The Effects of Media Velocity and Particle Size Distribution on Most Penetrating Particle Size and Filter Loading Capacity of 12”x12”x11.5” AG-1 HEPA Filters

Steven L. Alderman, Michael S. Parsons, and Charles A. Waggoner

Institute for Clean Energy Technology, Mississippi State University

Abstract

High-efficiency particulate air (HEPA) filters are widely used to control particulate matter emissions from processes that involve management or treatment of radioactive materials. Section FC of the American Society of Mechanical Engineers AG-1 Code on Nuclear Air and Gas Treatment currently restricts media velocity to a maximum of 2.5 cm/s in any application where this standard is invoked. There have been a variety of concerns expressed with respect to increasing this ceiling value and there has also been considerable discussion regarding controlling ventilation systems using the units of acfm or scfm. Both of these sets of concerns are directly related to the performance of HEPA filters as a function of media velocity.

A series of 12x12x11.5 inch AG-1 HEPA filters were loaded from initial differential pressures to 6 inches of water column using a set of solid KCl aerosols at media velocities ranging from 4 to approximately 8 feet per minute. The two-aerosol challenge conditions were established by either including or removing a cyclone (d50 cut point of 3 micrometers) from the aerosol generation process. A statistical description of the aerosol particle size distributions for the testing activities is included in the paper.

Test data were collected continuously as the filters were loaded and trends are presented to report the effects of media velocity on filter efficiency and most penetrating particle size as a function of both particle size distribution and differential pressure as the filters load. These data will serve as reference information in an additional discussion associated with process control using either the units of acfm or scfm.

Three major factors influence the difference in acfm vs. scfm values for a given gas flow. These are temperature, pressure, and gas composition (density or effective molecular weight). Temperature and pressure are routinely monitored and included in the conversion of mass flow rates to volumetric flow rates. This paper will also present a set of curves relating the variance between acfm and scfm as a function of relative humidity and gas pressure at three temperatures.

Variability of relative humidity is not always taken into account in the conversion of mass flow rates to volumetric units. The absolute mass of water per cubic meter varies significantly as a function of temperature calling for additional scrutiny if there is the possibility of variability in RH for gas flows in the 200 F range.

Introduction

A significant amount of discussion has occurred with respect to the AG-1 Section FC stipulation of a 5 feet per minute (fpm) maximum velocity. [1,2] The origins of this ceiling value in addition to the advances made in development of media over the past forty years have been discussed at length.

A related area of discussion has involved control of process equipment using either standard or actual values of volumetric flow rates. This issue contains two primary perspectives on this issue, one dealing with the more intuitive recognition that actual flow rates are directly capable of controlling media velocity and the more analytical perspective centered on the accuracy of converting mass flow data into either standard or actual volumetric units. Often these two perspectives are included in any discussion/debate associated with controlling equipment using the units of either acfm or scfm.

This paper addresses portions of the debate by providing results of filter loading experiments over a range of media velocities from four feet per minute to approximately eight feet per minute. Data are reported showing media velocity effects on the most penetrating particle size, filter loading rates, and loading capacity of filters. There is additional discussion of how this information can be used in identifying considerations and monitoring instruments needed when selecting either acfm or scfm units for controlling an operating system.

Media Velocity Experiments

A series of 12x12x11.5 inch AG-1HEPA filters from two different manufacturers was used in evaluating the effects of media velocity and particle size distributions on the loading. Filter evaluations were conducted using the Institute for Clean Energy Technology (ICET) HEPA filter test stand and high-output aerosol generator. The test stand and aerosol generator, depicted schematically in Figure 1, have been described in detail elsewhere.[3] The test aerosol employed in this set of tests was produced by spray drying a 30 %, by weight aqueous solution of KCl in the ICET aerosol generator. Test stand airflows were controlled at a nominal temperature of 25 C and at 20% RH.

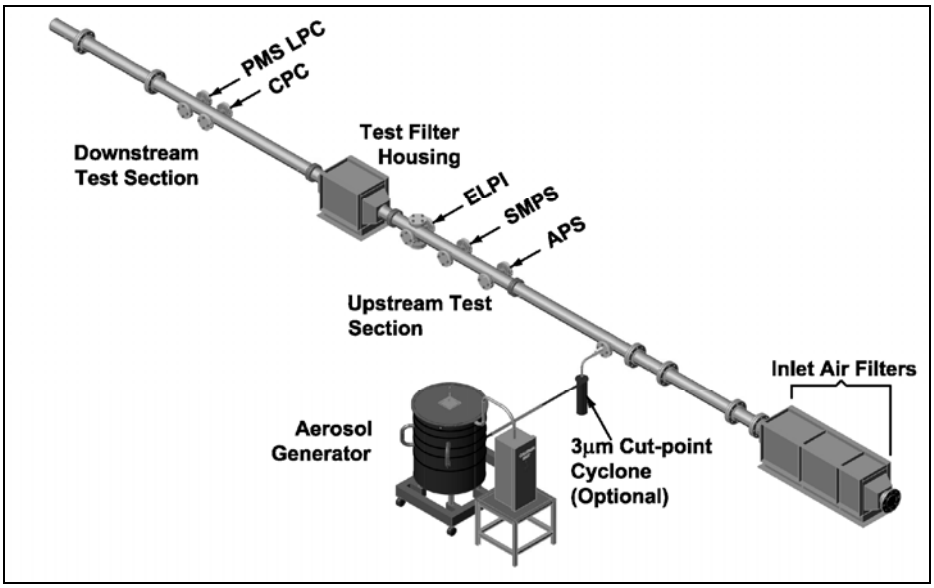

Figure 1. ICET HEPA Test Stand, High-output Aerosol Generator, and Aerosol Instrumentation Sampling Locations

Up and downstream measurements of aerosol sizes and concentrations were made using a variety of instrumentation. Upstream PSD measurements were made with a TSI scanning mobility particle sizer (SMPS) Model 3936-L22**.** Figure 1 illustrates the test stand sampling location of the aerosol measurement instrumentation. A more complete description of the determination of upstream particle size distributions and particle concentrations can be found in Alderman, et.al. [(4)]

A TSI Model 3321 aerodynamic particle sizer (APS) and Dekati electrical low pressure impactor (ELPI) were used to provide measures of aerosol challenge mass mean diameter (MMD) and as a means of verifying, in real time, that mass concentration levels remain essentially constant throughout the duration of testing. Total particle concentrations downstream of the test filter were measured using a TSI Model 3010 condensation particle counter (CPC). The PSD and concentration of aerosol passing through the filter were measured with a Particle Measuring Systems Model 0710 micro-laser particle counter (LPC).

Filters in this study were challenged both with and without passing the aerosol challenge stream through a cyclone with an aerodynamic cut-point diameter of 3 μm, which allowed testing at two distinct aerosol mass concentrations. For completeness, data collected with and without use of the cyclone will be indicated as such and should be considered redundant measures of filter efficiency and MPPS.

Statistics describing the KCl aerosol challenge for the tests are provided in Table 1 with and without installation of the cyclone.

Table 1. Particle Size Statistics describing the KCl challenge aerosol particle size distributions used in this study with and without the 3000 nm cut point cyclone installed.

	With Cyclone	**Without Cyclone**
CMD	185	175
GSD	2.2	2.3
MMD	1000	3000
N	1.3e5	2.0e5

Individual filters were loaded from initial, clean media dP that varied as a function of media velocity to a final differential pressure of 6 in. w.c. Media velocities included in the test series ranged from 4 to approximately 8 fpm. One filter was loaded with the cyclone in place and one without the cyclone in place. Aerosol output from the generator remained virtually constant during the range of media velocities tested. This resulted in variability of the upstream aerosol concentration and mass loading rate as the media velocity (volumetric flow rate of the test stand) increased. Table 2 provides the test conditions for each filter in the study.

Table 2. Test stand volumetric flow rate and average aerosol challenge mass concentration for the media velocity conditions encountered in this study.

MFR[A]	M.V. (cm/s)	Flow Rate (m^3/min)	Aerosol (mg/m^3)
A-Y	2.5	8.1	19.5
A-Y	3.2	10.1	13.9
A-Y	3.8	12.1	11.5
A-N	2.0	6.5	205.4
A-N	2.5	8.1	158.3
A-N	3.0	9.7	129.3
A-N	3.8	12.1	84.1
B-Y	2.5	7.1	20.2
B-Y	3.0	8.5	9.4
B-Y	3.8	10.6	14.2
B-Y	4.5	12.4	10.5
B-N	2.0	5.7	176.7
B-N	2.5	7.1	139.3
B-N	3.0	8.5	142.6
B-N	3.8	10.6	130.3
B-N	4.5	12.4	102.4

[A]Y denotes with cyclone, N denotes cyclone not used

Data Analysis

Filter efficiency measurements reported in this manuscript were calculated from upstream SMPS measurements and downstream CPC measurements. Filter efficiency measurements, by particle count, are expressed as percent filter efficiency, and were calculated according to the following equation:

$$\%\,FilterEfficiency = (\frac{N_{up} - N_{down}}{N_{up}})x100$$

where N_{up} and N_{down} indicate particle counts upstream and downstream of the filter, respectively.

Deriving MPPS values directly via ratios of the upstream and downstream PSDs acquired using the SMPS and LPC, respectively, was not convenient due to the limited number of particle size bins provided by the LPC. Therefore, MPPS values were determined by using the experimentally determined particle size distribution parameters (GMD, GSD, N) describing the nature of aerosol upstream and downstream of the test filter to construct representative lognormal upstream and downstream PSDs of equivalent bin numbers and bin widths. An example illustrating this is given in Figure 3, which shows the initial upstream and downstream PSDs generated from data collected using a MFR-B filter at 3.8 cm/s, with cyclone. Note that particle concentration units are given as percent of total. A data point was generated in 10 nm intervals in the MPPS region, thus the ratio of downstream to upstream particle counts provided the penetration at a given particle size within ± 5 nm.

Results

Data collected during filter testing were used to calculate filter efficiency, MPPS, and downstream values of the GMD and GSD. Measurements recorded during the first five minutes of testing of a new filter were used to compute measures of static filter performance. Continuous up and downstream measurements were made for the full time period of testing each filter. These values were used to compute equivalent performance values to describe the dynamic trends in the loading process of each filter. Lifetime filter performance measurements were made up to the point at which the filter ΔP increased to 6 in. w.c.

Figure 2 provides a comparison of up and downstream particle size distributions for a selected filter. This plot shows the relatively mono-disperse particle size distribution with inclusion of the most penetrating particle size.

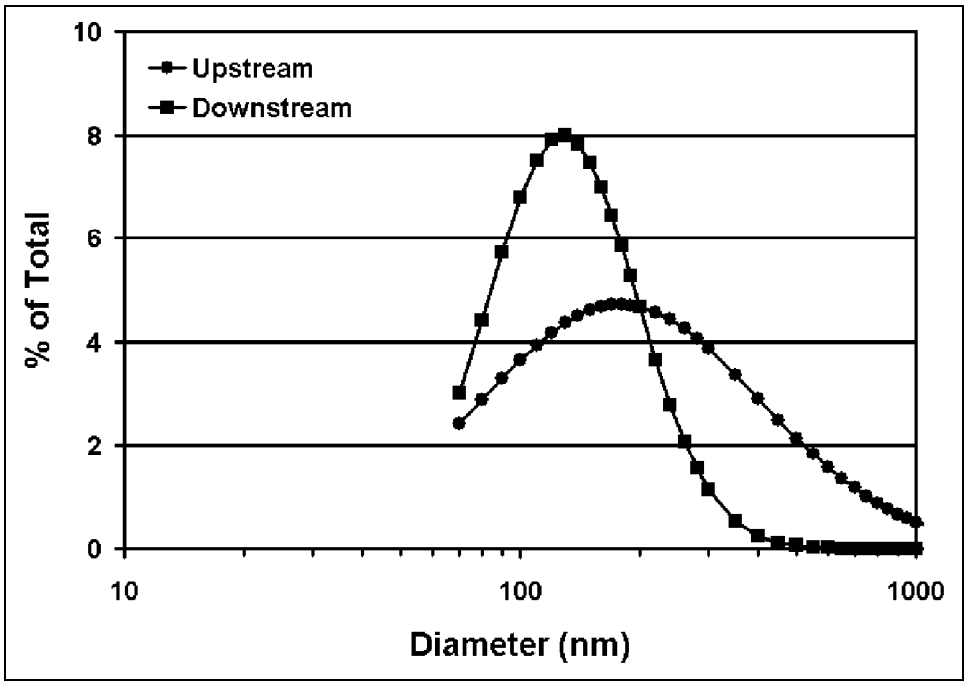

Figure 2. Initial Upstream and Downstream PSDs Generated from Data Collected using a MFR-B Filter at 3.8 cm/s with Cyclone

Table 3 contains a compilation of the initial filtering efficiency, most penetrating particle size, and geometric median diameter for each filter tested. Of this set of values, two filters showed abnormally large MPPS values of 190 nm. Each of these filters had been performance tested by the manufacturer using DOP and had filtering efficiencies sufficient to meet AG-1 requirements. However, testing the filters with a solid aerosol with the mode of the particle size distribution near the MPPS, especially at higher media velocities, revealed the presence of one or more pin holes that skewed the downstream PSD because of the very low downstream particle concentration. This is more an indication of the sensitivity of the testing and detection methods employed than the performance of the units as qualified HEPA filters.

In general, filter efficiency decreases with increasing media velocity. However, variability between individual filters also plays a significant role in filter efficiency. Manufacturer (MFR-A) DOP testing demonstrated a wide range of penetration values spanning 0.0100-0.0004 % (99.99000-99.99996 % filter efficiency). Not surprisingly, the filters showing the most significant deviation relative to other test filters at equivalent media velocity were the MFR-A filters challenged at 2.0 and 3.0 cm/s (no cyclone); filters with the highest manufacturer DOP penetration ratings of 0.0070 and 0.0100, respectively. Although MFR-B filters were not DOP tested, that data clearly indicate that 0.3 μm DOP efficiency would have been substantially better than 99.97 % for all filters tested.

TABLE 3. Initial percent filter efficiency (by count), most penetrating particle size, and count geometric mean diameter of aerosol penetrating the test filters. All values were averaged over the first five minutes of filter evaluation.

MFR[A]	M.V. (cm/s)	% F.E.	MPPS (nm)	GMD (nm)
A-Y	2.0	99.999	130	143
A-Y	2.5	99.998	130	142
A-Y	3.2	99.998	120	137
A-Y	3.8	99.997	110	126
A-N	2.0	99.991	190	188
A-N	2.5	99.999	130	133
A-N	3.0	99.977	190	181
A-N	3.8	99.998	120	125
B-Y	2.0	99.996	120	140
B-Y	2.5	99.995	120	136
B-Y	3.0	99.993	n/a	n/a
B-Y	3.8	99.995	110	128
B-Y	4.5	99.977	120	135
B-N	2.0	99.999	120	134
B-N	2.5	99.998	110	127
B-N	3.0	99.992	120	130
B-N	3.8	99.986	110	122
B-N	4.5	99.993	110	117

[A]Y denotes with cyclone, N denotes cyclone not used

Filter Performance over Filter Lifetime

Lifetime testing of each filter showed a rapid increase in filtering efficiency to virtually 100% for nearly all units tested. In all tests, initial downstream particle counts ranged as low as 0.9 particles/cm^3 to a high of 38 particles/cm^3. However, in all cases, after a ΔP gain of 250 Pa (1 in. w.c.) particle concentrations were typically less than 0.5 particle/cm^3 and often closer to 0.1 particles/cm^3. Figure 3 gives a graphical depiction of the performance of filters from the two manufacturers tested over the range of media velocities without the cyclone in place. Testing with the cyclone in place yielded equivalent patterns of increasing filtering efficiencies.

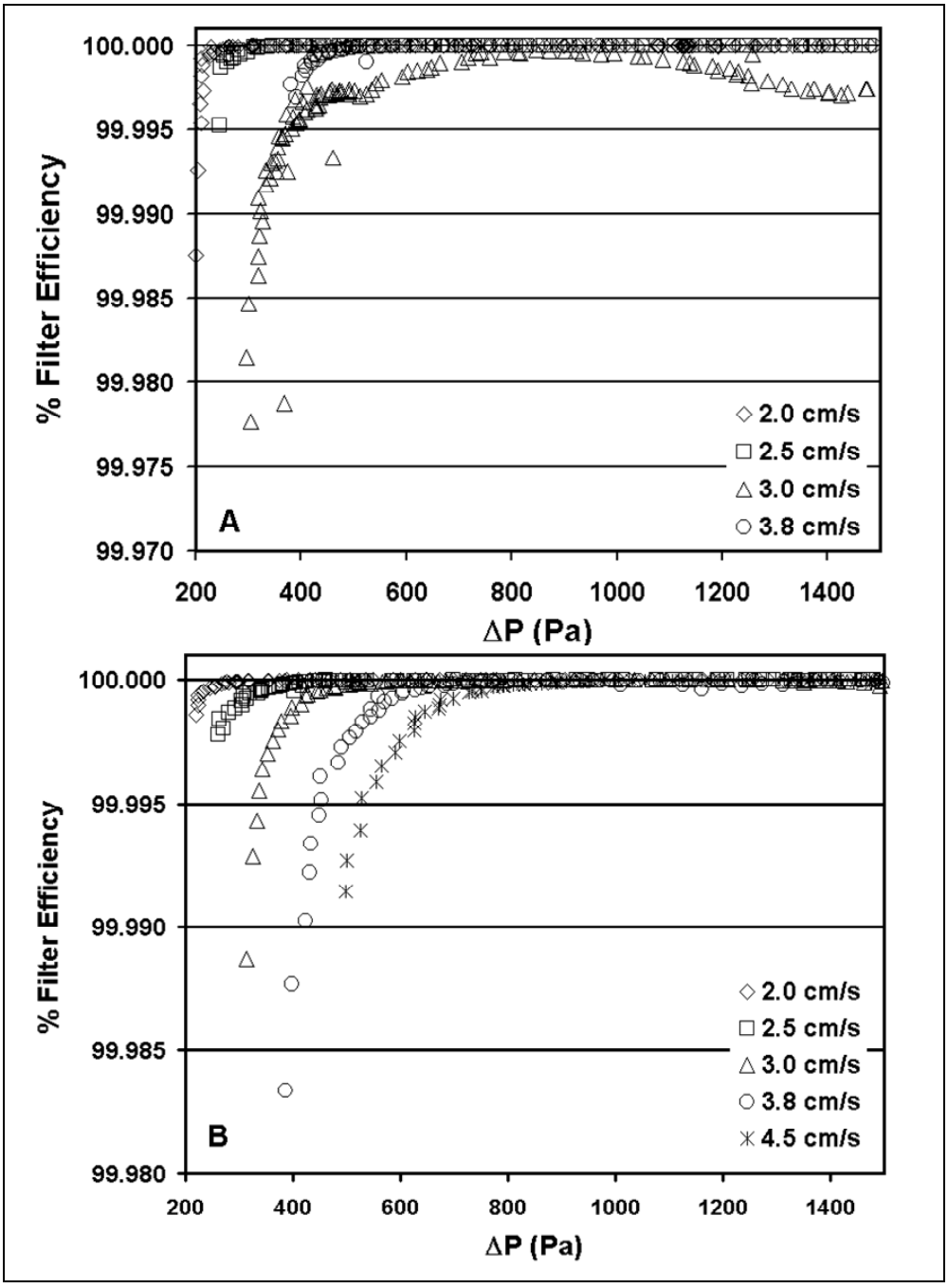

Figure 3. Particle Count Filter Efficiency for All Media Velocities Tested as a Function of ΔP for MFR-A and MFR-B Filters Loaded without Cyclone

Data in Table 3 demonstrates the how the measured GMD of the downstream particle size distribution closely approximates the MPPS of the filter. Figure 4 shows the correlation of downstream GMD and GSD for two media velocities as a function of increase in differential pressure across the filter.

The behavior observed at 2.5 cm/s is typical for 16 of the 18 filter evaluations presented in this study: as the filter loads, the GMD of the aerosol downstream of the filter decreases. At a 250 Pa increase in filter ΔP, the decrease was typically on the order of 10-15 nm. Beyond this point, downstream aerosol concentrations were sufficiently low as to not permit valid statistical analysis. Also evident in the data collected at 2.5 cm/s is a decrease in the GSD of the aerosol penetrating the filter. Here, the GSD decreased from 1.48 to 1.41. This behavior is also representative for the majority of filters tested.

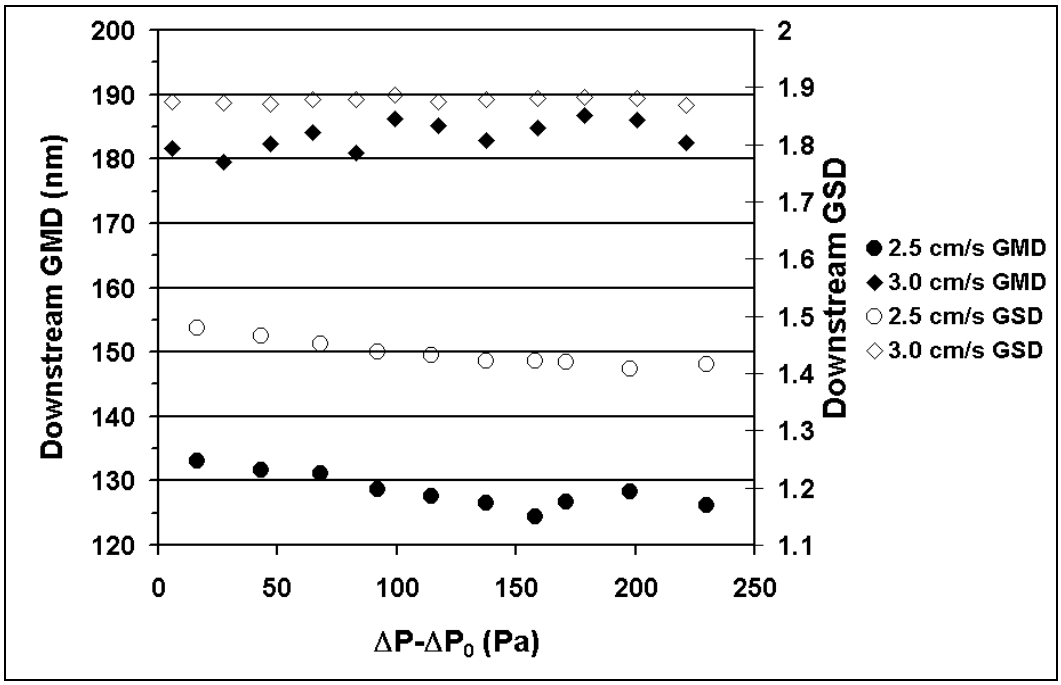

Figure 4. Changes in GMD and GSD of the Aerosol Stream Passing through a Test Filter

Contrasting the decrease in GMD and GSD typically observed with filter loading, the data shown in Figure 3 collected at 3.0 cm/s reveals no such decrease. Although data are shown only up to a 250 Pa (1. in. w.c.) increase in filter ΔP, these values remained essentially constant throughout the duration of testing. Only one other filter evaluation resulted in data showing significant deviation to that shown in Figure 6 for the 2.5 cm/s trial, which was the MFR-A filter evaluated at 2.0 cm/s with no cyclone. For this filter, the initial downstream GMD and GSD was initially high relative to other data set (188 nm and 1.85, respectively). At the start of filter loading the values remained constant up to an approximate 100 Pa increase in filter ΔP. Beyond that point, the GMD and GSD decayed to values observed for the majority of filters tested. Note that the two filters that did not follow the typical trends in GMD and GSD over the filter lifetime are the same two filters that had the highest manufacturer DOP penetration ratings.

Comparison of filter MPPS values and downstream GMDs at and below the current media velocity limit of 5 fpm with those at the higher media velocities of this study indicates only a marginal shift to smaller particle sizes. The initial MPPS for all filters evaluated in the 2.0-2.5 cm/s averaged 123 nm, with a GMD downstream of the filter of 136 nm. For the media velocity range of 3.0-4.5 cm/s, the initial MPPS was 115 nm, with a GMD of 128 nm. Excluded from these averages were the two filters with initial MPPS values of 190 nm.

The marginal shift of initial MPPS values to smaller particles sizes with increasing media velocity is seemingly negligible with respect to increased ultrafine particle emissions. Using the GMD of the aerosol downstream of test filters as a surrogate for MPPS, it was demonstrated that as the filter loads, the MPPS decreases. The extent of this decrease was on the order of 10-15 nm up to the point that the filter ΔP had increased 250 Pa (1 in. w.c.). Thus, this continued decrease in MPPS/GMD with filter loading is likely not significant and this is supported further when considering the extremely low particle concentration downstream of a HEPA filter by that point in the filter lifetime.

None of the test conditions of this study produced filtering efficiencies below 99.977% and all but 3 of 18 filter evaluations demonstrated filter efficiencies > 99.99%. This suggests current qualification requirements for AG-1 filters produce units that are capable of proper function at media velocities to at least 7 fpm. Evidence provided by this study is not conclusive because of the small number of units tested. Additional testing is needed to provide sufficient statistical confidence in the findings.

Variation Between ACFM and SCFM Values

The findings discussed above can be used to put into perspective the differences in filter performance when there is a difference between the target and real media velocity. The potential for this discrepancy between intended and real media velocity can arise from mathematical uncertainty associated with converting mass flow data to volumetric flow values. More specifically, equations relating flow through a filter media to mass flow measurements are not explicit. However, variability of gas composition resulting from variation in process chemistry or conditions may induce a much greater source of error.

There are three major categories of conditions that cause deviation between the actual and standard values of volumetric flow: variation of gas pressures, gas composition, and temperature. Conversion of temperature and pressure effects is relatively straightforward and the most frequently addressed because these parameters are monitored and easily incorporated into control software. Additionally, deviation of operating conditions from standard temperature and pressure are typically relatively constant. However, significant fluctuations can occur for gas composition episodically or over time and gas composition is not as frequently monitored. This is particularly true for relative humidity.

Gas density changes due to changes in composition may result from variations in reaction products, but it should be recognized that relative humidity changes as a

function of gas temperature offers significant potential for variability. To gain a better sense of the magnitude of the effect of RH as a function of temperature, a series of calculations was performed to generate curves correlating actual and standard volumetric flows as a function of gas pressure for.

A series of curves was generated showing the effect of RH on scfm to acfm conversions as a function of gas pressure for a given temperature. Three sets of curves are given: 80, 150, and 200 degrees F. Figure 5 provides a family of curves that show the variation of acfm values for a 250 scfm air flow as a function of gas pressure at 80 degrees F. Individual curves are given for 10 through 80% RH. At 80 F the amount of water in air to produce 20% RH is small and produces little error. The 10% RH curve in this figure can be used to represent the correlation between SCFM and ACFM for temperature and pressure effects. If the mass to volume conversion is accomplished including only pressure and temperature, the differential between SCFM and ACFM values will basically equate to the difference between the 10% RH line and corresponding values on the appropriate RH line. The error introduced by failing to take variation of RH into account at 80 F is minimal.

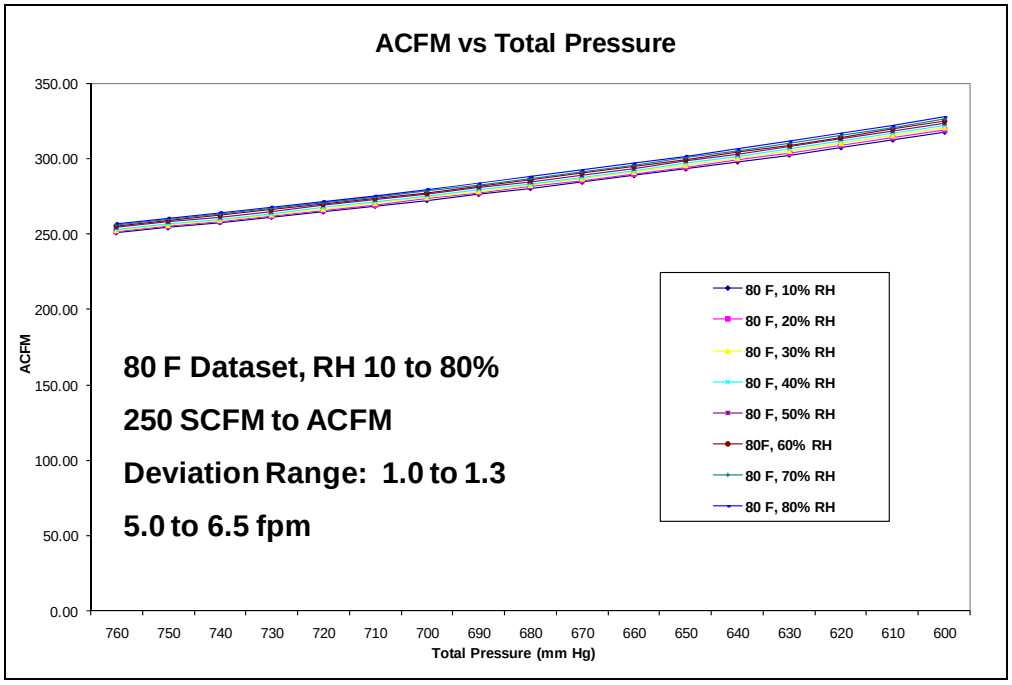

Figure 5. Plot of ACFM values equivalent to 250 SCFM at 80 F for Relative Humidity values ranging from 10 to 80%.

For very low RH values at 80 degrees F the SCFM to ACFM difference is neglible at 760 mm Hg. At 80% RH and 600 mm Hg the difference between SCFM and ACFM is on the order of 30%. If a filtration system is controlled using SCFM values and

neglects RH, then a 250 SCFM air flow at 600 mm Hg, 80% RH, and 80 degrees F would equate to 328 ACFM. This flow rate will produce an actual media velocity of 6.5 fpm. Based on the studies discussed in this paper a 6.5 fpm media velocity would have a minimal impact on most penetrating particle size and filtering efficiency. While the life time of the filter may be limited by this lack of control, it is not likely that the system would fail to function properly.

Equivalent sets of curves are presented for 150 and 200 degrees F in Figures 6 and 7, respectively. At these elevated temperatures it becomes increasing important to monitor for RH and correct gas densities in the mass to volume conversion calculations in order to ensure proper control of air flows. Within the pressure and humidity ranges represented in Figure 6, it can be seen that media velocities exceeding those tested in the above section may be achieved. Such elevated media velocities (exceeding 8 fpm) likely approach the point at which flows no longer follow Darcy's Law.

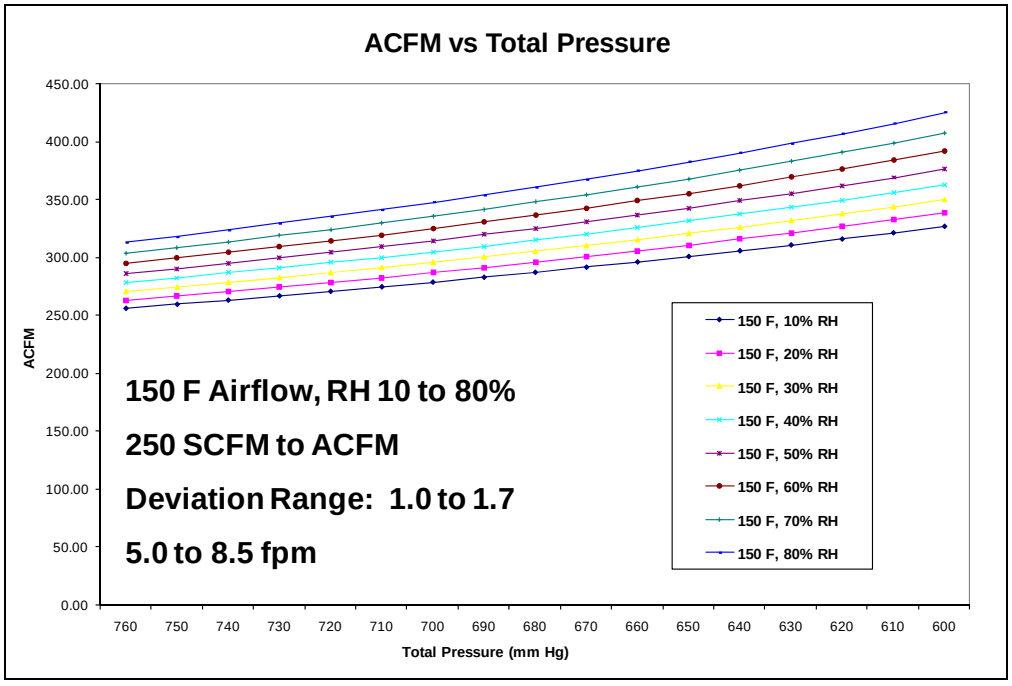

Figure 6. Plot of ACFM values equivalent to 250 SCFM at 150 F for Relative Humidity values ranging from 10 to 80%.

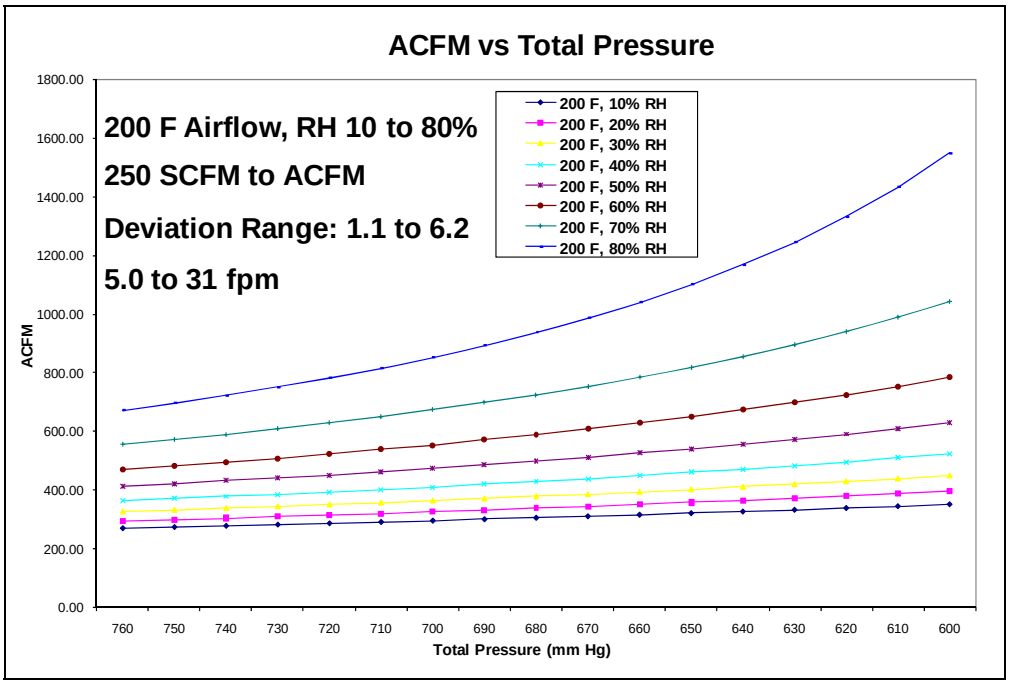

Figure 7. Plot of ACFM values equivalent to 250 SCFM at 200 F for Relative Humidity values ranging from 10 to 80%.

The effects of neglecting to take variation of RH into account as temperatures approach 200 degrees F become exaggerated relative to lower temperatures. While these theoretical curves are significant to point out the sensitivity of mass to volume calculations used to accomplish control of air flow systems, the actual flow rates that would be represented by higher RH curves in Figure 7 would likely produce significant elevated differential pressures for the filter experiencing such effects.

It is important to ensure accurate assessment of factors other than temperature and pressure that can influence gas densities in order to retain proper air flows during periods of process variability. This implies the need for thorough understanding of the ranges of variation and the identity of species in the air flows that may influence changes in gas density. For example, variation in CO concentrations may not have a large impact since its molecular weight is so close to that of air. However, variation in CO_2 concentrations, if large enough, can have a significant impact because of its higher molecular weight. The same is true for higher oxidation states of nitrogen, sulfur, and other oxides common to off gases from waste treatment activities.

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