AUTOMATED HEPA/ULPA FILTER SCANNING SYSTEM FOR LEAK DETECTION AND FILTER PERFORMANCE TESTING

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BIOGRAPHY

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Dr. Francisco J. Romay is currently a senior research and development engineer at MSP Corporation, Minneapolis, MN. His current activities involve the design and testing of aerosol samplers and filter testing equipment. Before joining MSP Corporation Dr. Romay was a Research Associate and the Assistant Manager of the Particle Technology Laboratory at the University of Minnesota (1996-97), where he worked on aerosol sampling and transport, contamination control and air filtration. Dr. Romay has been an Associate Professor (1993-95) in the Mechanical Engineering Department at ESPOL (Escuela Superior Politècnica del Litoral) in Guayaquil, Ecuador, teaching and doing research in Environmental Engineering. Dr. Romay is a member of the American Association for Aerosol Research. He has authored more than 20 professional publications. Dr. Romay received his Ph.D. degree in Mechanical Engineering at the University of Minnesota in 1992.

James J. Sun

Dr. James Sun is the Senior Manager of the Semiconductor Development Group at MSP Corporation. He has been involved in the development of particle sampling and deposition equipment for the microelectronics industry. Dr. Sun was the principal design engineer for a process to improve the fine particle collection efficiency of wet scrubbers. He has also developed instrumentation and methodology for stack sampling, ambient aerosol measurement, and indoor air quality diagnostics. Dr. Sun has conducted research on particle formation mechanisms due to radioactivity and on turbulent particle deposition. Dr. Sun received his Ph.D. in Mechanical Engineering at the University of Minnesota in 1992.

Dr. Benjamin Y. H. Liu

Dr. Benjamin Y. H. Liu is Regents’ Professor and the Richard C. Jordan Professor of Mechanical Engineering at the University of Minnesota. He is also the director of the Center of Filtration Research. At the University of Minnesota, he and his students have worked on a variety of problems in the field of aerosol science and technology, including fundamental aerosol properties, measurement methods, and the application of aerosol science to air pollution, filtration, and contamination control in semiconductor manufacturing. He has approximately 400 publications, including four edited books. He is a member of the National Academy of Engineering and has served as a technical VP (Contamination Control) of IES.

ABSTRACT

An automated HEPA/ULPA filter leak testing and efficiency certification system is described. The system has all the components required to test filters and includes: an air plenum with a frame to accommodate filters of several dimensions, a high-output PSL generator, an air handling system with flow meters and pressure transducers, a dilutor for upstream PSL aerosol sampling, a XY scanning system with three iso-kinetic sampling probes, three laser particle counters, and a computer with the hardware and software required to control the operation of the system. The evaluation of the system components, the selection of appropriate test parameters, and test results of real filters are discussed.

INTRODUCTION

High-efficiency particulate air filters (i.e. HEPA) and ultra-low penetration air filters (i.e. ULPA) are used in a wide range of HVAC applications such as in clean rooms for manufacturing of semiconductor devices and pharmaceutical products, in hospitals, and in clean benches for research facilities. A common practice of filter manufacturers is to leak-test every filter in addition to the particle removal efficiency test and resistance to air flow test. Such leak-testing is usually performed by challenging the filter with a high concentration aerosol and measuring the particle concentration downstream of
the filter with a suitable particle detector as the instrument’s probe is manually scanned across the filter.

Leak-testing equipment and procedures are described in the IES Recommended Practice Standard entitled “Testing Cleanrooms” (i.e. IES-RP-CC006.2). For leak testing two methods are recommended. The first method involves the generation of a liquid aerosol (typically DOP) with a Laskin nozzle and scanning the downstream side of the filter with an aerosol photometer probe. Leaks are reported whenever the penetration exceeds 0.01% at any location during scanning. In this method the filter is contaminated with the challenge oil particles and in many cases this is not acceptable to the final user, particularly in semiconductor manufacturing cleanrooms. The second method involves the generation of a high concentration aerosol (typically PSL spheres) and scanning the downstream side of the filter with a discrete-particle counter (typically a laser particle counter). Leaks are detected by defining a standard leak penetration based on the type of filter being tested. The use of PSL spheres minimizes contamination of the filter, since PSL spheres are inert.

In this paper an automated ULPA/HEPA filter leak testing and efficiency certification system is described in detail. The system has all the components required to test filters and includes: an air plenum with a frame to accommodate several filter sizes, an air handling system with flow and pressure transducers, a dilutor for upstream sampling, a XY scanning system with three sampling probes and a computer with software to control the operation of the filter tester. The evaluation of the system components, the selection of appropriate test parameters, and test results of real filters are discussed.

DESCRIPTION OF THE SYSTEM

Figure 1 shows a schematic diagram of the complete system (Model 3100, MSP Corporation, Minneapolis, MN). A high output PSL generator (Model 2045, MSP Corporation, Minneapolis, MN) is used to atomize a suspension of PSL spheres in de-ionized water. The PSL aerosol is introduced to the suction of the main air blower to provide good mixing of the PSL with the main air flow. A rectangular cross section box of dimensions 61 cm x 152 cm (24”x 60”) is used as a plenum upstream of the filter. The challenge aerosol is introduced to the plenum through a diffuser to distribute the flow uniformly. From the plenum a small aerosol sample is extracted by the dilution system to measure the upstream PSL concentration. Three sampling probes scan the entire face of the filter to measure the downstream PSL concentration as a function of filter location. Each probe is connected to a cleanroom laser particle counter (Model A2100B Met One, OR). The system has flow meters and pressure transducers to monitor the main air flow rate, the upstream sample flow rate, the total dilution flow rate, the filter pressure drop and the atomizer pressure. Three solenoid valves allow the system to switch between the upstream and downstream sides of the filter so that the complete operation of the filter tester could be automated. All the measurements are performed according to a recipe which specifies all the test parameters that constitute a test protocol. Once all the parameters are given the computer software takes over and controls the leak detection and filter certification test. Figure 2 shows a picture of the actual system.

Aerosol Generator

To test an ULPA filter of 99.9999% filtration efficiency with PSL spheres requires a challenge concentration of at least 3500 particles/cm³ (10⁸ particles/ft³). The expected average downstream concentration would be 3.5 x 10⁻³ particles/cm³ (100 particles/ft³). A laser particle counter with a sampling flow rate of 28.3 LPM (1 CFM) would give a counting rate of 1.67 particles/s or 100 particles/min. If the filter had a size of 61 cm x 122 cm (2’ x 4’) and the test face velocity were 45.7 cm/s (90 FPM), the required challenge PSL generation rate would be 7.2 x 10¹⁰ particles/min.

The high output PSL generator (Model 2045, MSP Corporation) is a 40-nozzle atomizer with a spherical re-atomization ring. This ring collects large atomized droplets and re-atomizes them as smaller droplets, increasing the droplet generation rate and reducing the size of the water droplets. The number mean droplet diameter is about 0.5 μm.

![Figure 3. Output aerosol size distribution from the single-jet atomizer when aerosolizing 0.10 μm PSL spheres.](image)
Figure 3 shows the number size distribution of 0.1 μm PSL particles generated by a single-jet atomizer with a re-atomization ring. The output aerosol shows a narrow monodisperse peak of the generated PSL particles with a small fraction of PSL doublets, and a broader mode of background residue particles produced from the impurities in the DI water with a mean size of 0.02 μm. The residue particles are smaller than the lower detection limit of typical laser particle counters which is normally about 0.10 μm.

Figure 4 shows the measured generation rate of 0.135 μm PSL spheres with a 40-nozzle atomizer with a re-atomization ring as a function of pressure. The PSL/DI water solution contains 15 cc of 10% solids PSL spheres (Duke Scientific, Palo Alto, CA) in one gallon of DI water. The measured generation rate is sufficient for testing 61 cm x 152 cm (2’x 5’) ULPA filters of 99.9999% rated efficiency.

**Dilution System**

Figure 1 also shows a schematic diagram of the dilution system. A low flow rate (i.e. 1 to 2 LPM) sample from the filter box is introduced to the diluter. A centrifugal fan suctions a total dilution flow rate of up to 4500 LPM through an ULPA filter. The flow inside the diluter is turbulent (i.e. Reynolds Number = 5 x 10^5) to achieve good mixing of the aerosol. An orifice plate is used to determine the total dilution flow rate by measuring the differential pressure through the orifice. The dilution ratio is calculated as ratio of the total dilution flow rate to the aerosol sample flow rate (i.e. R = Qd/Qs). The performance of the diluter was evaluated experimentally by measuring the diluted aerosol concentration as a function the calculated dilution ratio. For a constant upstream concentration the diluted aerosol concentration is directly proportional to 1/R = Qs/Qd. Figure 5 shows the test results confirming the expected linear relationship.

**X-Y Scanning System**

Samples downstream of the test filter are taken through three sampling nozzles which can be moved across the face of the test filter. The X-axis linear actuator is mounted on the stand which holds the test filter. The Y-axis linear actuator is mounted on the movable carriage of the X-axis actuator. The sampling nozzles are mounted on the carriage of the Y-axis actuator. The distance between the sampling nozzles and the face of the filter can be adjusted. A separation distance between 1 and 2.5 cm is recommended. Each sampling nozzle has a square cross section of dimensions 3.18 cm x 3.18 cm (1.25"x 1.25") to provide isokinetic sampling at 46.7 cm/s (92 FPM) with a 28.3 LPM (1.0 CFM) sample flow rate. The particles sampled by the three nozzles are counted simultaneously by the downstream laser particle counters (LPC-1, LPC-2 and LPC-3). The LPCs have been modified at the factory to provide a 0-5 V signal output, so that the particle counts for each sampling period could be processed by a counter/timer computer board.
Computerized Scanner Control Program

The computerized scanner control program conducts the entire filter scan and includes the following steps:

1. Commission an upstream sample and recovering the challenge PSL concentration.
2. Commission a full downstream scan (including a side scan) of the filter face and recovering the filter penetration as a function of nozzle position. The filter penetration is the ratio of downstream to upstream PSL concentration.
3. Commission a retest at the locations for which the penetration was larger than a user-defined retest trigger penetration. The retest is conducted at fixed nozzle locations with a user-specified sampling period (5 to 15 s at each nozzle position).
4. Conduct supporting calculations, reporting and archiving functions.
5. Allow manual upstream and downstream sampling, and manual nozzle positioning.

Figure 6. Control software flow chart

Figure 6 shows a flow diagram of the control computer program written in Microsoft Visual Basic 5.0. The

AutoScan mode initially requires input regarding the physical characteristics of the filter, the test protocol to follow, the setting of the origin in the XY coordinate system and the flow rate setting. Once all these parameters are defined, the filter is scanned across the entire area and along the edges. During the scanning procedure the control program controls the XY motion, the operation of the particle counters, the signal readout from the pressure and flow transducers, and the operation of the solenoid valves.

If the filter shows no leaks a label is printed with the test results. If the filter shows leaks with a penetration higher than the trigger penetration, a retest procedure is followed in which the penetration through the suspect leak areas is measured with the probe standing at each location for 5 seconds. If the new penetration values are higher than the pre-defined defect penetration, the leak position and penetration are recorded to generate a defect report. If the new penetration values are below the defect penetration the local efficiency is re-calculated and a label is printed with the updated test results.

TEST PROTOCOL DESIGN

A test protocol defines appropriate test parameters to ensure statistically significant results in a reasonable period of time. The smallest leak that must be detected and repaired can be defined as the threshold leak. There are no standardized definitions of threshold leaks. Filter manufacturers generally define a leak when the local penetration is 5 to 10 times the rated maximum penetration through the filter (i.e. for a 99.99% efficiency filter, the leak penetration is 500 to 1000 ppm). A detailed analysis of the equations that govern the filter scanning process when using particle counters has been reported by McDonald (1993).

Upstream Concentration

The upstream aerosol concentration is measured by one of the laser particle counters after dilution. The upstream particle count during one sample period is:

\[ N_u = \frac{Q C t_{us}}{R} \]

Where Q is the particle counter flow rate (i.e. 28.3 LPM), C is the upstream aerosol concentration, \( t_{us} \) is the upstream sampling time, and R is the dilution ratio. For an upstream concentration of \( C = 3530 \#/cm^3 \), a upstream sampling time \( t_{us} = 30 \text{s} \), and a dilution ratio \( R = 2500 \), \( N_u \) is 20000 counts.
Downstream Concentration

If a sampling nozzle is stationary in front of a leak, the number of counts measured downstream of the leak is given by:

\[ N_d = (Q_l C + Q P_f C) t_{ds} \]

Where \( Q_l \) is the leak flow rate, assumed to be much smaller than the sampling flow \( Q \). \( P_f \) is the filter media penetration, and \( t_{ds} \) is the downstream sampling period.

The apparent penetration (i.e. \( P = N_d/N_u \)) in this local area is given by:

\[ P = R (Q_l/Q + P_f) t_{ds}/t_{us} \]

From the above equation the leak flow rate can be calculated directly from all the other measured parameters.

If a sampling nozzle is moving at a linear scan rate \( S \), and the downstream sampling time is larger than the time the probe is over the leak (i.e. \( t_{ds} > L/S \)), the downstream counts are given by:

\[ N_d = Q C L/S + Q P_f C t_{dh} \]

Where \( L \) is the length of the probe in the direction of scanning motion.

In this case the apparent penetration is

\[ P = R (Q_l/Q * L/S + P_f t_{dh})/t_{us} \]

If the penetration through the filter media is much less than the apparent penetration due to the leak the required linear scan rate to detect a threshold leak can be calculated as

\[ S = P_l Q C L/N_l \]

Where \( P_l \) is the leak threshold penetration and \( N_l \) is the minimum specified number of counts to detect a leak. The value to use for \( N_l \) must be based on statistical considerations, which are discussed by McDonald (1993). Higher values of \( N_l \) improve the probability of finding a threshold leak and reduce the probability of false alarms. However, higher values of \( N_l \) result in lower scanning speeds and longer test times.

Table 1 shows typical scanning rates required for testing HEPA and ULPA filters for \( C = 3530 \) #/cm\(^3\), \( Q = 28.3 \) LPM, \( L = 3.18 \) cm, \( P_l = 10 P_f \) and \( N_l = 10 \). This table also shows the required downstream sampling time and the threshold leak flow rate that can be detected with the filter test system described in this paper. For filters of efficiencies up to 99.9995% the linear scanning rate is limited by the X-Y moving system with a maximum of 15 cm/s. For a 99.99995% efficiency filter the linear scanning rate must be reduced to 2.5 cm/s in order to detect a threshold leak flow rate of 1.3 x 10\(^{-4}\) LPM (4.5 x 10\(^{-6}\) CFM). This assumes that the counts due to particle penetration through undamaged filter media plus any background counts are only 10% of the total counts of a threshold leak.

Table 1

<table>
<thead>
<tr>
<th>Rated Efficiency (%)</th>
<th>( P_l ) (ppm)</th>
<th>( C_{down} ) (#/cm(^3))</th>
<th>( P_l ) (ppm)</th>
<th>Calculated ( S ) (cm/s)</th>
<th>Actual ( S ) (cm/s)</th>
<th>( t_{ds} ) (s)</th>
<th>( N_t )</th>
<th>( N_l )</th>
<th>( Q_l ) (LPM)</th>
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<tr>
<td>99.99</td>
<td>100</td>
<td>0.353</td>
<td>1000</td>
<td>528</td>
<td>15.2</td>
<td>0.21</td>
<td>34.7</td>
<td>347</td>
<td>2.5 x 10(^{-4})</td>
</tr>
<tr>
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<td>50</td>
<td>0.177</td>
<td>500</td>
<td>264</td>
<td>15.2</td>
<td>0.21</td>
<td>17.4</td>
<td>174</td>
<td>1.3 x 10(^{-4})</td>
</tr>
<tr>
<td>99.9995</td>
<td>10</td>
<td>0.035</td>
<td>100</td>
<td>52.8</td>
<td>15.2</td>
<td>0.21</td>
<td>3.5</td>
<td>35</td>
<td>2.5 x 10(^{-4})</td>
</tr>
<tr>
<td>99.9995</td>
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<td>0.018</td>
<td>50</td>
<td>26.4</td>
<td>12.7</td>
<td>0.25</td>
<td>2.1</td>
<td>21</td>
<td>1.3 x 10(^{-4})</td>
</tr>
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<td>0.0035</td>
<td>10</td>
<td>5.3</td>
<td>2.5</td>
<td>1.25</td>
<td>21</td>
<td>10</td>
<td>2.5 x 10(^{-4})</td>
</tr>
<tr>
<td>99.99995</td>
<td>0.5</td>
<td>0.0018</td>
<td>5</td>
<td>2.6</td>
<td>2.5</td>
<td>1.25</td>
<td>10</td>
<td>1.3 x 10(^{-4})</td>
<td></td>
</tr>
</tbody>
</table>
EXPERIMENTAL RESULTS

The described filter test system allows to test filters for efficiency certification and leak detection simultaneously. For this purpose the PSL particle size must be between 0.1 and 0.2 μm, which is the most penetrating particle size for high efficiency filters. The pressure drop through the filter is also measured during each test in order to provide actual air resistance information. The total number of downstream particle counts obtained during the entire scanning cycle is used to calculate the mean particle penetration. In general, the experimentally measured efficiency is higher than the rated efficiency of the filter. However, as the filter grade reaches the level of 6 nines (i.e. 99.9999%), the cleanliness requirements for the area where the filter tester is located become more stringent to minimize background particle counts. At the same time, the number of downstream particle counts is reduced dramatically and statistical significance is reduced. Table 2 shows efficiency measurement results for three leak-free filters rated with a 5.5 nine-efficiency. The measured efficiencies were above the rated filter efficiency. Note that the test velocity was above the standard face velocity of 45.7 to 50.8 cm/s (90 to 100 FPM).

Table 2
Test Results for Leak-free ULPA 99.9995% Efficiency Filters

<table>
<thead>
<tr>
<th>Serial No.</th>
<th>Filter Pressure Drop (cm wg)</th>
<th>Efficiency (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2.25</td>
<td>99.9998</td>
</tr>
<tr>
<td>2</td>
<td>2.26</td>
<td>99.9999</td>
</tr>
<tr>
<td>3</td>
<td>2.25</td>
<td>99.9999</td>
</tr>
</tbody>
</table>

Figure 7 shows test results for a filter with a center leak. The diagram shows the locations where the measured penetration is higher than the defined defect penetration. In this case the filter is rated to have a 99.995% efficiency (i.e. Pf = 5 ppm), and the defect penetration was defined as 750 ppm. Note that the measured mean efficiency of the filter is slightly higher than the rated efficiency. However, the local penetration at the five leak locations is over 1300 ppm, so the filter must be rejected. The defect report indicates the approximate location of the leaks and the measured local penetration with the probe stationary over the leak.

Figure 8 shows test results for another filter which has a big leak and a small leak. The filter is rated to have a 99.9995% (i.e. Pf = 5 ppm). The trigger penetration during scanning was set at 25 ppm and the defect penetration during retest was set at 50 ppm. The first big leak shows 13 locations with penetrations ranging from 60 ppm to 3600 ppm while the second small leak shows 2 locations with penetrations of 77 and 115 ppm. In this case the size of the leak is so large that the overall tested efficiency was well above the rated efficiency of the filter.

CONCLUSIONS AND RECOMMENDATIONS

A filter test system has been developed to provide ULPA/HEPA filter testing by combining simultaneous leak detection and efficiency testing all in one filter scan cycle. With the integration of the Recipe Control software to manage all the filter test parameters the operation of the filter tester is automated for faster filter certification and leak testing.

The Recipe Control software allows the user to design test protocols according to the rated efficiency of the filter and to enter specific characteristics of the filters to be tested such as filter and frame dimensions, part and serial numbers, etc. Each recipe can be saved in a file that can be retrieved by the operator from a folder containing recipes for all the types of filters manufactured in the facility. The Recipe Control prevents typical operator errors during routine filter testing and provides day to day consistency in the leak detection and certification of ULPA/HEPA filters. The software also generates certification labels with the measured efficiency, test flow rate and pressure drop for all the filters that satisfy the specifications. For leaky filters a report is generated with the measured penetration and coordinates of the leak areas.

Filters with efficiencies ranging from 99.99 to 99.9995% have been successfully tested using appropriate scanning parameters to ensure statistically significant results. A leak penetration equal to ten times the rated filter penetration seems to provide a reasonable threshold level to detect filter leaks. The linear scan rate and downstream sampling time are critical parameters that need to follow the guidelines of IES-RP-CC006.2 as a way to guarantee meaningful leak test results.

In addition to the selection of an adequate test protocol the cleanliness of the room where the filter tester is located is critical when testing ULPA filters so that the background particle counts are well below the typical aerosol concentration downstream of the filter. This is particularly important when scanning the perimeter of the filter.
REFERENCES
