Effect of Elevated Temperature and Humidity on Air Flow for HEPA Filter Testing

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ABSTRACT

Elevated temperature and humidity can greatly affect the high-efficiency particulate air (HEPA) filter performance. To properly evaluate and qualify HEPA filters at elevated conditions, it is critical to ensure that the airflow condition in test stands meets requirements from standards and field operations. Currently the Institute for Clean Energy Technology (ICET) at Mississippi State University (MSU) performs testing of prototype AG-1 Section FK 2000 cfm radial flow filters under elevated temperature and humidity conditions. This paper presents a method to determine the actual air flow rate based on measurements from differential pressure based flow meters (e.g., orifice and venturi meters), temperature, relative humidity measurements and findings from an experimental study on the elevated air flow conditions using a HEPA filter test stand at ICET.

INTRODUCTION

The importance of using actual volumetric air flow rate as opposed to standard volumetric air flow rate in HEPA filter testing has been discussed during ASME AG-1 committee meetings and Nuclear Air Cleaning Conferences (e.g., a panel discussion on ASME AG-1 Table FC-4110 ACFM versus SCFM during 29th Nuclear Air Cleaning and Treatment Conference in 2009 and a paper by Garcia [1]). As indicated by Garcia [1], the pressure drop and penetration results obtained at a standard air flow condition in the ASME AG-1 qualification tests can be largely deviated from those results obtained at an actual air flow condition and need to be properly corrected. He concluded that there is a lack of theoretical and experimental studies to substantiate the use of standard conditions for HEPA filter testing and this issue can be overcome by performing the testing at actual airflow conditions. An impact of the volumetric flow rate of the system with the corresponding media velocities on differential pressure, filter efficiency and filter lifetime was studied by Parsons and Waggoner [2].

Currently the Institute for Clean Energy Technology (ICET) at Mississippi State University (MSU) is tasked with performing testing of prototype AG-1 Section FK 2000 cfm radial flow HEPA filters intended for use in the Hanford Waste Treatment and Immobilization Plant (WTP). Bechtel National, Inc. (BNI) is the current prime contractor for bringing the facility to operable status. MSU ICET has developed a test stand, called Radial Flow Large-Scale HEPA Filter Test Stand (RLSTS) for evaluating current WTP filter designs under normal and elevated WTP operating conditions. The Technical Working Group for this project stipulated that actual volumetric airflow rate is required for the control of testing the prototype filters. This paper presents a method to determine the actual air flow rate based on measurements from differential pressure based flow meters (e.g., venturi) temperature, relative humidity, and findings from an experimental study on the elevated air flow conditions using a HEPA filter test stand at ICET.

METHOD

Air Flow Rate Calculation

ASME MFC-3M-2004 [3] specifies the method to determine the flow rate of fluid flowing in pipes for pressure differential devices including orifice plates, venturi tubes, and flow nozzles. According to this standard, the mass flow rate ($\dot{m}$) using differential pressure based flow meters can be determined using Eq. (1).

(*SI Units*)

$$\dot{m} = C\varepsilon\frac{\pi}{4}d^2\frac{\sqrt{2\Delta p\rho}}{\sqrt{1-\beta^4}} \tag{1-a}$$

(*U.S. Customary Units*)

$$\dot{m} = 0.09970190C\varepsilon d^2\frac{\sqrt{\Delta p\rho}}{\sqrt{1-\beta^4}} \tag{1-b}$$

where, C is the discharge coefficient, ε is the expansibility factor, d is the diameter of orifice or throat of primary device at flowing conditions, Δp is the pressure difference generated by the primary device, ρ is the density of the fluid, and β is the diameter ratio of orifice or throat diameter to the internal diameter of the pipe. The discharge coefficient (C) characterizes the pressure loss behavior through orifice or venturi by relating the actual discharge to the theoretical discharge and its numerical values can be determined based on experimental data. The expansibility factor (ε) is the coefficient used to take into account the compressibility of the fluid and can be determined using Eq. (2) for orifice and venturi meters [3].

(*Orifice*)

$$\varepsilon = 1 - (0.351 + 0.256\beta^4 + 0.93\beta^8)\left[1 - (\tau)^{\frac{1}{\kappa}}\right] \tag{2-a}$$

(*Venturi*)

$$\varepsilon = \left\{\left(\frac{\kappa\tau^{2/\kappa}}{\kappa - 1}\right)\left(\frac{1-\beta^4}{1-\beta^4\tau^{2/\kappa}}\right)\left[\frac{1-\tau^{(\kappa-1)/\kappa}}{1-\tau}\right]\right\}^{0.5} \tag{2-b}$$

where, τ is the pressure ratio (P_2/P_1) of the pressure at throat (P_2) to the pressure at the venturi inlet (P_1) and κ is the isentropic exponent, which is the ratio of the specific heat at constant pressure to the specific heat at constant volume.

The volumetric flow rate ($\dot{V}$) can then be calculated using Eq. (3).

$$\dot{V} = \frac{\dot{m}}{\rho} \tag{3}$$

Depending on the flow conditions (i.e., temperature and pressure) used in the calculation to determine the density, the volumetric flow rate can be determined in a different way. Using a set of standard conditions (e.g., 20 °C (68 °F), 101.325 kPa (14.696 psi) and 50 % Relative Humidity (RH) as specified in ISO 5011 [4]), the standard volumetric flow rate can be calculated while using actual temperature and pressure conditions, the actual volumetric flow rate can be determined. Therefore, the relationship between the standard and actual volumetric flow rates can be defined by Eq. (4) using the ideal gas law.

$$\dot{V}_a = \dot{V}_s \left(\frac{\rho_s}{\rho_a}\right) = \dot{V}_s \left(\frac{P_s}{P_a}\right)\left(\frac{T_a}{T_s}\right) \tag{4}$$

where, the subscripts of s and a correspond to the standard and actual conditions, respectively, P is the absolute pressure and T is the temperature.

Note that the properties of air at venturi, such as ρ and κ, can be determined using the equations or tables from ASHRAE Handbook [5]. It is also important to note that the thermal expansion of the differential pressure based flow meters can be neglected because it would have less than 1% impact on the air flow at 260 °C (500 °F) [5].

Experimental Study

To evaluate the effect of elevated temperature and humidity on air flow in the HEPA filter tests, an experimental study using the RLSTS at ICET (shown in Figures 1 and 2) was conducted. The downstream section is fitted with a venturi tube for determining the volumetric flow rate in the test stand. A fan capable of drawing 141.6 m^3/min (5000 ft^3/min [CFM]) through the filter is attached to the downstream section of the housing. A programmable logic controller (PLC) is used to control the volumetric flow rate through the test filter at a targeted value. Temperature and humidity are measured in both upstream and downstream sections. The test stand is insulated to minimize the condensation in the system. The specification of the RLSTS and venturi meter are summarized in Table 1.

Note that the test stand is well insulated as shown in Figure 1 to prevent condensation inside of the duct. With this condition, it is assumed that there is no condensation in the duct, so that a loss of vapor mass in the air flow with elevated conditions is neglected.

Table 1. Specification of the RLPTS and Venturi Meter

Volumetric flow rate range	0 – 141.6 m^3/min (5000 CFM)
Temperature range	Up to 82 °C (180 °F)
Humidity range	0 – 98 % RH
Venturi diameter ratio, β	0.4065 (= 6.3 in / 15.5 in)
Venturi discharge coefficient, C	0.988

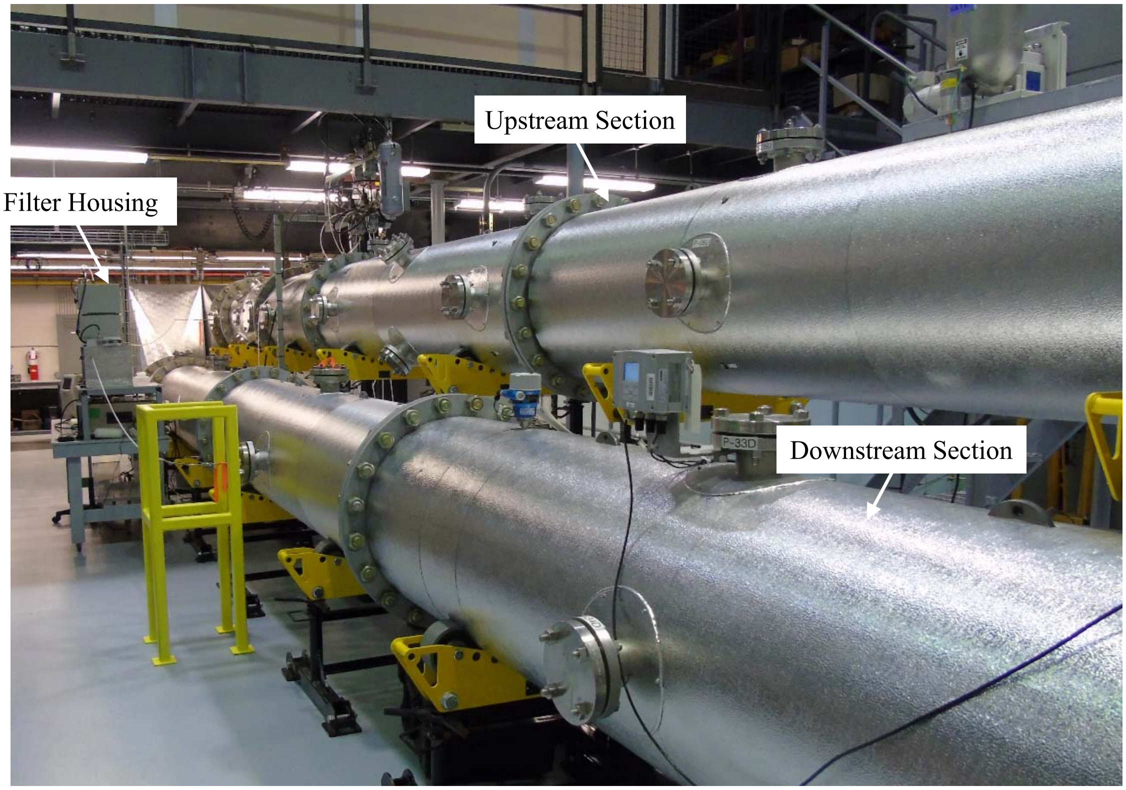

Figure 1. Photo of the Radial Flow Large-Scale HEPA Filter Test Stand (RLSTS) at MSU-ICET

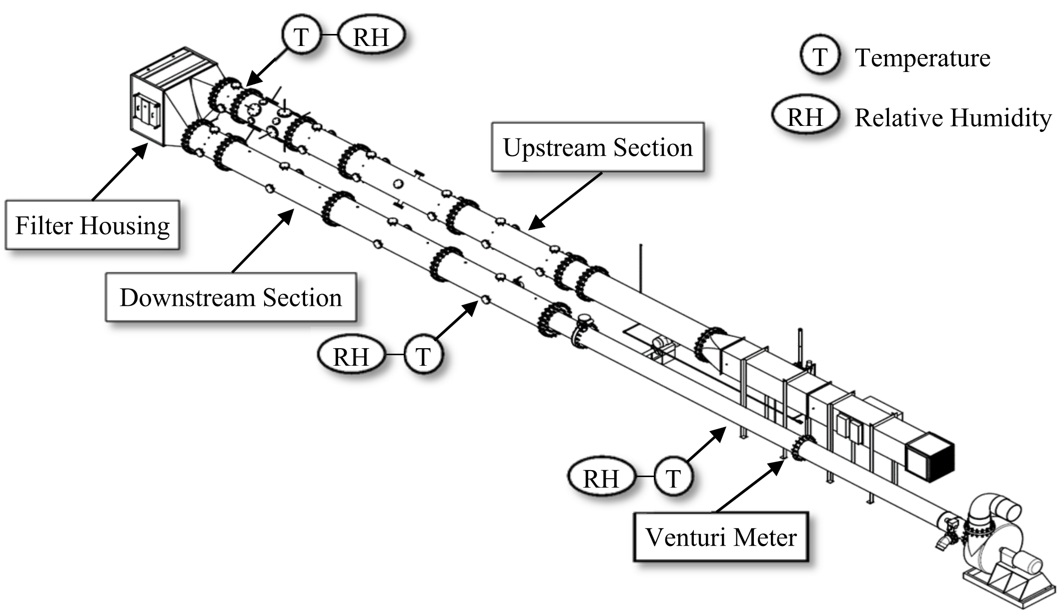

Figure 2. Schematic of the RLSTS at MSU-ICET

RESULTS AND DISCUSSION

The experimental study described above was conducted and data needed to determine the air flow conditions were collected from the test stand. The air flow rate calculation method presented above is used to determine the actual and standard volumetric air flow rates at various RH and temperature conditions. Note that the temperature and RH data are collected using the sensor close to the venturi shown in Figure 2. These results are illustrated in Figures 3 and 4. Figure 3 shows a comparison between the actual and standard volumetric air flow rates as the temperature increases. It illustrates that as the temperature increases from 64 °F to 169 °F, the RH decreases and the standard volumetric flow rate (i.e., 1,386 SCFM) will be significantly lower than the actual volumetric flow rate (i.e., 1,681 ACFM). The results shown in Figure 4 demonstrates comparisons between the actual and standard volumetric air flow rates at various RH and temperature conditions. The point 1 in Figure 4 shows that the standard volumetric flow rate is almost the same as actual volumetric flow rate when the temperature and RH are near the standard conditions (i.e., 68 °F and 50 % RH). The comparison between the points 2 and 3 in Figure 4 indicates the humidity effect on the air flow conditions. It reveals that 25% RH difference at 167 °F would cause 35 CFM difference between the actual and standard volumetric flow rates (i.e., 35 = [(1664 - 1213) - (1656 - 1240)]).

The theoretical impact of RH and temperature on the air flow rate using Eq. (4) is also carried out and the results are presented in Figure 5. Corresponding to 2,000 SCFM, the actual volumetric flow rate (ACFM) increases as the RH and temperature increases. When RH and temperature are 90% and 200 °F, respectively, the difference between the actual and standard volumetric flow rates becomes 1,373 CFM.

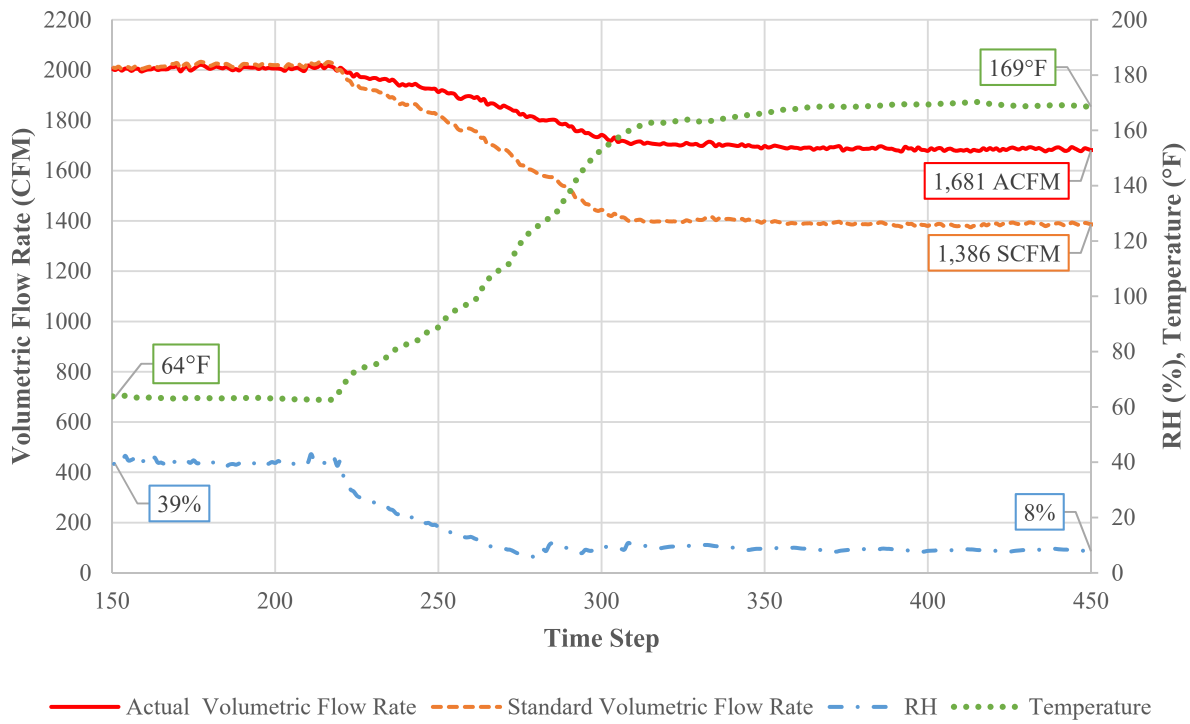

Figure 3. Actual vs. Standard Volumetric Flow Rates as Temperature Increases

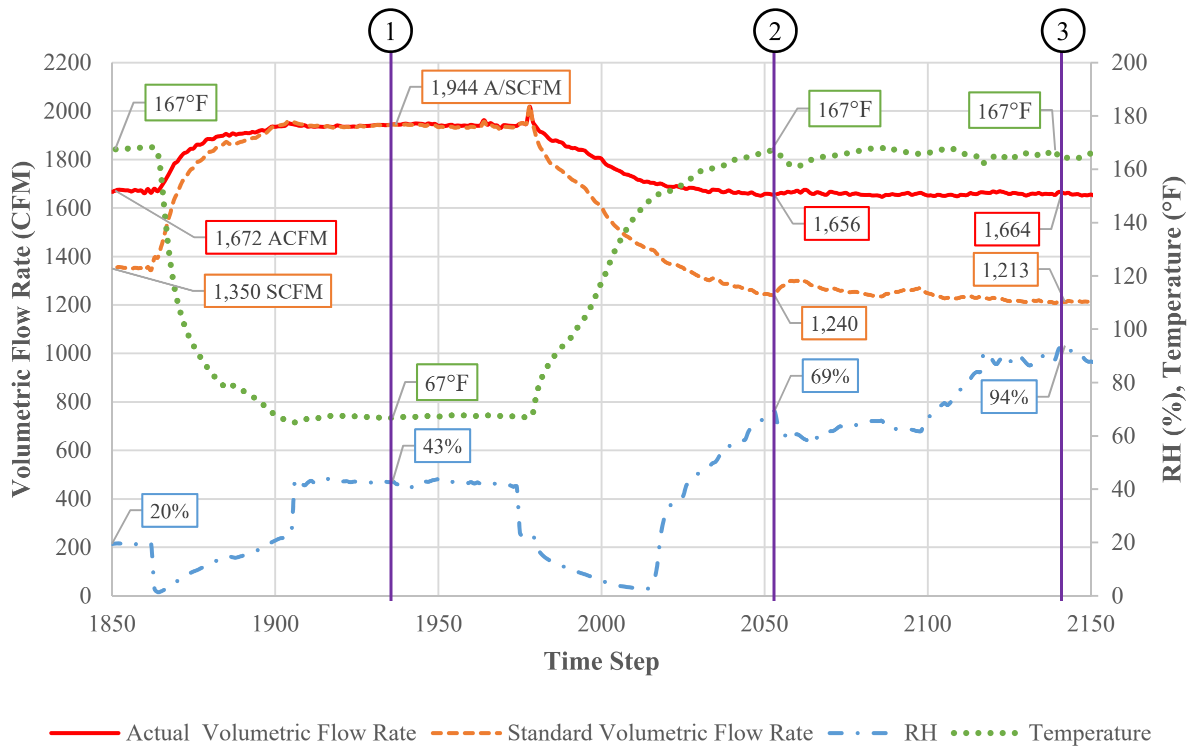

Figure 4. Standard vs. Actual Volumetric Flow Rates at Various RH and Temperature Conditions

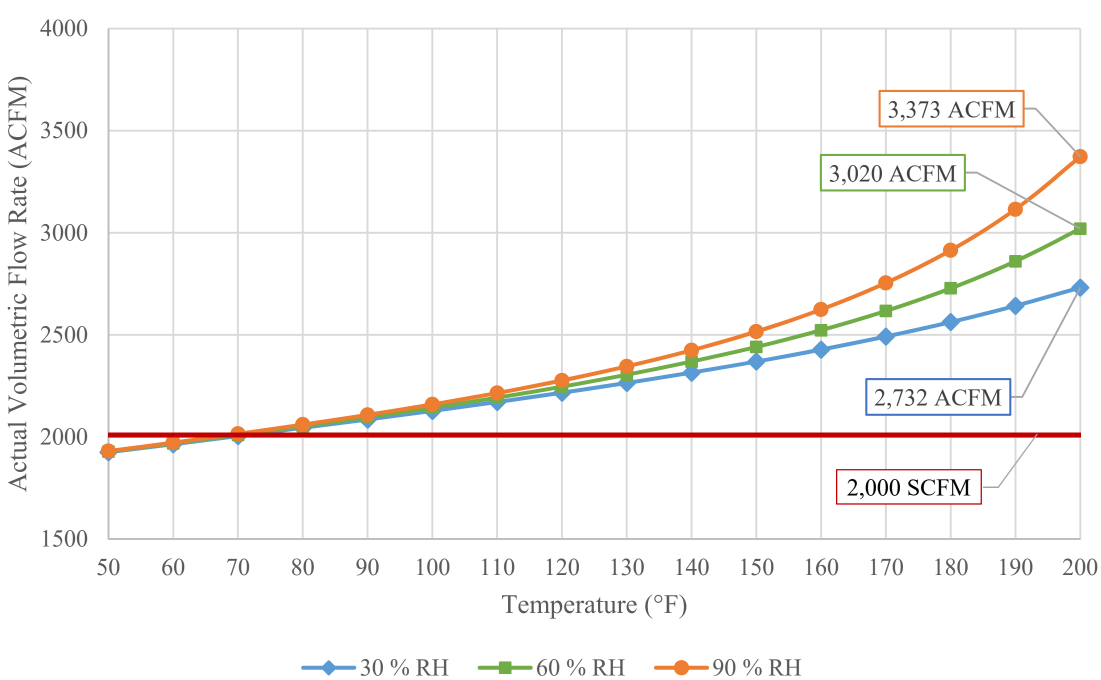

Figure 5. Actual Volumetric Flow Rates (ACFM) Corresponding to 2000 SCFM at Various RH and Temperature Conditions

CONCLUSION

The airflow rate calculation method from the ASME standard (i.e., MFC-3M–2004) is presented in this paper. This method can be effectively used to determine the actual volumetric air flow rate at various RH and temperature conditions using differential pressure based flow meters (e.g., orifice and venturi meters) in the HEPA filter testing. The experimental results obtained from the Radial Flow Large-Scale HEPA Filter Test Stand at MSU ICET are presented in the paper to demonstrate that the actual volumetric air flow rate at elevated RH and temperature conditions can be compared to the standard volumetric air flow rate.

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