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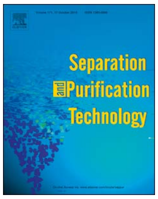

Air filtration performance of symmetric polypropylene hollow-fibre membranes for nanoparticle removal

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ABSTRACT

This work aimed to determine filtration performance of polypropylene hollow-fibre membranes (HFMs) for removing submicron particles from air. Experiments were performed in a glass chamber supplied with a nanoaerosol particles formed by burning incense sticks. Three types of HFMs varying in packing density, active filtration area and pore-size distribution were tested in an outside-in configuration. By measuring the number of particles upstream and downstream of the HFM, the filtration efficiency was determined. Three permeate velocities (5, 10 and 15 cm/s) were used to compare the velocity effect on filtration efficiency. Particle counting was carried out using a TSI 3075 condensation particle counter connected to a TSI 3080 scanning mobility particle sizer in 48 particle size channels from 18.1 to 100 nm. The results show high efficiency, mostly higher than 99% for particles above 60 nm size. The most penetrating particle sizes (MPPS) were between 35.9 and 40 nm at 5 cm/s with an efficiency of 82–86%. At permeate velocity of 10 and 15 cm/s, MPPS slightly decreased to range of 34.6–40 nm, with efficiency decreasing to 72–84% and 69–83%, respectively. The quality factor of HFMs was within the 2–28 kPa^{-1} range.

1. Introduction

Air filtration is the most common method for aerosol mitigation and is used in many various applications such respirators and breathing systems [1,2], compressed air production [3,4], vehicle cabin air filtration [5–7], engine air intakes and exhausts [8–10], process air cleaning [11] and demisting gas streams to remove water or oil droplets [12]. Last but not least it is removing nanoparticles [13] and respirable particles such as dust, microorganisms and allergens from the indoor air to alleviate associated health concerns [14–17]. The latter became of great importance as indoor air contains two to five times higher concentrations of pollutants than outdoor air [18]. In relation to nanotechnology and nanoparticle production, the use of membranes for air filtration has significantly increased over the past decade. Their unique performance and chemical, surface and physical properties are preferable in many air filtration applications [19].

Other applications have been studied in greater detail, particularly air treatment using HFMs for air humidification/dehumidification systems for air conditioning [20–22,11,23] and the treatment of gases using membrane contactors [24]. Most recently, HFMs for gas treatment as a subsystem of other operations such as desalination [25] and heat pumps [26] and non-porous HFMs as heat exchangers [27,28] have been of great interest. In another study by Federspiel et al. [29], pressure-flow relationships for gas flow through HFM were studied experimentally to develop an intravenous oxygenator. Thus far, HFMs have mostly been used for water treatment, mainly due to the compactness of HFM modules – they contain a high active filtration area within a small volume. This type of membrane can be used for air filtration and to provide high efficiencies in particulate matter removal down to submicrometric sizes when compared with HEPA filters.

This work investigated the air filtration performance of hollow fibre membranes (HFMs). There has only been one study which aimed to prepare and characterize HFMs for primary use in air filtration: Wang et al. [30] prepared HFMs of polyvinylidene fluoride-polyethylene glycol (PVDF-PEG), and intended to purify air containing ultrafine particles. Even though there is only one basic research study on this topic, there are three companies with HFM air filter products in their portfolio: KITZ Microfilter Corp. (Japan) [31], Pisco Inc. (USA) [32] and SMC Pneumatics Pvt. Ltd. (India) [33]. These filters are mainly used in compressed air/nitrogen and special applications such as microelectronics, print boards, precision machinery and medical equipment. Compared to classic air filters (for example, those made of a non-

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woven fabric) these filters have a smaller filtration area of 80–1000 cm^2, pore size of 0.01 µm and operate under low flowrates of 70–500 L/min. Due to these factors, the use of these HFMs is limited to low flowrate applications and those where efficiency and compactness are more important than pressure drop. The main aim of this work was to determine the filtration performance of symmetric polypropylene HFMs (0.4–0.8 m^2 filtration area) for nanoparticle removal. Transmembrane pressure and fractional filtration efficiency for particles in 18–100 nm range were determined. The tested HFMs were then compared using quality factor (*QF*) for individual particle sizes at a permeate velocity of 5, 10 and 15 cm/s.

2. Underlying phenomena

Aerosol particles carried by an air stream can be retained by a filter through different mechanisms. These mechanisms depend on the filtration conditions and mainly properties of the aerosol to be filtered particularly on particle-size distribution. Generally, collection efficiency (η) can be calculated as follows:

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

where C_{down} and C_{up} are the particle concentrations downstream and upstream of the filter, respectively. Theoretical prediction of filter efficiency is based on efficiency of a single collector which is defined as the ratio of the number of particles collected to the number of particles in the volume of air geometrically demarcated by the collector. The collection efficiency thus depends on geometrical parameters of the filter, particles and also flow characteristics during filtration. To assess which mechanism dominates the collection for given conditions, evaluation in terms of several dimensionless parameters characterizing the filtration conditions is often appropriated as these parameters are a function of collection efficiency:

$$\eta = \eta(Re,Pe,Stk,R,G) \tag{2}$$

where *Re*, *Pe*, *Stk* are Reynolds, Peclet and Stokes number, respectively and *R* and *G* are the interception and sedimentation parameter, respectively. Gravitation settling can contribute to particle capture but it can be neglected for nanoparticles [34–36]. To characterize the flow field around the collectors, Reynolds number, which is the ratio of inertia to viscous forces, is often used:

$$Re_{\text{f}} = \frac{d_{\text{f}} \nu \rho}{\mu} \tag{3}$$

where d_{f} is the average collector diameter, ν is the permeate velocity, ρ and μ is air density and dynamic viscosity, respectively. The same can be used to characterize the flow field around the particle, which is the particle Reynolds number. The relationship is the same as Eq. (3) but the particle diameter d_{p} and the particle velocity relative to the gas flow ν_{p} are used:

$$Re_{\text{p}} = \frac{d_{\text{p}} \nu_{\text{p}} \rho}{\mu} \tag{4}$$

For calculation of Re_{p}, we assumed $\nu = \nu_{\text{p}}$.

The diffusion mechanism is characteristic for particles undergoing Brownian motion which then hit the collectors and are captured. Diffusion dominates when nanoparticles are filtered. To consider the relative importance of convection and diffusion, the Peclet number is used:

$$Pe = \frac{\nu d_{\text{f}}}{D} \tag{5}$$

where *D* is the diffusion coefficient of particle calculated as follows:

$$D = \frac{k_{\text{B}} T C_{\text{s}}}{3\pi \mu d_{\text{p}}} \tag{6}$$

where k_{B} and *T* are the Boltzmann constant and absolute temperature, respectively and C_{s} is the Cunningham slip correction factor:

$$C_s = 1 + Kn\left[1.207 + 0.44\exp\left(-\frac{0.78}{Kn}\right)\right] \tag{7}$$

where *Kn* is the Knudsen number of particle with λ as mean free path:

$$Kn = \frac{2\lambda}{d_{\text{p}}} \tag{8}$$

The interception effect assumes that particles follow the airflow streamlines. Interception occurs if the particle centre is in a distance of one particle radius from the collector surface. Interception plays an important role in nanoparticle filtration for small collector diameters [37]. So called interception parameter is used to assess influence of interception mechanism which is a ratio of particle and collector diameter:

$$R = \frac{d_{\text{p}}}{d_{\text{f}}} \tag{9}$$

Inertial impaction is related to the flow field around the particle and dominates when particle inertia causes the particle to separate from airflow streamlines adjacent to the collector. The particle thus follows different trajectory and collides with the collector [38]. Stokes' number *Stk* characterizes the particle inertia and is defined as follows:

$$Stk = \frac{d_{\text{p}}^2 \rho_{\text{p}} C_{\text{s}} \nu}{18 \mu d_{\text{f}}} \tag{10}$$

where ρ_{p} is the particle density. If *Stk* is higher than unity, particles separate from streamlines and hit the collector. Conversely, for *Stk* lower than unity, the particles move along streamlines and the inertial effect does not take place. For high Reynolds numbers, the inertia effect is more appreciable as the streamlines adjacent to the collector turn around more rapidly.

3. Materials and methods

3.1. Hollow-fibre membranes

Three various types of low cost polypropylene HFMs from Zena Membranes s.r.o. Brno, Czechia [39] were tested (Table 1). These HFMs are manufactured via dry stretching of hollow fibres with no waste. The membrane packing density α is the fraction of the cross-sectional area of a fibre over the cross-sectional area of the bundle. The relationship after reducing can be written using the fibre outer diameter (D_{o}) and bundle (module) inner diameter (D_{bi}) as follows [40]:

$$\alpha_M = n\frac{D_{\text{o}}^2}{D_{\text{bi}}^2} \tag{11}$$

Table 1
Parameters of HFMs.

HFMs	P50	P60	P80
Fibre outer diameter, D_{o} (µm)	300	300	620
Fibre inner diameter, D_{i} (µm)	228	228	474
Fibre wall thickness, t_{w} (µm)	36	36	73
Number of fibres, *n*	1380	1380	300
HFMs net length (mm)	730	730	730
Potting thickness (mm)	15	15	15
Membrane packing density, α_{M} (%)	46	46	43
Bundle inner diameter, D_{bi} (mm)	16.4	16.4	16.4
HFM surface area (m^2)	0.95	0.95	0.43
Initial *TMP* (5 cm/s) (Pa)	543.2 ± 3.3	558.6 ± 3.6	284.6 ± 2.7
Average pore size (nm)	94	87	95
Porosity, ε (%)	52	52	54
Average collector diameter, d_{f} (nm)	130	90	112