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Aerosol filtration using hollow-fiber membranes: Effect of permeate velocity and dust amount on separation of submicron TiO_2 particles

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ABSTRACT

This work aimed to determine filtration performance of polypropylene hollow-fiber membranes in removing submicron particles from air. Experiments were performed in a chamber simulating dust environment with synthetic submicron-size particles (micronized TiO_2). Ahollow-fiber membrane with 300 fibers of a filtration area of 0.43 m^2 was tested. By measuring number of particles in chamber (upstream) and on the suction side of the membrane (downstream), the filtration efficiency was determined. Two different weights of synthetic dust (50 and 100 mg) and two permeate velocities (15 and 30 cm/s) were used to compare their influence on particle collection efficiency. Particle counting was carried out using a TSI 3075 condensation particle counter connected to a TSI 3080 scanning mobility particle sizer in 32 particle size channels from 17 to 600 nm. Pressure drop evolution with intense particle loading was recorded and fouling of the membrane was observed after 25, 50 and 90 h of filtration using SEM. The results showed high efficiency, mostly higher than 99.9% with higher pressure drops compared to other materials on HEPA level.

1. Introduction

Air and other gas filtration appears to be of less importance in general filtration compared to the liquid filtration business. This situation is not unusual, as gas filtration makes up only about 15% of the total filtration market [1]. Nonetheless, gas filtration can be found in almost every aspect of human activity, and some applications are growing in importance. As indoor air contains two to five times higher concentrations of pollutants than outdoor air [2], air filtration systems are necessary. The main function of these systems is to remove respirable particles such as microorganisms, dust and allergens from the air to alleviate associated health concerns [3–6].

The use of membranes for air filtration has significantly increased over the past decade. Their unique performance, chemical, surface and physical properties are preferred in a number of air filtration applications including nanoparticle separation [7,8]. Probably the largest number of air filters is used in the systems controlling air quality in living accommodations (domestic, commercial and institutional) and also in working spaces. Especially of growing interest are clean rooms installations for critical assembly processes. These are now being supplemented by the vent filters controlling discharges from working spaces where potentially hazardous atmospheres are used. These filters are being grouped under the term HVAC (heating, ventilation and air conditioning) and are basic means for improvement of indoor air quality. The other important applications of air and other gases filtration are:

- respirators and breathing air systems [9,10];
- compressed air production, typically for pneumatic and hospital air systems [11,12];
- vehicle cabin air filtration, including atmosphere control in buses, trains, airplanes etc. [13–15];
- mobile engines air intakes and exhausts, especially for diesel engines [16–18];
- process air cleaning, where the air is a process input or coolant [19];
- demisting of gas streams free of water or oil droplets [1].

The effort of this work was to study air filtration characteristics of hollow fiber membranes (HFMs) in removal of submicron particles. HFMs have been used very scarcely for this purpose so far as their main field of application was water/wastewater treatment [20]. They have also been used in air treatment applications including humidification/dehumidification systems for air conditioning [19,21,22], membrane contactors [23] or as non-porous hollow fibers in heat exchangers [24–27]. This type of membranes can be used for air

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filtration and provide high efficiencies in particulate matter removal down to submicrometer sizes comparable with HEPA filters. The main aim was to determine filtration efficiency characteristics for particle size range from 18 to 600 nm using a test dust of TiO_2 particles with a modal particle size of 340 nm. We chose TiO_2 because particles generated from solutions such as polystyrene latex (PSL), NaCl or DEHS were not suitable due mainly to low particle concentrations. TiO_2 was previously used to model pressure drop evolution during fouling of HFMs in water filtration [20] and also to assess air filtration performance of multilayered electrospun polylactide membranes [8]. The influence of permeate velocity and amount of testing dust was studied. Finally, we studied membrane fouling and pressure drop with time and observed the fouled HFMs using SEM.

2. Materials and methods

2.1. Experimental setup

Filtration was carried out in a chamber of 70 dm^3 volume (Fig. 1) where a HFM was placed. The HFM was connected to a fan using a pipe. The pipe was provided with an EE660 velocity probe (VP) and an Omega PX277-05D5V differential pressure sensor (Δp). The second output of the differential pressure sensor was connected to the chamber thus obtaining pressure drop caused by the HFM. Micronized titanium dioxide (titanium white pigment, Fig. 2a) was used as a test dust (particle-size distribution shown in Fig. 2b measured using a Malvern Mastersizer 2000 laser diffraction analyzer). TiO_2 dust was used due to an easier and faster formation of dust environment. Particles generated from a solution such as PSL, NaCl or DEHS could not be used because it was necessary to create a stable particle dispersion in a very short time and in an appropriate concentration in the whole volume of the chamber. The production of particles using a generator is slow and the concentrations are rather low. Using this method, it was practically impossible to create required amount of airborne particles in the chamber, also due to their sedimentation. Two or more generators/nebulizers in parallel would help to provide high aerosol concentrations. Unfortunately, these were not available. Therefore, we used TiO_2 powder which was dispersed using a pressure air nozzle (see further).

The test dust was fed through an opening on the chamber wall (the upstream concentration profiles shown in Fig. 2c). It was not possible to use dust feeder because, unlike in the planar filter testing, there was not any air stream inside the chamber and the fed dust just fell down without any dispersion. To ensure an adequate homogeneous dust dispersion into the chamber it was necessary to use pressure air. The weighed amount of dust was dispersed from a small dish using pressure air driven through an ejector (Fig. 1). The dust was thus uniformly dispersed in the chamber. Particles which passed through the membrane, carried by the airflow inside the pipe, are sampled using a TSI SMPS 3080 electrostatic classifier connected to a CPC 3775 particle counter. The particle sizer was linked to a laptop with software for data management.

2.2. Hollow-fiber membranes

Polypropylene HFMs (Fig. 3a) produced by ZENA Membranes s.r.o. [28] were tested on filtration performance. Parameters of HFM are shown in Table 1. They have a narrow pore-size distribution (Fig. 3b) with majority of pores within a size range of 90–100 nm (measured using a Quantachrome 3Gzh capillary flow porometer). Fig. 4 shows a single hollow fiber shell side (Fig. 4a) with a detail of the membrane porous structure (Fig. 4b, c). The strength of the membrane fibers is 2 N/fiber (measured using a LabTest 6.0051 tensile testing machine).

2.3. Evaluating the filtration performance

Air filtration materials or whole air filtration units are mostly evaluated in terms of filtration efficiency and pressure drop. The former describes the ability of a filter unit to remove particles from an air stream while the latter is mainly related to energy requirements. The filtration efficiency η is generally defined as follows:

$$\eta = 1 - \frac{C_{down}}{C_{up}} \tag{1}$$

where C_{down} and C_{up} are the number of particles downstream and upstream of the filter, respectively. The measurement consisted of several steps. First, we measured several times upstream particle concentration to assess the reproducibility of dust dispersion. It was necessary to use the same air pressure at the inlet to the ejector to obtain reproducible particle size distribution of the dispersed TiO_2 powder upstream of the HFM. We did seven measurements of upstream particle concentration and calculated average and standard deviation. This values were then used to calculate the filtration efficiency. This was carried out for two dust amounts of 50 and 100 mg. After dust dispersion in the chamber, the fan was turned on and immediately measured the particle size profile at downstream side of HFM. The downstream particle concentration was measured seven times .

Another important quantity was the pressure drop caused by the filtration medium, which is chiefly related to energy requirements which greatly affect the price of the overall filtration process. Here the pressure drop is considered as a sum of transmembrane pressure (*TMP*) (i.e.pressure gradient over the membrane wall) and pressure loss (i.e.pressure

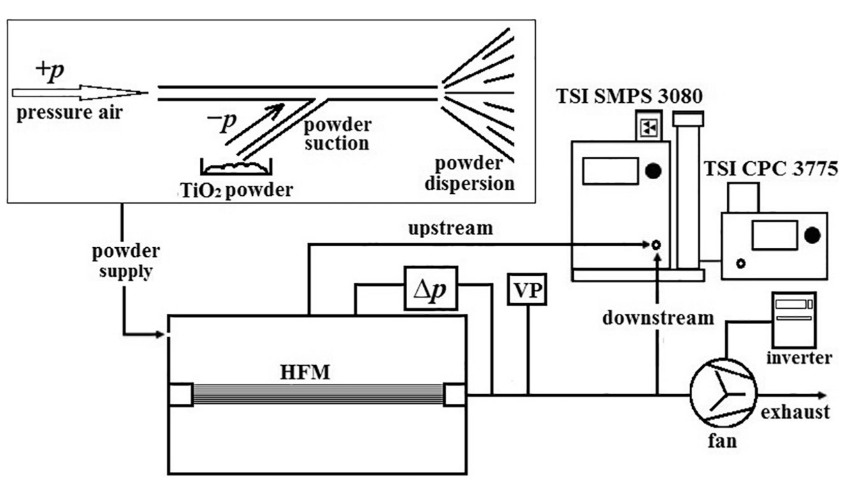

Fig. 1. A scheme of experimental setup.