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Filtration performance of electrospun acrylonitrile-butadiene elastic fiber mats in solid aerosol filtration

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ABSTRACT

Elastic acrylonitrile-butadiene copolymer fibers were electrospun to fabricate fiber mats of five different basis weights: 10, 20, 30, 45, and 60 g/m^2. The fiber mats were investigated for properties of pore diameter and permeability. As the basis weight increased, bubble point and mean flow pore diameters as well as the permeability/mat-thickness values decreased. The fiber mats were tested as filter media for capture of NaCl nanoparticles from aerosol flow. Due to the elastic nature of the fibers, the mats were tested in stretched and non-stretched conditions to evaluate changes in filter performance. The pressure drop and penetration of the filter media were calculated using correlations from literature and by assuming idealized properties of constant mat thickness or constant mat volume when the mat is stretched. Experimentally, the fiber mats of higher basis weights yielded higher pressure drops and lower penetrations compared to lower basis weight mats. The stretched fiber mats showed decreased pressure drops and increased particle penetrations compared to the non-stretched mats due to the enlargement of pores within the mats. The FI values were about the same between stretched and non-stretched mats of same starting basis weights.

1. Introduction

Solid particles dispersed in aerosols can be efficiently separated from the continuous gas phase using conventional HEPA and ULPA filters that are typically composed of microfibers. With the development of electrospinning during the past two decades [1–3], it has become common to produce and evaluate submicron sized fibers from a broad range of polymer materials [4]. The electrospun fibers of many polymers have been investigated for use in a variety of applications according to their specific properties, e.g., fibrous media with superhydrophobic and oleophilic surfaces for removal of water droplets from organic liquids [5,6], and biocompatible polymer fibers for drug delivery and tissue engineering [7–10]. Specifically for aerosol separations [11–14] the properties of high surface areas per mass and the small pores of electrospun fiber mats are useful to enhance particle capture according to the single fiber theory [15].

Three primary particle capture mechanisms [16] dominate filter performance when fine particles interact with the fibers: interception, inertial impaction, and Brownian diffusion. The performance of each mechanism is dependent upon the flow conditions (e.g., velocity) and physical properties of the fluid and the particles. Each particle capture mechanism contributes to the overall separation efficiency of a filter medium. Besides separation efficiency, the pressure drop generated from the drag of the aerosol passing through the porous filter medium is important in the evaluation of performance as it is proportional to the power required to operate the filter. The pressure drop across the medium is commonly characterized by the medium permeability defined by Darcy's law [17].

The filter efficiency and pressure drop are combined into a single measure of performance, the Filtration Index (FI), that simultaneously accounts for both the separation efficiency (E) and the magnitude of the pressure drop (ΔP), as defined by [18]

$$FI = \frac{-\ln(1-E)}{\Delta P} \tag{1}$$

Ideally the preferred filter medium has a greater Filtration Index when it performs with a high separation efficiency while maintaining a lower pressure drop.

Porosity is the fraction of the filter volume that is not occupied by the fibers, e.g. the void volume fraction. Void spaces within a filter medium are as important as the solid fibers as they constitute the porous structures through which the continuous phase flows and provide space for the particles to accumulate on the fibers. The properties of the pores are mainly characterized by porosity

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Nomenclature

BW	basis weight
$\mathfrak{D}$	diffusivity of particles in air
d_f	fiber diameter
E	filter efficiency
E_d	single fiber efficiency by Brownian Diffusion mechanism
E_R	single fiber efficiency by direct interception mechanism
E_s	sum of single fiber efficiencies, Eq. (6)
f	flow resistance function defined in Eq. (3)
FI	filtration Index
H	spherical cap height (or centerline depth) as indicated in Fig. 7
k	permeability of the fiber mat
Kn	Knudsen number as defined in Eq. (4)
Ku	Kuwabara Number, Eq. (10)
N	ratio of particle diameter to fiber diameter
Pe	Péclet number
ΔP	pressure drop across the mat due to air flow
R	radius of opening in filter holder
S	surface area of filter mat
T	mat thickness
V	face velocity of air through the filter
V_f	volume of fibers
ε	fiber mat porosity
λ	mean-free-path between air molecules
μ	air viscosity

Subscripts

n	property of non-stretched mat
s	property of stretched mat

and pore opening size. Pores are complex flow paths that often are multiple interconnected channels of varying internal dimensions. Characterization of the pore size often depends upon the method of measurement. For example, a bubble-point test is used to characterize the largest pore opening in a filter medium. In our work we consider the pore size as the distance between nearby fibers through which a particle may carried by the flowing fluid.

Pores are classified into three types [19]: open pores, dead-end pores, and closed pores. Open pores are accessible for the flow such that the flow can penetrate and pass through the medium via these pores. Dead-end pores have an inlet but no outlet and do not contribute to the fluid flow but may contribute volume for retention of captured particles if the particles can enter these pores. Closed pores are surrounded by solid phase and are not open to the flow, hence their presence does not contribute to the flow or the capture of particles, but may reduce to overall available space for fluid flow and thus restrict the flow and result in a higher pressure drop. Ideally a filter has open pores but no dead-end or closed pores.

For a nonwoven electrospun fibrous medium, the porosity and pore sizes are closely related to the amount and packing of the fibers. As electrospun fibers are collected onto a grounded surface, they randomly cross over each other to pack and fill in the void spaces. The porosity and the pore sizes gradually reduce as more fibers accumulate to form a medium, and simultaneously the thickness of the medium increases. Eventually, when enough fibers have layered on top of each other, the fiber structure approaches a packed state that the porosity and pore sizes become constant and further addition of fibers only contributes to increasing the thickness of the medium.

In most filter media applications the fiber mats are relatively rigid and inelastic. This may be deliberate to avoid complications associated with a mat that may change shape and properties when stressed due to the pressure drop of a flowing gas. To our knowledge, systematic studies of the performance of stretchable elastic fiber media are absent in scientific literature. In this work, elastic electrospun fiber mats were prepared and tested in aerosol filtration to capture solid NaCl particles. The filtration test results showed a general trend for efficiency and pressure drop to decrease as the mat was stretched such that the Filtration Index was not significantly affected.

Performance variations with basis weights of the fiber mat followed generally expected trends. A significance is the observation that pore sizes in the electrospun mats approach a minimum plateau value at about 45 g/m^2 for the mats tested in this work. This is useful because the flow through pore size affects fiber mat performance for many applications, not just filtration. This suggests that pore size distributions and basis weights should be included in the characterization of electrospun fiber mats.

2. Experimental description

2.1. Materials

Acrylonitrile-butadiene copolymer (33% Acrylonitrile, Scientific Polymer Products, Inc, Ontario, NY) was selected for its elastic properties. The copolymer was dissolved in acetone (Sigma Aldrich, St. Louis, MO) to prepare solutions with copolymer concentrations of 5% by weight. The solutions were stirred for 24 h at room temperature to be homogeneous. The solutions were directly used for electrospinning without further modifications.

2.2. Electrospinning

A typical single needle electrospinning setup (Fig. 1) was used to fabricate the fiber mats. The copolymer solution was filled into a 5 mL plastic syringe and fed through a charged metallic needle at a flow rate of 20 mL/hr by a syringe pump (New Era Pump Systems, Inc., Farmingdale, NY). A potential difference of 20 kV generated using a high voltage power supply (Gamma High Voltage Research, Ormond Beach, FL) was applied between the needle and a grounded aluminum foil that served as the fiber collector. The aluminum foil was located 20 cm distance from the needle tip. Fiber mats of five basis weights of 10, 20, 30, 45, and 60 g/m^2 were produced and cut to 6 cm × 6 cm squares mats for testing. Details of the electrospinning parameters are summarized in Table 1.

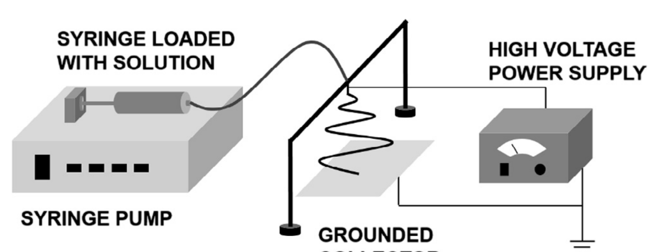

Fig. 1. Single-needle electrospinning setup.