ACFM versus SCFM for ASME AG-1 HEPA Filters

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Abstract

This paper evaluates the use of standard cubic feet per minute (SCFM) in ASME AG-1, Section FC. A very simple HEPA filtration system is used to evaluate filter performance at two different environmental conditions. Flow through a HEPA filter is characterized in terms of inertial, viscous laminar, slip, and turbulent flow. It is stated that flow through a HEPA filter is characterized predominantly by viscous laminar flow where flow rate in actual cubic feet per minute (ACFM) is dependent on viscosity and independent of the gas density, and that the affect of the inertial component is relatively small compared to the viscous laminar flow component. It is stated that the air density dependent inertial component is what causes the slight variation in volume flow rate (ACFM) for various atmospheric pressures.

Based on work by Douglas Fain, it is shown that the variation in volume flow rate (ACFM) between sea level and Denver is approximately 20 ACFM, and that better precision can be achieved if the measured pressure drop were corrected to a standard condition. However, it is stated, to correct performance data to a standard condition would require that a standard correction be made for the inertial, viscous laminar, and slip pressure drop components. In the absence of theoretical and experimental information to substantiate the use of standard conditions for HEPA filter pressure drop and efficiency data, it is concluded that using complex expressions to make these corrections is atypical. Since the equations for correcting all components of pressure drop to standard conditions are not readily available, and since large errors in pressure drop and efficiency would result without the correct equations, this paper recommends revising the tables in ASME AG-1, Section FC, to be based on ACFM.

Introduction

SCFM is a volumetric flow rate corrected to standard density conditions. SCFM is volumetric flow rate at a “standardized” pressure, temperature, and relative humidity. The “standard” ambient conditions are defined by 14.7 psig atmospheric pressure, some temperature (e.g., 68°F) depending on the "standard" used, and some relative humidity (e.g., 36%, 0%) depending on the "standard" used.

ACFM is the volume of gas flowing anywhere in a system independent of its density. If the system were moving air at exactly the "standard" condition, then ACFM would equal SCFM. Unfortunately, this usually is not the case as the most important change between these two definitions is the pressure. To move air a positive pressure or a vacuum must be created. When positive pressure is applied to a standard cubic foot of air, it gets smaller. When a vacuum is applied to a standard cubic foot of air, it expands. The volume of air after it is pressurized or rarified is referred to as its “actual” volume.

CFM is an often confusing term because it has no single definition that applies to all instances. In the most basic sense, CFM means cubic feet per minute. Sounds simple enough right? Unfortunately, air is a compressible gas. To further confuse the issue, a centrifugal fan is a constant CFM device or a constant volume device. This means that, provided the fan speed remains constant, a centrifugal fan will pump a constant volume of air. This is not the same as pumping a constant mass of air. Again, the fan will pump the same volume, though not mass, at any other air density. This means that the air velocity in a system is the same even though mass flow rate through the fan is not.

Centrifugal Fan Ratings

Ratings found in centrifugal fan performance tables and curves are based on standard air. Fan manufacturers define standard air as clean, dry air with a density of 0.075 pounds mass per cubic foot, with the barometric pressure at sea level of 29.92 inches of mercury and a temperature of 70°F. Selecting a centrifugal fan to operate at conditions other than standard air requires adjustment to both static pressure and brake horsepower. The volume of air will not be affected in a given system because a fan will move the same amount of air regardless of the air density.

If a centrifugal fan is to operate at a non-standard density, then corrections must be made to static pressure and brake horsepower. At higher than standard elevation (sea level) and higher than standard temperature (70°F), air density is lower than standard density (0.075 pounds per cubic foot). Centrifugal fans that are specified for continuous operation at higher temperatures need to be selected taking into account air density corrections. Again, a centrifugal fan is a constant volume device that will move the same amount of air at two different temperatures.

If, for example, a centrifugal fan moves 1,000 CFM at 70ºF it will also move 1,000 CFM at 200ºF. Centrifugal fan air volume delivered by the centrifugal fan is not affected by density. However, since the 200°F air weighs much less than the 70ºF air, the centrifugal fan will create less static pressure and will require less brake horsepower. Selecting a centrifugal fan to operate at conditions other than standard air requires adjustment to both static pressure and brake horsepower. When a centrifugal fan is specified for a given CFM and static pressure at conditions other than standard, an air density correction factor must be applied to select the proper size fan to meet the new condition. Since 200°F air weighs only 25% of 70°F air, the centrifugal fan will create less pressure. To get the actual pressure required at 200°F, the designer would have to multiply the pressure at standard conditions by an air density correction factor of 1.25 to get the system to operate correctly. To get the actual horsepower at 200°F, the designer would have to divide the brake horsepower at standard conditions by the air density correction factor.

The centrifugal fan performance tables provide the fan RPM and brake horsepower requirements for the given CFM and static pressure at standard air density (0.075 pounds per cubic foot). When the centrifugal fan performance is not at standard conditions, the performance must be converted to standard conditions before entering the performance tables. Centrifugal fans rated by the Air Movement and Control Association (AMCA) are tested in laboratories with test setups that simulate installations that are typical for that type of fan. Usually they are tested and rated as one of four standard installation types as designated in AMCA Standard 210.

AMCA Standard 210 defines uniform methods for conducting laboratory tests on housed fans to determine airflow rate, pressure, power and efficiency, at a given speed of rotation. The purpose of AMCA Standard 210 is to define exact procedures and conditions of fan testing so that ratings provided by various manufacturers are on the same basis and may be compared. For this reason, fans must be rated in SCFM.

ASME AG-1 HEPA Filter Ratings

The HEPA filter performance table found in ASME AG-1, Section FC, is based on SCFM. Therefore, this ASME AG-1 performance table must be based on an air density of 0.075 pounds mass per cubic foot, barometric pressure at sea level of 29.92 inches of mercury, and a temperature of 70°F. ASME AG-1 also requires two other performance parameters associated with the given SCFM shown in the Section FC performance table. These two other performance parameters are static pressure and percent penetration. The static pressure and percent penetration in ASME AG-1 must also be based on SCFM. In order for the HEPA filter manufacturer to qualify a HEPA filter to the requirements of ASME AG-1, Section FC, the actual environmental conditions during the qualification of a HEPA filter must be converted from actual conditions back to standard conditions to confirm that the ASME AG-1 performance requirements are achieved. If a HEPA filter is tested at a non-standard density, then corrections must be made to flow rate, static pressure, and percent penetration in order for these values to be used in the ASME AG-1, Section FC performance table, because this table is based on SCFM.

To understand how elevation and temperature affect flow rate and HEPA filter performance, consider a very simple HEPA filtration system to analyze the performance of a 24-inch by 24-inch ASME AG-1 HEPA filter operating at two different elevations and temperatures. Assume the HEPA filtration system includes a centrifugal fan, a 24-inch by 24-inch ASME AG-1 HEPA filter with 200 square feet of filter media area, and ductwork and fittings between the fan and filter. For this simple system, the HEPA filter velocity criterion governs the maximum system capacity because ASME AG-1-2003, Code of Nuclear Air and Gas Treatment, Article FC-4110 (b), requires a maximum media velocity of 5 feet per minute. The maximum allowable flow rate (CFM) for this system must be based on the following equation.

Q = Area x Velocity = (200 square feet) x (5 feet per minute) = 1,000 CFM

The volumetric flow rate for this system cannot exceed 1,000 CFM under any condition. This is a bounding condition because the amount of filter media area is constrained at 200 square feet and the 5 feet per minute maximum media velocity is constrained by ASME AG-1. Therefore, the maximum rated capacity of the centrifugal fan is 1,000 CFM. Assume that the system is initially installed at sea level and operates in a 70°F environment.

The system described above is shown in Figure 1. The maximum rated capacity of this HEPA filter at sea level would be 1,000 CFM. Since the system elevation is at sea level and all conditions are standard, the flow rate is 1,000 SCFM. In this special case, the standard conditions equal the actual conditions, so the flow rate can also be expressed as 1,000 ACFM or 1,000 SCFM. The mass flow rate for this system is 75 pounds mass per minute as shown in Figure 1. Since the HEPA filter shown in Figure 1 is being tested at standard density, corrections to flow rate, static pressure, and percent penetration are not required. If the HEPA filter shown in Figure 1 passes the ASME AG-1 static pressure and percent penetration requirements, then it would be ASME AG-1 qualified.

Now take the system shown in Figure 1 and move it to 5,000 feet above sea level. When we get to 5,000 feet, assume the air temperature is 100°F. We are no longer at standard conditions because we are no longer at sea level, the air temperature is no longer 70°F, the air pressure is no longer 14.7 psi, and the air density is no longer 0.075 pounds per cubic foot. The flow rate for this system may no longer be expressed in SCFM.

The air density is 0.0587 pounds per cubic foot at 5,000 feet above sea level when the air temperature is 100°F. What about the flow rate? What will be the flow rate at these actual conditions when we turn on the centrifugal fan that we selected above? To answer the above questions correctly, it must be known that a cubic foot of air has a constant volume regardless of temperature or elevation (i.e., regardless of air density), and it must be known that a centrifugal fan is a constant volume device. When the fan in Figure 2 is turned on, the actual volumetric flow rate will be 1,000 ACFM and the mass flow rate will be 58.7 pounds mass per minute.

Similar to Figure 1, the maximum rated capacity of the HEPA filter at 5,000 feet above sea level is 1,000 ACFM as shown in Figure 2. The change in elevation and temperature did not impact the ASME AG-1 velocity requirement of the HEPA filter. The velocity through the filter media in Figure 1 is the same as the velocity through the filter media in Figure 2. The discussion to this point shows that change in elevation and temperature does not impact the velocity through the HEPA filter because a cubic foot of air at sea level equals a cubic foot of air at 5,000 feet above sea level.

Compare the mass flow rate in Figure 1 to the mass flow rate in Figure 2. Obviously, the HEPA filter operated at 5,000 feet above sea level would be operating at a lower mass flow rate because the density of air at 5,000 feet is less than the density of air at sea level. How would a pressure drop test for the HEPA filter in Figure 1 compare to a pressure drop test for the HEPA filter in Figure 2? Would the ASME AG-1 qualification tests for penetration and airflow resistance yield different results depending on the elevation where the HEPA filter was tested? Douglas E. Fain evaluated these very questions in 1986 in his paper titled, "Standards for Pressure Drop Testing of Filters as Applied to HEPA Filters."

The Fain paper was presented at a symposium sponsored by ASTM Committee F-21 on Filtration and sponsored by The American Program Committee of the Filtration Society in Philadelphia, Pennsylvania on October 20-22, 1986. This paper is based on a study of pressure drop testing performed at three different DOE filter test facilities, including Oak Ridge, Rocky Flats, and Hanford. Note that Oak Ridge, Tennessee is located at 910 feet above sea level. Rocky Flats, Colorado is located at about 6,000 feet above sea level. Hanford, Washington is located at about 700 feet above sea level.

Fain performed both pressure drop and filter efficiency tests to assure that HEPA filters tested at these facilities were meeting nuclear industry specifications. The Fain paper shows that serious errors in pressure drop testing can occur if mass flow rate is used without correcting the pressure drop to a standard condition. When mass flow rate is used for the tests and no correction is made for ambient measurement conditions, variations in pressure drop of as much as 50% could be observed at different testing locations. In regard to percent penetration testing Fain states, "Such an error will not occur in the case of performance or characterization testing..." Therefore, the percent penetration testing component is addressed by normal operating procedures for acquiring penetration data.

Regarding airflow resistance testing, Fain states, "When pressure drop only is desired, a simple solution is to use a specified volume flow rate [ACFM] for testing. Specified volume flow rates [ACFM] will generally result in an accuracy of 5% or better regardless of where the filter is tested." Fain states, "A better solution is to correct the measured pressure drop to some specified conditions." Fain is implying that correcting pressure drop to standard conditions is a better solution. However, Fain states, "In this case the correction will be smaller if volume flow rates [ACFM] are used for the test measurements, but either volume or mass flow rates can be used for the tests. The correction can be made just for variations in ambient pressure and temperature or can also include corrections for know filter performance characteristics. A precision of 1% or better can be achieved with reasonable care and quality control." However, the Fain paper does not provide the correction factors.

Fain describes four flow regimes in his paper, including inertial, viscous laminar, slip, and turbulent flow. Fain states, "In a filter application, the predominate flow mode should be viscous laminar flow, with various amounts of slip and inertial flow." He states that tests performed at different locations may have different results because the different flow regimes have different dependencies on ambient pressure and temperature. Regarding the use of ACFM, Fain writes, "The volume flow rate [ACFM] is... a measure of the gas velocity averaged over a cross section normal to the flow path. With viscous laminar flow, the volume flow [ACFM] is independent of the gas density. Volume flow [ACFM] is simply proportional to the ratio of the pressure drop to the gas viscosity."

Since pressure drop is subject to flow rate, the ASME AG-1 filter certification parameters (i.e., pressure drop and penetration) need to be part of the discussion. Because of numerous experimental studies, it is now well established that for low speed Newtonian flow through fibrous filters, pressure drop follows Darcy's law in being proportional to the fluid viscosity, the gas velocity, and the filter thickness. It is also well established that flow through a HEPA filter is characterized predominantly by viscous laminar flow, but also includes inertial and slip flow components. With viscous laminar flow, the volume flow rate in ACFM is independent of the gas density. The equation for pressure drop for viscous laminar flow using volume flow rate (ACFM) is shown in the equation below.

$$\Delta \mathbf{P} = (\mathbf{K}_v) \times (\mu) \times (\mathbf{Q})$$

Where:

ΔP = HEPA Filter Pressure Drop
K_v = Constant Related to Viscous Laminar Flow
μ = Viscosity
Q = Actual Cubic Feet per Minute (ACFM)

In the equation above, note that HEPA filter pressure drop is independent of gas density. Therefore, with regard to pressure drop filter qualification, to infer that air density is a dominant factor is not consistent with the governing equation. In the equation above, note that pressure drop is directly proportional to gas viscosity. The concern with regard to pressure drop filter qualification at different elevations then shifts to the sensitivity of gas viscosity to barometric pressure. In other words, how does the gas viscosity between sea level and Denver, for example, impact filter qualification?

Viscosity of gases is primarily a temperature function and essentially independent of pressure. The impact of temperature is not a problem because filter pressure drop testing by the filter manufacturer takes place in areas maintained at constant temperature by air-conditioning. Since gas viscosity is essentially independent of pressure, the filter certification by pressure drop testing is essentially not impacted. If pressure drop through the filter were completely characterized by viscous laminar flow, then the volume flow rate in ACFM would show no variation for any atmospheric pressure. However, it must be kept in mind that flow through a HEPA filter is characterized by inertial, viscous laminar, slip, and turbulent flow. The turbulent flow component is not a factor because flow through a HEPA filters has a low Reynolds number. The inertial component is relatively small compared to the viscous laminar flow component. The inertial component of pressure drop is dependent on air density as can be demonstrated by the Bernoulli equation. It is this air density dependent inertial component that causes a slight variation in volume flow rate (ACFM) for various atmospheric pressures. This variation in volume flow rate (ACFM) is demonstrated in Figure 3 from the Fain paper.

Consider the "Volume Flow 77°F" curve shown in Figure 3 from the Fain paper. This temperature (i.e., 77°F) is the ambient air temperature at which most HEPA filters will be qualified for pressure drop. The variation in volume flow rate (ACFM) between 14.7 psi (i.e., sea level) and 12.3 psi (i.e., Denver) is approximately 20 ACFM. This variation in volume flow rate is less than 2% of the average volume flow rate between 14.7 psi and 12.3 psi. This demonstrated finding is the basis for Fain stating, "Specified volume flow rates [ACFM] will generally result in an accuracy of 5% or better regardless of where the filter is tested, so long as it is tested at ambient atmospheric pressure."

Fain further states, "A better solution is to correct the measured pressure drop to some specified condition. In this case, the correction will be smaller if volume flow rates [ACFM] are used for the test measurements, but either volume or mass flow rates can be used for the tests. The correction can be made just for variations in ambient pressure and temperature or can also include corrections for known filter performance characteristics. A precision of 1% or better can be achieved with reasonable care and quality control." Fain later adds, "For best results the pressure drop should be corrected to some standard temperature such as 25°C. In many cases the correction will be small enough to be ignored. The correction needed is relatively simple. The measured pressure drop will be multiplied by the ratio of the viscosity of the test gas at the standard temperature to the viscosity of the gas at the test ambient temperature. For more accuracy, specific filter characteristic correction for the contribution from inertial and slip flow may also be made."

The pressure drop correction indicated by Fain in the paragraph above is only for the component of pressure drop associated with viscous laminar flow. The inertial and slip components of pressure drop have been ignored completely. Again, the Fain paper does not provide these correction factors. If the filter manufacturer were to make a standard correction to a measured pressure drop, then a standard correction would have to be made to each component contributing to the pressure drop. That is to say, a correction would be needed for the inertial, viscous laminar, and slip pressure drop components. Presumably the HEPA filter manufacturer is making these corrections because the ASME AG-1 performance tables require it.

Werner Bergman, Ph.D., the Lawrence Livermore National Laboratory author of numerous papers on HEPA filtration states that the correction factors for HEPA filter pressure drop are much more complex than the ideal gas law because of the predominant viscous term and the subordinate inertial term in the pressure drop equation. If the flow rate, pressure drop and efficiency are to be corrected to standard conditions, then it is important to provide the equations for performing the corrections.

Bergman asks, “What are the corresponding equations for correcting pressure drop and efficiency? It is not correct to use the same correction factors for the pressure drop and efficiency. It is also not correct to assume the pressure drop and efficiency will be the correct values when only the flow rate is corrected. If the equations or correction tables are provided, then I see no problem with using SCFM. However, if these are not provided then large errors in pressure drop and efficiency are obtained in the process.”

To appreciate the complexity of correcting pressure drop to standard conditions, see equations 2, 3, and 4b in the Fain paper. Each equation for inertial, viscous laminar, and slip flow would each have to be corrected to standard conditions. Fain writes, “It should be noted that the pressure drop is affected differently by variations in the flow, ambient pressure, and temperature for each of the above types of flow. When all three types occur simultaneously, non-linear behavior occurs which might even appear to be random error in the measurement. A rather comprehensive set of flow measurements must be made in order to determine the relative magnitude of the effect on pressure drop of these various types of flow.”

With regard to correcting penetration to standard conditions, Werner Bergman adds, "Fain did not discuss the effect of ACFM versus SCFM in terms of the filter penetration. Here too, the effect must be examined in terms of the specific physical terms that make up filter penetration. For HEPA filters, the particle penetration is determined primarily by the diffusional capture (Brownian motion) and interception (air streamlines past the filter fibers). The diffusional capture is strongly dependent on the air velocity through the media, while the interception term is independent of the air velocity. The diffusional capture is also dependent on the mean free path of the air molecules, which is related to the gas density (or atmospheric pressure). As the pressure decreases at the same air velocity, the particles will be less efficiently trapped. Again, as in the pressure drop, we have two terms that behave differently with changes in pressure (or temperature) and thus do not have a simple PVT correction term. As before, it is possible to develop equations to correct the measured penetration for the changes in ambient conditions. However, since the ACFM measures the actual velocity of the air and hence controls the major portion of the penetration, using ACFM with no corrections will yield smaller errors than using SCFM with no corrections." Correcting to a standard condition would improve the accuracy of the penetration measurements. “Unfortunately,” as Bergman points out, “the corrections are quite complex and are not the standard PVT corrections."

Ronald Scripsick, Ph.D., the Los Alamos National Laboratory author of numerous papers on HEPA filtration states, “Specifications for HEPA filter media and HEPA filters depend on the velocity of gas through the filter media. This velocity is directly related to the volumetric flow rate divided by the area of the media. Changing of this velocity changes the penetration through the filter from 99.97% and the size of maximum penetration. Specifying filter flow rate in SCFM would require different flow rate specification for different barometric pressure. Specification in terms of ACFM allows for specification of one flow independent of barometric pressure and assures a single gas velocity through the media.”

Conclusion and Recommendation

HEPA filter performance has been studied for many years; some gaps remain in the knowledge base. How could it be possible that the equations for correcting pressure drop and efficiency for HEPA filters to standard conditions is one such subject? A review of the nuclear air cleaning literature reveals a predominant use of flow rate in units of cubic feet per minute (CFM). The pervasive use of CFM in the literature would seem to imply that the actual conditions were used as the basis for the published findings.

In the absence of theoretical and experimental information to substantiate the use of standard conditions for HEPA filter pressure drop and efficiency data, it can be concluded that using complex expressions to make this correction is atypical. This limitation seems to be overcome by basing HEPA filter pressure drop and efficiency on ACFM. This conclusion is supported by the Department of Energy who explicitly base HEPA filter certification on ACFM. Since the equations for correcting all components of pressure drop to standard conditions are not readily available, and since large errors in pressure drop and efficiency would result without the correct equations, the conservative approach would be to revise the tables in ASME AG-1, Section FC, to be based on ACFM.

References

Fain, D. E., *Standards for Pressure Drop Testing of Filters as Applied to HEPA Filter*,
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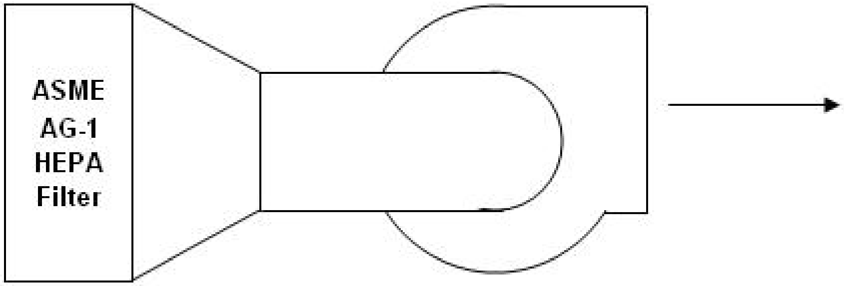
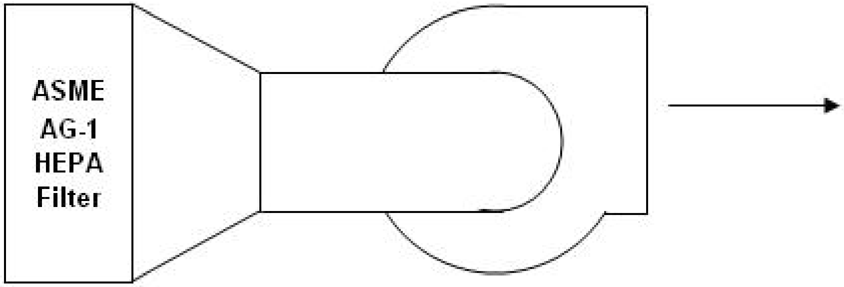
Filtration Society, Philadelphia, Pennsylvania, October 20-22, 1986.



Q = Actual Volumetric Flowrate = 1,000 ACFM
Elevation = Sea Level
Temperature = 70°F
ρ = Density = 0.075 LBm/FT^{3}
m = Mass Flow Rate = $\rho \times Q$ = 75 LBm/Minute

Figure 1



Q = Actual Volumetric Flowrate = 1,000 ACFM
Elevation = 5,000 Feet Above Sea Level
Temperature = 100°F
ρ = Density = 0.0587 LBm/FT^{3}
m = Mass Flow Rate = $\rho \times Q$ = 58.7 LBm/Minute

Figure 2

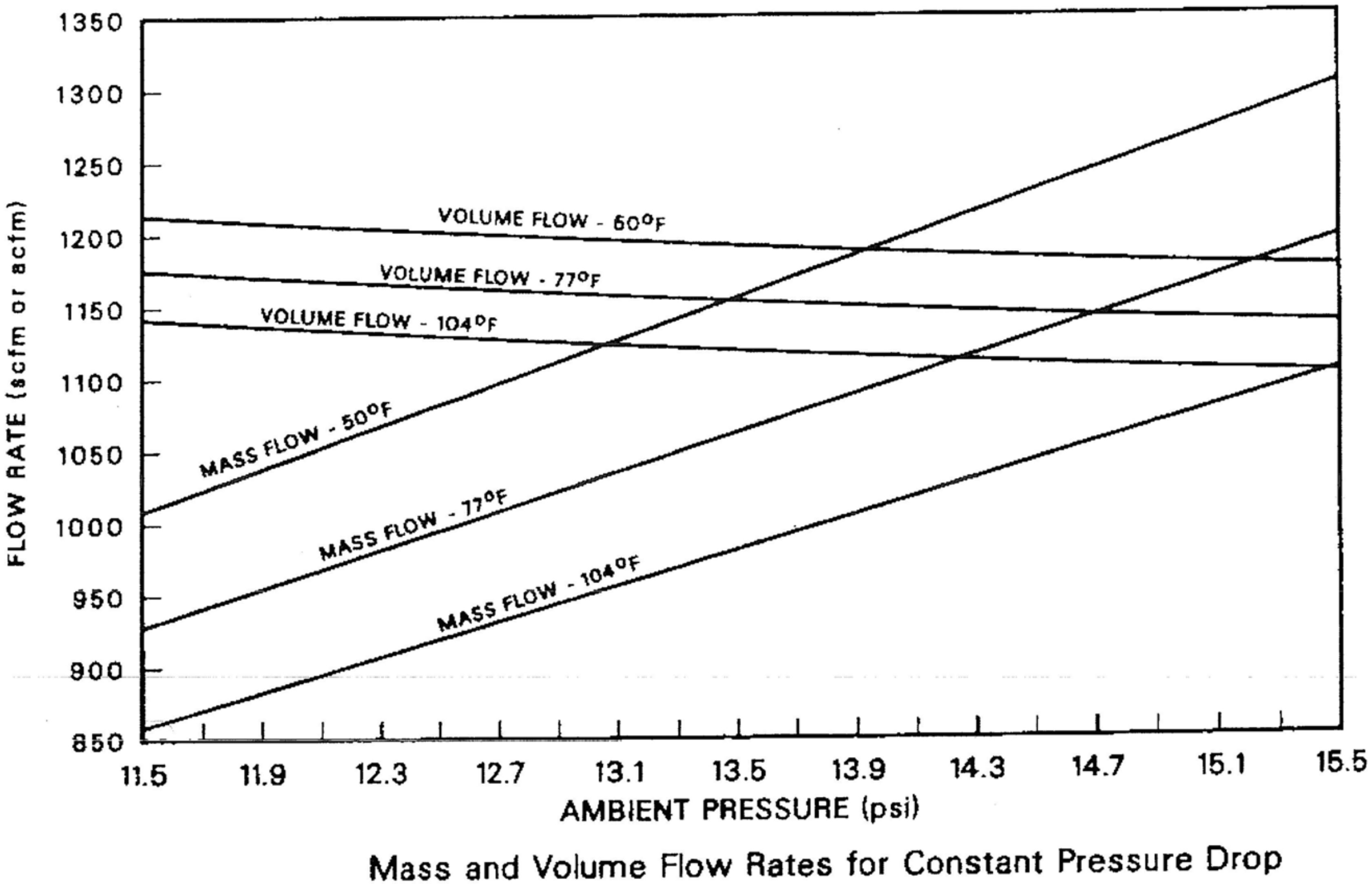


Figure 3

Source: Fain, D. E., Standards for Pressure Drop Testing of Filters as Applied to HEPA Filter, Figure 6, ASTM Committee F-21 on Filtration and the American Program Committee of the Filtration Society, Philadelphia, Pennsylvania, October 20-22, 1986.