EXTENDED-LIFE NUCLEAR AIR CLEANING FILTERS VIA DYNAMIC EXCLUSION PREFILTERS

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Abstract

The primary objective of this feasibility investigation was to ascertain whether a dynamic, self-cleaning particulate exclusion precleaner, previously designed for relatively large dust removal (2 to 100+ μm diameter particles) from military helicopter turbine inlets, could be extended to **submicron** filtration capabilities. If successful, the improved device could then be utilized as a prefilter for many types of HEPA filtration systems, significantly increasing their service life. In applications such as nuclear air cleaning, its use would reduce the amount of nuclear particulate matter that would otherwise be entrapped in the HEPA filter cartridge/panel, causing fouling and increased back pressure, as well as requiring subsequent disposal of the contaminated media at considerable expense.

A unique (patent-pending) mechanical separation device has recently been developed to extract particulate matter from fluid process streams based on a proprietary concept called **Boundary Layer Momentum Transfer (BLMT)**. The device creates multiple boundary layers that actively exclude particles from entering the perimeter of the device, while allowing air to traverse the boundaries relatively unimpeded. A modified two-dimensional (2-D) computerized flow simulation model was used to assist in the prototype design. Empirical results are presented from particle breakthrough and ΔP experiments obtained from a reduced-scale prototype filter. Particles larger than 0.23 μm were actively excluded by the prototype, but at a higher pressure drop than anticipated.

Experimental data collected indicates that the filter housing and the inlet flow configuration may contribute significantly to improvements in device particle separation capabilities. Furthermore, preliminary experiments have shown that other downstream pressure drop considerations (besides those just across the spinning filtration disks) must be included to accurately portray the ΔP across the device. Further detailed quantitative investigations on a larger scale (1,000 CFM) prototype are warranted.

Introduction

High efficiency particulate air (HEPA) cleaning systems perform an important function in nuclear facilities - removal of very fine airborne nuclear particulate matter from the installation. Since nuclear HEPA systems have been proven extremely safe over the years, their extensive use in all major nuclear installations will continue to provide adequate safety margins, but at a high cost of disposal of contaminated filter media. The market for nuclear HEPA systems has been estimated at over a million units annually just in the U.S.[1] Assuming a cost of contaminated HEPA cartridge/panel disposal of many thousands of dollars per unit, millions of taxpayer dollars could be saved each year by simply extending the service life of these conventional HEPA filters. Environmental benefit would result from reductions in the amount of nuclear contaminated media targeted for high- and low-level radwaste sites.

The use of a medialess (dynamic) *submicron prefilter* would be an expedient solution to this problem. Until recently, an effective medialess prefilter (i.e., such as a high efficiency cyclone or vortex separator) did not exist that could discriminate submicron particle matter. However, a recent development in supermicron medialess particulate separators, developed by **Micro Composite Materials Corporation (MCMC)**, was believed to be extendible to the submicron regime. The patent-pending device is currently being developed for the Army to mitigate erosion damage due to sand ingestion in helicopter turbine engines. The mechanical separation/extraction of particulate matter from air or process gas streams, which requires no barrier filter media, is based on a proprietary concept called **Boundary Layer Momentum Transfer (BLMT)**. Boundary layers, generated on multiple closely-spaced rotating disks, actively *"exclude"* particles from entering the 360° perimeter of the filter. Conceivably, a BLMT device designed to have submicron discrimination could be effectively used as a nuclear HEPA prefilter. If operated upstream of a conventional HEPA panel, submicron contaminated particulate matter could be extracted from the air stream, collected and disposed or reprocessed without contaminating the HEPA media. The downstream HEPA panel(s) would still provide the added margins of safety that the nuclear industry demands, but would last much longer due to reduced particulate loading from the BLMT prefilter upstream. The degree to which service life could be extended would be dependent upon the extent of BLMT submicron discrimination. Separation of smaller submicron sizes (down to 0.3 μm) with the BLMT prefilter would lead to longer HEPA service life. Conversely, BLMT discrimination of only larger particle sizes (micron or larger) would lead to shorter downstream HEPA lifetime enhancements.

Theoretical Development

The basic concept of BLMT filtration is to transfer inertia from the boundary layer of a rotating disk to entrained particulate matter; centrifugal force is used to expel particles. This is accomplished by spinning the fluid between each disk pair in solid body rotation: the boundary layers that extend from the sides of each rotating disk must thick enough to touch or overlap. If boundary layer overlap does not occur, either because the disks do not rotate fast enough or because the spacing between disks is too great, the device does not function as a filter.

There are three different means of by which particles are addressed by the BLMT device:

- Particles that are too small to be excluded follow a spiral path through the device and eventually pass through to the exit,
- Particles that are small enough to enter the device but large enough to keep them from passing through to the exit spiral into orbit around the device somewhere between the disks (these particles are eventually excluded from airflow based on secondary effects), and
- Particles that are large enough to be excluded from flow prior to entering the BLMT device.

This paper presents the theory associated with particles that are large enough to be excluded from flow prior to entering the BLMT device. Radial airflow velocity into the BLMT device is small compared to the tangential airflow velocity that circulates outside the rotating disk assembly. Other airflow characteristics in the radial and tangential directions differ greatly, including Reynold's number and pressure drop.

Theoretical Particle Size Exclusion

The particle size discrimination ability of the BLMT filter device is derived by equating the inertial force developed by the particle to the drag force imposed on the particle. The inertial force developed by the particle is the direct result of being captured in a disk boundary layer. The drag force on a particle is due to the upstream airflow pressure or downstream suction.

Particle Centrifugal Force Development

The basic assumption made in particle centrifugal force development is that a boundary layer rotates with each surface of a disk when it is rotated. The strength, depth, and profile of the boundary layer is related to the rotational velocity of the disk and the physical properties of the fluid surrounding it. Under appropriate conditions, a particle will rotate with the boundary layer at the same speed as the disk. With this assumption, the beginning step in theoretical development is to make use of Newton's second law, where the force, $\mathbf{F}$, on a particle is:

$$\mathbf{F} = \mathbf{ma} \qquad \textbf{Equation 1}$$

Where: $\mathbf{m}$ is the mass of the particle, and
$\mathbf{a}$ is the acceleration of the particle.

From this starting point, a number of substitutions are made to relate acceleration to rotational speed and the relative position of the particle on the disk, and mass of the particle based on density and assumed spherical volume. The result is a solution for the centrifugal force, $\mathbf{F}_C$, in terms of known particle and disk parameters:

$$\mathbf{F}_C = \frac{4\pi\rho_p \mathbf{R}_p^3 \omega^2 \mathbf{R}_o}{3} \qquad \textbf{Equation 2}$$

Where: ρ_p is the particle density,
$\mathbf{R}_p$ is the particle radius,
$\mathbf{R}_o$ is the outside radius at the perimeter of the disk.
ω is the angular velocity of the particle, and

Equation 2 describes the centrifugal force acting to eject a particle as it attempts to enter the flow field outside the disk. The centrifugal force acting on a particle at this point is:

- Directly proportional to the particle location, or radius (relative to the center of the disk pack), and the particle density,
- Directly proportional to the square of the angular velocity of the disks, and
- Directly proportional to the cube of the particle radius.

Particle Drag Force Development

Drag forces serve to counteract the centrifugal forces due to either downstream suction at the filter exit or pressure at the inlet. In conditions where flows permit low Reynolds' Numbers, the drag force, $\mathbf{F_D}$, on a spherical particle can be approximated by Stoke's Law:

$$\mathbf{F_D = 6\pi R_p V_g \mu_g} \qquad \textbf{Equation 3}$$

Where: $\mathbf{R_p}$ is the particle radius,
$\mathbf{V_g}$ is the gas velocity, and
μ_g is the gas dynamic viscosity.

Substituting known relationships involving gas/fluid mass flow rate, density, cross sectional area, and velocity, the equation can be rearranged to provide a closed-form solution for particle drag force in terms of known gas properties, BLMT filter device attributes, and particle geometry:

$$\mathbf{F_D = \frac{3\mu_g R_p \dot{M}}{R_o d n \rho_g}} \qquad \textbf{Equation 4}$$

Where: $\mathbf{\dot{M}}$ is the gas mass flow rate,
$\mathbf{R_o}$ is the outside radius of the BLMT device disk,
ρ_g is the gas (e.g., air, process flow, or otherwise filtered medium) density,
$\mathbf{d}$ is the distance between disks, and
$\mathbf{n}$ is the number of disks

Equation 4 describes the drag force acting to push a particle in as it enters the perimeter flow field. The drag force acting on a particle in the flow field is:

- Directly proportional to the particle size and mass flow rate,
- Inversely proportional to the radius of the disks, inter-disk spacing, and the number of disks, and
- Directly proportional to the gas kinematic viscosity ($\nu = \mu / \rho$).

When Drag Force Equals Centrifugal Force

Equating the centrifugal force expression, Equation 2, to that for the drag force, Equation 4, results in an expression to be used for identification of particle size cutoff.

$$\mathbf{\frac{\rho_p 4\pi R_p^3 \omega^2 R_o}{3} = \frac{3\mu_g R_p \dot{M}}{R_o d n \rho_g}} \qquad \textbf{Equation 5}$$

Rearranging and substituting particle diameter, $\mathbf{D_p}$, for $\mathbf{2 \cdot R_p}$, results in:

$$\mathbf{D_p = \frac{3}{R_o \omega}\sqrt{\frac{\nu_g \dot{M}}{d n \pi \rho_p}}} \qquad \textbf{Equation 6}$$

The analytical solution for particle size exclusion, Equation 6, varies according to two different sets of parameters: BLMT device parameters and airflow parameters. The device parameters include disk outer radius, angular velocity, disk spacing, and number of disk spaces. The airflow parameters include mass flow rate, gas dynamic viscosity, and particle density.

For filter parameters, the critical particle diameters is:

- Inversely proportional to disk outer radius and angular velocity, and
- Inversely proportional to the square root of the disk spacing and number of disk spaces.

For airflow parameters, the critical particle diameter is:

- Proportional to the square root of mass flow rate and dynamic viscosity, and
- Inversely proportional to the square root of the particle density.

The above equations define, for a given set of BLMT device and airflow parameters, a critical particle diameter (and anything larger) that will "orbit" outside the BLMT device. The following figure schematically illustrates the conceptual BLMT device, showing airflow, particulate matter in orbit, and critical BLMT components.

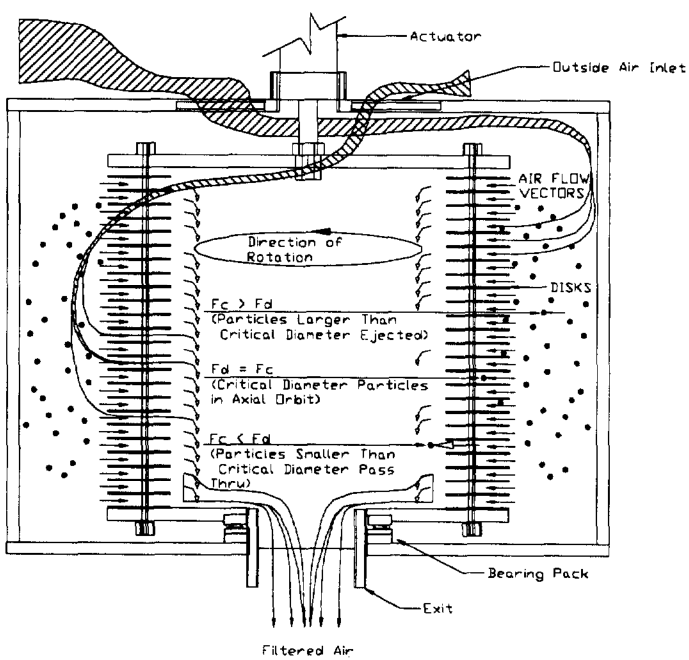

Figure 1. Schematic Representation of the BLMT Filter

Theoretical Pressure Drop

The pressure differential developed in the filter is due to several different factors, primarily including:

- Decreasing flow area,
- Centrifugal forces acting on the rotating gas, and
- Frictional drag along the disk surfaces.

Pressure Loss Due to Decreasing Flow Area

According to Bernoulli's Law, pressure loss is defined as:

$$\Delta P = \frac{\rho_g}{2}\left(V_o^2 - V_i^2\right)_g \qquad \textbf{Equation 7}$$

Where: Subscripts **i** and **o** designate the position at the inside and outside radius, respectively, and all other variables have been previously defined.

Substituting relationships for gas velocity as a function of available flow area and mass flow rate yields:

$$\Delta P_A = \frac{\rho_g}{2}\left(\frac{\dot{M}}{2\pi\rho_g dn}\right)^2\left(\frac{1}{R_o^2} - \frac{1}{R_i^2}\right) \qquad \textbf{Equation 8}$$

Due to the inverse relationship to the square of the inner and outer radii, this component of the total pressure loss is small, and rapidly decreases in importance as the outside radius increases in size.

Pressure Loss Due to Centrifugal Forces on the Rotating Gas

The pressure loss for flow from the disk outside radius to the disk inside radius is inversely proportional to the differences between their respective flow areas. Starting again with Bernoulli's Law and substituting the relationship of acceleration to rotational speed and the relative position of the particle on the disk yields:

$$\Delta P_B = \frac{\rho_g \omega^2}{2}\left(R_o^2 - R_i^2\right) \qquad \textbf{Equation 9}$$

Due to the direct relationship to the square of the inner and outer radii, this component of the total pressure loss dominates the total pressure loss expression, and will increase in importance as the outside radius increases in size.

Pressure Loss Due to Frictional Drag Along the Disk Surfaces

The pressure loss due to frictional drag, $\mathbf{D}$, at the boundary layer surface area, $\mathbf{A}$, can be expressed as:

$$\Delta P_C = \frac{D}{A} = \frac{C_f \rho_g V_o^2}{2A} \qquad \textbf{Equation 10}$$

Where: C_f is the coefficient of friction.

The effect of friction has little or no meaning at these flow rates. This term is considered to be negligible.

Total Pressure Loss

The total pressure loss through the BLMT filter is expressed through the combination of Equations 8 and 9.

$$\Delta P = \frac{\rho_g}{2}\left(\left(\frac{\dot{M}}{2\pi\rho_g dn}\right)^2\left(\frac{1}{R_o^{\ 2}} - \frac{1}{R_i^{\ 2}}\right) + \omega^2\left(R_o^{\ 2} - R_i^{\ 2}\right)\right) \qquad \textbf{Equation 11}$$

BLMT Gas Velocity

The equation defining the air velocity, $\mathbf{V}$, entering the perimeter of the BLMT device is:

$$V = \frac{\dot{M}}{2\pi\rho_g R_0 dn} \qquad \textbf{Equation 12}$$

Relationship Between Reynolds Numbers for BLMT Tangential and Radial Flows

To evaluate the ratios of the Reynolds Numbers of flow between the individual disks and circling the BLMT disk pack, the relationship with previously developed equations defined. The Reynolds Number for tangential flow circling the BLMT device is:

$$Re_\omega = \frac{\rho_g R_o \omega h}{\mu_g} \qquad \textbf{Equation 13}$$

The Reynolds Number for radial flow between the individual disks is:

$$Re_h = \frac{\rho_g V_g h}{\mu_g} \qquad \textbf{Equation 14}$$

Using Equation 6, substituting Equation 12, and rearranging terms it can be seen that the following is true:

$$D_p^2 \geq \left(\frac{18}{R_o\omega^2}\right)\left(\frac{\mu_g V_g}{\rho_p}\right)\left(\frac{\rho}{\rho}\right)_g\left(\frac{\mu}{\mu}\right)_g\left(\frac{h}{h}\right) = \left(\frac{18\mu_g}{\rho_p\omega}\right)\left(\frac{\rho_g V_g h}{\mu_g}\right)\left(\frac{\mu_g}{\rho_g R_o \omega h}\right)$$

So the relationship linking particle diameter (to be excluded from flow) to the ratio of radial to tangential BLMT Reynolds Numbers is:

$$D_p^2 \geq \left(\frac{18\mu_g}{\rho_p\omega}\right)\left(\frac{Re_h}{Re_\omega}\right) \qquad \textbf{Equation 15}$$

Future BLMT research involves the scale-up from small-scale and prototype models of the BLMT filter. This relationship will be important in the scale-up to larger models.

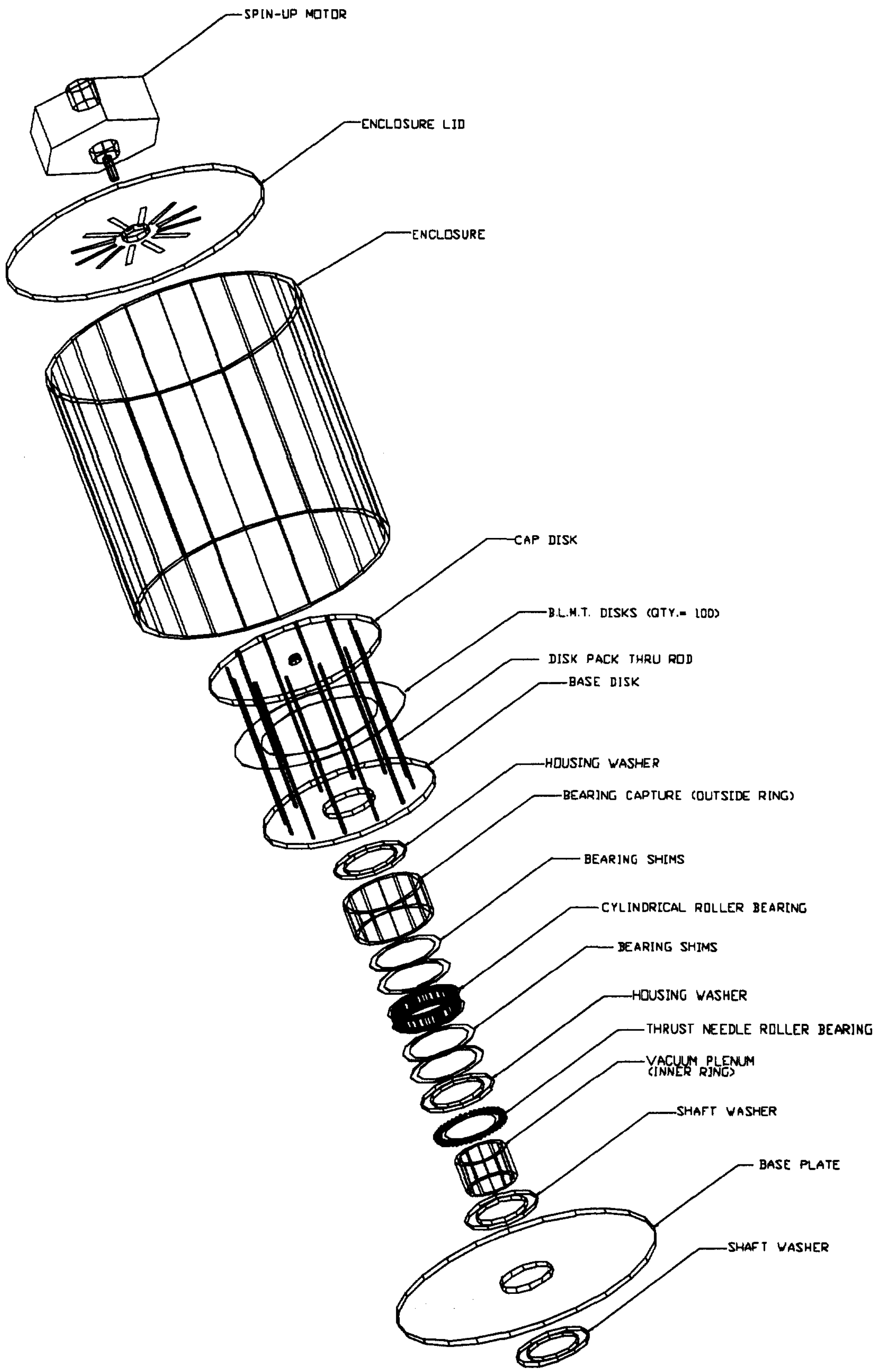

Figure 2 Exploded View of the BLMT Filter

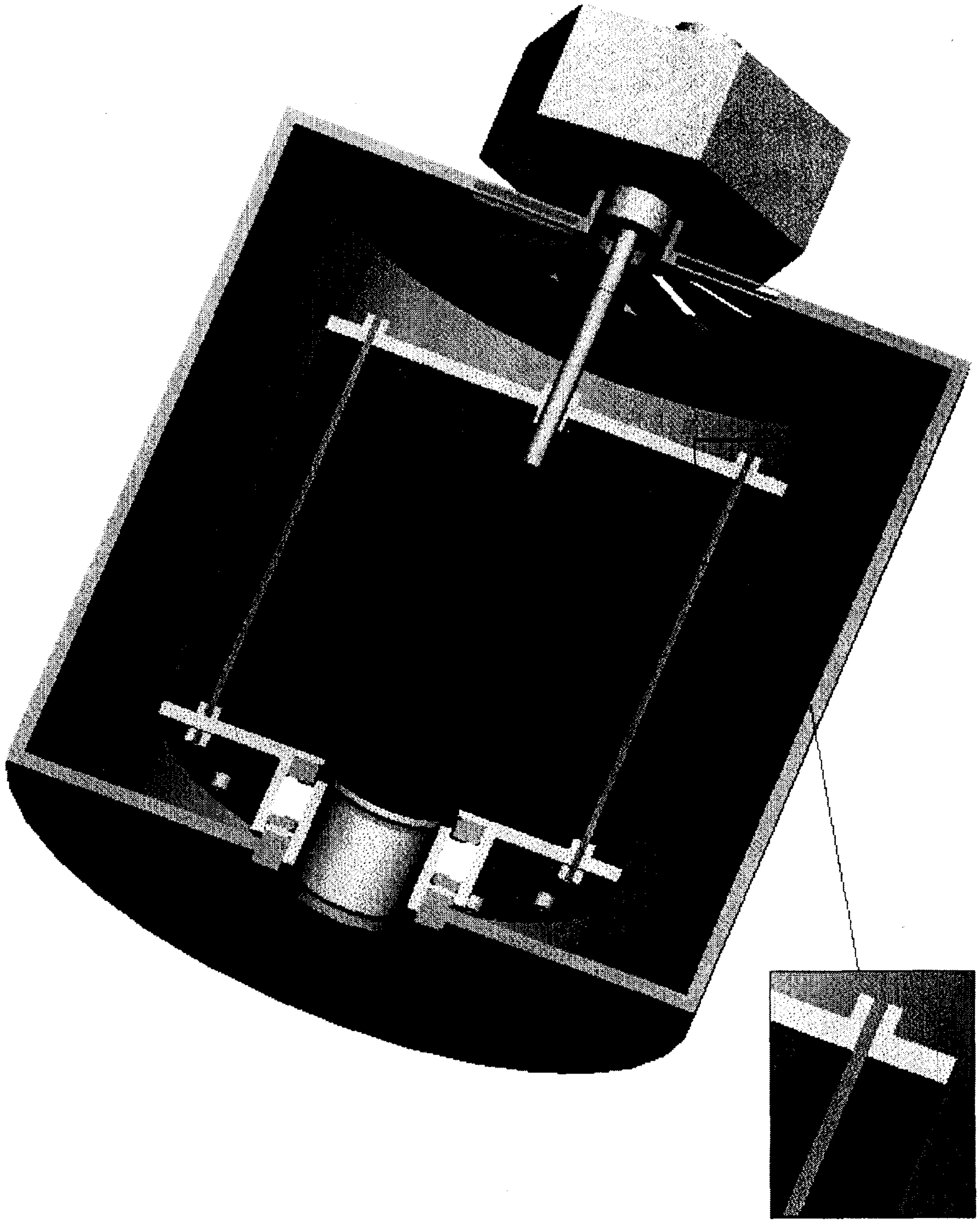

Figure 3 Cut-Away CAD Rendering of the BLMT Filter

Results of BLMT Testing

Bench testing was performed in accordance with our DOE SBIR Phase I program. Figures 1, 2, and 3 illustrate the general arrangement of the BLMT filter. Powdered aluminum oxide, Al_2O_3, was added to the air intake of the reduced-scale BLMT filter to test filtration efficiency. Results of the testing exceeded expectations, as no particulate was observed to pass through the BLMT device. The chosen particulate is pure white in color and is made-up of particle diameters ranging from 0.1 micron to 10 micron, with a median value of 0.46 micron. Density is 3,965 kg/m^3. Figure 4 illustrates the particle size distribution provided by the supplier.

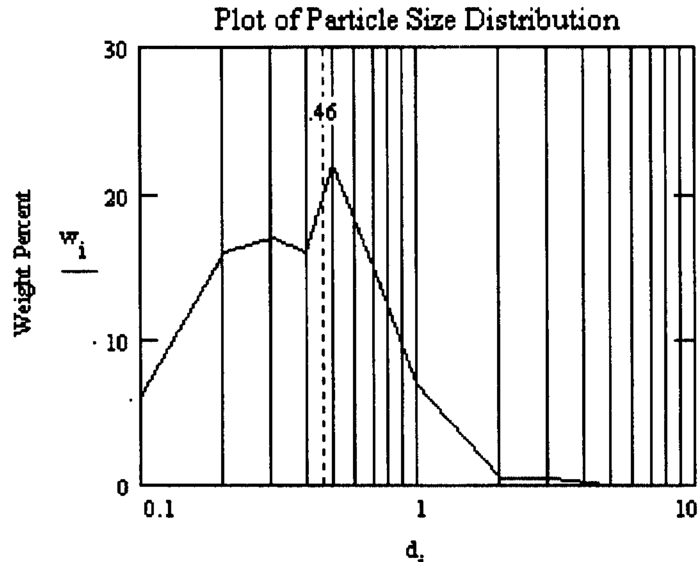

Figure 4 Al_2O_3 Particle Size Distribution

The initial test parameters were as follows:

- Disk pack rotating speed: 1500 rpm
- Flow rate: approximately 12 cfm
- Particulate: approximately 60 cc's of aluminum oxide

The test results were both impressive and successful. With extremely high particulate loading inside a 12-inch diameter, 12-inch high filter housing, none of the particulate was observed to pass into the exhaust chamber. The pressure drop across the prototype filter was higher than expected, at approximately 5-1/2 inches of water. To provide some perspective, the military defines "zero visibility" for larger dust sizes as 0.025 gram/ft^3. During this test run, particulate loading was approximately 0.0043 gram/cm^3, a factor of 4800X higher than zero visibility conditions (assuming all particles remain suspended).

In an attempt to force "breakthrough" on the filter, the gas flow rate was increased. This parameter variation increases drag on particles as they circulate the BLMT device. At a flow rate of approximately 60 cfm there was no observed particulate loss into the exhaust chamber. In another attempt to overload the filter, the flow rate was increased to the maximum capacity of the laboratory blower (approximately 90 cfm) and an additional 60 cc's of aluminum oxide were added to the filter intake. Although the circulation inside the filter (but outside the BLMT device) was essentially "blinded" with particulate matter, still no breakthrough was observed.

The next step taken was to reduce the rotating speed of the disk pack. This parameter variation decreased the centrifugal force (resistance) imparted to particles attempting to enter the BLMT device. With all other parameters maintained, the speed was reduced to 1000 rpm. Once again, no breakthrough was observed. Testing was concluded at this point as the exhaust blower used to develop the flow through the filter shut down on thermal overload.

The filter housing was a clear acrylic tube, allowing observation during the test. Several different vortex patterns developed during the test, seemingly dependent upon a combination of flow rate, particulate loading, and disk pack rotating speed. It was observed that the vortex action within the housing may have contributed to the efficiency of the filter by keeping particulate matter away from the periphery of the BLMT device. This is a "second order" effect that deserves additional study, most likely in combination with tasks associated with housing design and particulate collection. Taking advantage of naturally occurring particulate behavior in addition to the intended action will yield a more efficient filter.

Upon disassembly of the prototype filter and test setup, a light coating of extremely fine powder was found on the inside of the ductwork exiting the prototype filter. The filter had experienced breakthrough of the aluminum oxide material, but the small size and volume of the breakthrough made visual identification during the test impossible. A sample of the material was collected for measurement under a scanning electron microscope (SEM). The material sample was prepared for inspection by sputtering with a conductive material and placing it in an appropriate inspection crucible. The SEM inspection revealed the material that achieved breakthrough was sized below the 0.3 μm cutoff normally associated with HEPA filtration requirements. A photograph of the SEM results is presented in Figure 5. The magnification of the SEM was 0.91 x 15,000 = 13,650X. The average maximum particle size in the SEM viewfinder was determined to be approximately 0.32 cm. Therefore the average maximum particle size is: $0.32/13{,}650 \approx 2.3 \times 10^{-5}$ cm $\approx 2.3 \times 10^{-7}$ m ≈ 0.23 μm.

Based on the known test parameters (summarized in Table 1, below) and making use of the equations previously developed, the anticipated filter performance can be calculated.

Type of Parameter	Parameter	Parameter Value
Design Parameters	Flow Rate ($\dot{\mathbf{M}}$)	90 cfm = 0.0467 kg/sec
	Kinematic Gas Viscosity (ν_g)	1.636×10^{-5} m^2/sec
	Gas Density (ρ_g)	1.1 kg/m^3
	Particle Density (ρ_p)	3.96×10^3 kg/m^3
BLMT Filter Parameters	Number of Disks	100
	Number of Disk Spaces ($\mathbf{n}$)	99
	Disk Spacing ($\mathbf{d}$)	0.001 m
	Disk Outside Radius ($\mathbf{R}_o$)	4 in = 0.1016 m
	Disk Inside Radius ($\mathbf{R}_o$)	2.75 in = 0.0699 m
	Angular Velocity (ω)	1,000 rpm = 104.7 rad/sec

Table 1 Summary of Design and Filter Parameters

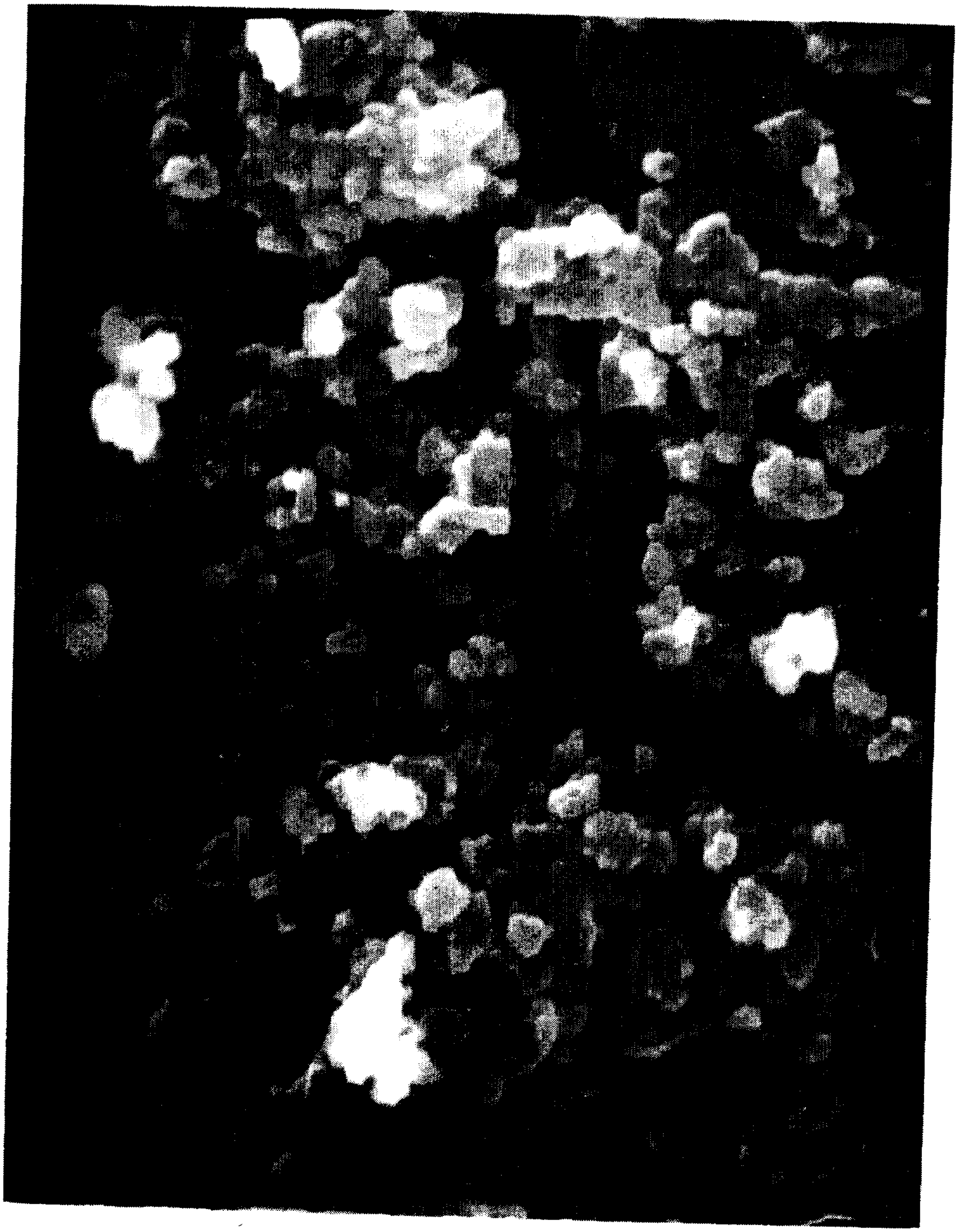

Figure 5 SEM Photograph Showing 0.23 Micron Aluminum Oxide Particles

Substituting into Equation 6, the expected critical diameter for the filter and design parameters is:

$$D_p = \frac{3}{R_o\omega}\sqrt{\frac{\nu_g \dot{M}}{dn\pi\rho_p}}$$

$$D_p = \frac{3}{(0.1016)(104.7)}\sqrt{\frac{(1.636x10^{-5})(0.0467)}{(0.001)(99)\pi(3.965x10^{3})}} \approx 7\mu m$$

The anticipated pressure differential across this filter is determined by substituting into Equation 11:

$$\Delta P = \frac{\rho_g}{2}\left(\left(\frac{\dot{M}}{2\pi\rho_g dn}\right)^2\left(\frac{1}{R_o^{\,2}} - \frac{1}{R_i^{\,2}}\right) + \omega^2\left(R_o^{\,2} - R_i^{\,2}\right)\right)$$

$$\Delta P = \frac{1.1}{2(6895)(14.7)} \cdot \left(\begin{array}{l}\left(\left(\frac{0.0467}{2\pi(1.1)(0.001)(99)}\right)^2\left(\frac{1}{(0.1016)^2} - \frac{1}{(0.0699)^2}\right)\right) \\ + \left((104.7)^2\left((0.1016)^2 - (0.0699)^2\right)\right)\end{array}\right) \cdot 100 \approx 0.032\%$$

The airflow velocity entering each individual disk space is based on Equation 12:

$$V = \frac{\dot{M}}{2\pi\rho_g R_0 dn}$$

$$V = \frac{0.0467}{2\pi(1.1)(0.1016)(0.001)(99)} = 0.67 m/sec$$

The following table summarizes the differences between the analytical (expected) and empirical (actual) results.

Result Description	Expected Results	Actual Results
Critical Diameter	7 µm	0.23 µm
Differential Pressure	0.032% (0.0089 in. of H_2O)	approx. 5-1/2 in. of H_2O
Airflow Velocity Between Disks	0.67 m/sec	not measured

Table 2 Summary of Expected and Actual Test Results

The difference between the expected and actual critical diameter was substantial, and likely due to the following:

- The boundary layers effect airborne particles before they enter the BLMT device.
- Vortices and airflow patterns within the housing contribute to inertial effects that prevent particle passage into the BLMT device (i.e., the device housing acts similar to a cyclone in that particle density is suspected to be highest closest to the inside wall and falls off rapidly as it approaches the BLMT device).
- The analytical models predict that there is a third size range of particle, those that enter, but do not exit the BLMT device. They settle into and orbit within the device, and particle interaction and other second-order effects eventually eject the particle.

The difference between the expected and actual pressure differential is also substantial, and is probably due to one or more of the following:

- Reduced exit port size (cross-sectional area) in relation to the disk pack inside radius. The diameter of the suction line from the filter assembly was approximately 2 inches. The inner diameter of the disk pack was 5.5 inches. This transition alone, at 90 cfm, generates a pressure differential of as much as 1.7 inches of H_2O.
- Inefficient placement of pitot tubes for pressure differential measurement.
- Measurement of pressure differential attributable to the BLMT device combined with that for other system components.
- Vortices and airflow patterns within the housing contribute to inertial effects that increase the pressure differential.

Conclusion

The empirical data collected to date establish that it is feasible to extend the BLMT filtration concept to the submicron size range for prefilter applications. Significantly more data, however, must be gathered in subsequent experiments for accurate quantification. The SEM microphotographs of the breakthrough particles (the particulate matter that passed through the filter when operational parameters were minimized) definitively show that, at the filter parameters reported, sub-HEPA particle sizes (i.e., less than 0.3 μm) were not excluded, but at conditions (purely from theoretical considerations) that would normally reject particles 7 μm and larger. In other words, there is a discrepancy between the particle size empirically rejected (0.23 μm) and that theoretically predicted to be excluded (7 μm).

A hypothesis has been suggested to explain this "better than predicted" particle exclusion phenomena (still to be definitively ascertained). Note that the equations used to describe the particle size rejection and ΔP across the filter do not take into account any contribution due to the housing size, shape or configuration. Logically, both the housing geometry/flow conditions (e.g., involute design) and the input flow characteristics (i.e., tangential rather than normal) will influence the BLMT filtration efficiency, as well as the pressure drop. The magnitude to which the housing affects the separation efficiency will be the subject of further R&D over the next several years.

This feasibility investigation has demonstrated the merit in proceeding with a full-scale prototype BLMT prefilter, in which far more sophisticated submicron particle generation and detection equipment can be used to accurately quantify the prefilter. Since only approximately 90 CFM flow rate through the device was measured to demonstrate feasibility, nearly 11 times this flow rate (or 1,000 CFM) will be required for demonstration of the full-scale BLMT device in the next phase of experimentation. From a scale-up perspective, the least risky alternative for full-scale demonstration of the prefilter is simply to have multiple (10 to 11) reduced-scale units operate in parallel. However, the scale-up criteria suggested by the Reynold's numbers analysis offers another alternative - use of larger disks (both outside and inside diameters) and more of them. This would result in a larger prototype design with perhaps three or four parallel units operating simultaneously to achieve the desired submicron cut-off size and flow rate.

Acknowledgments

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DISCUSSION

ENGELMANN: It is very difficult when one collects particles in chains at the end of a system to know just what size particle one is dealing with, whether the chain agglomerated afterwards or during the process, or was created that way. Do you have any plans to determine this with a moving filter paper or something else at the end of the system?

WRIGHT: For phase two we are acquiring \$100,000 worth of test equipment. We will have a standard DOP generator ahead of the filter. We have not been set up to do filter work, and that is why we were using indirect methods. When we ran this particular experiment we were expecting a large plume of material to come through, and had a flow visualization chamber ahead of the fan, but we never saw anything. We increased flow to push material through and we added another 60cc of material. At the end of the test we had 120cc in the unit. This corresponded to 0.029g/m^3, which is a fairly heavy loading. At the end of this test, we increased the STET rate of the unit to about 100CFM. When you increase flow rate and reduce spin rate particles should go through. Since we did not have a filter downstream, we had a fairly clean system to start off with. We had noticed there was a small amount of dusting and dust was what we ended up taking over to the SEM. I admit this was a very crude method but it was just to show feasibility. In phase two we will be able to do a lot more to quantify it.

WEBER: Did you have a chance to examine the condition of the disks at the end of the tests and the gap between the disks?

WRIGHT: The gap does not change. We have a dozen bolts running through them with spacers. The disk thickness was 30mils. We saw no effects due to erosion, but the test was not long enough to establish any kind of erosion pattern, we would not expect to see erosion except over a very long period of time.

WEBER: Any residual particles?

WRIGHT: We were trying to push particles through but we had quite a bit of material that stuck to the inside part of the chamber. All we were able to do was get some extremely light dusting at the very end that we ran through the SEM. We did a number of samples and the average particle size that had gone through was around 0.2-0.3μm. Other than that we did not have enough to measure.

DAUBER: Given that the particle size that you found was more than an order of magnitude smaller than you had predicted, is it possible to bring it down another order of magnitude by some refinement so as not to have a prefilter, but a HEPA filter?

WRIGHT: We would like to get to that point. Some of our early modeling showed that if we had tangential inflow rather than coming in radially, or perpendicularly, to our inflow, that we would get about an order of magnitude increase in terms of our separation efficiency. What we are trying to do is achieve solid body rotation between the disks. As long as our disk spacing is such that we can make sure that there is no core flow going through there, then this thing will continue to act as a filter. Yes, we are trying to look at this. We can envision a truncated cone housing design so that we have a natural pressure distribution that forces the particles to the outside so that you could extract them from the lower portion. You have a large particle concentration toward the outer edge of the filter housing and therefore you are only literally filtering a fairly clean core of air inside. That gives us hope that we will be able to get further down in terms of particle size and also increase our flow rate, to get into a more industrial size.

DAUBER: Then all you have to do is add another concentric ring.

WRIGHT: Exactly. There is a lot of additional work that needs to go on and we need to look at what else we can incorporate. We have quite a bit of surface area and we could add catalysts or other things on to the surface of the plates themselves. It is a fairly simple design. We have to protect the motor (which could be hermetically sealed) and the bearing, they are our critical parts.