Nanofiber Layer Morphology and its Role in Air Filter Applications

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ABSTRACT

Nanofiber polymer layer deposited on regular cellulose filter media usually shifts resulting air filtration parameters of this material several classes higher. This evident benefit becomes to be widely commercially accessible due to availability of productive industrial-scale technology.
Influence of morphology of the nanofiber layer (fiber diameter, porosity) on filtration parameters of the air filtration media has been studied. All samples analyzed in this paper have been prepared using an industrial production Nanospider^{TM} machine. Preparation method of the filtration media samples and their analysis are described in the paper. It has been shown that the morphology of nanofiber layer plays usually more important role than its basis weight. Some new physical/geometrical values are proposed to reflect these relationships.

KEYWORDS

air filtration media, nanofibers, nanofiber layer morphology, basis weight, filtration efficiency, pressure drop, electrospinning

1. INTRODUCTION

Electrospinning technology matured to industrial stage [1], and it is currently moving from laboratories to production plants. Filtration applications of nanofiber layers are most developed, there is no doubt that nanofibers bring great added value in this field.

Usual parameter, discussed (and required) by nanofiber filtration media users, is the basis weight of nanofiber layer. However, experience with final (product) parameters of resulting filters shows that there is not very strong correlation between basis weight, filtration efficiency and permeability (or pressure drop), at least in the case of cellulose substrate combined with relatively low-weight (0.01 gm^{-2} to 0.1 gm^{-2}) polymer nanofiber layer.

Mechanism of filtration process on fibrous media has been discussed in several publications [2-5]. For example, for cellulose filtration media of solidity β in the range of 0.11-0.33 and an average pore diameter of 12-84 µm, it has been shown that pressure drop depends on fiber diameter d_f according to relation [2]:

$$\Delta p = \frac{\mu \cdot v \cdot w_b \cdot h}{d_f^2 \cdot \rho_f \cdot \left(-0{,}84 \cdot \ln \beta - 0{,}47\right)} \qquad (1)$$

where μ is air dynamic viscosity, w_b - media basis weight, h - media thickness, ρ_f - fiber density, β - filter solidity (or packing density) - volume of fibers/volume of filter.

However, in the case of low basis weight nanofiber layer, where molecular (or transition) flow regime takes place, following equation is considered to be valid [5]:

$$\Delta p = \frac{\mu \cdot v \cdot w_b \cdot h}{r_f \cdot \lambda} \qquad (2)$$

where r_f is radius of nanofiber and λ is mean free path of molecules.

Hence, the combination of cellulose medium with polymer nanofiber layer will require more complex models to describe behavior of final filtration material. Systematic experimental study of correlations between final product parameters (filtration efficiency, pressure drop) and morphology of cellulose/nanofiber media can provide useful data for both theoretical understanding of filtration mechanisms and practical design of air filters.

2. EXPERIMENTAL

For this study, we prepared forty-two samples of controlled basis weight and fiber diameters (six series, seven samples in each). Nanospider production machine has been used, as it provides good long-term consistency of filtration media parameters (16 hours run with repeatability in the range of ±5%).

To obtain various basis weights, substrate speed had been varied from 0.2 m/min to 4 m/min for each series of samples, while polymer solution parameters (concentration, etc.) together with electric field intensity determined the range of nanofiber diameter. Nanofiber diameter distribution has been measured using scanning electron microscope (SEM). Basis weights were obtained either directly using analytical balances Mettler (higher values) or by extrapolation from its known dependence on substrate velocity (lower ones).

Pressure drop and initial gravimetric filtration efficiency have been chosen as representatives of product parameters. They were measured according to EN 779 using NaCl aerosol at following settings: air flow speed: 5 m/min, sample area 100 cm^2, flow rate 50 l/min.

3. RESULTS AND DISCUSSION

Fig. 1 illustrates very good correlation between initial gravimetric filtration efficiency and pressure drop, regardless of nanofiber layer parameters (d_f, w_b). As pressure drop monitoring can be relatively easily incorporated into the nanofiber production line, it can be used as a very good value for on-line quality control of final filtration media.

Samples in Fig. 2 show how different nanofiber layers can exhibit similar filtration properties. The first sample is made of thin nanofibers (around 80 nm) and lower basis weight (0.03 gm^{-2}), while the second one is characterized by almost 2-times thicker fibers (144 nm) and more than 3-times higher basis weight (0.10 gm^{-2}).

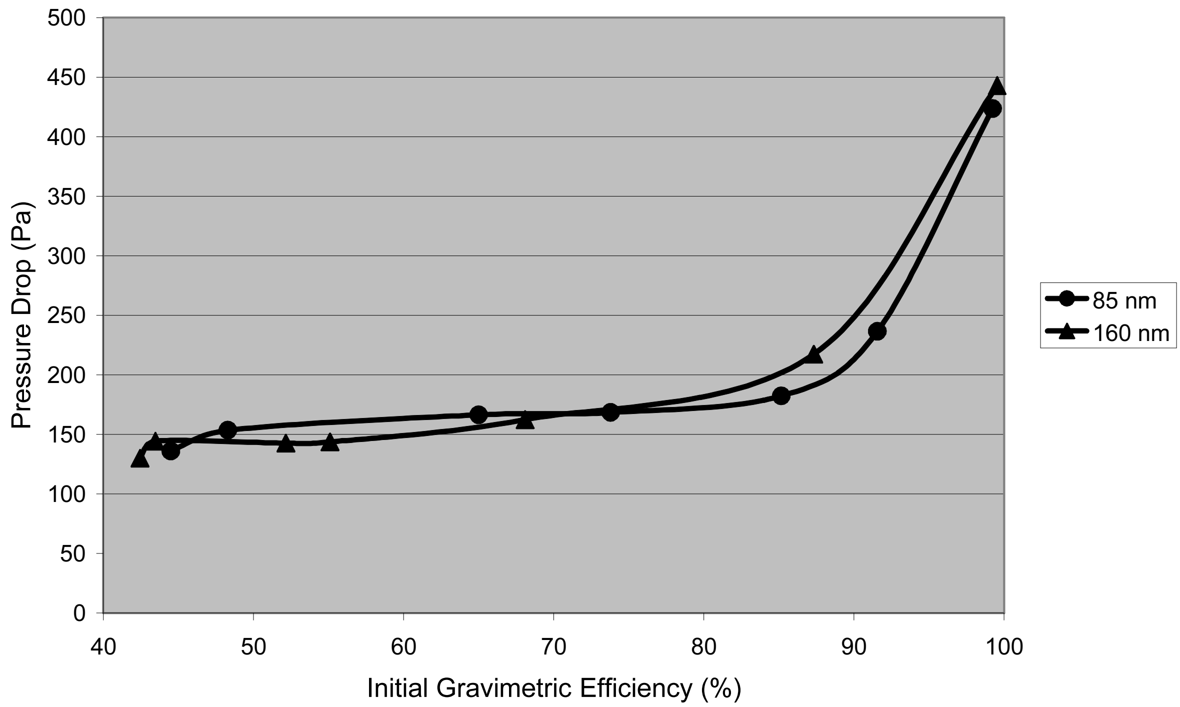
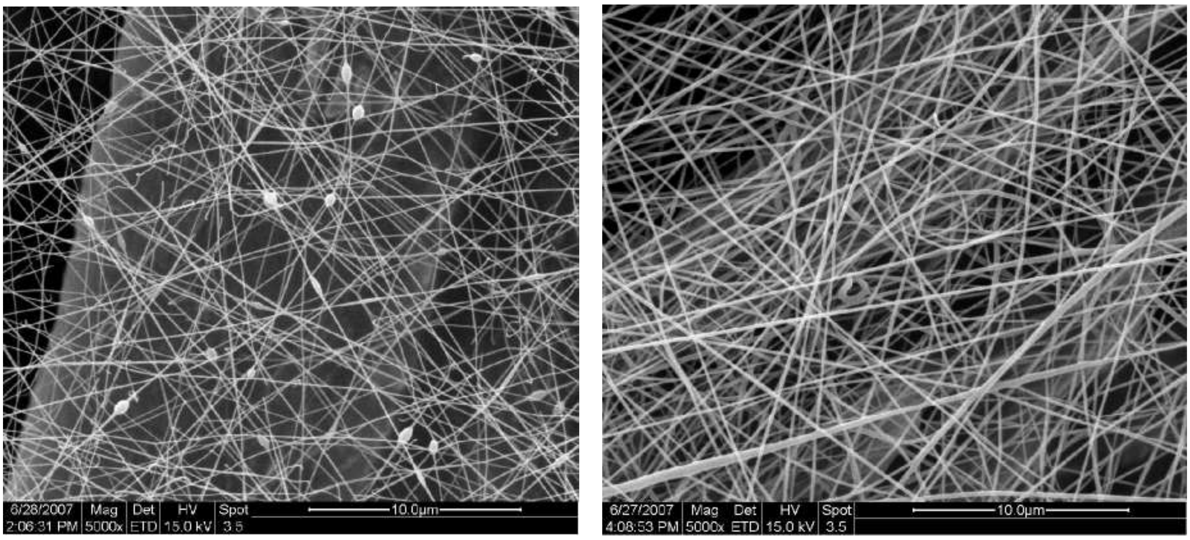


Fig. 1. Correlation between pressure drop and initial gravimetric filtration efficiency

To consider the influence of both basis weight and fiber diameter on final product filtration parameters, we can define a simple value (Relative Fiber Length L_f) expressing the total length of nanofibers (in kilometers) deposited on unit surface of filtration medium (in square meters):

$$L_f = \frac{w_b}{\pi \cdot \rho \cdot \left(\frac{d_f}{2} \right)^2} \tag{3}$$

where ρ is density of material of nanofibers.



$IGE = 73 \pm 1$ %
$\Delta p = 168 \pm 5$ Pa
$L_f = 6114$ km.m^{-2}
$w_b = 0.03$ gm^{-2}
$d_f = 83 \pm 22$ nm

$IGE = 68 \pm 1$ %
$\Delta p = 163 \pm 4$ Pa
$L_f = 6128$ km.m^{-2}
$w_b = 0.10$ gm^{-2}
$d_f = 144 \pm 36$ nm

Fig. 2. Two nanofiber filtration media with different morphology, but similar product parameters

As can be seen from the graphs in Fig. 3 and Fig 4, both filtration efficiency and pressure drop are in much better correlation with Relative Fiber Length L_f than with nanofiber layer basis weight (w_b).

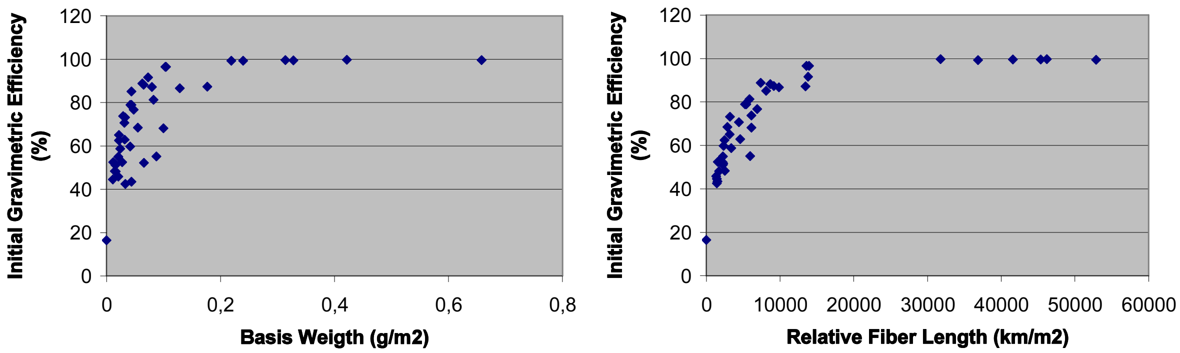


Fig. 3. Initial efficiency vs. basis weight and "relative fiber length"

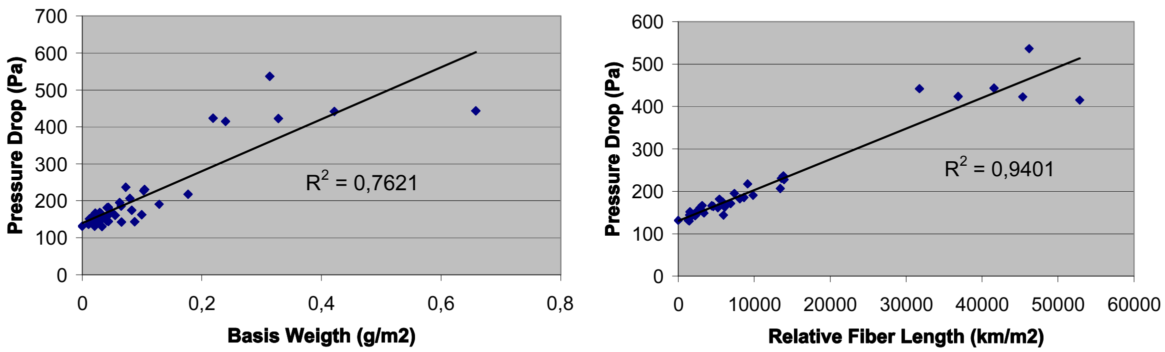


Fig. 4. Pressure drop vs. basis weight and "relative fiber length"

4. CONCLUSIONS

Experimental results obtained in this study showed that:

- Basis weight of nanofiber layer does not predict filtration parameters well enough. The same initial gravimetric efficiency can be obtained using nanofibers of very different mean diameters, or in other words, of very different basis weights.
- Filtration properties of cellulose media with low-weight polymer nanofibrous layer depend mostly on the total length of nanofibers per media surface unit ("Relative Fiber Length").
- "Relative Fiber Length" is in good correlation with both pressure drop and filtration efficiency.
- Image analysis of SEM pictures can be used for predicting of filtration properties of the media.

For more detailed understanding and predicting of filtration properties of the media studied here, it will be useful to investigate similar relationships using:

- Measurements of fractional filtration efficiency of the samples.
- Observations of the role of dust cake formed on media surface during filter lifetime or in field tests.
- Investigations of the effect of final filter design, pleating of the media, etc.

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