

Automotive nonwoven filter media: their constructions and filter mechanisms

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ABSTRACT *A review of the types of nonwoven filter media commonly used in high efficiency, long life, automotive filtration systems for both induction air and lubricating oil. The construction of the media, the filtration mechanisms by which they function, and some traditional design approaches used to optimize their performance are described. Also, a new computer based approach to predicting the filtration performance of flat sheet media is discussed.*

KEYWORDS

Analysis
Filter papers
Nonwovens
Mathematical models
Porosity

Excessive foreign matter in fuel, air, and oil can damage the engine and severely hamper its performance. The most damaging contaminant is hard, abrasive particulate matter, which can enter the engine in the induction air or can be present as residual left over from the engine's original fabrication or rebuild. Nonwoven fibrous materials have been commonplace filter media for automotive oil, fuel, and air filters, which protect engines and help assure optimum performance.

The best-suited nonwoven structures for automotive filter media are random fiber mixtures of various types and dimensions, preferably in a gradient-density array. The prime objectives in automotive filter media design are: (a) to achieve full utilization of the limited space available for filtration under the hood, (b) to remove appropriately large quantities of contaminant, (c) to maintain a low operating pressure differential at the rated fluid flow, and (d) to maintain the highest possible contaminant removal efficiency.

Our purpose here is to describe optimum constructions for automotive filter media, the filtration mechanics or phenomena, by which these filter media function, and some design techniques which may be useful in devel-

oping such media. We will look at two proven nonwoven filter media product designs: one for lubrication oil and one for induction air filtration. Finally, we will consider an approach to the mathematical modeling of automotive filter media.

Fibrous filter media constructions

Types of fibrous nonwoven structures which best delineate the automotive filter media covered here are illustrated in Figs. 1-3. Figure 1 shows a top-surface scanning electron microscope (SEM) picture and a cross section of a wet-laid nonwoven paper commonly used in pleated oil filters and air filters. It usually consists of a blend of coarse, fine, and curled cellulose fibers derived from various wood pulps. In some cases, it contains a small amount of synthetic fibers. It has a resin binder that supports the medium in its eventual pleated (or extended area) filter state. For effective filtration, the medium has a depth of at least 20 fiber layers, with a denser fiber layer on the filtrate's exit side and a less dense fiber layer on the entering fluid side. For fuel filtration, the medium is usually more densely

packed and may have microfibers.

Figure 2 is the same SEM photograph array of a high-performance, pleatable, water-laid nonwoven. It has the same coarse fiber interlacing and pore structure as the media in Fig. 1, but the large pores are crisscrossed with much finer microfibers. In addition, the fiber mass has a much more open structure (with higher void volume), as exhibited in the cross section.

Figure 3 illustrates the cross section of dry-formed, gradient-density, pleatable media for an air filter. The same media is shown in its final configuration in Fig. 4. This medium consists of an open-structured, prefilter, fleecy top web of blended synthetic fibers integrated to a much denser web of shorter and finer fibers such as wood pulp cellulose and synthetic fibers.

Filtration mechanisms

Optimum contaminant removal and optimum service life in automotive filtration are achieved by a combination of four filtration mechanisms, as follows:

1. Surface (top) and cross section (bottom) of a wet-laid automotive filter paper



2. Surface (top) and cross section (bottom) of a wet-laid automotive filter paper with microscopic fibers



3. Cross section of a gradient-density, automotive, nonwoven filter material



1. The inertial impaction of a particulate on the fiber surface and the factors responsible for its permanent attachment

2. The buildup of cluster particulate aggregates on fiber surfaces as a function of the triboelectric nature of the fiber network, or its ability to pick up electrostatic charge due to friction produced by the fluid flow.

3. Entrapment of the particulate within the interstices or "pores" described by the fiber entanglement

4. Interactions of fluid flow through fibrous media as they affect pressure drop.

The impaction-impingement phenomenon is initiated with the smaller particulate size of the contaminant to be removed within the initial open fiber fleece (1). Larger particulates and some finer particulates are strained out by a denser fiber structure downstream. By a balanced combination of impingement-entrapment phenomena in automotive air filtration, it is possible to fill over 90% of the filter medium void volume with contaminant within an acceptable operating pressure drop during its "life" cycle.

Figure 5 illustrates a progressive

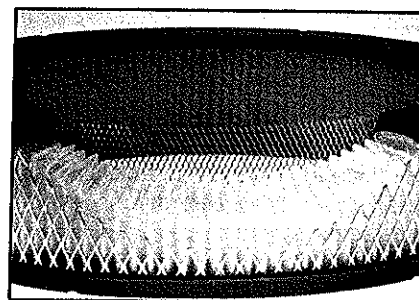
I. Particle size distribution of AC fine dust

Particle size, μm	Weight, % smaller than
5.5	38 $\pm$ 3
11	54 $\pm$ 3
22	71 $\pm$ 3
44	89 $\pm$ 3
88	
176	100

contaminant buildup by impaction-impingement (2). Initial single-particle impingement takes place on the outer surfaces of the fleece fibers. Further impaction and impingement creates clusters that adhere as fiber appendages. Further accumulation results in a porous filter cake formation of the aggregates filling the pores delineated by the fiber configuration (3).

Figure 3 is a cross section of a gradient-density filter material designed to function in accordance with the particulate removal phenomenon as illustrated in Fig. 5. Figure 6 is a similar cross section of the exhausted filter material filled with filter test

4. Pleated automotive air filter showing the gradient structure of its nonwoven filter media construction



contaminant, AC fine dust. This SAE (Society of Automotive Engineers) standard air cleaner (AC) contaminant, whose particulate size distribution is given in Table I, is derived from a source of Arizona desert dust. The filter element from which specimens were taken to obtain SEM microphotographs of the type shown in Fig. 4 has been subjected to an SAE bench test for automotive air filters.

Figure 7 illustrates three mechanisms of contaminant particle capture on fiber surfaces (4, 5). The first is the direct interception of the particle on the fiber surface. The second is inertial impaction, in which the particle leaves the fluid flow stream,



collides with the fiber surface, and sticks. If the particle is too large or too heavy, it collides with the fiber surface and drops away. The third mechanism is Brownian diffusion, in which the particle size is extremely small and its trajectory is governed by a Brownian spin phenomenon. The particle eventually becomes attached to the fiber surface.

Designing fibrous nonwoven filter media for optimum performance

Imagine the filter medium to be challenged by a particulate with an upstream concentration denoted by C_{in} and a downstream or exiting concentration denoted by C_{out} .

The difference between these concentrations represents the captured contaminant.

$$C_{out} - C_{in} = C_{in} D_{av} L \eta \quad (1)$$

where

D_{av} = the average diameter of the fibers in the filter

L = the total length of all the fibers in a unit area

η = the proportionality constant, which represents an efficiency for particle capture by an individual fiber.

The overall filter efficiency E is defined as

$$E = (C_{in} - C_{out}) / C_{in} = \eta D_{av} L \quad (2)$$

The basis weight of the filter is

$$\text{given by } W = \rho_{av} \pi (D_{av}^2 / 4) L \quad (3)$$

which is the product of the volume of fibers per unit face area of the filter times the average fiber weight density ρ_{av} . This relationship may be used to eliminate L from the efficiency expression, giving

$$E = (4 \eta / \rho_{av} \pi) (W / D_{av}) \quad (4)$$

The fiber efficiency η is, in reality, a complicated function of the geometry of the fibers in the filter and of the physical characteristics of the particulate material involved in the separation. If, however, we focus on the mechanism of interception as the dominant effect, then first order η is simply proportional to the ratio of the average particle diameter D_p to the average fiber diameter. Then

$$E \propto (4 D_p / \rho_{av} \pi) (W / D_{av}^2) = K (W / D_{av}^2) \quad (4)$$

Therefore, filters that are composed of fibers having essentially the same weight density and that are challenged by a similar particulate contaminant would be characterized by a constant K and might be expected to exhibit efficiencies which plot linearly against W/D_{av}^2 . This is indeed the case, as shown by the data plotted in Fig. 8, which were used to develop a filter material of long life and high efficiency.

In practice, it is possible to establish a design of experiments whereby two filter media of different W/D_{av}^2 can establish a linear W/D_{av}^2 relationship for contaminant removal efficiency. By choosing a desired efficiency rating, it is possible to design media of varying

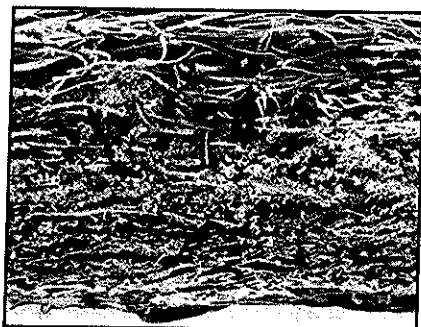
permeabilities all having the same W/D_{av}^2 . The medium having the highest permeability will have the best life or contaminant-holding capacity for a particular removal efficiency threshold. Specimens 5 and 6 in Table II fall into such a preferred category.

Designing nonwoven filter media for optimum liquid filter performance

Because the viscosities of lubricating oil and fuel are so much greater than that of air, the impaction-impingement mechanism of particulate collection is offset considerably. The viscous shear effect of the fluid on particulate accumulations tends to minimize the formation of cluster filter cakes, as shown in Fig. 5. Entrapment by a depth-structured fibrous nonwoven can be explained as the mechanical collection and containment of particulate material within the interstices of a torturous path of three-dimensional pores or openings delineated by the fiber entanglement. Hence, for filtration of automotive lubrication oil, the pore opening distribution, the void volume of the fibrous web, and the web's fluid permeability are the filter medium's most important parameters (6, 7).

By establishing a relationship between mean pore size and particle-size removal performance, we would be able to use the mean pore size as a design parameter. To achieve this relationship, two procedures were used: (a) the determination of mean pore by a "bubble pressure," or a mercury intrusion method, and (b) a test method to

6. Section of a gradient-density medium for air filter plugged with AC fine dust



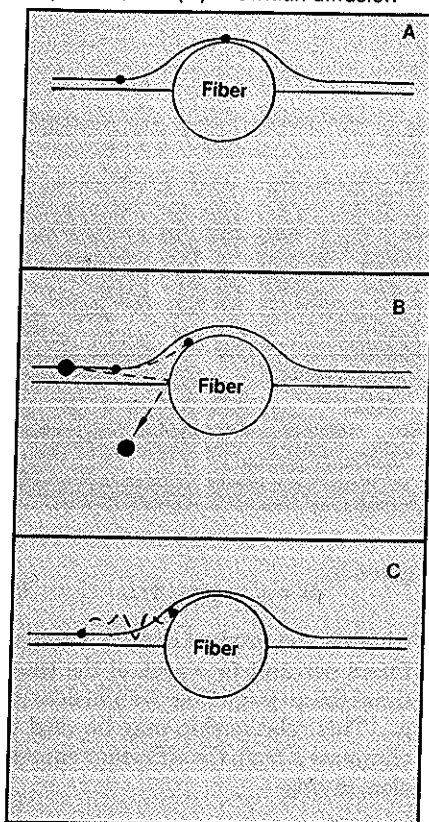
determine multipass particle-size removal efficiency (8). Figure 9 depicts the type of relationship which can be developed for a variety of nonwoven materials ranging from wet-laid papers, to needled felts, to dry form, to spun-bonded and melt-blown nonwovens. The contaminant used in the multipass filtration tests was AC fine dust. The 95%-retention particle size in micrometers is the threshold value obtained during the multipass test.

As an example of this approach, two oil filter media identified as Papers A and B are compared. Medium A is a typical water-laid paper used in automotive oil filters made out of a furnish of wood pulp fibers. Medium B is an experimental filter paper made out of the same base fibers as Paper A but with an addition of microfibers whose diameters range from about 1.0 to 3.0 μm . Table III gives the physical properties for these papers using standard procedures, "bubble pressure," and mercury intrusion measurements. Table IV presents the removal efficiency at specified particle size. Figure 10 is a plot of the data in Table IV. At 20 μm , Paper B had a 90.3% removal efficiency, whereas Paper A had only a 66% removal efficiency.

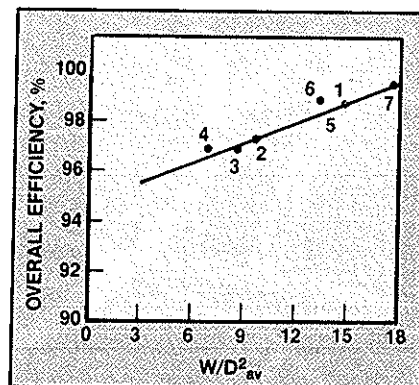
Improved automotive air and oil filters

These design concepts and their corresponding filter media structures have been developed to optimize the performance of conventional automotive filter systems. The design process has involved design engineers, manufacturing engineers, test engineers, and media vendors. The purpose of the effort was to produce viable cost-effective products for the marketplace.

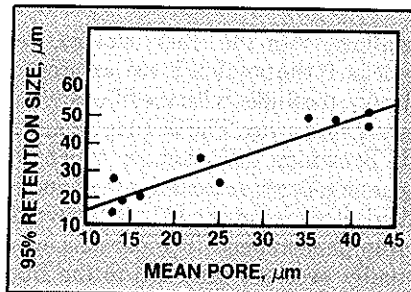
7. Three mechanisms of contaminant capture: (A) direct interception, (B) inertial impaction, and (C) Brownian diffusion



8. Removal efficiency as a function of the parameter W/D_{av}^2



9. Relationship of the average pore diameter to the particle size at which 95% retention is achieved



II. Seven experimental dry-formed air filter media

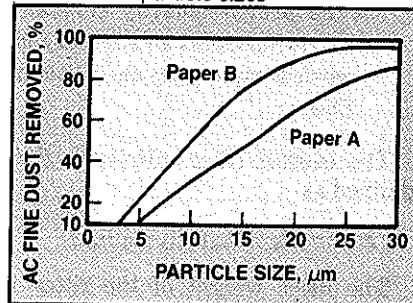
No.	Basis weight, g/m ²	W/D_{av}^2	Overall removal efficiency, %	Air permeability,* (m ³ /min)/m ²
1	288	14.25	99.0	21.2
2	203	9.20	97.6	42.5
3	203	8.76	97.2	34.0
4	203	6.94	97.0	45.3
5	203	13.12	98.5	28.3
6	203	13.10	98.8	39.6
7	237	17.67	99.5	25.5

* At 0.50 in. (1.28 cm) water pressure.

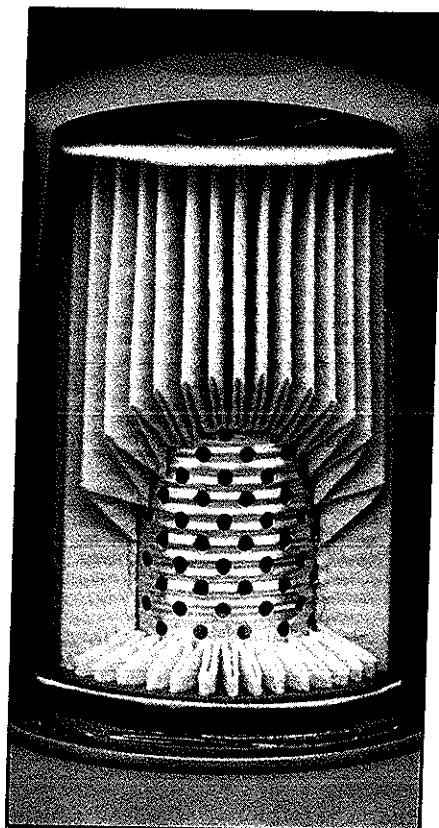
Air filter

Table V presents a statistical average of multiple tests of air filters made out of a new two-stage medium and a one-stage, water-laid paper. Figure 11 shows the pleated construction of the filter medium. The two-stage, gradient-density filter medium developed has 2.96 times greater capacity for holding dust than a conventional water-laid specialty paper, area for

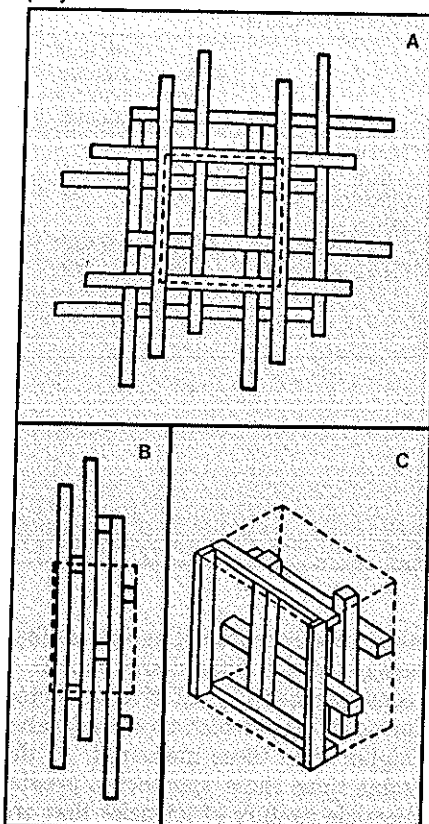
10. Removal efficiency of AC fine dust as a function of particle sizes



11. Pleated construction for the oil filter



12. An idealized "unit cell" showing (A) front view, (B) side view, and (C) isometric projection



III. Physical properties of Papers A and B

	Paper A	Paper B
Basis weight, g/m ²	180	188
Caliper, mm	0.66	0.96
Permeability, ^a (m ³ /min)/m ²	1.23	1.25
Max. pore size, μm	74	68
Mean pore size, μm	26	20
Void volume, % ^b	88	92
Fiber surface area, ^b cm ² /cm ³	972	1004

^aAt 0.5 in. (1.28 cm) water pressure.
^bBy mercury intrusion.

IV. Multi-pass dust removal efficiency for Papers A and B

	Particle size, μm				
Media	>5	>10	>15	>20	>30
A	10.8	30.8	46.91	66.0	87.4
B	21.4	49.8	75.71	90.3	96.4

area. It also has a 3:1 reduction in dust penetration (99% vs. 97% removal efficiency).

The bench test used to evaluate automotive air filters is the SAE test code SAE J726. The filter element is tested at a variable flow rate with pressure differentials taken at its rated air flow. AC fine dust (Table I) is fed into the test air stream. Efficiency is determined on how much dust has been fed, up to the test end point of a differential rise of 10 in. H₂O over an initial clean restriction, and on how much has been collected downstream on a filter pad. The dust distribution in the spent air filter media is almost complete throughout the void volume of the medium. However, the dust distribution in the spent water-laid paper is limited to the first third of its depth (3).

Oil filter

Figure 11 shows the pleated construction for the oil filter. When microfibers are added to the furnish and the fiber composition is chosen for higher loft and lower density, a bulky, thicker sheet results, with a three-dimensional, spiderweb-like microfiber network within each larger pore or "capillary" (Fig. 2).

Field and dynamometer studies (9, 10) of engine oil filtration were made in which critical engine parts such as bearings and piston rings were irradiated. Conditions were set up with and without filters and with and without abrasive dust classified as to particle size ranges added to the crankcase.

In this study, abrasive dust particles above 15 μm produced the most deleterious engine wear. Also, with a filter having a single-pass removal efficiency of 90% or higher, engine wear was kept to a minimum. Employing the concepts and principles presented here, it was possible not only to develop a fibrous oil and filter medium which achieved the optimum in efficiency and capacity, but it was also possible to keep engine wear at a minimum and still be cost effective (3).

The improvement in oil filtration performance with the high-bulk, low-density microfiber filter is notable. Table VI presents test data of the filter with this media vs. the conventional oil filter paper.

Future developments

Automotive power plants continue to

evolve and to improve with each passing year. New manufacturing technologies, materials, and lubricants promise to accelerate the pace of change. At the same time, new fibers become available from which to fabricate nonwoven media, and new packaging requirements and performance standards are placed on successive generations of automotive filtration systems. To remain competitive in this and other markets for filtration technology, it is time to rethink the entire design process. In part, this activity is being brought about through industry-sponsored work in progress at the University of Rhode Island Center for Filtration Research.

The philosophy behind this effort is simply that a great deal of the empirical and interactive nature of the design process, with its associated time and expense, can be eliminated if the engineer has at his disposal a modern computer-based design and system simulation package, including graphical output and perhaps an artificial-intelligence monitoring program, aimed specifically at the problem of filtration system design and optimization. This concept is not an original one, as program packages of this type

have been successfully applied to other technologies.

What is new is the attempt to develop reliable and comprehensive building blocks for such a design tool in the area of filtration. An example is the need for an accurate way of computing the filtration performance of a nonwoven media that is firmly based on a realistic microstructural model of the material.

Three historical approaches

Historically, there have been three main approaches to modeling nonwoven fibrous materials: the single-fiber or single-cylinder model, the parallel-cylinder array model, and the pore theory approach (5). Single-fiber theory was important because, for the first time, it clarified the role played by capture mechanisms such as impaction-impingement and diffusion. But this simple model cannot be taken seriously as a representation of real materials except perhaps for the most porous of media.

Parallel-cylinder models were introduced in an attempt to account for interfiber influences in a real nonwoven fiber structure through the parameter of packing density, or porosity. The most elegant work along these lines is the two-dimensional flow field solution of Kuwabara (11), which represents the limit of practically useful analytical complexity for predicting filtration performance. Based on a parallel cylinder model, both pressure drop and particle capture efficiency can now be routinely handled by numerical computer simulation.

The pore theory represents an attempt to be more realistic about the microstructural geometry of filtration media in that it accounts for the statistical variation in pore size created by the random orientation and intersection of fibers in planes transverse to the mean flow. Unfortunately, it idealizes this structure into an ordered system of round pores each having a diameter equal to the flow mean hydraulic diameter of the fiber array. This necessitates the introduction of an artificial factor for the more tortured flow path, which results in an overly complicated theory that inaccurately accounts for variations in porosity.

None of the historical approaches to the modeling of fibrous filters are capable of adequately predicting pressure drop. The theories on which they are based do not properly account for

V. Air filtration performance of an air filter design made out of a monolithic water-laid paper and a two-stage, gradient-density, dry-formed material

	Water-laid paper	Air-laid, 2-stage, nonwoven media
Test capacity, g/m	79	140
Efficiency, %	97	99
Media area employed, m ²	0.732	0.438
Capacity, g/m ²	108	319

the three-dimensional nature of fiber arrays or for fiber clumping. As a consequence, they all give predicted pressure drops which are considerably higher than those measured. At the same time, these approaches predict particle capture efficiencies that are in error by about the same ratio as the ratio between the predicted pressure drop and the actual pressure drop.

Offset screen theory

To overcome these difficulties, the research group at the University of Rhode Island has proposed a new microstructural model to describe the filtration performance of nonwoven fiber structures. This approach, the "offset screen theory," is based on the hypothesis that an adequate model for fibrous filter materials must account for:

1. Anisotropy of fiber orientation, which is an inevitable result of the manufacturing process
2. Inhomogeneity of fiber dispersion, which is always involved to some extent but which is most important for relatively thin media
3. The three-dimensional nature of fiber structures, which implies that flow inside the media is also three dimensional.

An additional constraint on the model is that it must be tractable from the standpoint of the capabilities of modern numerical fluid mechanics.

Figure 12 shows an idealized "unit cell" of material constructed according to the offset screen model. For com-

VI. Oil filtration performance tests on a spin-on automotive oil filter made out of conventional filter paper and paper with microfibers

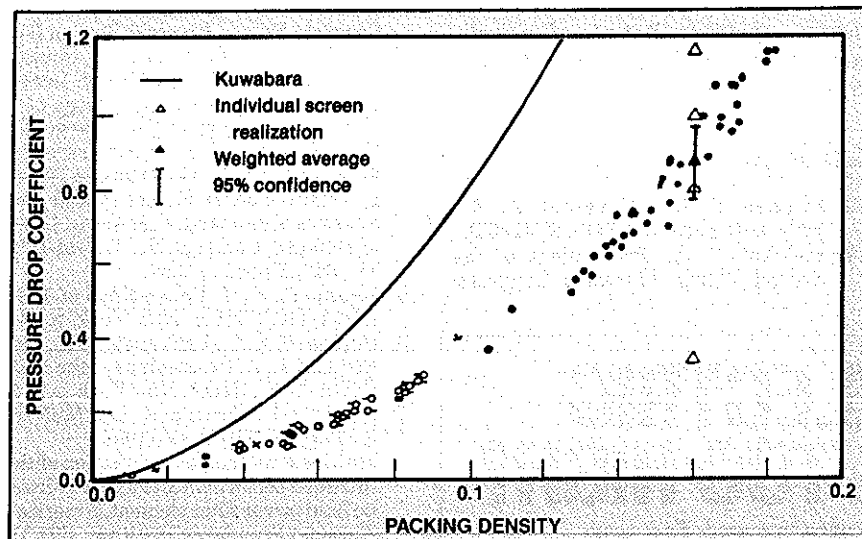
	Conventional media	Micro-fiber media
Single-pass* efficiency, %	77	92
AC fine dust holding capacity per filter, g	13	19
Dust removal efficiency, wt. avg. %	84	92
Area media in filter, m ²	0.229	0.141
Dust capacity per unit area, g/m ²	56.8	134

*10-20 μ glass beads.

putational convenience, the fiber cross section is taken to be square, but this is not an essential limitation of the approach. This example shows a unit cell composed of three contiguous screens, with each being two fiber diameters thick. Successive screens are randomly offset in planes perpendicular to the mean flow direction. It is assumed that such a unit cell comes from the depth of the media and, hence, repeats itself many times to make up the actual thickness of the filter.

This assumption implies that the flow field is periodic in the mean flow direction, and the geometry of the offset screens is such that it is also periodic in the two cross-flow directions. Periodicity in this context means simply that the velocity vectors at corresponding points on alternate faces of the unit cell must be identical. Thus, the flow field in the unit cell is fully three dimensional and triply periodic. Computing such a flow is not trivial and in fact represents a real extension of the state-of-the-art in numerical flow simulation.

To be useful, the offset screen model must be intimately connected to appropriate parameters which describe real materials. First, the cross-sectional area of a fiber used in the model is chosen to be equal to the area of a round fiber whose diameter squared is given by the mean square diameter as calculated by averaging over the actual fiber size distribution of the real medium. Second, we imagine that the medium is reconstituted into



screens composed of N vertical fibers and M horizontal fibers, with each fiber having a length equal to the actual average fiber length.

The number of fibers composing a screen is determined by two conditions. First, the packing density of each screen must equal the overall average packing density of the filter. Second, the ratio of horizontal fibers to vertical fibers $M:N$ is given by the ratio of (a) the percent of fibers with orientations lying within 45° of the machine direction of manufacture to (b) the percent of fibers which lie between 45° and 90° off the machine direction. If M equals N , the screen will have square mesh openings, but if M does not equal N , the openings will be rectangular. Such cases represent anisotropic media.

This still leaves open the question of the appropriate number and arrangement of successive screens in the direction of flow. It may prove possible to relate the appropriate number of screens, in a useful way, to the cover of the media. "Cover" is simply the fraction of the face area of the material which appears to be occupied by fibers. This possibility is being studied. One difficulty is that the number of possibilities as to the orientation of successive screens is infinite, and the best that can be done is to statistically sample this population and average the results to make a prediction.

To date, the offset screen model has been used to predict pressure drop, and the results have been compared to available data in the pertinent liter-

ature. A two-screen unit cell was chosen for this initial study because of its relative simplicity. Since these results have been excellent, it may not be necessary to get more complicated to produce acceptable predictions for particle capture efficiency. The pressure drop prediction was made as a weighted statistical average of four discrete two-screen arrangements, which represent a sample size of ten because two of these selected cases each correspond to three other arrangements which have identical pressure drops. The arrangements used were zero offset (which gives the lowest possible pressure drop), a 0.5×0.5 mesh spacing offset (which results in the highest pressure drop), and the two redundant cases of 0.25×0.5 mesh and 0.25×0.25 mesh offset.

Figure 13 shows the results of this type of prediction for one particular value of the packing density. The ordinate is a nondimensional pressure drop based on the face velocity, the filter thickness, the viscosity of the flowing fluid, the mean square fiber diameter d^2 , and the average Cunningham slip factor. This factor is included to account for the fact that the filter might contain significant numbers of microfibrils whose diameters are so small that they experience noncontinuum flow.

The data in Fig. 13 were carefully selected from experiments on nonwoven media fabricated in such a way as to ensure nearly perfect fiber dispersion and hence to exhibit essentially no anisotropy. Thus, the model used to

make the prediction employed screens with square mesh openings. The open triangles plot the pressure drops predicted by the discrete screen arrangements sampled, and the closed triangle plots the weighted average prediction. This prediction is in excellent agreement with the data. The uncertainty band represents a 95% confidence limit and is approximately equal to the data scatter. Also shown is a curve which predicts the pressure drop based on the two-dimensional flow field of Kuwabara calculated for the parallel cylinder model. Obviously, this prediction is in substantial error when compared to the data.

Anisotropic media can be modeled directly using rectangular mesh screens. This results in a higher predicted pressure drop because these cases are closer to two-dimensional parallel cylinder flow. For commercially available media, empirical pressure drop correlations such as the one by Davies (12), as compared to results for carefully prepared laboratory samples as presented in Fig. 13, typically fall somewhere between the Kuwabara curve and the data. This implies that properly accounting for anisotropy is probably important.

Including the effects of media inhomogeneity is a different question. Such inhomogeneity, arising primarily because of imperfect fiber dispersion, should manifest itself as a measurable variation in average packing density across the face of the filter. Knowing this distribution, one can treat the filter as a series of parallel flow passages each with a different packing density but having the same pressure drop and average over the appropriate anisotropic but homogeneous pressure drop coefficient curve. This treatment results in a prediction which is generally lower than the data shown in Fig. 13.

Conclusions

Predictions such as these require extensive computer time on a large computer, which is impractical for day-to-day use by a designer. Consequently, the approach is intended to be used first to generate a large number of numerical results, varying such parameters as packing density, the degree of anisotropy, and the degree of inhomogeneity and second to curve fit this numerical "data" to produce simple polynomial expressions that will make the theory conveniently

accessible. The same approach will be taken to the prediction of particle capture efficiency, which is work already underway.

The development of offset screen theory for the prediction of the filtration performance of clean nonwoven media is a small but significant step toward creating a comprehensive computer-based design tool. When completed, it should be valuable for optimizing new media formulations to meet specific design requirements and for explaining observed perfor-

mance variations in existing materials. When combined with other program packages, the result should be a new, cost-effective, and time-saving design capability that can effectively meet future challenges facing the filtration industry.

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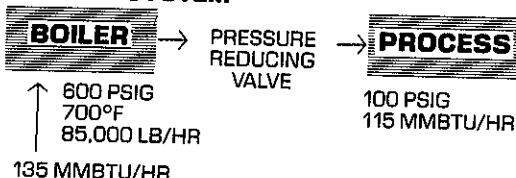
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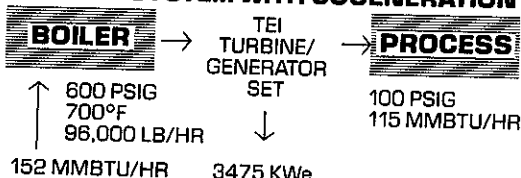
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 Additional fuel costs (\$3.00/MMBtu): \$ (428,400)
 Additional O + M costs (\$0.002/kWhr): \$ (58,380)

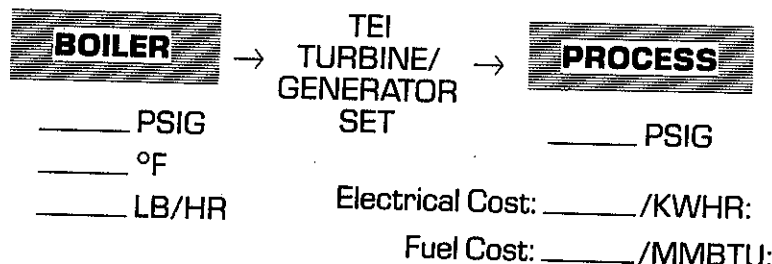
NET ANNUAL SAVINGS: \$1,264,620

Turbonetics Energy Inc.

968 Albany-Shaker Road Latham, NY 12110
 518/899-2976
 Call toll-free: 1-800-828-8210
 In N.Y. State: 1-800-342-4047



YOUR SYSTEM



NET ANNUAL SAVINGS: \$ _____