–61

Contents lists available at ScienceDirect

Separation and Purification Technology

journal homepage: www.elsevier.com/locate/seppur

Combination of Single-Photon Emission and X-Ray Computed Tomography to visualize aerosol deposition in pleated filter

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ARTICLE INFO

Article history:
Received 6 September 2013
Received in revised form 2 December 2013
Accepted 10 February 2014
Available online 24 February 2014

Keywords:
Pleated filter
Aerosol filtration
Initial deposit
Clogging rate
Nuclear imaging

ABSTRACT

We use a combination of Single-Photon Emission Computed Tomography and X-Ray Computed Tomography to visualize the behavior of a radioactively marked aerosol in pleated filters under different operating conditions. We first validate this atypical method as a mean to comprehensively observe the filtration process in a filter at the macroscopic scale. This non-intrusive technique highlights the influence of the filtration velocity on the areas where the particles first tend to settle out in blank HEPA filter. We demonstrate that the pleating geometry and the local media permeability act on the flow and account for the preferential location of the deposit. Moreover, e show that the increase in the filtration rate leads to a more homogeneous distribution of the tracer on the entire height of the pleats and hence a more uniform arrangement of the flow. The rigid separators, placed on the media to increase the effective filtration surface, act as obstacles around which the flow is splitted, thus reducing the available area of filtration. Surface observations of loaded filters show that an inhomogeneous growth of the cake induces the formation of preferential channels for the solid aerosol to flow in. Caution should then be taken when carrying out the tomographic analyses because of the competition between the local air resistance and the local efficiency that can prevent from determining the areas where the radioactive aerosol accumulates.

1. Introduction

When it comes to air purification, media filters are so far the most efficient filters within the different filtration devices. Among them, fibrous pleated filters are widely used in areas related to air treatment such as air admission, bacteriological and nuclear containment, clean rooms, etc. In addition to the fact that they are easy to use and maintain, High Efficiency Particulate Air (HEPA) pleated filters provide excellent purification efficiency. Their lifetime is however conditioned by the pressure drop due to the clogging. Pre-filters are usually installed upstream of HEPA filters. In normal conditions of use, these latters are not exposed at high concentration of particle. But, in accidental circumstances, typically in event of fire, the particle concentration can become very high. The pre-filter clogging can lead to its rupture. The HEPA filter is then in a position of last barrier to maintain the efficiency. The velocity can be affected and the pressure drop can drastically increase. For example, the experiments of [1], using soot combustion aerosols, were performed until 20 times the initial pressure drop of the filter. The topic is of great interest in occupational and environmental hygiene research as well as nuclear safety. Models have been developed in an attempt to predict the pressure drop and the efficiency of pleated filter media. They can be classified as follows:

- The specific models [2–5]. They have originally been developed to optimize the design of a specific pleated filter element, for a given application. They come from numerical analysis from which the equations describing the motion of the fluid are determined through finite element methods. Although the results obtained with these models are satisfactory, they are limited to a specific geometry of pleat. Moreover, they are generally difficult to use and/or to adapt for a user who is not familiar with numerical analysis.
- The generalist models [6,7]. They do not require numerical analysis and are easier to use than the specific models. They come from phenomenological approaches and are intended to cover

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http://dx.doi.org/10.1016/j.seppur.2014.02.011
1383-5866/

a wide range of pleat geometries. Nevertheless, they require an experimental fitting in order to fix a parameter due to the pressure drop of the singularities.

In the current state of knowledge, the use of models is hardly convincing due to the wide range of operating conditions (filtration rate), the aerosol characteristics (nature, size distribution) as well as the geometry of the pleated filter itself. Besides, in this specific case, clogging results in the variation of the local velocity in the pleats. This leads to an inhomogeneous deposition and thus a partial filling of the pleats. Del Fabbro et al. [8] notably observed the formation of arches in between pleats, deposit at the bottom of the pleats and fully clogged pleats. Clogging is then a complex phenomenon and calls for the development of new models relevant for pleated filters. One can decompose the clogging into three distinct phases, the first two being equivalent to those observed for flat filters. First of all a period of in-depth filtration, during which the particles are trapped within the media, has to be considered. Then, a filtration at the surface of the media, with the formation of a cake of particles, follows. The final step, specific to pleated filters, consists in a reduction of the filtration surface that results in a significant rise in the pressure drop. Developing a thorough model requires full comprehension of all the physical processes involved: flow in porous media, particle deposition and particle/media interactions. Unfortunately, it remains very time-consuming to observe them experimentally due to the large number of parameters to take into account. As a consequence numerical approaches, consisting of building virtual structures together with solving transport equations, can be considered as a powerful tool even if they require a validation step. They allow an overall characterization of each process within a reasonable time compared to experiments [9–12]. Observing the preferential deposit in a specific filter can give some clue about the physical phenomena involved. Furthermore, the implementation of an original technique in order to characterize aerosol deposit on a particular type of filter, could be used to experimentally prove the efficiency of the numerical tool. The purpose of this work is to contribute to improve the knowledge of the flow in HEPA pleated media as well as the clogging phenomenon in the particular case of a micron-sized solid aerosol filtration thanks to the combination of Single-Photon Emission Computed Tomography (SPECT) and X-Ray Computed Tomography.

2. Influence of operating conditions on the pressure drop of filter media

This review focuses on solid aerosols. Numerous experiments conducted on HEPA flat filters showed the influence of solid particles size on the evolution of the pressure drop [13]. During the in-depth filtration period, the geometry of the deposit depends on the collection mechanisms and consequently on the particle size [14]. Submicron-sized particles, mainly subjected to interception and Brownian diffusion mechanisms, preferentially deposit on top of each other and form dendrites [15–17]. This type of highly porous deposit, composed of particles with high specific surface area, offers a large apparent volume and therefore a high resistance to the flow. Accordingly, for the same collected mass, submicron-sized particles cause a higher pressure drop than the micron-sized particles. Those latters are collected as compact clusters of low specific surface area.

Thomas et al. [18] conducted experiments to measure the pressure drop of fiberglass flat filter during the filtration process. A 0.31 μm uranine aerosol was used in a range of velocity from 0.01 to 0.5 m/s. The results indicate that the pressure drop due to the cake of particles does not depend on the filtration velocity. Similar findings have been observed in a previous work on submicron-sized particles [19]. For larger particles, contradictory results have been reported and no clear trend emerged [20,21]. This shows the complexity of the filtration velocity influence on the pressure drop associated to the collection of micron-sized particles.

In the case of pleated filters, the first experimental study on the influence of operating conditions on the aerosol deposit has been carried out by Del Fabbro et al. [6]. Through surface observations of filters after clogging, the authors noticed that the filtration velocity influences the heterogeneity of particles deposit in the pleats. When increasing velocity, from 0.01 to 0.10 m/s, the particles lay at the bottom of the pleat due to inertial effects. For low velocities, the particles are arranged progressively causing a faster filling. Regarding to the particle diameter, ranging from 1 to 8 μm, for the same collected mass, the pressure drop for smaller particles increases due to their higher specific surface. Nevertheless surface observations require the cutting and unfolding of the filter, which obviously induces a change in the structure of the deposit. Moreover, no observation has been made at the beginning of the filtration process, and consequently the role of in-depth filtration on the heterogeneity of the initial deposition has not been evidenced yet.

Recently, [22] achieved the only experimental study of three-dimensional visualization identified to date. This work has been performed by X-ray microtomography and the aim was to validate a numerical simulation method to predict the clogging point of pleated filter elements [23]. The author finds encouraging results by comparing the values of cake heights from numerical and experimental results. These conclusions from three-dimensional visualizations are still limited to a single case study. Unfortunately they do not allow characterizing the influence of the operating conditions on the heterogeneity of particle deposit.

3. Experimental work

3.1. Experiments principle

Experiments aim for the *in situ* visualization of the filtration process with no alteration of the three-dimensional structure of the particle deposit. We based our approach on medical imaging techniques and the determining of the position of a ^{99m}Tc marked aerosol by combining SPECT with X-Ray Computed Tomography. Two kinds of experiments have been carried out:

- First, we wanted to highlight the influence of the filtration velocity on the preferential area of initial deposit in the blank HEPA filter. To achieve this, we have generated, filtrated and located a monodisperse radioactive aerosol, which traces the flow.
- In a second step, we focused on the dynamics of the deposition to determine the impact of the clogging level on the flow. Filters were preloaded by means of a solid aerosol of alumina and then the radioactive aerosol was generated, filtered and located using SPECT-CT.

3.2. Materials

3.2.1. Mini-pleated filters

The studied HEPA filters are H14 classified by the European norm EN1822/2009 that defines classes for filters by their retention at most penetrating particle size (MPPS). H14 class corresponds to an efficiency over 99.995%. A mini-pleated filter (Fig. 1) consists of a 15 cm × 15 cm square stainless steel frame; the fibrous medium is made of fiberglass to which organic binders have been added at low concentration to ensure the mechanical rigidity. To avoid the media/media contact in order to optimize