MODELING FILTER PERFORMANCE WITH AND WITHOUT NANOFIBERS

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ABSTRACT

Recent experimental works have demonstrated the benefits of adding nanofibers to microfiber nonwoven filter media. In this work single fiber efficiencies and drag are applied to model filter performance for steady state coalescence of oil drops from air streams. The model results show the same trends as observed in the experiments, namely that the addition of small amounts of nanofibers significantly increase the quality factor. New results from the model and experiments show that an optimum amount of nanofiber is determined.

INTRODUCTION

Recent work show improved performance of nonwoven filter media by addition of small amounts of nanofibers (Chase and Reneker, 2004). The purpose of this work is to determine whether there is an optimum amount of nanofibers to add to the filter media.

Our approach to this project is to model the filter using single fiber capture mechanisms and single fiber drag forces. The coalescence filter is assume to operate at steady state with a uniform saturation of 10% (a typical value from our experimental data). The filter performance is determined using the quality factor. The model results are compared with experimental data.

Our model results show there is an optimum amount of nanofiber. The highest quality factors occur when the ratio of surface area of nanofiber to surface area of microfiber is in the range of 1.0 to 2.0. Our experimental results agree with the optimum occurring in the same area ratio. Qualitatively the model and experimental results are similar but the model overpredicts the value of the quality factor due to simplifying assumptions used to developing the model.

DESCRIPTION OF COALESCING FILTERS

Coalescing filters are used throughout industry to separate small liquid droplets from gas streams or from another liquid phase. A number of factors influence the efficiency and economics of the separation. In general, droplets in a range of about 0.1 to 0.8 micron in size are the most difficult to remove. Polymer nanofibers, made in our laboratory, provide a flexible and adjustable system for optimizing the filter structure to capture particles in the size range which has the highest probability for passing through the filter.

Unlike other filter media whose primary purpose is to stop the particles from moving with the fluid stream, the coalescing filter media have the additional requirements of making the drops coalesce together into larger drops and of providing a means for the larger drops to drain out of the medium. In operations such as gas compression, coalescing filters may be used upstream of the compressor to protect the equipment and they may be used downstream to collect compressor oil. The compressor oil is typically an expensive synthetic oil used in the compressor as a coolant, sealant, and lubricant. Coalescence filters are used to recover and recycle the oil back to the compressor. Recovering even smaller droplets also reduces airborne emissions in many processes and helps in regulatory compliance.

There are a number of mechanisms that control the coalescence filtration process (Sherony *et.al*, 1978). The process is sketched in Figure 1. Single fiber capture mechanisms (described by Brown, 1993) control the rate at which drops are captured within the filter media. The filter media act to slow down the movement of the drops to cause the drops to collide. Microscopic observation of the coalescence process shows that most of the drops visible to the microscope (20 to 200 micron size range) are captured on the fibers (Chokdeepanich and Chase, 2000). When the captured drops form beads on the fiber that are of large enough to see with an optical microscope, the growth of the beads is rapid (Yarin *et al.*, 2005). Drag of the gas phase and gravity forces cause the enlarged drops to migrate out of the filter media.

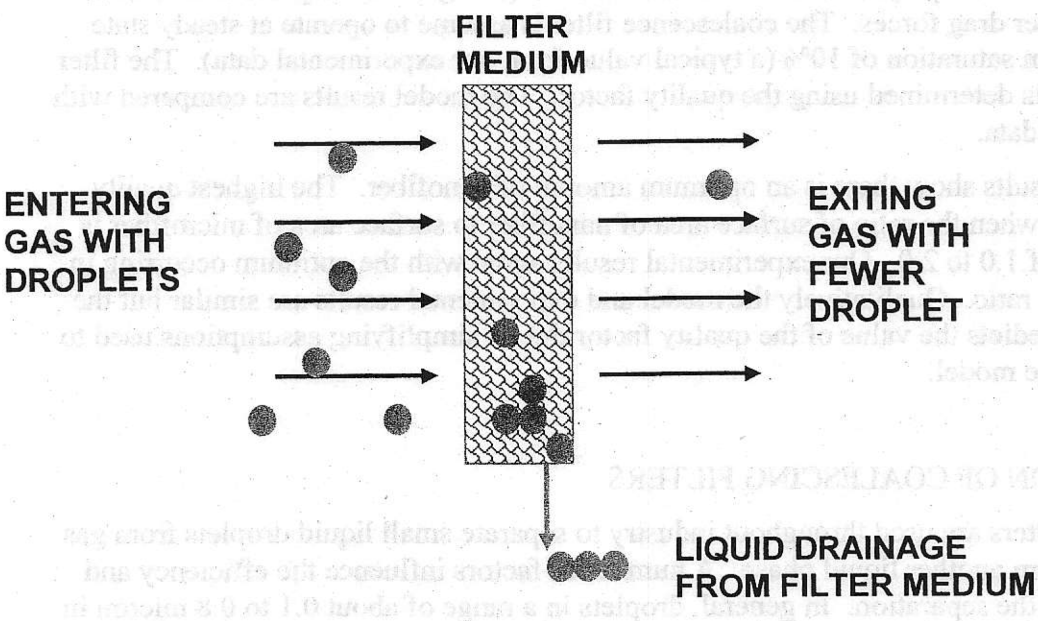

Figure 1. Coalescence filtration removes drops from the flow stream and drains the drops from the filter.

Several parameters, including pressure drop and capture efficiency, characterize the performance of filter media. It is convenient to have one parameter that accounts for multiple effects. Brown [1993] recommends using the quality factor, QF, defined by

$$QF = \frac{-\ln\left(C_{out}/C_{in}\right)}{\Delta P} \tag{7}$$

where $\left(C_{out}/C_{in}\right)$ is the penetration defined as the ratio of the concentration of particles passing through the filter to the concentration of particles entering the filter, and ΔP is the pressure drop. The nature of capture efficiency is such that if you double the thickness of a filter medium the penetration decreases by the square of the thickness, hence the logarithm of the penetration is proportional to the thickness. On the other hand, the pressure drop is directly proportional to the filter thickness. Hence ideally the quality factor is independent of the thickness of the medium and provides a means of direct comparison between various media.

MODEL DESCRIPTION AND RESULTS

The numerical model applies volume averaged continuum equations to account for conservation of mass for the gas and liquid phases. Capture rates are calculated for the dominant mechanisms of Brownian diffusion and direct interception using literature correlations (Brown, 1993).

The gas phase momentum balance is applied to determine the pressure drop. Drag correlations for flow around fibers are determined from literature correlations (Brown, 1993). The capture and drag correlations account for continuum, slip, or molecular flow regimes depending on the Knudsen number for the materials.

To compare performance results with filter media without nanofibers the Quality factor for a medium is divided by the quality factor of a medium with no nanofibers. Hence, improved performance occurs when this ratio is greater than unity.

Figure 2 shows the calculation results for capture of 150 nm particles on 3 micron fibers with varying amounts of nanofibers for three different sizes of nanofibers. The amount of nanofibers is shown by the fiber area ratio of nanofiber area divided by microfiber ratio on the horizontal axis. The areas of the fibers are calculated as pi times fiber diameter times total fiber length. The relative quality factor (RQF) plots show a rapid increase in RQF with small amounts of nanofibers. The graphs have maximum for area ratios between 1.0 and 2.0 followed by a gradual decline in RQF for larger area ratios of nanofibers.

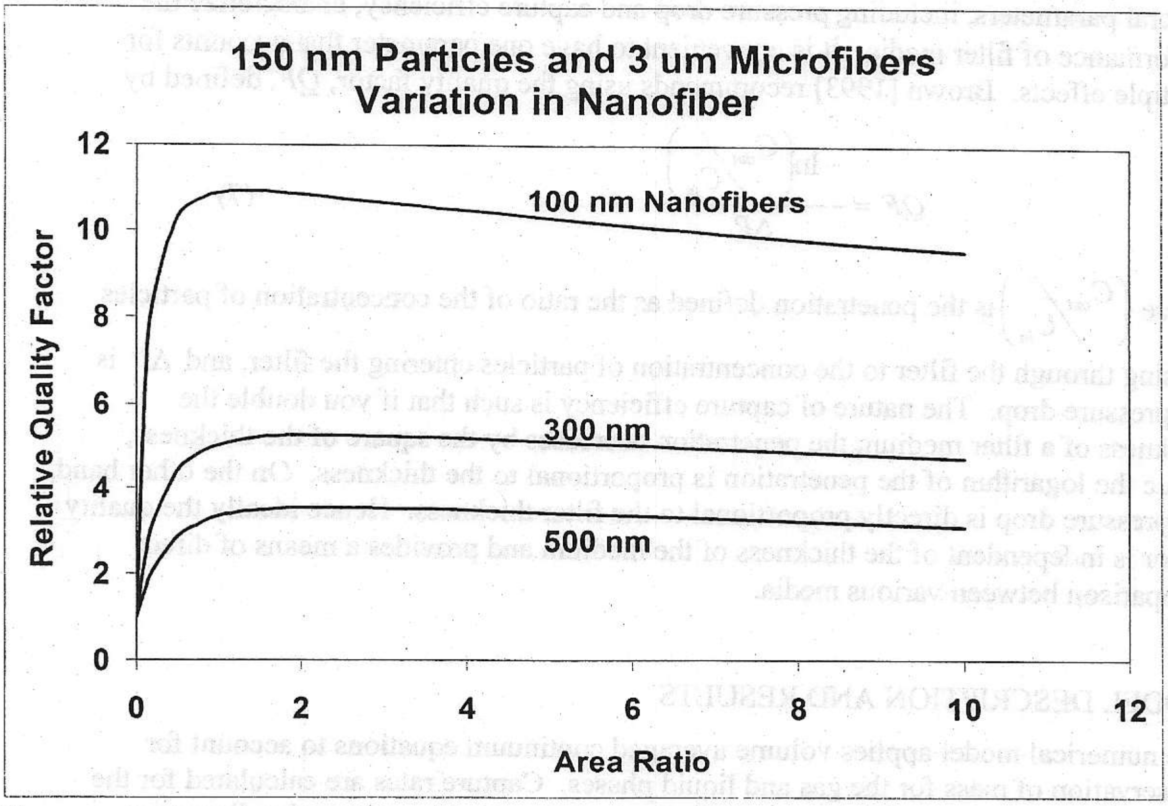

Figure 2. Relative quality factors for capture of 150 nm particles in a filter medium of 3 micron fibers and augmented with varying amounts of nanofibers. The relative quality factor is the quality factor of the medium divided by the quality factor of a medium of microfibers only. The area ratio is the total external surface area of the nanofibers divided by the area of the micro fibers. The plot shows an optimum occurs for area ratios between 1.0 and 2.0.

EXPERIMENTAL DESCRIPTION AND RESULTS

The experimental setup is shown in the diagram in Figure 3. A detained description of the experimental set up is contained elsewhere (Chase and Reneker, 2004). The filter media are challenged with a distribution of particle sizes shown in Figure 4, as measured using a Scanning Mobility Particle Counter (TSI). The average particle size is between 150 and 200 nm.

The filter media are formed by vacuum molding an aqueous slurry of glass microfibers, nylon nanofibers, and an acrylic binder to hold the fibers together. The glass fibers have diameters between 2 to 5 microns in diameter and the nanofibers have diameters of about 150 nm. The glass fibers are obtained commercially (Hollingsworth and Vose) and the nanofibers are produced locally by a process of electrospinning (Reneker and Chun, 1996).

The experimental results plotted in Figure 5 show a rapid increase in RQF for small area ratios, the RQF passes through a maximum for area ratio of about 1.0, and gradually declines for larger area ratios, similar to the model results. Qualitatively the model and experimental results are similar. Quantitatively the model over predicts the RQF, most likely due to the simplifying assumptions used to form the model. For the materials used in the experiments the optimum RQF occurs for 0.1 grams of nylon nanofibers added to 2.0 grams of glass fibers, or about 5% nanofibers by mass.

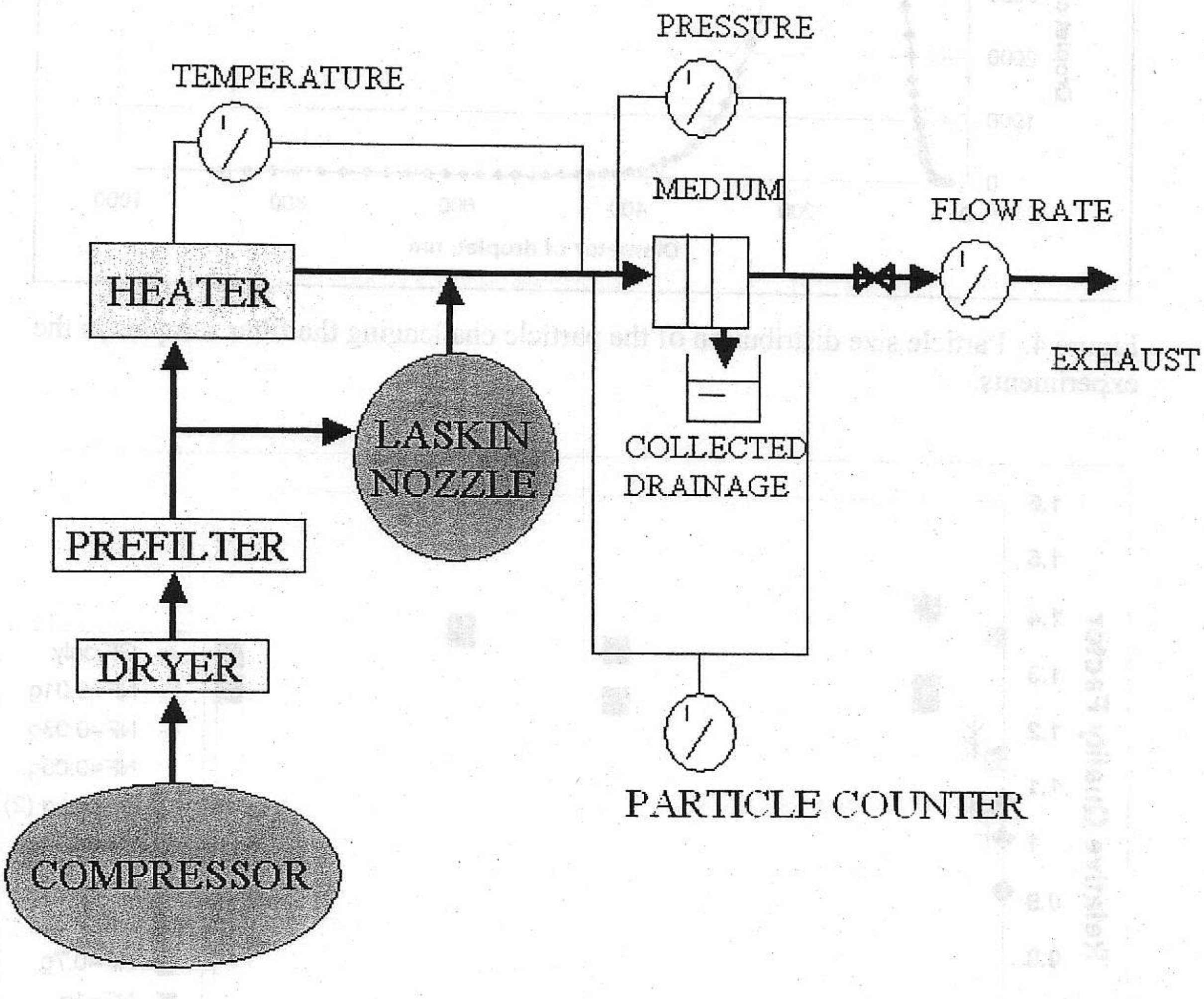

Figure 3. Experimental Setup. Air is pretreated, combined with particles from the Laskin Nozzle, and passes through the filter sample. Pressure drop, flow rate, liquid drainage, and particle size distribution are measured.

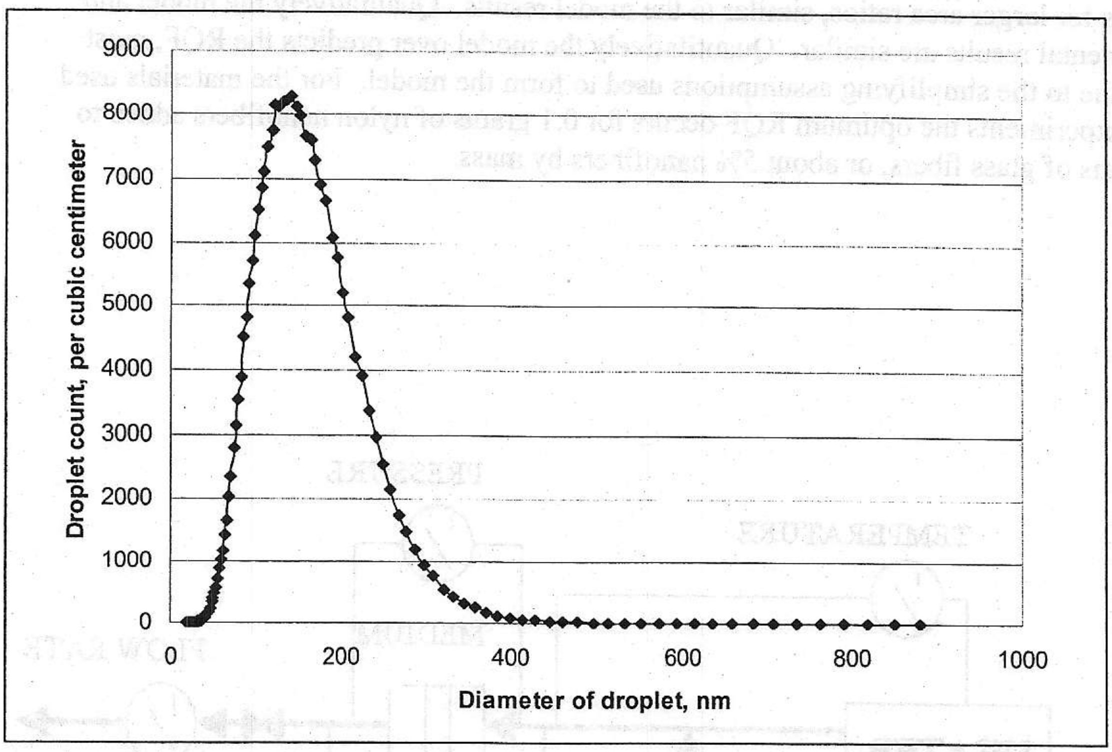

Figure 4. Particle size distribution of the particle challenging the filter samples in the experiments.

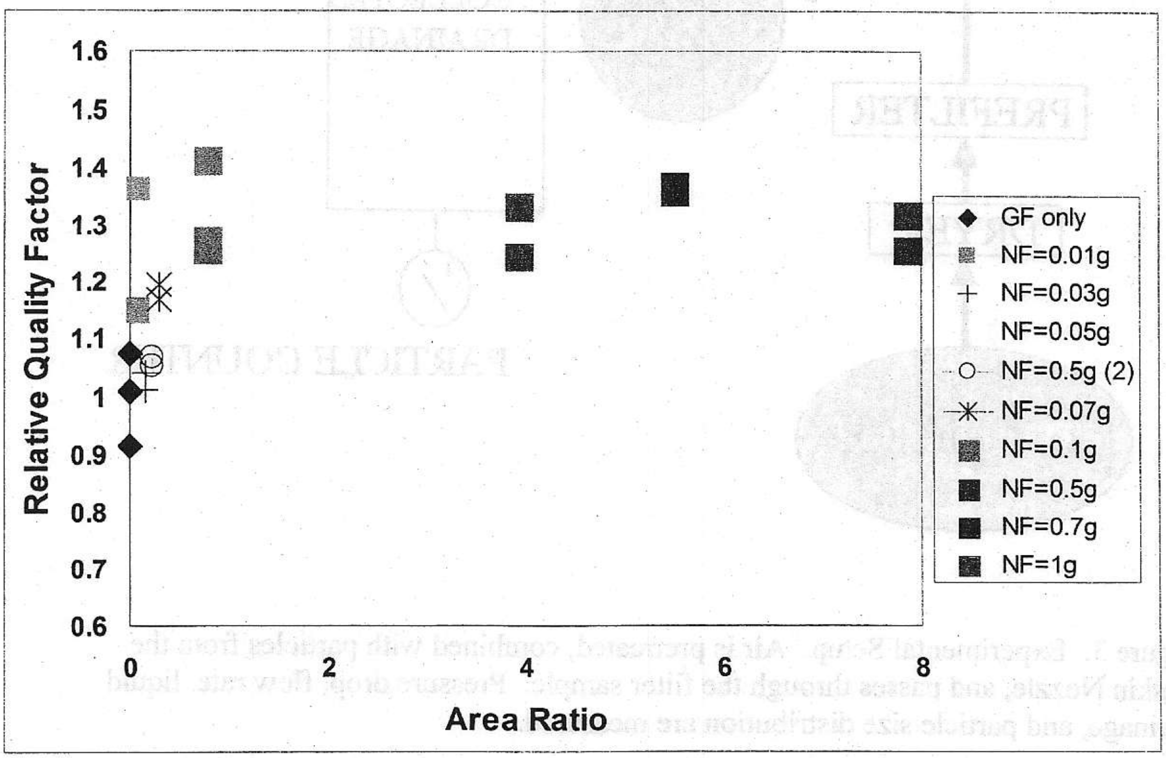

Figure 5. Experimental values of Relative Quality factor versus area ratio of nanofibers to microfibers.

CONCLUSIONS

The model and experiments show similar qualitative performance in the Relative Quality Factor. The RQF increases sharply for increasing area fraction of nanofiber area to microfiber area. At an area ratio of about 1.0 to 2.0 the RQF reaches a maximum and the RQF gradually decreases for larger area ratios. Quantitatively the model over predicts the RQF due to simplifying assumptions applied to the model.

ACKNOWLEDGEMENTS

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