MODEL OF MICROFIBER COALESCENCE FILTERS AUGMENTED WITH NANOFIBERS

G.G. Chase* and S. Dharmanolla
Department of Chemical and Biomolecular Engineering
The University of Akron

ABSTRACT

The effect of adding nanofibers to a non-woven microfiber filter media is determined theoretically. The filter performance is characterized by a Relative Quality Factor and the amount of nanofiber added to the filter is measured as the ratio of surface area of nanofibers per surface area of microfibers. Calculations show the Relative Quality Factor passes rises rapidly with addition fo small amounts of nanofiber, reaches a maximum, and gradually decreases as more nanofibers are added to the medium. This shows that the amount of nanofibers mixed into the microfiber can be selected to optimize filter performance.

* Corresponding author: PHONE 330.972.7943, EMAIL gchase@uakron.edu

INTRODUCTION

A model of the performance of mixed micro and nanofiber media in coalescence filter media is presented in this paper. Similar models may be applied for filtration of solid particles. Typical coalescence filters are vacuum formed using glass fibers with average diameters of about 2 to 5 microns. The glass fibers are held together with a binder material. The performance of the filter is measured by its capture efficiency and pressure drop. The capture efficiency and pressure drop are combined together to define the quality factor (Brown, 1993). The greater the quality factor the better the filter performance.

Coalescing filter media augmented with nanofibers having diameters in the range of 100 to 200 nm are known to improve filter performance. The presence of the nanofiber increases the surface area available for capture of the droplets but because the diameters are so small the gas phase “slips” around the fibers and the corresponding increase in pressure drop is not as large as when micron fibers are used. The net effect is an increased quality factor with the use of nanofibers.

This paper describes a theoretical model to determine the amount of nanofiber added to the microfiber filter media to optimizes the filter performance.

THEORY DEVELOPMENT

A volume averaged continuum theory is used to model the process (Chase, 2002) To simplify the model equations the following assumptions are made:

1. Media fibers are rigid and stationary.
2. The media is incompressible.
3. The process is isothermal.
4. The flow is constant and unidirectional in the z direction (see Figure 1).
5. The liquid droplets are captured by the fibers. Capture of droplets by other droplets on the fibers or by binder are neglected.

6. The permeability of media is uniform and isotropic.

7. The porosity and saturation of the medium are uniform and constant.

8. The coalesced droplets do not re-entrain into the air stream.

9. The concentration of liquid droplets in the inlet stream is low enough to assume the bulk density of inlet air stream is equal to density of air at that temperature.

At steady state the amount of liquid holdup (saturation) in the medium and the pressure drop are steady. The mass rate of droplets in the inlet stream that are captured in the filter is equal to the rate of liquid that drains from the filter medium.

The conservation of mass of each phase (gas phase and liquid captured on the fibers), the conservation of species (air, liquid droplets), and momentum balance of the gas phase are the starting equations for the model. The mass and species balances in the model are used to determine the outlet droplet concentration. The gas phase momentum balance is used to determine the pressure drop across the media. At steady state the rate of droplet capture by the fibers must equal the rate of liquid drainage from the medium. Hence, a model applying the mechanisms of droplet capture, along with the assumed average saturation value, is sufficient for closure of gas phase equations for the purpose of determining whether there is an optimum amount of nanofibers.

The full set of conservation equations are too complex to model directly. The above assumptions are applied to simplify the volume averaged continuum equations. The simplified gas phase equations are:

Oil Species Balance

$$\frac{\partial\left((1-S)\varepsilon w_0{}^G \rho^G v_z^G\right)}{\partial z} + I_0^G = 0 \qquad [1]$$

Momentum Balance (z component)

$$(1-S)\varepsilon \frac{\partial P}{\partial z} + F_Z{}^G = 0 \qquad [2]$$

The species balance is solved by introducing a constitutive equation for the mass transfer term $I_0{}^G$. The momentum balance is solved by introducing a constitutive relation for the drag force, $F_z{}^G$.

CALCULATION OF OUTLET CONCENTRATION

To determine the outlet concentration Eq.[1] is rearranged to obtain

$$\frac{d}{dz}(w_0{}^G) = \frac{-I_0{}^G}{(1-S)\varepsilon\rho^G v_z^G} \quad [3]$$

where the interphase mass transfer term is related to the filter coefficient, α, by

$$I_0{}^G = \alpha w_0{}^G \rho^G (1-S)\varepsilon v_z^G \quad [4]$$

Substituting [9] into [8] and canceling terms gives,

$$\frac{d}{dz}(w_0{}^G) = -\alpha w_o{}^G \quad [5]$$

On integrating equation [5] from 0 to z,

$$w_0{}^G(z) = w_0{}^G(0)\exp(-\alpha z) \quad [6]$$

and the outlet concentration is

$$w_{OUT} = w_{IN}\exp(-\alpha L) \quad [7]$$

The overall filter coefficient, α is related to the single fiber efficiency by

$$\alpha = E_i\alpha_i \quad [8]$$

$$\alpha_i = \frac{4\varepsilon_i}{\pi d_i} \quad [9]$$

where E_i is the capture efficiency and ε_i is the volume fraction of the filter media occupied by fibers of diameter d_i. For a mixture of fibers the filter coefficient is given by

$$\alpha = \sum_i E_i \alpha_i \qquad [10]$$

Correlations for the single fiber capture efficiencies, E_i, are available from literature (Brown, 1993). For submicron sized droplets the dominant mechanisms are direct interception and Brownian diffusion. Other mechanisms such as inertial impaction are present but are considered negligible.

CALCULATION OF PRESSURE DROP

The total force acting on all fibers, F_{tot}, is related to the pressure drop by

$$F_{tot} = A\Delta P \qquad [11]$$

We define the force per unit length of fiber as f_i. For a filter of one fiber diameter the pressure drop is related to the force per unit length by

$$A\Delta P = L_i f_i \qquad [12]$$

where L_i is the total length of fibers of diameter d_i within a differential volume element of the filter. For a medium with multiple fiber diameters,

$$A\Delta P = \sum L_i f_i \qquad [13]$$

Integration of Eq.[2], assuming uniform properties over the filter thickness, the pressure drop is related to the drag force by

$$\Delta P = \frac{F_z^G L}{(1-S)\varepsilon} \qquad [14]$$

where F_z^G is the total drag force and L is the thickness of media.

Combining equations we get the expression for the drag force to be

$$F_z^G = \frac{(1-S)\varepsilon \sum L_i f_i}{AL} \qquad [15]$$

We can relate the length to the volume fraction of the fibers as

$$L_i = \frac{4AL\varepsilon_i}{\pi d_i^{\,2}} \qquad [16]$$

Substituting equation [16] in [15],

$$F_z^G = \frac{4\varepsilon(1-S)}{\pi} \sum \left(\frac{\varepsilon_i}{d_i^{\,2}} f_i\right) \qquad [17]$$

For a medium of just one fiber size, combining Eqs.[16] and [12] gives

$$f_i = \frac{\Delta P}{L} \frac{\pi d_i^{\,2}}{4\varepsilon_i} \qquad [18]$$

If we have correlation for the pressure drop for a filter medium of fibers of one size then by inspection with Eq.[18] we can deduce an expression for f_i. The correlations for f_i should account for continuum, slip, or molecular flow phenomena depending on the diameters of the fibers. The flow regimes are distinguished by the Knudsen number.

For $Kn < 0.25$ (for continuum and slip flow of the microfibers), from Brown (1993), we get a correlation for the pressure drop to be

$$\Delta P = \frac{16\mu L v_Z^{\,G} (1 + 1.996Kn)\varepsilon_i}{d_i^{\,2}\left[\begin{array}{l}(-0.5\ln(\varepsilon_i) - 0.75 + \varepsilon_i - \frac{\varepsilon_i^{\,2}}{4} \\ +1.996Kn\left(-0.5\ln(\varepsilon_i) - 0.25 + \frac{\varepsilon_i^{\,2}}{4}\right)\end{array}\right]} \qquad [19]$$

By inspection we derive the expression for f_i to be

$$f_i = \frac{4\mu\pi\upsilon_Z{}^G(1+1.996Kn)}{\left[\begin{array}{l}(-0.5\ln(\varepsilon_i)-0.75+\varepsilon_i-\frac{\varepsilon_i{}^2}{4}\\ +1.996Kn\left(-0.5\ln(\varepsilon_i)-0.25+\frac{\varepsilon_i{}^2}{4}\right)\end{array}\right]} \quad [20]$$

For Kn >10 (for molecular flow with very small nanofibers) we have

$$\Delta P = \frac{4.58\mu\varepsilon_i L v_z^G}{d_i \lambda} \quad [21]$$

hence

$$f_i = \frac{2.29\pi\mu\upsilon_Z^G}{K_n} \quad [22]$$

There is no correlation for the flow conditions between the slip flow regime ($Kn < 0.25$) and free molecular regime ($Kn > 10$). For fibers and conditions resulting in a Knudsen number in the intermediate range $0.25 \le Kn \le 10$ the model uses a linear interpolation to estimate the f_i .

These equations allow us to calculate the pressure drop for a medium with multiple fiber diameters, by the equation

$$\Delta P = \frac{4L}{\pi}\Sigma\frac{\varepsilon_i}{d_i{}^2}f_i \quad [23]$$

CALCULATION OF QUALITY FACTOR

The Quality Factor (also known as figure of merit) is given by Brown (1993) as

$$QF = \frac{-\ln\left(\frac{w_{OUT}}{w_{IN}}\right)}{\Delta P} \quad [24]$$

which represents the ratio of the capture performance to the power required to achieve the capture performance. In general, media with higher quality factors perform better than media with lower quality factors. A filter with a larger quality factor has a greater capture efficiency than a filter with a lower quality factor when operated at the same pressure drop. Substitution of Eqs.[7] and [23] into [24] gives the working equation,

$$QF = \frac{\alpha}{\frac{4}{\pi}\sum(\frac{\varepsilon_i}{d_i^{\,2}} f_i)} \qquad [25]$$

for calculating the Quality Factor. Of most interest is how much change occurs in the Quality Factor due to the presence of the nanofibers. We define the Relative Quality Factor, RQF as

$$RQF = \frac{QF}{QF_{Basis}} \qquad [26]$$

where the basis quality factor is the quality factor for the filter medium without nanofibers.

MODEL RESULTS

The model is easily programmed into a spreadsheet for calculations. As an example the filter is modeled at room temperature, atmospheric pressure, with air face velocity of 2.1 m/s, and constant, uniform 10% saturation. All filters are 1 cm thick. Porosity is determined from the volumes of the fibers present in the filter.

The amount of nanofibers in the filter is calculated as the ratio of the external surface area of the nanofibers divided by the external surface area of the microfibers in the filter medium. An area ratio of zero means no nanofibers are present in the filter.

Figure 2 shows the RQF curves for three droplet sizes for 3 micron diameter microfibers and 300 nm diameter nanofibers. The RQF increases rapidly with small additions of nanofiber, reaches a maximum at an area ratio of about 1 to 3, then slowly declines. The rapid increase in RQF is due to the significant increase in surface area available for capture of particles. However, as more nanofibers are added to the filter the pressure drop due to the added fibers increases

faster than the corresponding increase in particle capture and the RQF passes through a maximum and then declines. Figure 2 also shows that the RQF is sensitive to the size of the particles being captured.

Figure 3 is similar to Figure 2, but in Figure 3 three sizes of microfibers are compared. The 5 micron fiber curve shows the largest RQF because these fibers have the largest difference in size between the micro and nanofibers. If the magnitudes of the quality factors were compared instead of the relative quality factors the 1 micron fibers have the highest quality factors. This plot shows the filters made of larger microfibers will show the greatest increase in RQF. These plots show the same trend of a rapid rise in RQF with a maximum occurring with area ratios of about 1 to 3.

Figure 4 shows a similar plot for different sizes of nanofibers. For the 150 nm droplet size the 100 nm fibers have the highest RQF of those compared. Maximums in the RQF curves occur in the range of about 1 to 3 area ratios.

The plots in Figures 2 through 4 show the RQF has a maximum relative to the amount of nanofibers added to the filter medium. The RQF also varies with fibers sizes and particle sizes. These variations suggest that it may be possible to optimize the filter design for the capture of particular drop sizes.

The improvement in filter performance may not be obvious from the Quality Factor calculations. Comparisons of filter performances in Figures 5 and 6 show how the filter properties change with addition of nanofibers. Both figures have a common base case of a 6 cm diameter filter 1 cm thick made of 3 micron fibers occupying 28.3% of the filter volume; the air is at room temperature, atmospheric pressure, contains 150 nm droplets, and has at a face velocity of 2.1 m/s (flow rate of 0.00603 m3/s).

In Figure 5, to maintain a constant pressure drop (21.4 kPa) across the filter, the filter thickness is reduced as the area ratio of nanofibers to microfibers increases from 0 to 6. As nanofiber is added to the microfiber medium the capture efficiency significantly increases as shown by the rapid decrease in outlet concentration. The relative outlet concentration is the the

concentration for a given condition divided by the corresponding outlet concentration for a medium with zero nanofibers. As more and more nanofibers are added to the medium the effect on the outlet concentration diminishes and the relative outlet concentration approaches a constant value. This is due to most of the particles being captured near the filter inlet surface. This result is consistent with the Quality Factor plots in Figures 1-3, a small amount of nanofiber added to the filter results in a large change in the filter thickness.

Figure 6 shows a similar plot as in Figure 5 but here the outlet concentration is held constant (at 38.2% of the inlet concentration) and the pressure drop is allowed to vary. The outlet concentration is maintained constant for the varying amounts of nanofiber by adjusting the medium thickness. Here we see that to maintain the same outlet concentration the medium thickness must be significantly reduced. The reduction in the medium thickness also contributes to a decrease in the relative pressure drop (normalized to the pressure drop required for a medium with no nanofibers).

These model results demonstrate the advantages of adding nanofibers to microfiber filter media. Validation of the model through experiments is the subject on-going work.

CONCLUSION

A model was developed to calculate the Relative Quality Factor for filter media mixed with micro and nanofibers. The model was based on assumptions such as uniform saturation and porosity to obtain a tractable set of equations. The mechanisms of drag force and droplet capture apply a linear summation of single fiber mechanisms to predict filter performance. The mechanisms account for the effects of slip and molecular flow phenomena.

The model results show a significant increase in the Relative Quality Factor with the addition of small amounts of nanofibers. The RQF plots pass through a maximum and gradually decline as greater amounts of nanofibers are added to the filters. The dependence of the RQF on the fiber amounts, fiber sizes, and drop sizes suggest that it may be possible to optimize the filter design.

ACKNOWLEDGMENTS

This work was supported by the Coalescence Filtration Nanomaterials Consortium: Ahlstrom Paper Group, Donaldson Company, Cummins Filtration, Hollingsworth and Vose, and Parker Hannifin.

REFERENCES

Chase, G.G, "Transport Phenomena in Porous Media," in Fluid Flow Handbook, J. Saleh ed., McGraw Hill, New York, 2002.

Brown, R.C., Air Filtration: An Integrated Approach to the Theory and Applications of Fibrous Filters, Pergamon Press, New York 1993.

NOTATION

A =Area

d_i = fiber diameter

E_i = Single fiber efficiency

F_z^G =Drag force

F_{tot} = Total force acting on the filter

f_i = Drag force per unit length of fiber of diameter d_i

I_0^G = mass flux of oil droplets captured from gas phase onto fibers

Kn =Knudsen number

L = Filter thickness

L_i = Total length of fibers of diameter d_i within elemental volume of the filter medium

P, ΔP = Gas phase pressure, pressure drop across filter

QF = Quality Factor

RQF = Relative quality factor (QF of the medium/QF of medium of only microfibers)

S = saturation, volume fraction of the void space occupied by liquid

v_z^G = intrinsic gas phase velocity in the z direction

w_0^G = Mass fraction of oil in gas phase

w_{in}, w_{out} = Inlet and outlet mass fractions of droplets in gas phase

α = Overall Filter Coefficient for the filter medium

α_i = Filter Coefficient of a100% efficient fiber

ε = porosity of the media

μ = viscosity of gas phase

ρ^G = gas phase density

ρ_0^G = mass concentration of liquid oil droplets in the gas phase, kg/m3

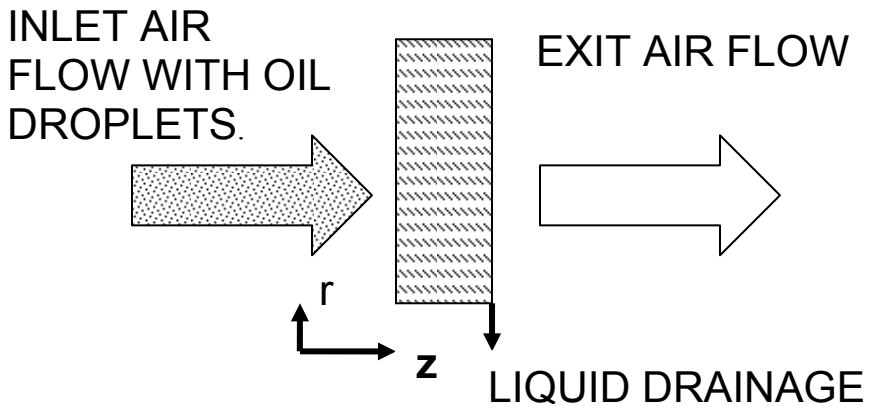

Figure.1 Diagram of a coalescing filter medium. The inlet gas stream enters the medium, droplets are captured and coalesce into large drops, and the coalesced drops drain from the medium by gravity.

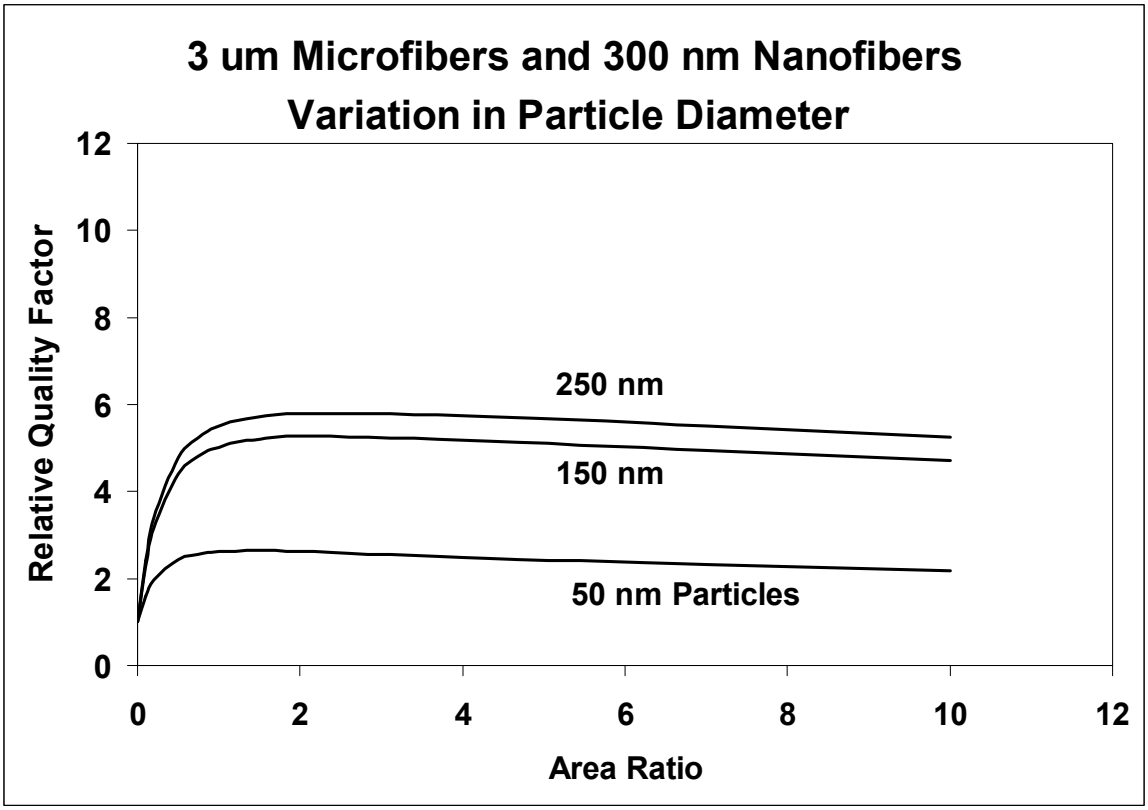

Figure 2. Relative quality factors for different sizes of droplets.

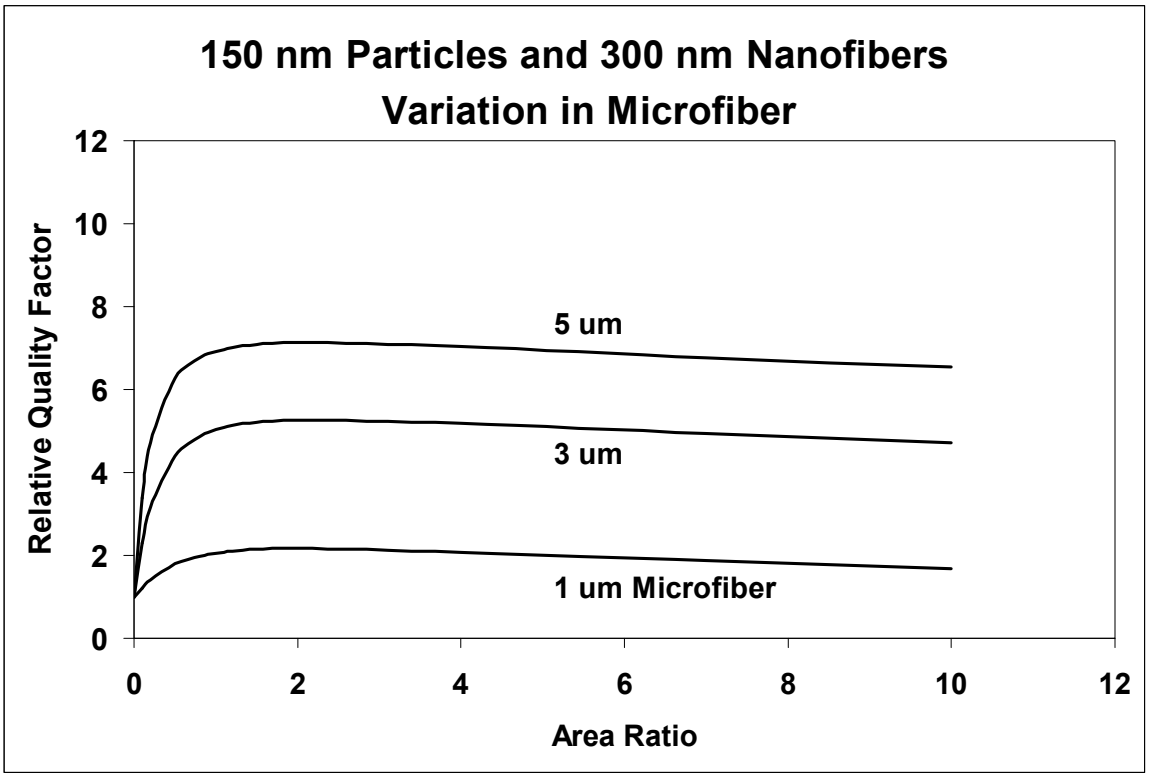

Figure 3. Relative Quality Factors for different size micro fibers.

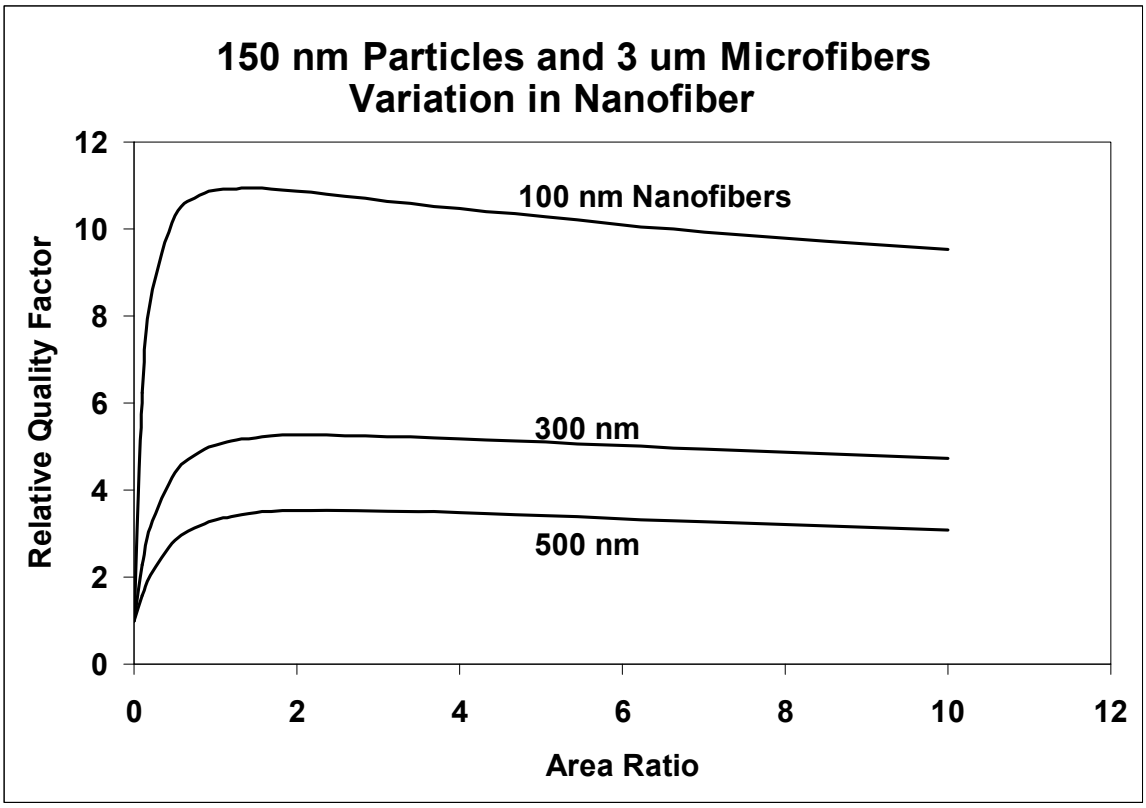

Figure 4. Relative Quality Factor for different size nanofibers.

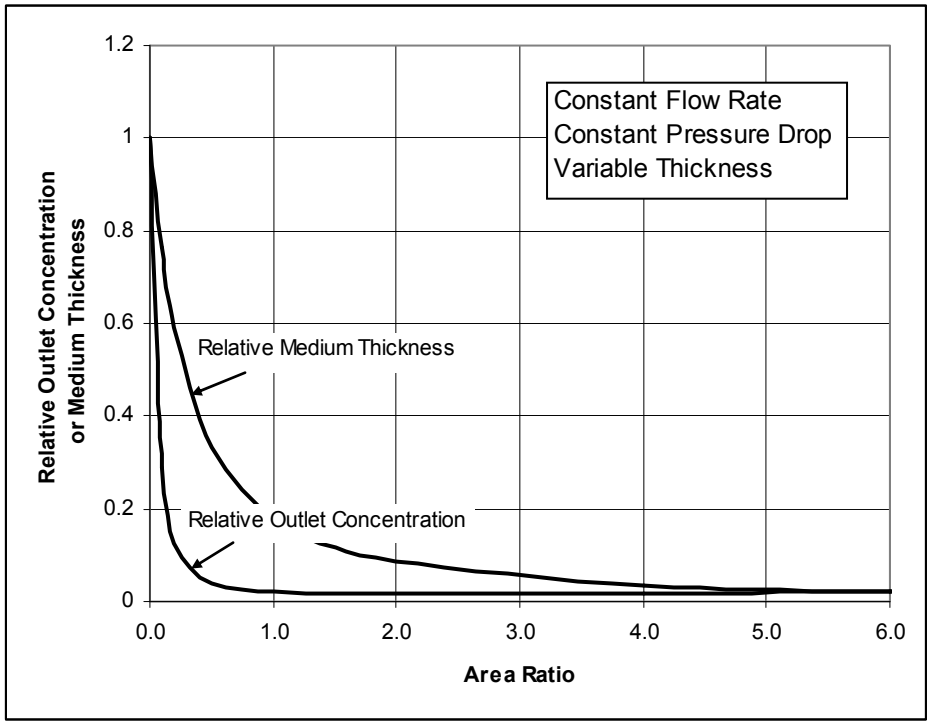

Figure 5. Comparison of relative filter outlet concentration and relative thickness with addition of nanofibers holding flow rate and pressure drop constant. The relative outlet concentration is the ratio of the outlet concentration divided by the outlet concentration for the base case of no nanofibers. The relative medium thickness is the medium thickness divided by the thickness of the medium with no nanofibers (ie, 1 cm).

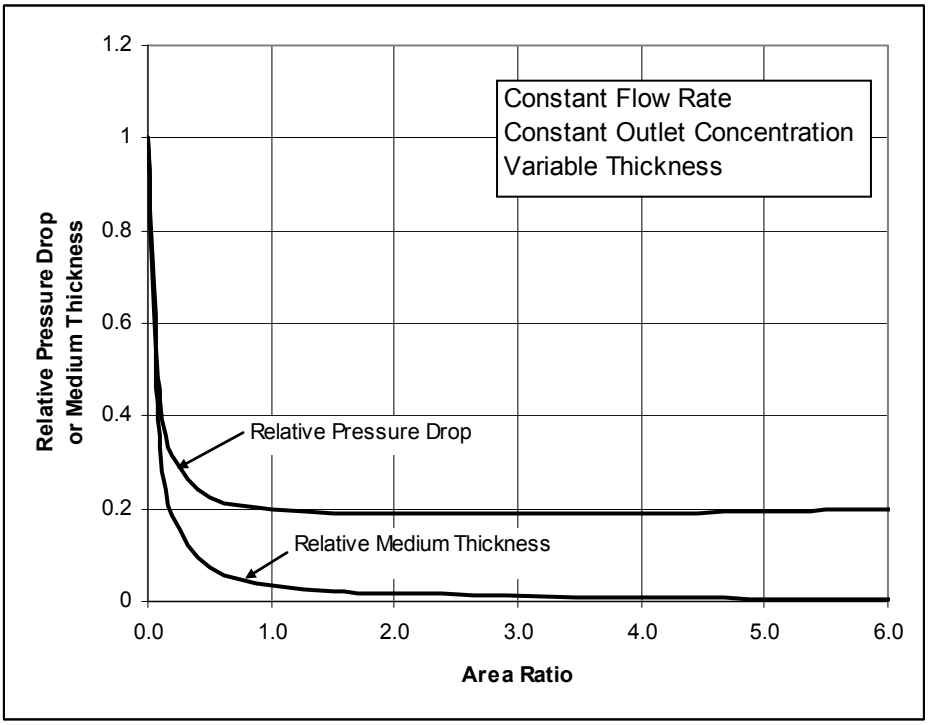

Figure 6. Comparison of relative filter pressure drop and relative thickness with addition of nanofibers holding flow rate and outlet concentration constant (at 38.2% of the inlet concentration). The relative pressure drop is the ratio of the pressure drop divided by the pressure drop for the base case of no nanofibers. The relative medium thickness is the medium thickness divided by the thickness of the medium with no nanofibers (ie, 1 cm).