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Evaluation of a Test Stand to Assess the Performance of a Range of Ceramic Media Filter Elements

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ABSTRACT

High efficiency particulate air (HEPA) filters are utilized to remove particulate from an air stream in a number of applications and environments. In the nuclear industry, HEPA filters most commonly use glass fiber media. Metal and ceramic filters are currently considered in nuclear applications because of their numerous benefits to nuclear aerosol filtration in extreme conditions. Specifically, ceramic media HEPA filters provide better performance at elevated temperatures, are moisture resistant and nonflammable, can perform their function if wetted and exposed to greater pressures, and can be cleaned and reused. The ability to test ceramic filters is important to both R&D as well as qualification under the relevant industry code in development, ASME AG-1, Section FO.

The objective of the ceramic filter test stand project is to develop methods of ceramic filter qualification, which will pave the way towards developing ASME AG-1 Section FO. Data collection will help facilitate the necessary steps in order to develop a protocol to qualify ceramic media filters. Specifically, this paper describes the design and evaluation of a large scale test stand which properly tests the filtration characteristics of a ceramic HEPA filter challenged with a nuclear aerosol agent. The test stand used at the Institute of Clean Energy Technology (ICET) at Mississippi State University was initially designed to evaluate sintered fiber metal media under ASME AG-1 Section FI, but was modified in order to test ceramic media HEPA filters in support of ASME AG-1, Section FO. The test stand is able to produce volumetric flow rates of approximately one cubic foot per minute (CFM) to 25 CFM. This test stand is uniquely equipped to be able to challenge ceramic HEPA filters with dioctyl phthalate (DOP), potassium chloride (KCl), sugar, sodium chloride (NaCl), and iron(II) sulfate ($FeSO_4$) to determine filter properties, such as differential pressure (dP), filtering efficiency (FE), mass loading, mass median diameter (MMD), and particle number concentration. In this study, DOP is chosen as the challenge aerosol. To properly evaluate the DOP aerosols going through the test stand system, a Scanning Mobility Particle Sizer (SMPS), a Laser Aerosol Spectrometer (LAS) and an Electrical Low Pressure Impactor (ELPI) are utilized. The test results outlined in this study verify the design of the test stand, show the characteristics of ceramic HEPA filters challenged with DOP at ambient temperatures, and help develop section FO of the Code on Nuclear Air and Gas Treatment (AG-1).

INTRODUCTION

High-efficiency particulate air (HEPA) filters are an extremely important component of nuclear facilities that help to ensure proper ventilation, air cleanup, and removal of particulate matter from air and gas streams. HEPA filters are a key credited element in the defense-in-depth safety strategy for many DOE facilities. HEPA filters are not only found in the nuclear industry but are also employed in several different areas such as medical facilities, automobiles, aircraft, and homes. The definition of a HEPA filter is found in Section FC of ASME AG-1 code on general HEPA filters. They are extended-medium dry type filters with: (1) a minimum particle removal efficiency of no less than 99.97 percent for 0.3-µm diameter test aerosol particles, (2) a maximum clean filter resistance of 1 inch water column (w.c.) when operated at rated airflow capacity, and (3) a rigid casing enclosing the full depth of the medium [1]. Conventional nuclear grade HEPA filters are made of glass-fiber media with diameters that provide the required particle retention efficiency without surpassing the maximum airflow resistance. These glass-fiber filters are one time use filters that must be safely discarded after loading up.

The U.S. Department of Energy (DOE), Defense Nuclear Facility Safety Board (DNFSB), and the Institute for Clean Energy Technology, Mississippi State University (ICET) have conducted a number of studies and documentation highlighting the need for HEPA filter research and development for nuclear facilities. Metal and ceramic filters are currently considered as advantageous for nuclear and radiological applications because of their numerous benefits to radiological aerosol filtration in extreme conditions. In this project, a ceramic media filter is under evaluation in order to assist in the development of Section FO of the ASME AG-1 code on HEPA filters. Ceramic HEPA filters pose many potential benefits compared to glass-fiber HEPA filters such as [2]:

- Better resistance to higher temperatures, fires, and moisture
    - Capability of improving facility safety during fires
    - Capability of providing continuous ventilation system operation during a fire in facilities
- Potential for large life-cycle cost savings due to ability to clean and reuse filters
    - Significant cost savings in reducing radioactive waste (LLW and TRU) volumes
    - Improvements in the fire and water survivability of HEPA filters improve facility safety and can allow less dependence on support systems
- Potential to be used in special applications (e.g., explosive applications).

The overall objective of ceramic filter R&D is to develop and deploy advances in HEPA filter technology related to ceramic HEPA filters to benefit DOE nuclear facilities by providing lower life-cycle costs and reducing or eliminating costs associated with safety class and safety significant systems in nuclear facilities.

The specific objective of this project is to develop methods of ceramic filter qualification, which will pave the way towards developing ASME AG-1 Section FO. This project will ultimately lead to qualification of ceramic media filters and include the requirements currently found in Sections FC and FK of the AMSE AG-1 code, such as resistance to airflow, test aerosol penetration, resistance to rough handling, resistance to pressure, resistance to heated air, spot flame resistance, structural requirements, and many other qualification criteria. Data collection will help facilitate the necessary steps in order to develop a protocol to qualify ceramic media filters. In order proceed from where Section FO currently stands, data on ceramic media filters must first be collected. To collect data, initial tasks such as test stand modification and design are imperative, which will ultimately help determine ceramic media filter characteristics. Therefore, a key step of the ceramic filter project is to evaluate a large scale test stand which properly tests the filtration characteristics of a ceramic media filter challenged with a nuclear aerosol agent. The test stand used at the Institute for Clean Energy Technology (ICET) at Mississippi State University (MSU) was initially designed to evaluate sintered fiber metal media filters (ASME AG-1 Section FI), and has been modified to properly test ceramic media filters. The current test system is designed to accommodate lower flow rates for ceramic filter testing. The testing framework of the ceramic filters at ICET involves challenging the filters with dioctyl phthalate (DOP) and potassium chloride (KCl) and analyzing the characteristics of the filters as well as differential pressure (dP), filtering efficiency, mass loading, mass median diameter (MMD), and particle number concentration. Since some ceramic filter elements have the capability to be washed and reused, a wash tank system was designed in tandem with the filter testing system. From the design work, test data, and overall development of this project, much more can be understood about how ceramic filters behave under certain conditions, which ultimately helps develop the ASME AG-1 Section FO code.

METAL TEST STAND DESCRIPTION

The current test stand used to evaluate the characteristics of ceramic HEPA filters was previously designed to test sintered metal media filters. The details of the original test stand design for the metal media filters can be found in [3] and a schematic of the test stand is displayed in Figure 1.

The following list identifies the most important components of the metal test stand and ceramic test stand:

1. Upstream section
2. Test stand base
3. Housing/middle section
4. Housing cap
5. Downstream section

The metal test stand is composed of upstream and downstream sections made of 6 inch diameter stainless steel piping and a housing (middle) section made of 12 inch diameter schedule 40 stainless steel piping. Each section of the metal test stand is comprised of a number of flanges used for aerosol injection and sampling and also included numerous ports for sensors. In order to install the metal media filters into the test stand, tube sheets were fabricated at ICET, which are able to hold up to four metal filters. These tube sheets are placed in between the housing cap and the housing (middle) section to secure the filters for testing. The metal test stand consisted of two air supply systems including two Spencer Vortex blowers connected in series and also a claw compressor connected with a variable speed drive. These two systems provided the test stand with a positive pressure air flow and were employed due to the high pressure drop characteristic of metal media filters.

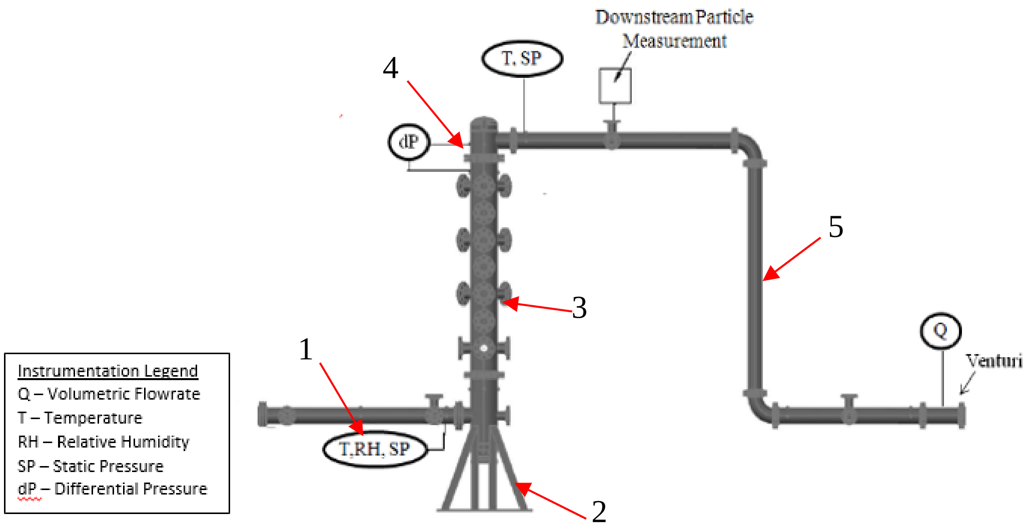

Fig 1. Metal Test Stand Drawing with Instrument Locations Indicated

CERAMIC TEST STAND DESCRIPTION

Design and operating conditions of ceramic media filters differ in several ways from those of metal media filters. The Technical Working Group developed initial test performance requirements/test matrix details. Table 1 summarizes key differences between the initial and modified test stand performance characteristics. Test stand components were evaluated in consideration of these difference conditions and capabilities were enhanced accordingly.

Table 1. Comparison of Initial (Metal) and Modified (Ceramic) Test Stand

Initial Test Stand Design (Metal)	Modified Test Stand Design (Ceramic)
• House up to three 8 foot long filter elements • Produce 50 – 160 ACFM of air flow at pressures up to 10 PSI (positive pressure system) • Maintain conditions of 60 – 80 °F, 40 – 60% RH, up to 10 psig • Continuously measure and record static pressure, dP, temperature, RH, flow rate, particle concentration, and particle size	• House single element or six-element ceramic filters (0.75 – 0.92 feet long) • Produce 0 – 23 ACFM of air flow (induced draft system); positive pressure system also included • Ambient conditions during testing; elevated temperature system (400 – 500 °C) currently in development • Continuously measure and record static pressure, dP, temperature, RH, flow rate, particle concentration, and particle size

In order to properly evaluate the ceramic media filters, several aspects about the metal test stand were modified in the ceramic test stand. First, the upstream piping section of the test stand is significantly shortened. The reason for reducing the length is to minimize the heat loss in the upstream piping section, so that the target temperatures of 400 °C and 500 °C can be effectively achieved. The shortened upstream section is shown in Figure 2.

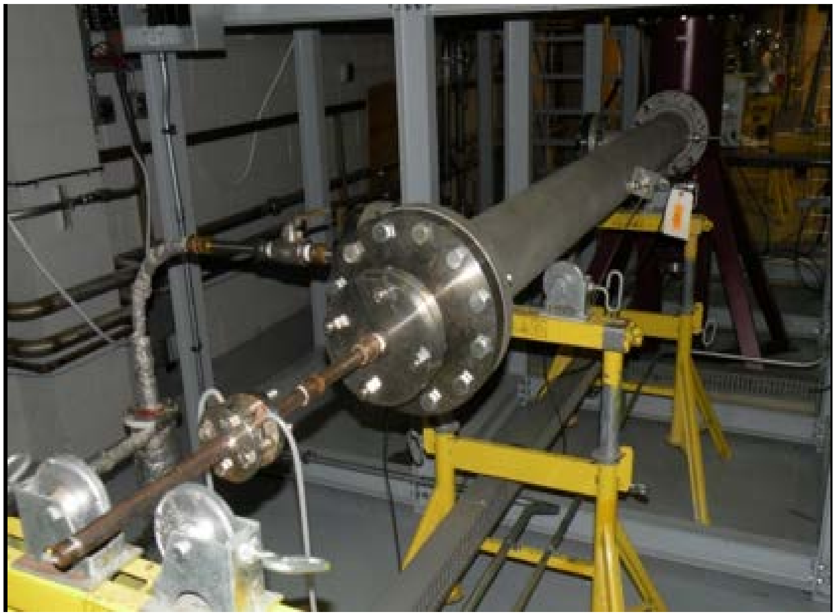

Fig 2. Upstream Section of Modified Test Stand

Ceramic media filter elements are significantly different from both metal media and glass-fiber media filters. The design and operating conditions of ceramic media elements are listed in Table 2.

Table 2. Design and Operating Conditions of Ceramic Media Filters

	Ceramic Media
Filter Surface Area	• 0.62 ft^2 (Filter Media 1 single element) • 0.58 ft^2 (Filter Media 2 single element) • 3.73 ft^2 (Filter Media 1 six-element) • 3.67 ft^2 (Core six-element)
Testing Conditions	• Ambient temperature (21°C) • Elevated temperature (400°C and 500°C)
Rated Flows	• 5 CFM (single element) • 20 CFM (six-element)

Due to the much smaller size of the ceramic media filters, new tube sheets are fabricated in house at ICET. These tube sheets are capable of holding a single element ceramic filter and also a multiple-element ceramic filter, which is depicted in Figure 3.

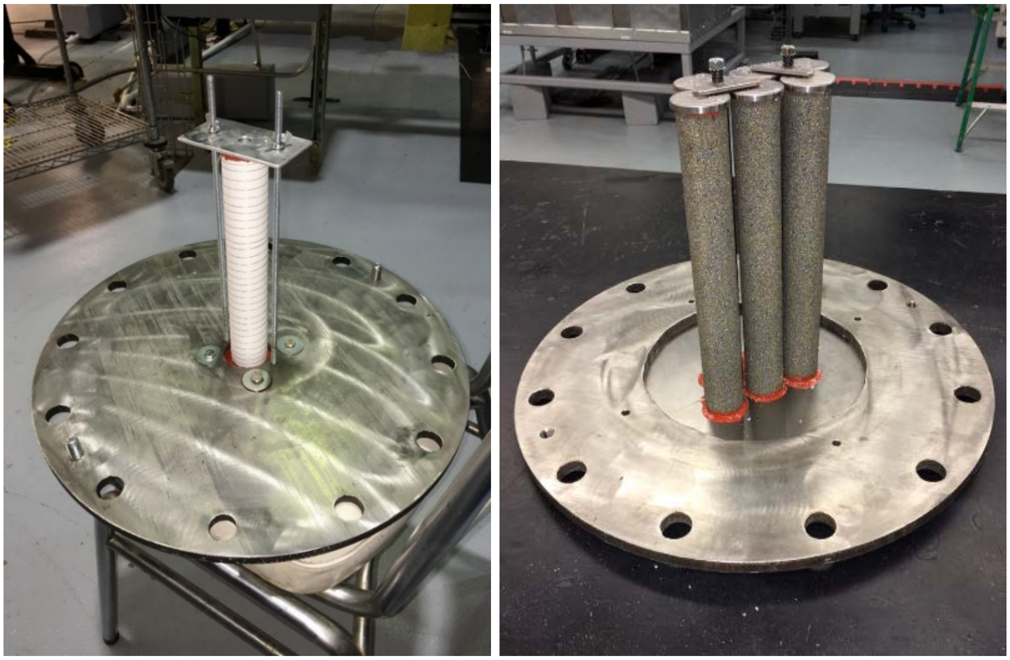

Fig 3. Single Element and Six-Element Ceramic Filter Tube Sheets with Filters Installed

In addition to these modifications, another change in the ceramic test stand is the air supply system. The positive pressure air flow system is shown in Figure 4 and includes several items. First, an air hose is connected to the system to supply compressed air from an Atlas Copco air compressor capable of providing 0 – 429.4 CFM at 132 psi. After the air hose, there is a manual pressure regulator that is able to control how much of the air is allowed to go into the system. A Spence Engineering Type J control valve is used to control how much air flow is travelling through the system. Connected to the flow control valve are two pressure gauges and a current to pressure transducer, which converts the analog signal (4 to 20 mA) to a proportional pneumatic output. The next item in the air flow system is an Oripac Model 5300 orifice plate. This orifice plate is made of 304 stainless steel and is designed for 20 CFM air flow in a 0.5 inch diameter line. Finally, the orifice plate was connected to a differential pressure sensor. This system operates based off of how much air is going through the orifice plate. Both the orifice plate and the flow valve are connected to a programmable logic controller (PLC) in the main computer. A PID controller is used in the PLC to control the set points of the air flow.

In addition, an induced draft air flow system is also introduced. A Spencer Vortex blower (Model VB-037B) is used to create an induced draft air flow system. This blower is capable of producing low flow rates and also a negative pressure environment inside the ductwork. The vortex blower is connected to the test stand by welding stainless steel piping from the test stand exit pipe to the inlet of the blower. An image of the vortex blower is shown in Figure 5.

Fig 4. Positive Pressure Air Flow System for Ceramic Filter Testing

Fig 5. Spencer Vortex Blower used for Induced-Draft Air Supply System

The induced draft air flow system is beneficial for ceramic media filter testing for various reasons. Ceramic media filter testing requires low flow rates and low pressure drops compared to metal media filter testing, so by using an induced draft system, ceramic media filters can be properly tested. Also, an induced draft system creates favorable conditions for the aerosol measurement instrumentation and helps increase the concentration of aerosol generation through negative pressure inside the ductwork. In the case of testing metal media filters in addition to ceramic media filters, the positive pressure flow system can be used.

Aerosol sampling components are also added to the test stand, which includes a Scanning Mobility Particle Sizer (SMPS) and Laser Aerosol Spectrometer (LAS) sampling system and also an Electrical Low Pressure Impactor (ELPI). The sampling system, shown in Figure 6, allows for both upstream and downstream sampling. It is composed of two TSI Model 3302 diluters (100:1 and 20:1 dilution ratios, respectively), the LAS particle sizer, the SMPS particle sizer, an Omega FMA 1700/1800 flow meter, three T valves, and a mini vacuum pump. Two diluters are utilized in this system, which decrease the aerosol concentration in the test stand, so that the LAS can operate in the correct concentration range. The LAS operates based on light scattering techniques where a particle is sized based on how much light is scattered in the laser cavity. This instrument is important to include in this study because it offers advantages that other instruments could not. For example, it includes a wide size range for ceramic media testing (0.09 to 7.5 µm) and has a high sensitivity and resolution. Another instrument used in this project is the SMPS, which offers a view of particles in the size range of 10 nm to 1000 nm using a TSI Long DMA combined with the Electrostatic Classifier (EC) and Condensation Particle Counter (CPC). The SMPS system separates the particles by size for high resolution measurements in order to produce reasonable particle size distributions (PSD). Using the LAS in conjunction with the SMPS, meaningful data can be collected and analyzed to characterize the ceramic media filters. The sampling nozzles used in the test stand are ensured to provide isokinetic sampling using a combination of calculations and sampling system design. The LAS sampling nozzle is placed in the housing (middle) section of the test stand upstream of the ceramic media filter.

Fig 6. LAS and SMPS Sampling System on Test Stand

TEST METHODS

Testing ceramic media filters at ICET involves the development of detailed testing procedures, which are some of the most important documents to reference. Procedures on test stand startup and shutdown, aerosol generation, aerosol measurement instrumentation, tube sheet installation, filter element installation, filter loading, and filter washing are all integral parts of collecting valuable filter data. These procedures are in a developmental phase and will be finalized after they incorporate lessons learned from testing. At that time, they will be qualified under the Nuclear Quality Assurance (NQA-1) standard.

Aerosol generation is a necessary component of filter testing, which provides a means to characterize filters of any kind. In this project, a TSI six-jet atomizer (Model 9306) is used as the aerosol generator to provide DOP to test the ceramic media filters. A large scale aerosol generator is also included in the test stand system, which is capable of providing potassium chloride (KCl) as a challenge agent. The design for this system is outlined in [4]. This system is unique in that it can provide a challenge agent of both 1 µm and 3 µm diameter size. Therefore, the test matrix for ceramic media filter testing includes challenging filters at both parameters of 1 µm and 3 µm of KCl. In addition to providing these particular aerosol diameters, the generator used for this project is also capable of producing particle number concentrations above 10^5 particles per cubic centimeter (particles/cc).

The particles produced by the aerosol generator are released into the test stand and then travel through the test stand at rated flows of 5 CFM (single element ceramic filter) and 20 CFM (multiple element ceramic filter). Assuming a face velocity of 5 feet per minute (ft/min) onto the effective area of the filter, the rated flows are calculated, which would ensure proper filtering efficiency (FE) and particle loading data from testing. The essential pieces of data collected in this project included PSD curves, FE, particle penetration, differential pressure of the filters tested, and data from the test stand itself. The testing matrix is shown in Table 2. Filter Media 1 is a legacy filter media and core material from prior work. Filter Media 2 is an intermediate improvement step upon current ceramic filter development that utilizes a new core material and new filter media. It is expected that Filter Media 2 will have a reduced pressure drop by more than a factor of 2 for the same flow rate and is expected to have similar or better filtering efficiency.

Table 2. Testing Matrix of Ceramic Media Filter Project

Type of Test	Filter Type Tested	Notes on Testing
Differential Pressure vs. Flow Rate (dP vs. Q)	• Filter Media 1 + Core • Core • Filter Media 2 + Core	• Ambient Conditions • 5 – 20 CFM Airflow in Test Stand
Filtering Efficiency (FE)	• Filter Media 1 + Core • Core • Filter Media 2 + Core	• Ambient Conditions • 5 – 20 CFM Airflow in Test Stand
Particle Loading	• For 3 µm MMD KCl o Filter Media 1 + Core o Core o Filter Media 2 + Core • For 1 µm MMD KCl o Filter Media 1 + Core o Core o Filter Media 2 + Core	• Ambient Conditions • 5 – 20 CFM Airflow in Test Stand
High Temperature Testing	• Filter Media 1 + Core • Core • Filter Media 2 + Core	• This phase of testing is currently in development

TEST RESULTS

The results outlined in this study include both data from the test stand operation and data from ceramic filter testing. The test results presented in this section are based on testing of a single element ceramic media filter challenged with DOP at 5 CFM flow rate. The ceramic media filter is composed of an inner core wrapped with a fibrous filter media 1 material as shown in Fig. 3. Ambient conditions were used in this test, in which indoor air was drawn through the test stand inlet. The DOP generator was set to a pressure setting of 25 psi and two jets were used to produce a higher particle concentration.

To effectively analyze particle behavior on the ceramic media filter, a SMPS was used. To show that the test stand, combined with the induced draft air flow system, is capable of effectively challenging a ceramic media filter, data for flowrate, orifice plate dP, temperature, and relative humidity are presented in Figure 8. The data in this figure describes a test stand characterization and does not include a filter element inside the housing. The air flowrate for the system, initially at 5 CFM, was increased incrementally up to 23 CFM without any aerosol added in the test stand.

The test stand data collected during the DOP tests are shown in Figure 9. It illustrates the flow, temperature, and relative humidity. The relative humidity data fluctuates as a result of turning the DOP generator on and off. When the DOP generator is turned on, the RH values decrease, and when it is turned off, the RH values increase. As for temperature and flowrate, these parameters remain relatively constant throughout testing.

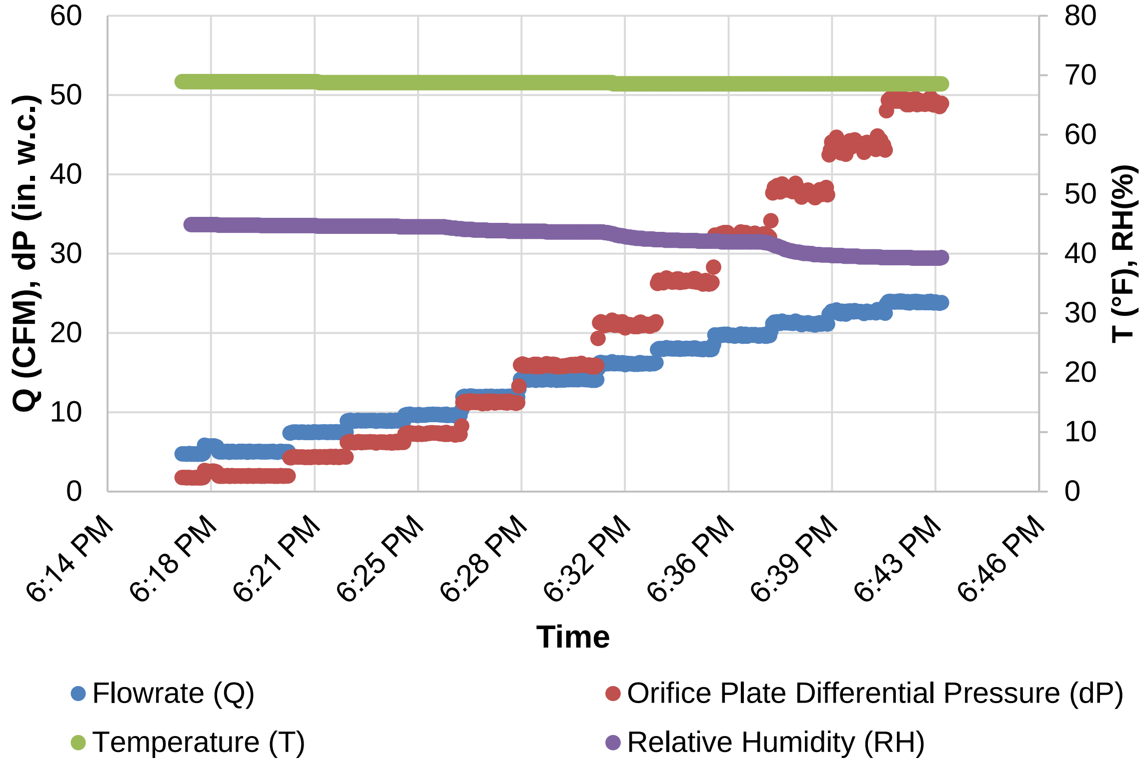

Fig 8. Test Stand Data for Induced Draft System Characterization

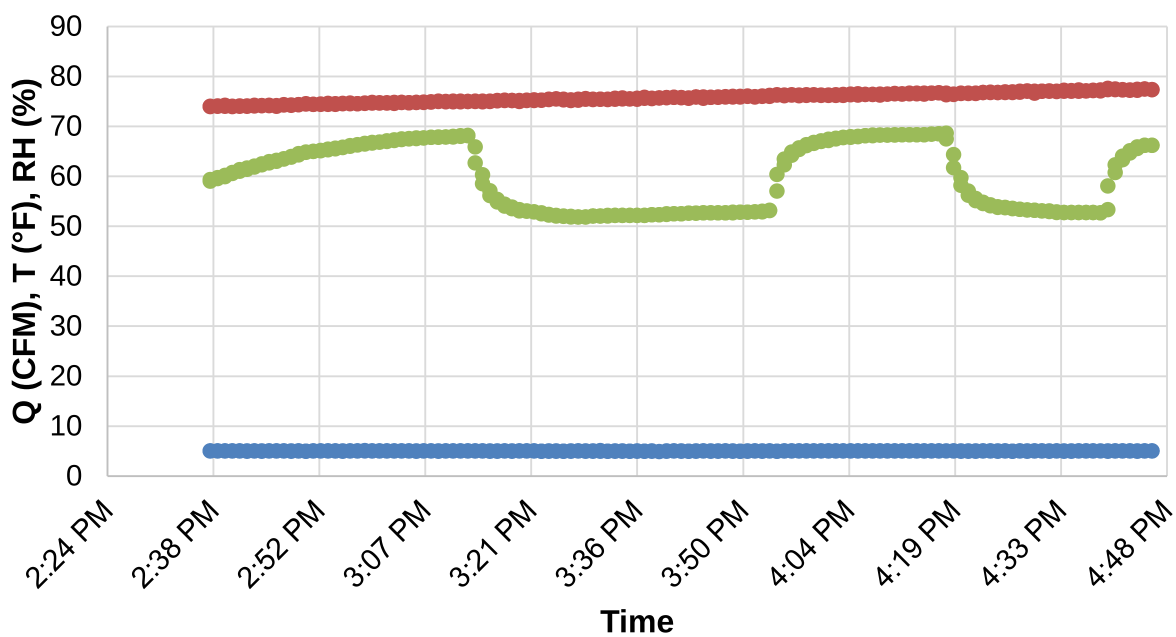

Fig 9. Test Stand Data from DOP Testing

Also included in this study is the differential pressure data for the single element filter challenged with DOP. In this particular test, the DOP generator is set to use 2 jets instead of one so that the particle concentration would be increased. In Figure 10, the ceramic media filter shows an initial dP below 5 inches water column and increases all the way up to 45 at 5 CFM airflow. The fluctuations, again, are due to the DOP generator being turned on and off. The large pressure drop was anticipated for this combination of filter media and core material with improvements expected with Filter Media 2. Filter Media 1 and 2 were selected for initial testing as diverse samples to test the performance range of the ceramic test stand. The test results indicate that the ceramic filter components are capable of performing at pressure drops well in excess of the nominal expected pressure drop. Figure 9 shows a pressure drop of nearly 10 times the pressure drop expected under nominal flow conditions for the single ceramic tube filter element.

After testing was completed, analysis was performed on the collected data using Mathcad and Excel spreadsheets. Figure 11 shows the upstream and downstream particle size distribution (PSD) curves with background data included. The data in Figure 11 include the average of two samples taken during testing, which summarize the particle concentration vs. diameter of both upstream and downstream of the filter media.

Particle penetration, a very important parameter to analyze, is outlined in Figure 12. This data shows the penetration (units of number/number) of the particles from the DOP test, which is found by dividing the downstream concentration by the upstream concentration.

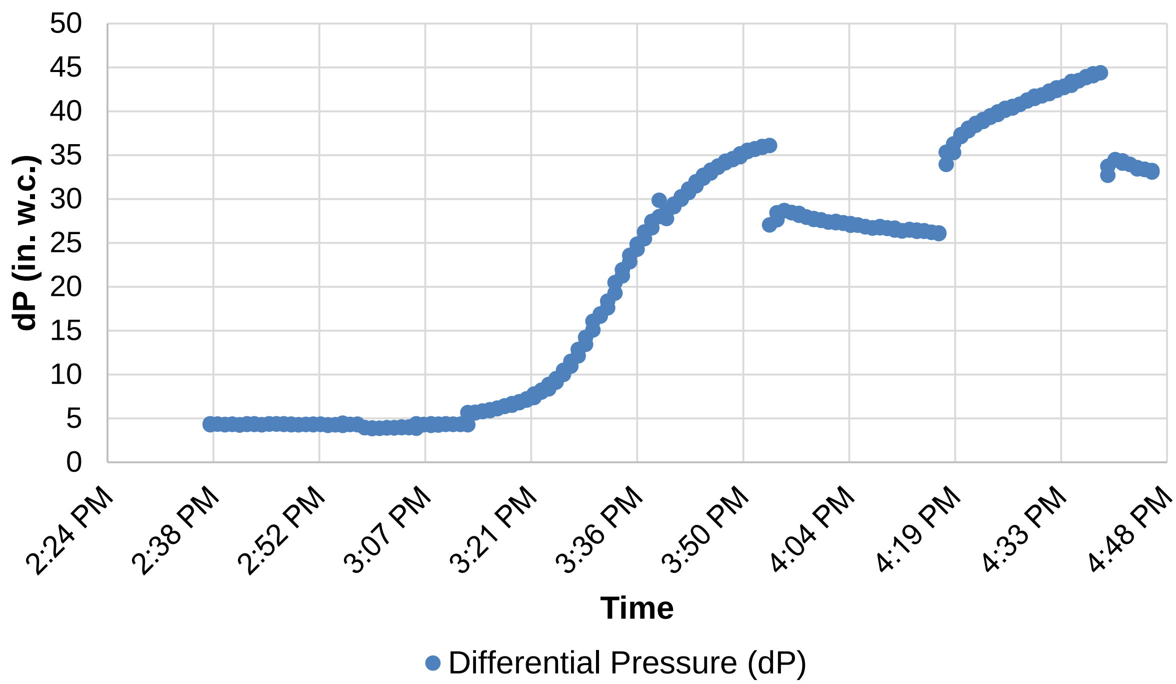

Fig 10. Differential Pressure Data for Single Element Ceramic Filter from DOP Test

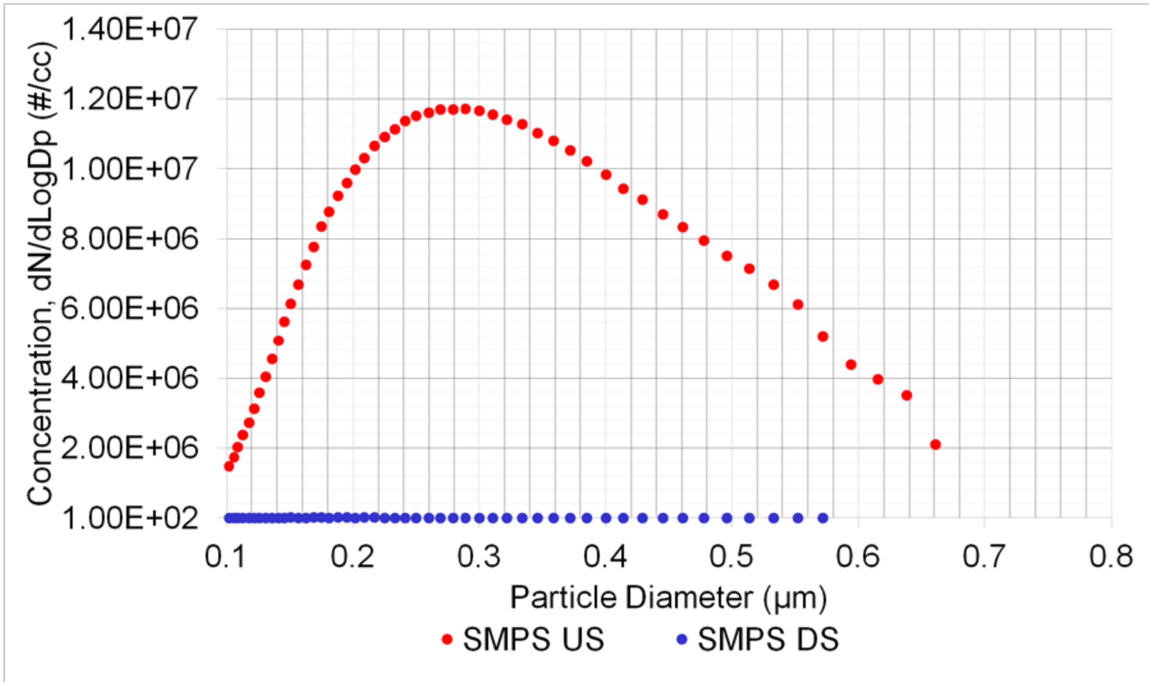

Fig 11. Upstream and Downstream PSD Curves with Background Data

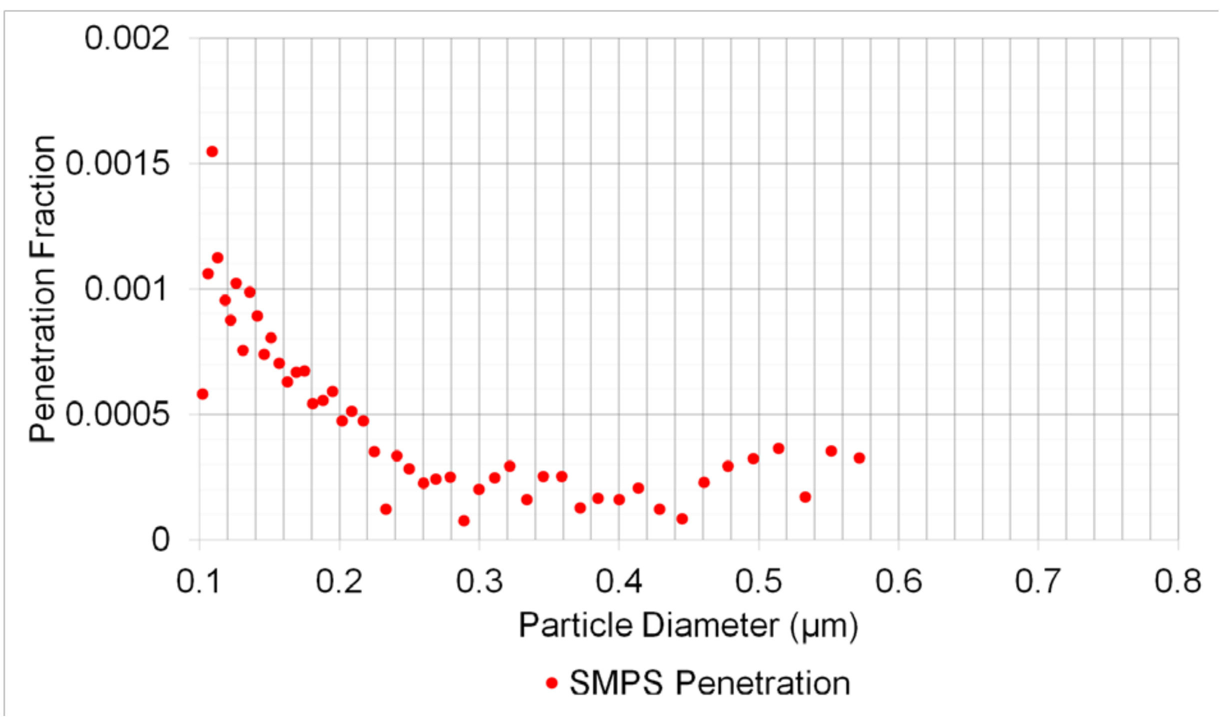

Fig 12. SMPS Penetration Data Points from DOP Test

Further analysis of Figure 12 leads to the production of Figure 13. This figure displays a zoomed-in view of the penetration curve (from 0.2 µm to 0.4 µm) and includes an exponential curve fit. Examination of the circled data point at 0.3 µm shows a penetration fraction value of 0.000202. Using the equation for particle size removal efficiency (PSE), a value of 99.9798% is calculated.

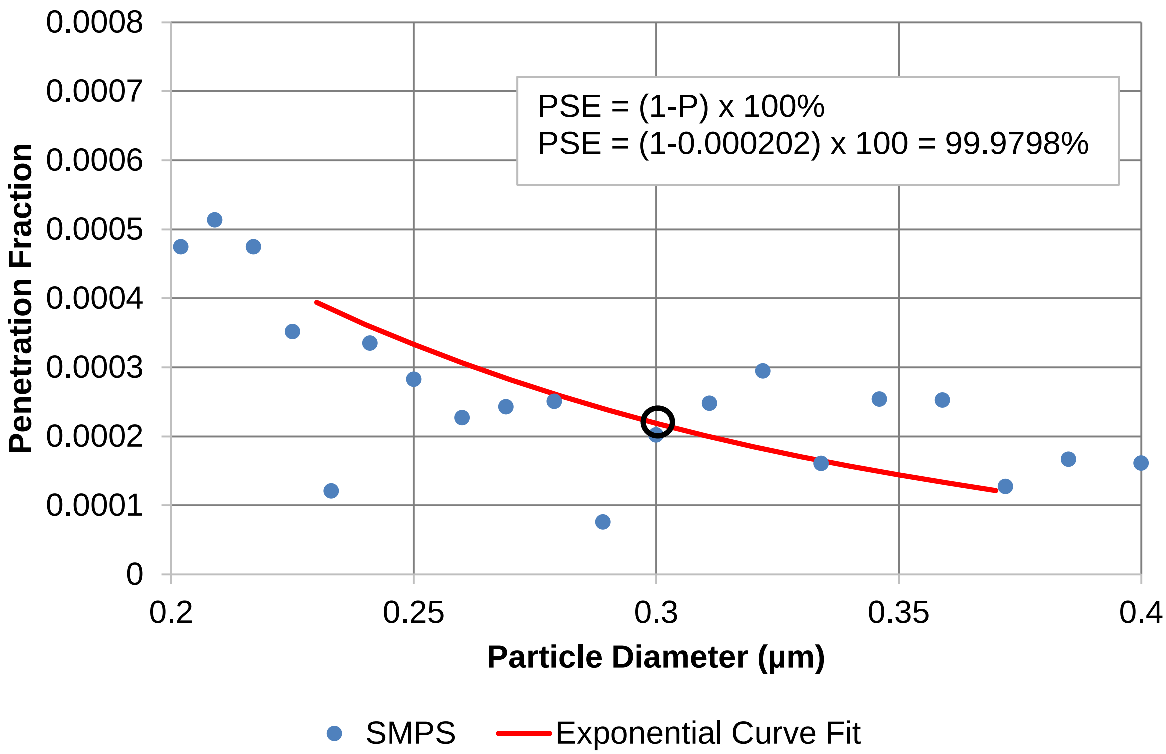

Fig 13. Penetration Curve with Exponential Curve Fit

CONCLUSION

The goal of this study was to design and evaluate a test stand to properly test the filtration characteristics of a ceramic media filter with a challenge aerosol agent in order to further develop Section FO of ASME AG-1. To expand on Section FO, data to characterize ceramic media filters must be generated. Therefore, in order to collect data, a test stand to evaluate ceramic media filters must first be established. The test stand used in this study is equipped to test both ceramic media filters and sintered metal fiber filters to determine filter characteristics such as filtering efficiency, penetration, most penetrating particle size, and other parameters. An SMPS system was used in this study to collect data during a test which used DOP as the challenge agent to evaluate a single element ceramic media filter. With the newly added ceramic test capability, lower flow rates are achievable, several types of aerosols can be used as challenge agents, two (or more) filter media types are able to be tested, and essential filtration data can be collected during testing. Future work for this study combines the work presented here along with the capability of testing at elevated temperatures. Additionally, further testing with KCl challenge particles will be conducted along with wash studies. The option of testing flat sheet media filters is also being considered for this test stand. As this work continues, more can be understood about how ceramic filters behave under certain conditions, which ultimately helps develop the ASME AG-1 Section FO code and support deployment of advances in HEPA filter technology related to ceramic HEPA filters to benefit DOE nuclear facilities.

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