Oriented Fiber Filter Media

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ABSTRACT
Coalescing filters are widely used throughout industry and improved performance will reduce droplet emissions and operating costs. Experimental observations show orientation of micro fibers in filter media effect the permeability and the separation efficiency of the filter media. In this work two methods are used to align the fibers to alter the filter structure. The results show that axially aligned fiber media improve quality factor on the order of 20% and cutting media on an angle from a thick layered media can improve performance by about 40%. The results also show the improved performance is not monotonically correlated to the average fiber angle of the medium.

INTRODUCTION
The effects of fiber orientation have been studied by various industries including polymer [1], paper [2] and textiles [3], to enhance their product lines. This has also been proven beneficial to the filtration industry because orientation of fibers can lead to lower pressure drop. Unfortunately, the lowered pressure drop usually is accompanied by a decrease in particle capture efficiency [4]. However, in coalescing filter media the fiber orientation with axes parallel to the direction of flow can have an added benefit of improving drainage which reduces the liquid saturation in the filter media and reduces the pressure drop as compared to media with fibers perpendicular to the flow.

Two methods are described in this paper to orient fibers in the filter media. One method applies an electric field to a non-polar solvent with dispersed fibers to achieve axial orientation of fibers [4]. The other is by cutting at different angles the filter media out of larger thick layered filter media made by gravity settling [5]. Cutting samples at different angles creates filter media with different average fiber angles relative to the flow direction. Both methods result in filter media with a distribution of fiber angles (as measured from the axis of flow). The length weighted average fiber angles of the media are used to characterize the fiber angle for the media [3].

The orientation of fibers in filter media can be categorized as axially aligned, layered and random. Axially aligned filter media have fibers lying parallel to the direction of flow as shown in the *Figure 1(a).* Layered media have fibers randomly oriented in the plane normal to the flow direction (*Figure 1(b)*). The random media have fibers randomly distributed in all 3 directions (*Figure 1(c)*).

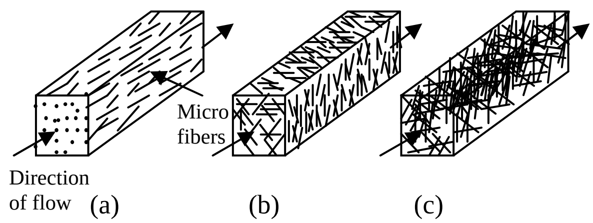

FIGURE 1. (a): Axially aligned media, (b): Layered media, (c) Random Media.

Even though the methods of construction are different the performance of the media show similar improvements in filter performance. Fiber orientation relative to the flow direction is not generally applied by the filtration industry as a way to design filters with specific performance characteristics. Our results presented here show that such media have potential application in liquid aerosol filtration.

Fibrous filters have proven to be useful in aerosol filtration. An ideal filter should have a low pressure drop and high capture efficiency. Filter performance is directly dependent on the structure of the media and fiber, void fraction, thickness, permeability etc. A non-woven filter medium formed by gravity settling has fibers randomly distributed in the horizontal plane and most fibers have angles measured from the vertical axis are on the order of 70 degrees. In contrast a medium with its fibers parallel to the vertical axis has significantly different performance. This kind of oriented media is not available commercially, but tests have shown that the fiber orientation actually increases the performance of the filter media. The filter media are characterized by the average angle relative to flow direction. Media with different orientations have different liquid drainage rates, which change the filter performance [5].

LAYERED MEDIA FORMED BY GRAVITY SETTLING

To form layered media slurry containing the fibers is stirred in vertical tank. The bottom of the tank is a porous plate covered with a filter paper to stop the fibers but let the liquid pass (*Figure 2*).

A value at the bottom of the tank is opened and the liquid slowly drains from the bottom while the fibers form a cake. The stirrer is removed from the slurry to prevent it from distributing the cake. The method can be applied to form thin or thick cakes of fibers by controlling the amount of slurry that is processed. Slurries are made by adding 4 grams of 50 %w/w glass fibers to bicomponent fibers to each liter of water. The bicomponent fiber is a PE/PET (polyethylene/polyethylene teraphthalate) sheath core fiber (INVISTA, Charlotte, North Carolina).

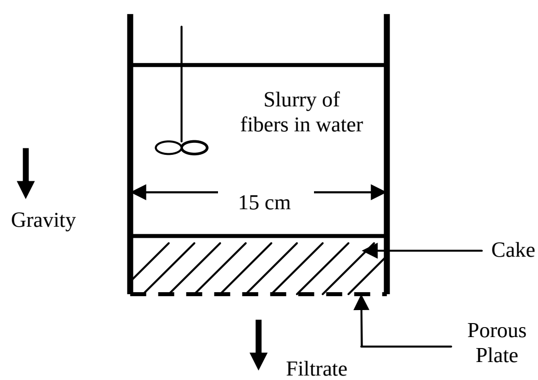

FIGURE 2. Filter media formed by gravity settling of the fibers and draining the water from the tank.

The filter media formed by gravity settling have (0.92-0.96) porosities and average fiber angles from 66 to 69 degrees (as determined by the length weighted fiber mapping method in [4]). The bicomponent fibers were melted to bind the fibers together. Filter samples were cut out of the cake for comparison with dimensions 50x10x35mm for comparison with the electric field formed filter media.

AXIALY ALIGNED MEDIA FORMED BY ELECTRIC FIELD

To form axially aligned media of short cut fibers, the fibers are dispersed in a non-conducting liquid and the slurry is exposed to an electric field. Such slurries are similar to an electrorehelogical fluids [6]. To demonstrate the fiber alignment some glass fibers were dispersed in silicone oil and an electric field was applied [2]. Two different geometries were used in the experiment as shown in *Figure 3*. When the electric fields were applied the fibers rotated their axis in the direction of the current flux for the rectangular and cylindrical geometries, shown in *Figures 4* and *5*.

The orientation achieved by the electric field was retained in the fibers after the voltage was removed [5]. In experiments described below carbon tetrachloride is used as the non-conducting liquid phase. The CCl_4 is easier to separate from the fibers (by evaporation) than the silicone oil.

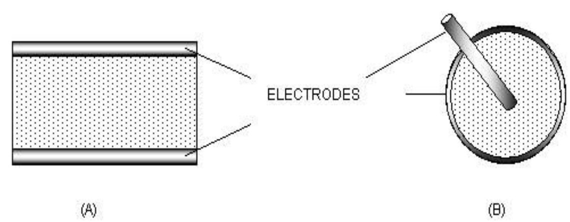

FIGURE 3. (A) Rectangular geometry and (B) cylindrical geometry for demonstrating the effect of an electric field to align glass fibers.

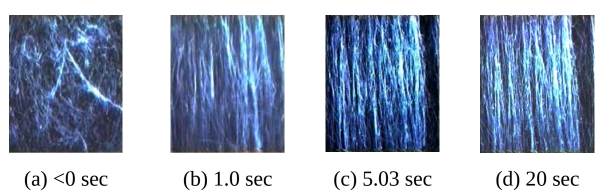

FIGURE 4. Rectangular geometry at different time intervals observed under a microscope. The electric field was turned on at 0 sec and off at 5 sec.

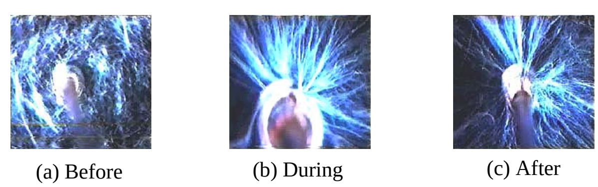

FIGURE 5. Cylindrical geometry showing before during and after the electric field was applied.

For the construction of the filter media a 50% w/w mixture of glass and bicomponent fibers, were dispersed in a CCl_4 slurry with the fibers having a volume fraction of 0.00055. The slurry was exposed to an electric field of strength of 1 kV/mm in the apparatus sketched in *Figure 6*.

The space between the electrodes in *Figure 6* was filled with 40 ml of the slurry of fibers dispersed in CCl_4. The piston was slowly lowered to push the CCl_4 out through the porous plate and to concentrate the fibers. This process was repeated until the desired size of filter medium was formed [4].

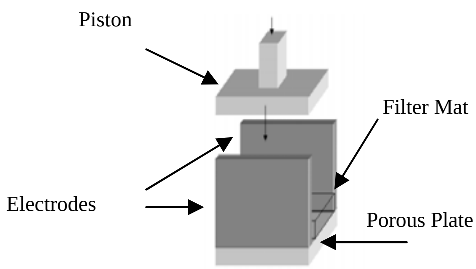

FIGURE 6. Sketch of the apparatus using an electric field to prepare axially oriented filter media. The separation distance between electrodes is 1 cm.

Multiple filter media samples were formed using this method having dimensions 50x10x35mm. The average porosity of the samples was in the range of 0.94-0.96. The media had average fiber angles between 36 to 40 degrees for the axially oriented media compared to 66 to 69 degrees for the gravity settled (i.e. layered) filter media.

COALESCENCE FILTRATION

Filter samples described above were tested in a liquid aerosol coalescence experiment. Coalescence filtration occurs in 3 steps. First, droplets are captured on the fibers. Second, captured droplets coalesce into larger drops. Third, the enlarged drops migrate through the medium. In the first step the particles are captured by the medium by mechanism of inertial impaction, direct interception and diffusional deposition [7, 8]. For submicron sized particles the mechanisms of direct interception and diffusion dominate [9].

The coalescence of droplets in the second step can occur when a drop carried by the gas stream collides with a drop attached to a fiber [10]. Coalescence can also occur between two drops attached to fibers when drops are close enough together. The coalescence results in formation of larger drops that are dragged through the fiber structure by the moving gas [11]. Liquid also can migrate through the medium by film drainage [12].

The lab scale setup is sketched in *Figure 7*. Filtered air is introduced into the laskin nozzle where the formation of aerosol takes place. This aerosol is mixed with air stream and is passed through the filter media. The pressure drop across the filter is measured using a pressure transducer and the droplet concentration and size distribution are measured using a scanning mobility particle sizer (SMPS 3180, TSI, Minneapolis, MN).

Figure 8 shows that the media with axially aligned fibers have a lower pressure drop as compared to the layered media. After sufficient time the pressure drop reaches a steady value. The mass concentration of droplets in the inlet and outlet streams similarly reach steady values.

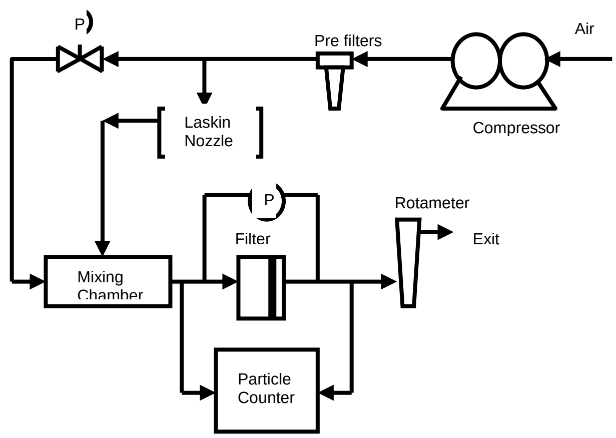

FIGURE 7. Diagram of coalescence filtration.

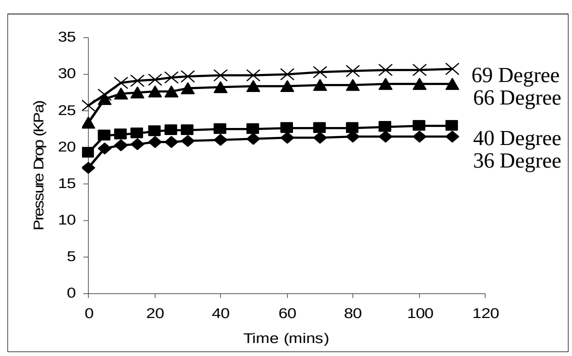

FIGURE 8. Pressure drop of axially oriented filter media made by electric field method (average angles of 36 and 40 degrees) compared to layered media made by gravity settling (average angles of 66 and 69 degrees).

The steady state values are used to compare the filter performance. The efficiency of droplet removal from the gas stream is defined as

$$E(\%) = (1 - \frac{Cout}{Cin}) \times 100 \quad (1)$$

Where *Cout* and *Cin* are the steady state mass concentrations of the inlet and outlet streams. The Quality factor, which accounts for the capture and pressure drop performance of the filter, is defined in reference [10] as

$$QF = \frac{-\ln(1-E)}{\Delta P} \quad (2)$$

Media with larger quality factors perform better than the media with lower quality factors. *Figure 9* compares the quality factors between the axially aligned fiber media and the layered media. The axially aligned media of average angles of 36 and 40 degrees have a 10 to 20% improvement in quality factor.

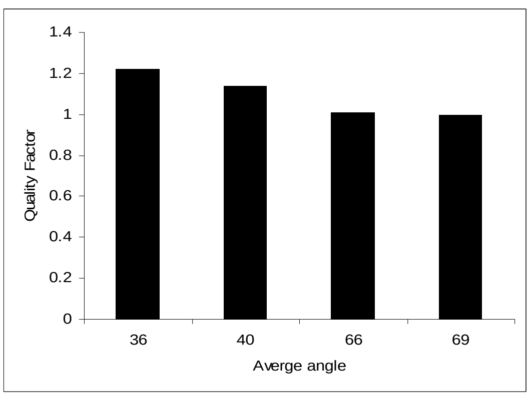

FIGURE 9. Steady state quality factor normalized by dividing by QF for the 69-degree media. The axially oriented media made by the electric field method show an increase of 10 to 20% in quality factor.

ORIENTED MEDIA FORMED BY CUTTING LAYERD MEDIA AT DIFFERENT ANGLES

Filter media with different average fiber angles can be obtained by cutting media samples from a large thick-layered medium at different angles.

A thick cake of fibers approximately 15 cm in diameter and 15 cm thick was formed by gravity settling. Twenty grams of glass fibers were mixed in water at a pH of 2.5 and 15 ml of carboset 560 acrylic binder (BF Goodrich, Cleveland, OH) was added to the slurry as binder. The slurry was poured 2 liters at a time into the settling tank. After the water drained out of the settling tank, the cake was removed and dried at 120 degrees for 2 hours. Filter media samples were cut out of the thick-layered cake at several angles relative to the gravity direction shown in *Figure 10*. The new cut samples have a different orientation [5] than the original sample because of the angle of the cut.

The cut angles are related to the average fiber angles as determined from the fiber mapping method [4] and are listed in Table 1. The data show that the average angle does not vary monotonically with the cut angle. This relationship between the cut angle and the average fiber angle was verified in a computer simulation.

The steady state quality factors for the media cut at different angles are shown in the bar chart in *Figure 11*. The quality factor generally increases as the cut angle decreases. The maximum quality factor of the zero degree cut angle medium showed a 38% improvement over the 90 degree cut angle medium.

Because the average fiber angle does not vary monotonically with the cut angle we conclude that the average fiber angle alone cannot correlate the improved performance. The improvement in quality factor must also depend upon the orientation of the fiber layers in addition to the average fiber angle.

TABLE I. Average fiber angles from media cut at different angles from the thick layered filter medium.

CUT ANGLE (Degrees)	AVERAGE ANGLE (Degrees)
0	48
30	67
45	75
90	69

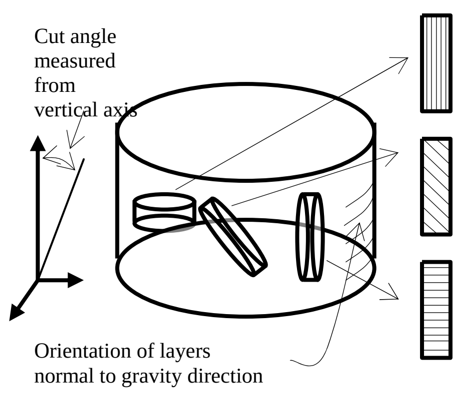

FIGURE 10. Samples cut at different angles to form different fiber orientations. Cut angles are the angle the filter disk surface makes relative to the direction of gravity.

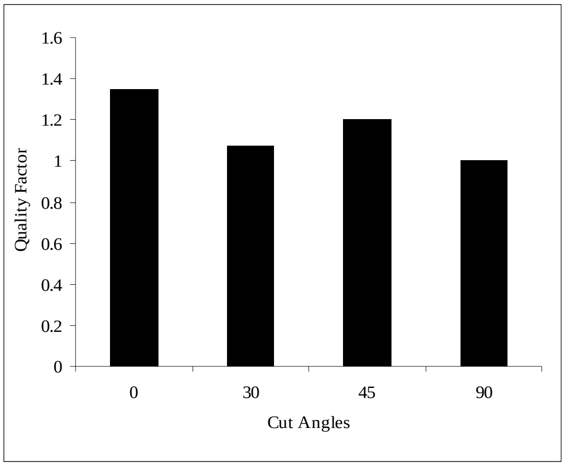

FIGURE 11. Quality factor for media cut at different angles from a thick layered media.

COMPARISON BETWEEN APPROACHES

Both methods to control fiber structure and orientation produced filter media that have significant improvement in filter performance [13]. The methods of construction are different and results in media of different structures. In the electric field method, the media are formed with the fibers predominately oriented one direction within the formed layers. The layers are compressed by a piston as a medium is formed. The layers are distinct and the fibers may not be as tightly packed between the layers as they are within each layer.

In the media cut from a thick cake the fibers predominately lay randomly in the horizontal plane as the cake is formed instead of being axially aligned. Cutting the media at different angles from the cake creates media with layers of fibers at an angle relative to the media surface. The layers are not as distinct as in the axially aligned media and the fiber packing is more uniform through out the filter medium.

From a construction point of view, cutting media out of a thick sample is simpler and less complicated than the electric field method. However, the latter results in unused material after cutting.

CONCLUSION

Two methods for forming filter media with control of fiber orientation within the media are described in this work. Experimental results show that fiber orientation has a significant effect on filter performance. These results suggest that the average angle alone is not sufficient to characterize the effects of fiber structure on the filter performance.

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