

Investigation of highly efficient particulate air filter media performance
in existence of internal leak

by

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B.S., Lebanese International University, 2009

B.S., Kansas State University, 2013

M.S., Texas A&M – Central Texas (Tarleton State University), 2011

AN ABSTRACT OF A DISSERTATION

submitted in partial fulfillment of the requirements for the degree

DOCTOR OF PHILOSOPHY

Department of Mechanical and Nuclear Engineering
Carl R. Ice College of Engineering

KANSAS STATE UNIVERSITY
Manhattan, Kansas

2025

Abstract

High-efficiency particulate air (HEPA) and ultra-low particulate air (ULPA) filters are extensively utilized in nuclear and National Bio and Agro-Defense facilities as the last line of defense for eliminating particles from a contaminated gas stream prior to its release into the surrounding environment. The objective of the present study is to develop a computational tool capable of simulating the microstructure of such a filter medium. This tool will provide valuable information for enhancing the design and manufacturing of the scanning device used in the leak penetration test. It will also help in investigating the testing criteria set in the standards for classifying filter types. Consequently, it will assist in assessing the likelihood of a successful filtration leak test, thereby reducing the risk of an inaccurate test.

The initial phase of this study was the design and construction of a biofiltration testing rig that adheres to the standards set by the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) 52.2 for HEPA testing. The purpose of this rig is to assess various prototypes of biocontainment housings used in the National Bio and Agro-Defense Facility (NBAF), along with their corresponding auto scan technologies against the traditional penetration test method. We evaluated the local and overall filter efficiency of two of the available housing units using their associated auto scanning methodologies, and we compared the results with the efficiency obtained using the conventional penetration test approach described in ASHRAE 52.2. A series of prerequisite tests were carried out to verify aerosol distribution uniformity upstream and downstream as well as the consistency of the injection and sampling probe measurements. This allowed us to investigate the impact of the filter pinholes (leaks) on the pressure drop and efficiency of the filter and enhanced our understanding of the

protocols and requirements for comprehensive testing of large-scale pleated $610 \times 610 \times 292 \text{ mm}^3$ HEPA and other filters at different flow rates.

In the second part of the study, following an understanding of the scanning technology used to test the filter in the first part, we developed a three-dimensional fibrous computational model featuring non-homogenous fibers that replicates the HEPA filter sheet. This model was utilized to simulate and analyze the pressure drop and collection efficiency of the HEPA filter sheet, considering scenarios both with and without leaks. We expanded our work by building a small-scale filter sheet testing rig to compare experimental and computational results and determine a correlation between HEPA intact and leaky filter efficiencies. Our research revealed the optimal most penetrating particle size (MPPS) at which to test a filter and the minimum leak size at which the filter efficiency becomes independent of particle size and filtration velocity, which can be used to derive a designated leak penetration value for a successful leak penetration test under particular sampling and scanning conditions.

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Nomenclature

A_b	Area of the remaining fiber bed of a filter medium
A_f	Area of a filter medium
A_h	Area of a pinhole
C_c	Cunningham slip correction factor
C_D	Drag coefficient
C_s	Sampling concentration of aerosol
C_u	Upstream aerosol or challenge concentration
D	Particle diffusion coefficient
d_f	Fiber diameter
d_h	Pinhole diameter
d_p	Particle diameter
E_d	Single fiber efficiency caused by diffusion
E_{dr}	Single fiber efficiency caused by the interception of the diffusing particles
E_f	Filter media efficiency
E_g	Single fiber efficiency caused by gravitational settling
E_i	Single fiber efficiency caused by impaction
E_r	Single fiber efficiency caused by interception
E_s	Single fiber efficiency
g	Gravitational constant
k	Filter medium permeability
K_B	Boltzmann constant
Kn	Knudsen number

Ku	Kuwabara hydrodynamic factor
L	Thickness of a filter medium
L_f	Length of a cylindrical fiber
L_s	Designated leak penetration value
P_d	Single fiber penetration caused by diffusion
P_e	Peclet number
P_f	Penetration through a filter medium
P_h	Penetration through a pinhole
P_i	Single fiber penetration caused by impaction
P_r	Single fiber penetration caused by interception
q_f	Filter quality factor
Q_b	Flow rate through the remaining fiber bed of a filter medium
Q_f	Flow rate through a filter medium
Q_h	Flow rate through a pinhole
r_f	Fiber radius
R	Ratio of particle diameter to fiber diameter
Re_f	Reynolds number for a cylindrical fiber
Re_p	Reynolds number for a particle
St	Stokes number
V	Airflow speed
V_p	Particle speed

Abbreviations

2D	Two-dimensional
----	-----------------

3D	Three-dimensional
AFMS	Air flow measurement station
ANSI	American National Standards Institute
ASHRAE	American Society of Heating, Refrigerating, and Air-Conditioning Engineers
ASME	American Society of Mechanical Engineers
BMBL	Biosafety in Microbiological and Biomedical Laboratory
BRI	Biosecurity Research Institute
BSC	Biological safety cabinet
CDC	Centers for Disease Control and Prevention
CFD	Computational fluid dynamics
CFM	Cubic feet per meter
CPC	Condensation particle counter
CV	Coefficient of variance
DEHS	Di-ethyl-hexyl-sebacat
DHS	Department of Homeland Security
DNA	Deoxyribonucleic acid
DOP	Diocetyl phthalate
DPM	Discrete phase model
FC	Filter containment
HEPA	High-efficiency particulate air filter
IER	Institute for Environmental Research
IEST-RP	Institute of Environmental Sciences and Technology Recommended Practices
ISO	International Organization for Standardization

IWC	Inches of water column
MERV	Minimum efficiency reporting value
MPPS	Most penetrating particle size
NBAF	National Bio and Agro-Defense Facility
NIH	National Institute of Health
OPC	Optical particle counter
PAO	Poly alfa olefin
PSL	Polystyrene latex
RNA	Ribonucleic acid
SEM	Scanning electron microscope
SMPS	Scanning mobility particle sizer
SVF	Solid volume fraction
UDF	User defined function
ULPA	Ultra-low particulate air filter
USDA	United States Department of Agriculture

Greek Symbols

α	Fiber solidity or fiber packing density
δ	Mean displacement of particle
ΔP	Pressure drop
ε	Inhomogeneity factor of fibers
λ	Mean free path of air particles
μ	Dynamic viscosity
μ_p	Particle mobility

ν Kinematic viscosity

π Pi

ρ Air density

ρ_p Particle density

ψ Air stream function

Subscripts

b Filter media fiber bed

h Pinhole

θ Angle between the line segment and the x-axis

p Particle

r Length of the line segment from the point (x, y) to the origin

s Sampling

x x-component

y y-component

Operators

∇ Del

∂ Partial derivative

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Dedication

To my family.

Chapter 1 – Introduction & Research Objectives

1.1 Introduction

The performance of a high-efficiency particulate air (HEPA) or ultra-low particulate air (ULPA) filter, which is widely used in biological safety cabinets (BSCs), can be greatly impacted by a small leak that may occur during manufacturing, handling, or installation processes. This is why, in order to prevent the risks to laboratory workers, the public, and the environment, BSCs shall undergo field performance testing at the time of installation and then at least once a year or whenever the filter is replaced, according to the Biosafety in Microbiological and Biomedical Laboratory (BMBL) guidelines published by the Centers for Disease Control and Prevention (CDC) and the National Institutes of Health (NIH). Hence, the investigation of the initial filtration state in the presence of a very small leak is necessary and critical due to the impact of that leak on filter performance behavior.

Studies on damaged fibrous filters are few and limited to experimental work. Multiple investigations have been conducted on large-scale filter sizes, while others have concentrated on small-scale filter media housed in a test apparatus to assess the filter's performance in the existence of a leak and develop mathematical models. A study done by Osaki & Kanagawa (1990b) investigated the performance of full-scale conventional deep-pleat HEPA filters of $610 \times 610 \times 292 \text{ mm}^3$ size under various conditions, including pinholed HEPA filters. In contrast to the filter with a smaller leak, which performs like an intact filter since the efficiency is not entirely controlled by the pinhole, they found that the filter with a larger leak has a reduction in efficiency that becomes independent of particle sizes. It should be emphasized that only two separate pinholes were employed in this part of the study, and no other details regarding their sizes were provided. Ward & Siegel (2005) developed a model to estimate how different external

leak or bypass gaps or cracks (1, 5, 10 mm with 0 or 2 bends) around the frame of typical residential and commercial full-scale filters affect their performance for particle sizes between 0.01–10 μm . Their calculations showed that the smallest leak of 1 mm had a minimal effect on the performance of all filters, with the exception of the higher-efficiency filters that are typically designed and rated with higher pressure. In such cases, the smallest leak had a greater impact. A larger leak began to affect the performance of all filters, with a substantial influence on the efficient filters. The presence of bends in a leak did not make large enough differences in the filters' efficiency to the extent that it would have altered their rating. However, this work did not include experimental validation of the estimated particle fractional efficiency derived from the model, which relies solely on the pressure drop measurements. Moreover, the model was not validated for leak sizes below 1 mm, which can be challenging or even unattainable experimentally because of the unchangeable pressure drop associated with smaller leaks. The study conducted by Mouret et al. (2009) on small-scale filter media revealed a noteworthy aspect and successfully distinguished between different filtration regimes that may occur in the presence of a leak. Their findings showed that the efficiency of the two non-HEPA tested filter media is less affected by leaks where the filtration bed regime remains dominant. However, a leakage regime occurred only at smaller specific particle sizes ($0.005 \mu\text{m} \leq d_p \leq 0.01 \mu\text{m}$) depending on the leak size and face velocity. Conversely, the results obtained for the tested HEPA filter medium consistently showed that efficiency is compromised by even the smallest leak and becomes independent of particle size and face velocity. The positive aspect of this work is that it focused on the initial filtration state. Nevertheless, only nanoparticles smaller than 0.03 μm were examined with two face velocities of 5 cm/s and 15 cm/s in this work, and measurements of the pressure drop difference between intact and leaky filters proved challenging

even with the use of highly sensitive instruments. Also on small-scale polyester filter media with a diameter of 150 mm and a thickness of 0.72 mm, Li et al. (2022) examined the impact of external leakage with diameter sizes of 2.64 mm and 4 mm established and regulated using a filter medium bypass tube on the filtration performance, taking into consideration the particle loading and the formation of dust cake during the filtration process with time. They derived appropriate mathematical expressions based on their experimental data to describe the filter efficiency in relation to the leakage ratio for a given flow rate. Their results showed that when there is a leak and in contrast to intact filter medium, the filtration efficiency decreases linearly with time and as the leakage ratio increases. Analysis revealed that flow variation has a little impact on the filtration efficiency, measured as the average efficiency within 2400 seconds. A slight gain in efficiency was also observed in the event of a small leak, which continued to rise somewhat for a larger leak as the flow rate increased. Further investigation of three different types of filter media with various efficiencies revealed that the most efficient medium is more sensitive to the leakage ratio. Nevertheless, fractional efficiencies were not investigated or reported in this study since a total dust concentration of 20 mg/L was injected upstream of the filter media, with more particles in the 15 μm size as displayed on the provided particle size distribution graph. Additionally, the study lacks accuracy as it considered external leaks to be equivalent to internal leaks and presumed that the filter medium would perform similarly in both scenarios. We drew this conclusion based on the paper's discussions of filter media with pinholes and breakage of filter medium, together with the use of a filter bypass cylindrical tube in the experimental setup to create and regulate leakage.

Previous studies used the traditional approach of testing and assessing filters, which included generating a challenge aerosol in the laboratory and measuring the particle counts both

upstream and downstream of the filter using isokinetic probes. Moreover, with respect to a leak in the filter medium, earlier studies concentrated on the experimental assessment of filters that were challenged by only millimeter-sized pinholes. Leak detection is challenging in practical applications and cannot be quantified by penetration tests using the conventional method unless the leak is of significant size to cause failure of the filter media. In such circumstances, the leak (scan) test becomes very crucial. This research seeks in its first part to address gaps in prior studies by examining the auto scanning technology for testing and evaluating leak detection in full-scale HEPA filters. The testing results of this technology will be compared with the traditional method for testing HEPA filters established by the ASHRAE 52.2 standard. Our objective in the second part is to computationally evaluate the performance and sensitivity of HEPA filter media when challenged with micro-sized leaks. This aims to address the limitations of prior studies, where experimental investigations were not feasible due to the inability of even highly precise pressure instruments to detect pressure differential changes across the filter media in the presence of very small leaks.

1.2 Research Objectives

This research seeks in its first part to cover the gaps in earlier studies by assessing full-scale filter performance using auto-scan technologies rather than just the traditional method specified by ASHRAE 52.2 and comparing the two methods for their integrity of detecting small leaks. This necessitates the implementation of several prerequisite tests, including the examination of the housing that contains the filter with pressure decay testing for leakage, along with aerosol dispersion uniformity upstream and downstream of the filter. The ultimate goals of this part at the university level, in conjunction with our collaboration with USDA and DHS entities, are to support biological containment design and operations of the National Bio

and Agro-Defense Facility (NBAF) at Kansas State University (KSU), as well as to operate an education and training center that can evaluate prototypes of the NBAF filtration units over a range of conditions and functions. However, the primary outcome of this part is to enhance our understanding and use of the test criteria outlined in standards such as the Institute of Environmental Sciences and Technology (IEST), the International Organization for Standardization (ISO), and ASHRAE to evaluate the performance of intact and leaky HEPA and ULPA filters. This will enable us to progress and establish a solid foundation for further investigation of a HEPA filter medium in the second part of this research.

The objective of the second part of the research is to further investigate both intact and micro-pinholed HEPA filter medium by computationally modeling its microstructure and simulating airflow through it with particles up to 0.5 μm in size to determine the pressure drop and filter media efficiency. This will be regarded as the most comprehensive and realistic modeling of intact and leaky HEPA filters to date. It also has the potential to be used in other types of filter media, guide the design and development of filtration scanning devices, and offer standards a tool for setting and improving criteria for successful filter leak (scan) testing.

1.2.1 Research Methods

We derived extensive knowledge from reading the existing literature and the various standards in this subject, which greatly facilitated our research methods and approaches.

1.2.1.1 Full-Scale Filter Housing Auto-scan Test System

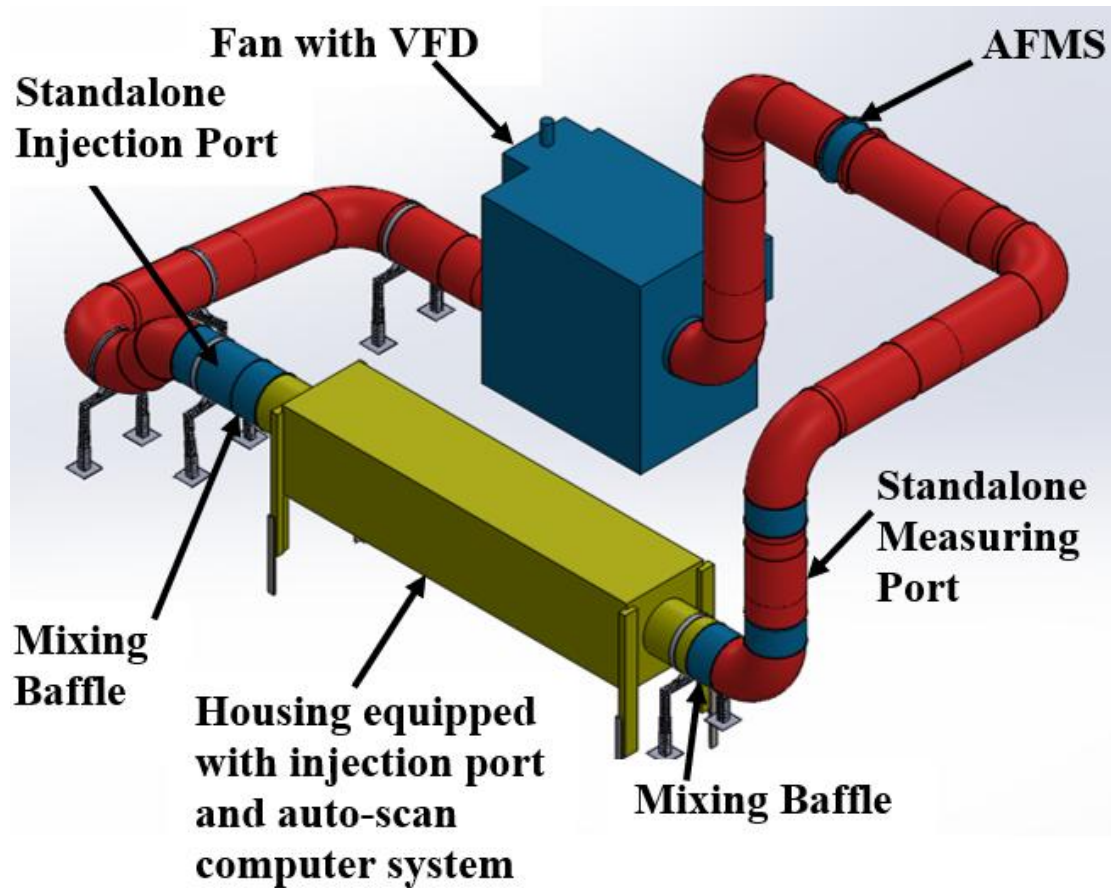
For the first part of the research, we have designed and constructed a biofiltration testing center in the Biosecurity Research Institute (BRI) at KSU that can provide objective testing and evaluation of HEPA filter performance used in NBAF, assess HEPA housings and auto-scan

systems, evaluate failure modes in HEPA filters and decontamination procedures, and support long-term training and education modules for the auto-scan systems.

The center's HEPA test stand consists of a closed air loop as shown in Figure 1.1 that can be used to test interchangeably containment and auto-scan technology from two of the most reputable companies. The ductwork is made of stainless-steel tubing with an inner diameter of 14 inches and joining sections that are custom fabricated to prevent air infiltration and ease filter testing using both housings. The ductwork is occupied with upstream and downstream mixing baffle sections that are designed per the ASHRAE 52.2 standard and contain, respectively, the injection and sampling tubing for independent testing the filter efficiency and authenticating the results obtained using the auto scan technology. A duct-mounted air flow measurement station (AFMS) with a differential pressure transmitter that has $\pm 0.5\%$ accuracy for a pressure up to 5.0 IWC was installed and connected to a data acquisition (DAQ) system to measure the airflow and velocity. The air inlet is drawn into the housing by a floor-mounted centrifugal fan of 2400 CFM maximum capacity, and the volumetric flow rate is regulated through a variable frequency drive (VFD), which gives flexibility to test a filter at different flow rates. The two housings undergoing testing contain a pre-filter compartment that won't be employed in our current testing since our main objective is to challenge the HEPA filter, include tight dampers at the inlet and outlet, and other ports for decontamination injection, humidity, and temperature sensors, and also Magnehelic pressure transmitters to determine the pressure losses across the pre-filter, HEPA filter, and housing. These housings accommodate a standard $610 \times 610 \times 292 \text{ mm}^3$ HEPA filter into their seatings. The aerosol generator is a Laskin nozzle capable of producing poly alpha olefin (PAO 4) oil challenge aerosol particles with a geometric mean diameter of $0.229 \mu\text{m}$, which are then delivered into the duct system. The challenge aerosol concentrations will be

measured upstream and downstream of the filter using optical particle counters and then displayed on the auto-scan computer monitor to verify compliance with the minimum requirements in the standards.

Figure 1.1. Diagram of Filter Housing Auto-scan Test System



1.2.1.2 Modeling and Software

For the second part of the research, we utilized free and open-source software, including Python 3.11 for developing fiber generation codes, Ansys SpaceClaim for importing the fiber model STL file and establishing the computational domain, ANSYS Fluent meshing and solver tools for configuring the mesh and solving the problem, and C++ programming language for creating user defined functions (UDFs) to improve the built-in equations in Fluent solver.

1.2.1.3 Filter Media Test Rig

We constructed another testing apparatus, as shown in Figure 1.2, in the Institute of Environmental Research (IER) at KSU that accommodates small-sized filter sheets (media) in order to further validate experimentally our developed model in the second part of the research and conduct additional analysis. The major components of the test stand are: the multi-speed blower, the pre and post filter to enclose the tested filter media and insure a clean test chamber, the PAO generator that introduces the poly-disperse aerosol to the chamber through a regulating splitter valve to prevent the high generated aerosol concentrations which can clog the filter very rapidly, the differential pressure transmitters to measure the airflow and the pressure across the tested filter medium, and the scanning mobility particle sizer (SMPS) consisted of a TSI 3080L electrostatic classifier and a TSI 3775 condensation particle counter (CPC) shown in Figure 1.3 to analyze the number concentration for different size particles with diameter smaller than $1\ \mu\text{m}$ over 120 seconds for each sampling scan and 15 seconds for retrace time. This mini flow loop allows us to test more and different types of filters, including pleated and flat ones.

Figure 1.2. Experimental Setup for Testing Filter Media

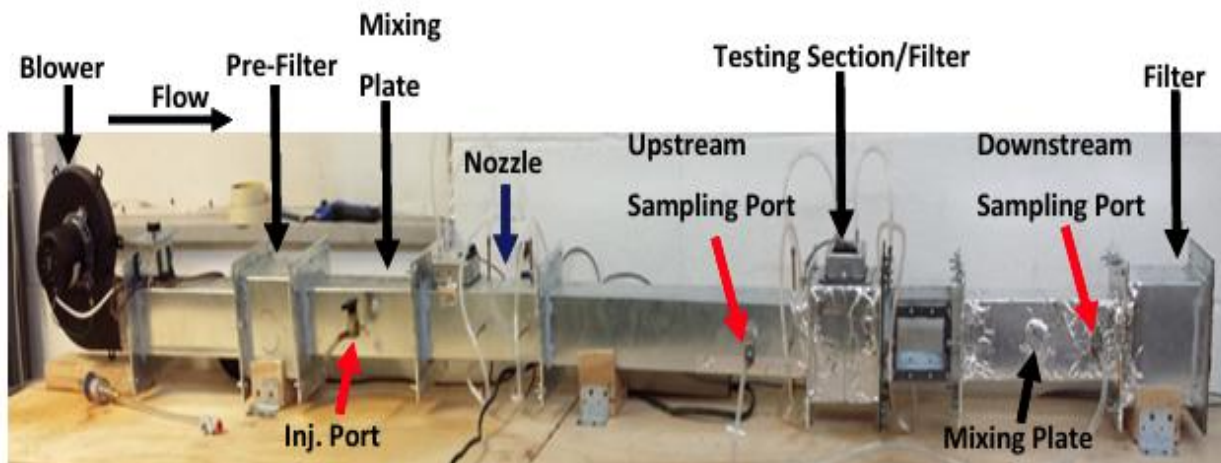
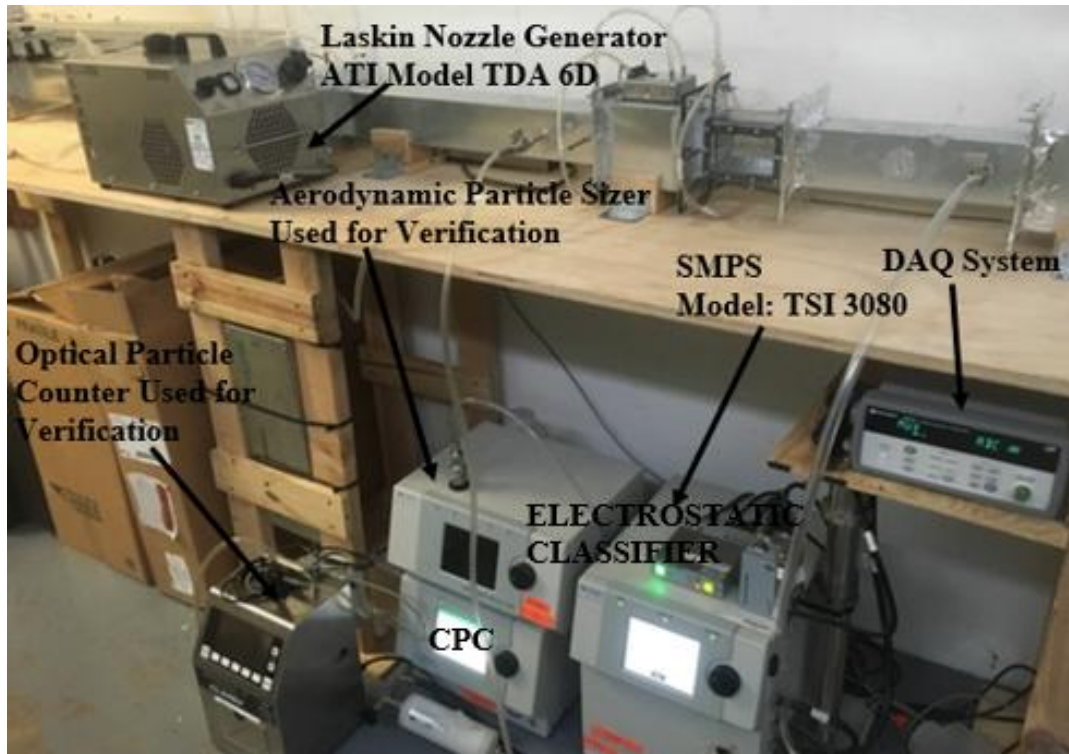


Figure 1.3. Standalone Testing Equipment



1.2.1.4 Techniques and Testing Instrumentation

Prior research conducted by Mouret et al. (2009), Bach & Schmidt (2007), and Li et al. (2022) employed various techniques to induce a leak in filter media. These techniques included respectively calibrated needles, the use of CO₂ laser with pinhole sizes dictated by the laser energy, and a filter bypass tube equipped with a control valve. The utilization of hypodermic needles with larger gauges has been adopted in our experimental work due to their greater availability and ability to achieve smaller leaks compared to those created in prior investigations. Table 1.1 provides the nominal outer and inner diameters of these calibrated hypodermic needles.

Table 1.1. Used Hypodermic Needle Sizes

Needle Gauge	Nominal Outside Diameter (mm)	Nominal Inside Diameter (mm)
34	0.159	0.051
31	0.260	0.133
26	0.464	0.260
25	0.514	0.260
22	0.718	0.413
21	0.819	0.514
20	0.908	0.603
18	1.270	0.838

The measuring instruments used for testing the full-scale filter and filter media include the Lighthouse R3104 and Solair 1100LD optical particle counters integrated within the auto-scan system, along with our standalone devices such as the Climet Spectro 0.3 optical particle counter (OPC) and the TSI SMPS. The R3104 OPC was utilized by one of those two reputable companies to measure the upstream and subsequently the downstream aerosol concentrations. This OPC covers a single channel of 0.3 μm particle size. The alternative company's housing and auto-scan system utilized two of the Solair 1100LD to simultaneously measure the upstream and downstream aerosol concentrations. This OPC accommodates the measurement of particle sizes in four ranges: 0.15–0.2 μm , 0.2–0.25 μm , 0.25–0.3 μm , and greater than 0.5 μm . The Climet laser diode OPC supports up to 16 channels of user-adjustable measurements, and it measures the mass and/or count of aerosols between 0.3–10 μm in diameter with a sampling volume of 0.1 CFM that enables the OPC to sample a concentration range of 0– 10×10^6 particles/ ft^3 . In an OPC, the concentrated aerosol passes a laser beam, resulting in light scattering. The scattered light is collected by an elliptical mirror positioned at a scattering angle of $90^\circ \pm 60^\circ$ and subsequently detected by a solid-state photodetector. Particles are then counted and measured in size based on the intensity of the scattered light. The SMPS can be configured

to measure particles in the range of 0.01–1 μm based on the particle's electrical mobility. It comprises the TSI model 3080L electrostatic classifier integrated with the model 3081 long differential mobility analyzer, and the TSI model 3775 CPC. This electrostatic classifier segregates particles until they ultimately achieve a monodisperse aerosol sample. Following separation, the aerosol particles leave the electrostatic classifier and proceed to the condensation particle counter for measurement. This CPC works on the basis of a butanol condensation technique that grows small particles into larger droplets that can then be detected optically with an optical detector. Technical specifications for the operation of these devices can be found in TSI manuals.

1.2.1.5 Uncertainty of the Particle Measuring Instruments

The OPCs use laser diode technology and employ scattered light intensity to ascertain particle size. The Lighthouse R3104 OPC features two standard particle-size channels of 0.3 μm and 0.5 μm , and it operates at a sampling flow rate of 1 CFM. Its manufacture specified uncertainty is $\pm 3.4\%$ of the reading for concentration at an upper count limit of 2×10^6 particles/ cm^3 , with size separation uncertainties of $\pm 0.9\%$ and $\pm 1\%$ for 0.3 μm and 0.5 μm particle sizes, respectively. The Solair 1100DL OPC has four particle-size channels capable of detecting particles as small as 0.1 μm and as large as 1 μm , with a sampling flow rate of 1 CFM. Its manufacture specified uncertainty is $\pm 3.4\%$ of the reading for concentration at an upper count limit of 21×10^6 particles/ cm^3 , with size separation uncertainties of $\pm 0.2\%$, $\pm 0.5\%$, $\pm 0.8\%$, $\pm 0.6\%$, $\pm 0.9\%$, and $\pm 1\%$ for 0.1 μm , 0.15 μm , 0.2 μm , 0.25 μm , 0.3 μm , and 0.5 μm particle sizes, respectively. The particles counted by the Climet OPC are binned into 16 channels of different sizes, with a sampling flow rate of 0.1 CFM. The particle size range of this OPC is 0.3 μm to 10 μm , with an uncertainty of $\pm 3.5\%$ for size. Additional specifications of this device

include a size resolution of 0.03 μm at 0.33 μm , an operating temperature range of 0–37.8°C, and an operating humidity range of 10–90%. The TSI SMPS is made up of the TSI model 3080L electrostatic classifier integrated with the model 3081 long differential mobility analyzer and the TSI model 3775 CPC. The SMPS system therefore has the uncertainties of the electrostatic classifier and the CPC, generally about 3–3.5% for the size separation of the electrostatic classifier, and $\pm 10\%$ at $< 5 \times 10^4$ particles/cm³ and $\pm 20\%$ at $< 5 \times 10^7$ particles/cm³ for the CPC.

1.2.1.6 Challenge Aerosol

The NBAF's mission is to conduct research and develop countermeasures for several high-risk pathogens, including rift valley fever (RVF), crimean-congo hemorrhagic fever (CCHF), Nipah, and Japanese encephalitis (JE), which are spherical enveloped viruses with a diameter of $\leq 0.3 \mu\text{m}$. A virus particle comprises genetic material, either DNA or RNA, surrounded by a protective protein coat or an outer envelope. A virus is neither liquid nor solid; however, it can exhibit liquid characteristics due to its mode of transmission involving liquid body fluids. Bacteria and fungi can exist in both solid and liquid forms when cultured in laboratory settings, such as NBAF laboratories. Therefore, most particulate matter in the air, including these microorganisms, must be trapped by the HEPA filtration systems installed in NBAF. Mullins et al. (2003) conducted an experimental analysis to assess the filtration efficiency of two types of aerosols utilizing three distinct fibrous filters. They examined monodispersed PSL (solid) and DEHS (liquid) aerosols with diameters of 0.52 μm , 0.83 μm , 1.5 μm , and 3 μm , evaluated at three velocities: 0.3 m/s, 0.45 m/s, and 0.57 m/s. Their results indicated minimal variation in filtration efficiencies between solid and liquid aerosols for smaller particle sizes, with negligible differences observed at the lowest test velocity. The particle size range of interest in this research is $\leq 0.3 \mu\text{m}$, with airflow velocities through the HEPA fibrous

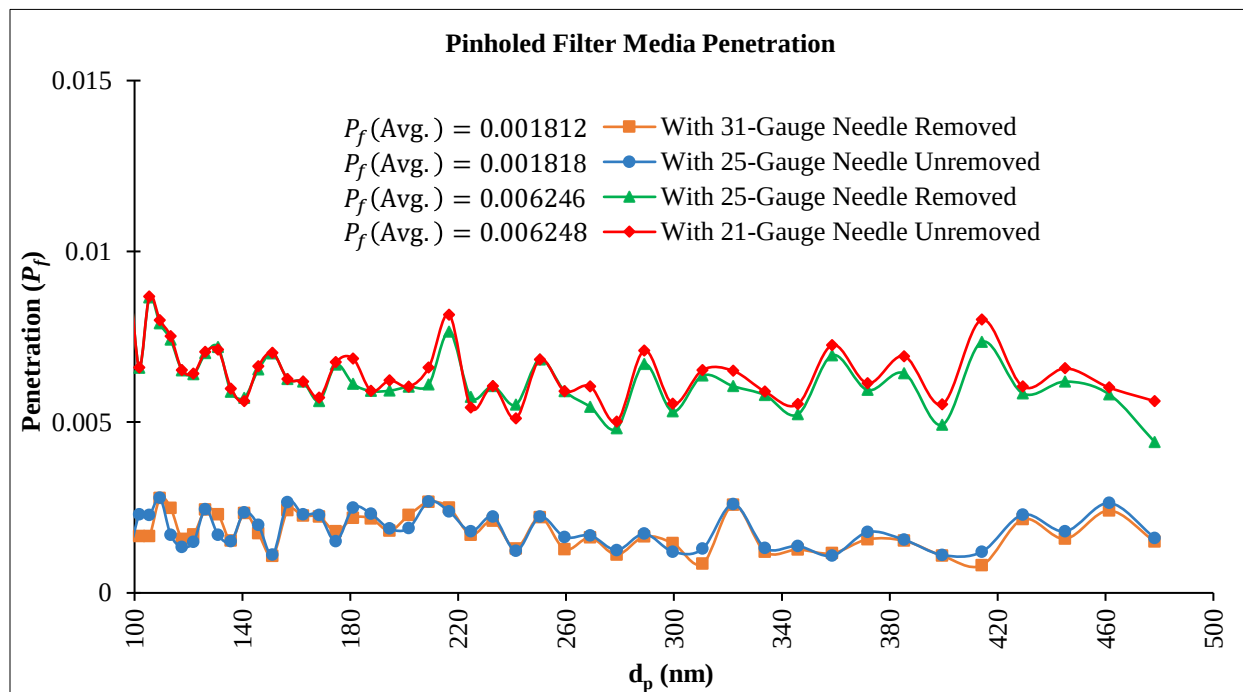
material at or below 0.05 m/s. The application of either solid or liquid challenge aerosol will then yield comparable outcomes in filtration efficiency. The challenge aerosol employed in our experimental work to evaluate these HEPA filtration systems was generated using a Laskin nozzle. It is liquid and spherical in nature, with a geometric mean diameter of 0.229 μm and a standard deviation of 1.68 nm. This method adheres to all HEPA filter testing and procedural standards that specify the use of liquid challenge aerosols, such as DOP, PAO, and DEHS, for HEPA and ULPA filter leak tests.

1.2.1.7 Pinhole Shape

The pore size in HEPA filter media is generally not characterized by a singular pore diameter, as the media comprises a non-uniform membrane of densely packed fibers. A hole created by a sharp circular pin, such as a needle tube, will displace fibers and establish a direct internal bypass through the media, despite its tiny size relative to the filter surface area. Zhang et al. (2014) evaluated the efficacy of a blunt sampling probe in leak detection by puncturing a standard large HEPA filter measuring 610×610×110 mm³, with pinhole leaks introduced using needles of diameters 0.25 mm, 0.35 mm and 0.4 mm. The shape of the leaks was examined using a scanning electron microscope (SEM), revealing that the pinhole displayed minimal deformation post-puncture and maintained a distinct circular diameter, with a certain degree of bridging attributed to the fiber's elasticity for the 0.25 mm pinhole size. In their analysis and calculations, the diameter of the pin-made hole was equated to that of a circular hole. We conducted a series of tests using the filter media test rig to further examine the shape of the leaks in pinholed filter media. The objective was to evaluate the aerosol penetration results of pinholed filter media using 25-gauge and 31-gauge needles, which have external diameters of 0.514 mm and 0.260 mm, respectively, thereby simulating the diameter of a pin-made hole following the

removal of the needle tube post-puncture. These results as illustrated in Figure 1.4 were then compared to those obtained using 21-gauge and 25-gauge needles, which have internal diameters of 0.514 mm and 0.260 mm, respectively, with the needle's circular tube fixed in the media to represent a circular hole diameter. The average penetration resulted in an efficiency difference of 0.0002% for the larger hole and 0.0006% for the smaller hole, particularly for particle sizes greater than 0.3 μm . Therefore, in the evaluation of filtration efficiency at the MPPS and for particles smaller than 0.3 μm , it is justifiable to consider the diameter of a pin-made hole as equivalent to that of a circular hole.

Figure 1.4. Pinholed Filter Media Penetration



1.3 Chapter Progression

The following chapters of this dissertation will thoroughly address the objectives specified in this chapter (Chapter 1), beginning with a comprehensive review of relevant literature concerning air filtration in Chapter 2 and progressing to the research design and data

collection methods for the in-situ assessment of full-scale HEPA filters and their housings used in NBAF in Chapter 3. Chapter 4 introduces a computational model of H14 HEPA filter media that examines conditions both with and without internal leaks, along with the related findings and conclusions. Chapter 5 presents further experimental investigations on HEPA filter media, with an emphasis on perforated media with varying pinhole sizes to establish correlations for aerosol penetration in leaky filter media. Finally, Chapter 6 provides a summary of the research findings and offers recommendations for future efforts and studies.

Chapter 2 – Overview of Literature

High-efficiency particulate air (HEPA) filtration is one of the most efficient air filtration methods that are required in clean air environments. These HEPA filters provide the last barrier for removing particles from a contaminated gas stream before releasing them to the external environment. Filters are rated based on their minimum particle collection efficiency and pressure drop, which is sometimes expressed as filter permeability. Then, the important parameters in assessing an air filter are particle collection efficiency and pressure drop, which are influenced by several parameters such as filter medium properties, filter design, particle loading, and operating conditions. However, a low pressure drop across the filter and a high collection efficiency are the critical desires in the filter design process. Monitoring the pressure drop and testing the filter efficiency are essential to determine the optimum performance results and filter change-out frequency.

The National Air Filtration Association (NAFA) uses Equation (2.1) to determine the energy cost based on the final pressure drop as follows:

$$\text{Energy Consumption (KWH)} = \frac{Q \cdot \Delta P \cdot t}{1000\epsilon} \quad (2.1)$$

Where:

Q = airflow (m³/sec)

ΔP = average pressure loss (Pascal)

t = time in operation (hours)

ϵ = fan efficiency

This formula shows that a lower average pressure drop causes lower overall electrical operating costs since we know that the filter operates at a specific air flow rate and fan efficiency. It also

helps in determining the optimal operational pressure drop range and the best time to change out or clean the filter.

In contrast to other types of filters like granular and fabric filters, HEPA filters often have a lower flow resistance and need to be disposed of rather than cleaned. Also, the HEPA filtration system requires periodic checkout for the collection efficiencies since it does not remove particles of different diameters with equal efficiencies to determine whether it passes or not the minimum efficiency rating listed in the standards at a rated airflow. This minimum efficiency rating is specified at a design point of 0.3-micron particle size, even though recent filtration studies have revealed that the particle size that most easily passes through the filter media, which is called the most penetrating particle size (MPPS), is typically within the range of 0.11–0.16 μm in aerodynamic diameter. The current minimum efficiency testing at 0.3-micron particle size is still reliable since cheaper laser particle counters do not have enough size resolution around 0.1 μm , and the MPPS will vary with velocity.

High flow velocity through a wet filter media or in a humid filter environment condition, periodic decontamination testing for the filter element, manufacturing defects, and poor seating of gaskets to a filter housing can cause small holes in the filter paper and cracks in the sealing. It has already been demonstrated that these small holes through the filter media can result in a leak that does not contribute significant changes in the efficiency values and is not detected by conventional control systems based on monitoring pressure drop in the filter medium. It is therefore essential to scan the filter in order to detect and size that leak and to be able to predict the behavior of the filters in terms of performance and particularly the changes in efficiency and pressure drop in the existence and under the condition of a leak regime.

Standards and recommended practices, such as the Institute of Environmental Sciences and Technology (IEST-RP-CC001.7 and CC034.5, 2022) and the International Organization for Standardization (ISO 14644-3, 2019), provided test procedures for in-place testing HEPA filters for leaks. New technology, such as the auto-scan system available from Camfil Farr and Krantz filter systems, has been developed based on these standards to provide a safe filtration system. Using this automated system, we are able to detect a leak through the filter media and housing, monitor the pressure drop across the filter, test the filter efficiency, and decontaminate the filter element and housing to replace the filter when it is needed. We should recall that there are a set of prerequisite tests that are required by the standards prior to performing the filter penetration leak test, such as filter housing pressure decay and aerosol uniformity, to make sure of equally challenging the upstream side of the filter.

2.1 HEPA Filter Structure and Fabrication

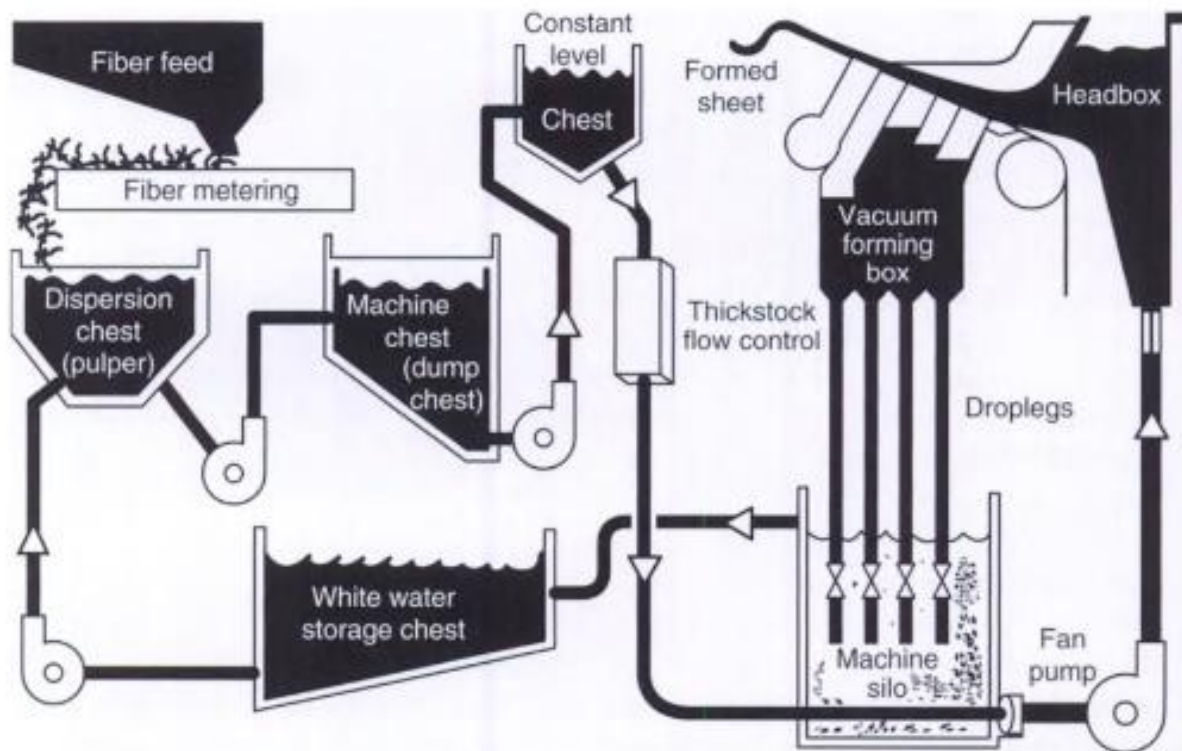
A large-scale industrial HEPA filter is constructed using deep space folds of nonwoven micro-glass fiber media in an extended-surface structure. The media, which are packed into the enclosing frame using urethane sealant or alternative glues depending on the manufacturer, are kept safe from damage by the tapered corrugated aluminum separators with hemmed edges. A gasket is placed on one side of the enclosing frame to create a positive and tight seal upon installation to the filter seat of the containment housing. The media's microscopic structure reveals that it is made of a randomly arranged and oriented array of fiberglass fibers measuring between 0.075 μm and 2.35 μm , with a predominance of fibers in the 0.075 μm to 0.3 μm size range (Bortolassi et al., 2017). The fibers in the fiberglass media have an average diameter of 0.59 μm , according to their scanning electron microscope (SEM) analysis. There are more small

fibers than large ones, with a few fibers ($< 10\%$) in the diameter $> 1\ \mu\text{m}$ range and fewer (1%) in the diameter $> 1.6\ \mu\text{m}$ range.

Nonwoven media can be formed using two main processes: dry formed and wet laid. However, most glass fiber media used in filtration are made using wet lay machines, and the wet lay process requires very complicated chemistry to make high-quality glass media (Hutten, 2016). The initial step in fabricating fiberglass media is the dispersion of glass fibers, which come in a variety of diameters and lengths, into an aqueous slurry known as fiber stock utilizing a closed-loop process water system (white water). Glass fibers are then fed into a pulping machine (pulper) that separates and suspends the fiber bundles to create a homogeneous slurry before being fed into the web former's headbox. Common types of headboxes are inclined wire shown in Figure 2.1 and Rotoformer. However, the traditional type of paper machine utilized to make microglass fiber media is called the Fourdrinier headbox. The headbox, which feeds the diluted stock from the pulper to a forming screen where it is shaped into a wet sheet, is the core component of the wet lay process. Applying a binder is essential after formation to achieve the best strength and performance because the produced wet sheet still has a relatively low strength. A variety of acrylics, including formaldehyde-free and bio-based ones, have been created over years of development, replacing the urea-formaldehyde binders used in the early fiberglass nonwoven webs (mats). Several types of resins or chemical agents can be added to the fiber stock or slurry prior to the formation of the wet sheet to increase the strength of the web when it is dried. It is crucial to drain the water and activate or cure the binder before proceeding to the drying stage of the process, which yields the final product. A continuous conveyor belt next transports the wet web into the dryer, where draining the water and curing the binder are completed. To dry the sheet and remove any remaining water, a mix of heat and mechanical

techniques might be employed. Wet presses, foils, and suction slots are examples of mechanical devices. Infrared and microwave drying technologies, hot air dryers, hot air ovens, and steam heater dryers are the most common types of thermal devices. The residual chemicals and fiber-containing white water will drain to the silo from the web-forming machine during the drying process. They then circulate back around in a closed loop to recover the drained resources (materials) for further reuse in the sheet formation and to maintain the suspension of fibers. The final media properties can be customized to meet the specific requirements of the final applications through adjustments of the settings in the formation step and by modifying the binder system (material), the media thickness and density, as well as the fiberglass type, size, length, diameter, and mixture.

Figure 2.1. Inclined Wire Wet-Lay Process



2.2 Testing Methods

HEPA filter efficiency and leak scan testing are performed to confirm that the filters are free of damage and small leaks. Photometers or particle counters are the methods used to test and scan the filters for a leak. The photometer and the particle counter use different detection principles. The photometer measures the total area of the light scattered, which will be converted to a voltage and then to the mass concentration of the aerosol. The optical particle counter collects a single particle light scatter and measures the size and the actual number concentration of the aerosol. Table 2.1 shows the filter classifications and ratings in accordance with the IEST-RP-CC001. The smallest leak size that can be detected is called the designated leak size, and it is associated with the filter type. The designated leak size is normally 0.01% for HEPA and smaller for ultra-low particulate air (ULPA) filters. Other common filter performance specifications are shown in Table 2.2. Those filters are generally used in Europe and correspond to the European standard (EN 1822, 2019), which differs from the IEST by the method of testing and scanning used, the requirements of one or two separate tests for some filter types, and the tests that are conducted either at a specific particle size or at the MPPS for each standard.

Table 2.1. Filters Classifications and Ratings per IEST-RP-CC001.7

Filter Type Per IEST	Minimum Efficiency (Max. Penetration)	Test Method	Tested at particle size (µm)	Scan Test Method	Designated Leak Penetration	Comments
A (HEPA)	99.97 % (0.03 %)	Photometer	0.3 MMD	Not required	None	Tested at rated air flow rate
B (HEPA)	99.97 % (0.03 %)	Photometer	0.3 MMD	Not required	None	Tested at rated air flow rate and 20% of the rated flow rate
C (HEPA)	99.99 % (0.01 %)	Photometer	0.3 MMD	Photometer	0.01%	Tested at rated air flow rate
D (HEPA)	99.999 % (0.001 %)	Photometer	0.3 MMD	Photometer	0.005%	Tested at rated air flow rate
E (HEPA)	99.97 % (0.03 %)	Photometer	0.3 MMD	Not required	None	Tested at rated air flow rate
F (ULPA)	99.9995 % (0.0005 %)	Particle counter	0.1-0.2 or 0.2-0.3	Particle counter	0.0025%	Tested at rated air flow rate
G (Super ULPA)	99.9999 % (0.0001 %)	Particle counter	MPPS	Particle counter	0.001%	Tested at rated air flow rate
H (HEPA)	99.97 % (0.03 %)	Particle counter	0.1-0.2 or 0.2-0.3	Not required	None	Tested at rated air flow rate
I (HEPA)	99.97 % (0.03 %)	Particle counter	0.1-0.2 or 0.2-0.3	Not required	None	Tested at rated air flow rate and 20% of the rated flow rate
J (HEPA)	99.99 % (0.01 %)	Particle counter	0.1-0.2 or 0.2-0.3	Photometer or Particle counter	0.01%	Tested at rated air flow rate
K (HEPA)	99.995 % (0.005 %)	Particle counter	0.1-0.2 or 0.2-0.3	Photometer or Particle counter	0.008%	Tested at rated air flow rate
Note: Tests are done at temperature = 70 °F, uniform velocity, and filter resistance ≤ 1 IWC						

Table 2.2. Other Common Filters Classifications and Ratings per EN 1822:2019

Filter Type Per IEST	Minimum Efficiency (Max. Penetration)	Test Method	Tested at particle size (μm)	Scan Test Method	Designated Leak Penetration	Comments
H10	85 % (15 %)	Particle counter	MPPS	Not required	None	Tested at one flow rate
H11	95 % (5 %)	Particle counter	MPPS	Not required	None	Tested at one flow rate
H12	99.5 % (0.5 %)	Particle counter	MPPS	Not required	None	Tested at one flow rate
H13	99.95 % (0.05 %)	Particle counter	MPPS	Particle counter	0.25%	Tested at one flow rate
H14	99.995 % (0.005 %)	Particle counter	MPPS	Particle counter	0.025%	Tested at one flow rate
U15	99.9995 % (0.0005 %)	Particle counter	MPPS	Particle counter	0.0025%	Tested at one flow rate

2.3 Aerosol Filtration Theories

2.3.1 Mechanisms of Collection

Mechanical capture of a particle passing through a fibrous filter is achieved by three major mechanisms: diffusion deposition, inertial impaction, and direct interception. Diffusion deposition is dominant for the particle diameter size less than $0.2 \mu\text{m}$, and it decreases as the particle diameter gets larger due to the decreased random motion of particles as the size increases. Inertial impaction is increasingly dominant for a larger particle size greater than $1 \mu\text{m}$ because of its size and inertia that make it unable to adjust quickly to the suddenly changing streamlines in the vicinity of a fiber. Interception is dominant gradually for the particle size range greater than $0.2 \mu\text{m}$ because of its finite size, which causes the particle to follow a gas streamline

in the vicinity of a fiber and then collide with it. Consequently, the diffusion and interception are relatively weak in the 0.1–0.3 μm particle diameter size range. The combined effect of these three collection mechanisms results in the classic collection efficiency curve, which is a convenient way of describing the performance of a filter. The performance of a filter is generally rated by the collection efficiency at a certain flow rate and a particle size within 0.1–0.3 μm , which is called the most penetrating particle size range.

2.3.2 Single Fiber Efficiency

The single fiber efficiency (E_s) is called a fractional efficiency, which is the collection of a particle by an individual fiber. It is a function of the physical properties of the filter sheet, the aerosol particle size, and the operating condition of the air flow, such as velocity, absolute temperature, viscosity, and pressure. It is a result of all the major collection mechanisms plus any particles contacting the fiber by means of gravitational settling, which has itself less effect on the single fiber efficiency and can be ignored.

The first study on filtration with fibrous pads was carried out by Albrecht in 1931 and Kaufmann in 1936, who expressed the single fiber efficiency as the product of the penetrations due to each mechanism (P_m), which can be explained by using the probability concept of mutually exclusive events, where events cannot occur together and thus their intersection probability is zero:

$$\begin{aligned}
 E_s &= 1 - P_d \times P_i \times P_r = 1 - (1 - E_d)(1 - E_i)(1 - E_r) \\
 &= E_d + E_r + E_i - E_r E_d - E_r E_i - E_d E_i + E_r E_d E_i \\
 &= E_d + E_i + E_r - (E_r \cap E_d) - (E_r \cap E_i) - (E_d \cap E_i) \\
 &\quad + (E_r \cap E_d \cap E_i) = E_d + E_i + E_r
 \end{aligned} \tag{2.2a}$$

One of the simplest ways to approximate the single fiber efficiency is to add the collection efficiencies due to each mechanism, keeping the assumption valid that only one mechanism happens at a time and each mechanism is prevalent at different particle sizes. This idea gave reasonable accuracy when comparing it with the experimental data (Lee, 1982). It is based on the probability concept of mutually exclusive events as well:

$$\begin{aligned}
 E_s &= E_d \cup E_r \cup E_i \\
 &= E_d + E_i + E_r - (E_r \cap E_d) - (E_r \cap E_i) - (E_d \cap E_i) \\
 &\quad + (E_r \cap E_d \cap E_i) = E_d + E_i + E_r
 \end{aligned} \tag{2.2b}$$

Hinds (1999) added the E_g term to address aerosol gravitational settling and the interaction E_{dr} term to account for collection due to the interception of diffusing particles where neither of these mechanisms is leading.

E_d : is the single fiber efficiency caused by diffusion deposition

E_i : is the single fiber efficiency caused by impaction

E_r : is the single fiber efficiency caused by direct interception

E_{dr} : is the single fiber efficiency caused by the interception of the diffusing particles

E_g : is the single fiber efficiency caused by aerosol gravitational settling

2.3.2.1 Single Fiber Efficiency Ratio

Consider a cylindrical fiber of d_f diameter and length $L_f = W$ inside a filter matrix of a $H \times W$ face area in which the air flow is perpendicular to the fiber as shown in Figure 2.2. We assume in this case that only the particles flowing in between the center and surface lines of the fiber are to be removed by that particular fiber and that the streamlines are unchanging and not diverting. The distance (y_0) is from the center line of the fiber to the highest streamline carrying aerosol particles at a specific time that is within the center and the surface lines of the fiber.

Therefore, a fiber that has an efficiency of unity or less removes the particles that would lie within the volume cleaned out by its vertical cross-sectional area and the velocity vector of the air. Then, we can express the value of the single fiber efficiency by taking the ratio of the collected particle rate, which is $N(\text{entering particles concentration}) \times V(\text{flow velocity}) \times 2y_0 \times W$ to the total particle rate that can be filtered by that individual fiber, which is $N \times V \times d_f \times L_f$.

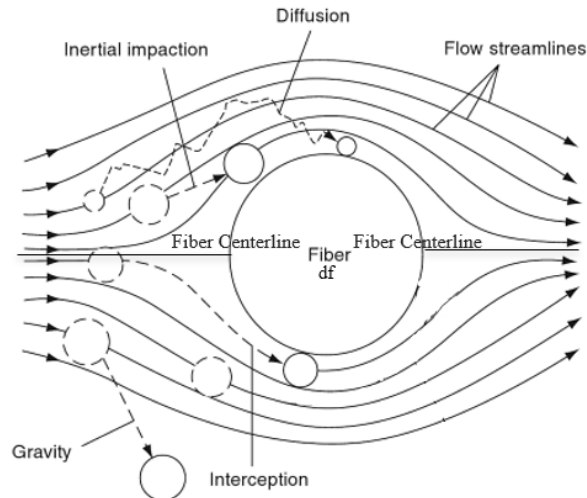
This is equivalent to the ratio of $\frac{2y_0}{d_f}$, i.e., the value of the single fiber efficiency:

$$E_s = \frac{2y_0}{d_f} = \frac{y_0}{r_f} \quad (2.3a)$$

The y_0 variable is strongly dependent on the airflow field and the streamline pattern that carries the particles. Using the general equations of a stream function, which illustrate the flow pattern, its direction, and speed ($V_x = \frac{\partial \psi}{\partial y}$; $V_y = \frac{-\partial \psi}{\partial x}$), and if the stream function describes a uniform airflow in the x-direction ($V_x = V = \frac{\psi}{y}$), then the single fiber efficiency can be simplified as:

$$E_s = \frac{2\psi}{Vd_f} = \frac{\psi}{Vr_f} \quad (2.3b)$$

Figure 2.2. Particle Capture Mechanism by a Single Fiber



The single fiber efficiency can be defined in a substitute way in case the path line of the particles cannot be predicted as in the situation of the diffusional or impaction deposition of the particles (Brown, 1993).

$$E_s = \frac{n}{NVd_fL_f} \quad (2.3c)$$

Where N is the concentration of particles in the air, and n is the particle capture rate by a single fiber per unit time.

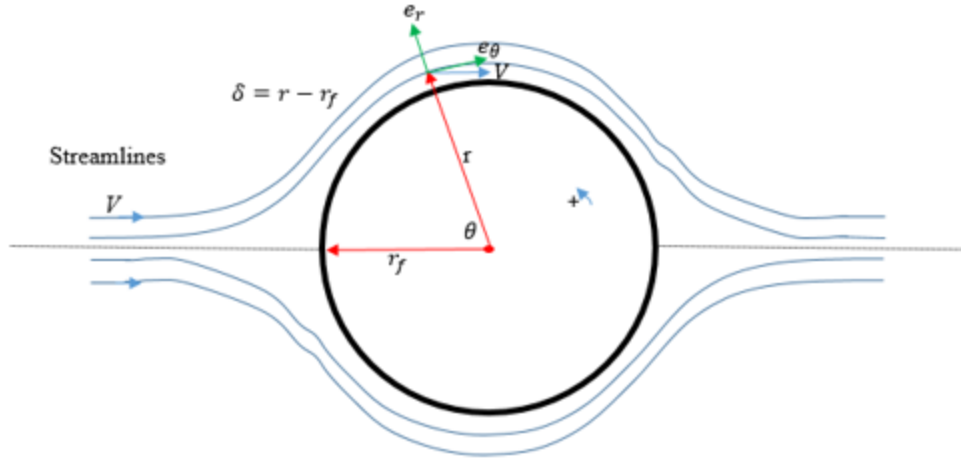
2.3.2.2 Flow Field Around a Cylindrical Fiber

The nature of the airflow field around a cylindrical fiber is commonly controlled by the viscous rather than inertial forces of the air, and that is because of the low Reynolds number. For example, for a maximum air velocity, we run in our lab on a large industrial HEPA filter of $V = 0.034$ m/s and an average fiber diameter of $d_f = 0.6$ μm , the Reynolds number at standard conditions of dynamic viscosity of $\mu = 1.825 \times 10^{-5} \frac{\text{Kg}}{\text{m.s}}$ and air density of $\rho = 1.2 \text{ kg/m}^3$ is

$Re_f = \frac{\rho d_f V}{\mu} = 0.00134 < 1$, which is also considered purely viscous according to Bouland and Renoux flow regimes where $Re_f < 0.2$. Therefore, the flow inside a filter and around a filter's fiber is laminar and incompressible since the filter pressure drop is very low (a few inches of water) and can be characterized by a smooth pattern of streamlines that have the same upstream-downstream symmetry around a fiber as shown in Figure 2.3. It can also be classified in the continuum or slip flow regime based on the Knudsen number ($Kn = \frac{\lambda}{r_f}$), whether the size of the fiber is large or not compared to the mean free path (λ) ($\lambda = 0.067$ μm in the normal temperature and pressure condition). The airflow becomes continuous if the frequency of air molecule collisions is high, and their effects (Knudsen layers) then can be neglected. This implies a very small Knudsen number approaching zero and will be achieved if the fiber radius is

large enough ($r_f > 67 \mu\text{m}$). For the fiber diameter range of $0.075\text{--}2.35 \mu\text{m}$ in the HEPA filter medium, the range of Knudsen numbers becomes $0.057 \leq Kn \leq 1.787$ which makes the flow in the transient slip regime.

Figure 2.3. Air Streamlines Over a Single Fiber



The classical theories of filtration have been developed for the continuum regime where the velocity of the air stream at the fiber boundary is equal to zero, and the collection on the isolated fiber is found from the flow field around a cylindrical tube, ignoring the effect of other fibers in the filter sheet on the flow field around that fiber (cylinder).

For the flow field to be known around a fiber, the equations that characterize the flow should be solved, and the continuity equation should be satisfied. In most filter models, the air flow is considered steady and two-dimensional around one isolated fiber or in an array of fibers, then the Navier-Stokes equations in terms of the streamlines function at different boundary conditions in conjunction with the mass conservation equation shall be solved to obtain the streamlines equation that closely describes the real flow around a fiber. The complete equations of motion in two dimensions are as follows:

- Conservation of mass equation:

$$\frac{\partial \rho}{\partial t} + \frac{\partial(\rho V_x)}{\partial x} + \frac{\partial(\rho V_y)}{\partial y} = 0 \quad (2.4a)$$

- Stream function φ :

$$V_x = \frac{\partial \psi}{\partial y} ; \quad V_y = \frac{-\partial \psi}{\partial x} \quad (2.4b)$$

Equation of motion: Navier-Stokes, which represents the microscopic momentum balances for Newtonian fluid, and it balances the inertial forces on the left side with the pressure, viscous, and gravitational forces in the right side:

$$\left(\frac{\partial \rho V_x}{\partial t} + V_x \frac{\partial \rho V_x}{\partial x} + V_y \frac{\partial \rho V_x}{\partial y} \right) = \frac{-\partial P}{\partial x} + \mu \left(\frac{\partial^2 V_x}{\partial x^2} + \frac{\partial^2 V_x}{\partial y^2} \right) + \rho g_x \quad (2.4c)$$

$$\left(\frac{\partial \rho V_y}{\partial t} + V_x \frac{\partial \rho V_y}{\partial x} + V_y \frac{\partial \rho V_y}{\partial y} \right) = \frac{-\partial P}{\partial y} + \mu \left(\frac{\partial^2 V_y}{\partial x^2} + \frac{\partial^2 V_y}{\partial y^2} \right) + \rho g_y$$

The modern filtration theories account for the flow interference due to the neighboring fibers and the model of what is called a cell unit. The cell theory is based on deriving the general equation of the streamlines through a system of parallel staggered fibers (staggered model) or a channel model where the parallel fibers are distributed equally in the horizontal direction. Then, a cell unit can be taken from that system as an average for all other fibers by assuming a periodic condition for the flow between the fibers. The particular solution of the streamline equation through that cell unit will be found after describing the cell unit and specifying the boundary conditions of the space around it. The difficulty concerning modeling the inhomogeneity of the fibers was solved by adding the inhomogeneity factor (ε) with $\varepsilon = \frac{\Delta P_{theoretical}}{\Delta P_{experimental}}$. The equations of motion were solved excluding and including the slip condition at the surface of the fiber and at low and high Reynolds number to account for the inertial forces. All investigators, including Kuwabara (1958), Happel (1958), Pich (1966), and Lee & Liu (1982), employed the same

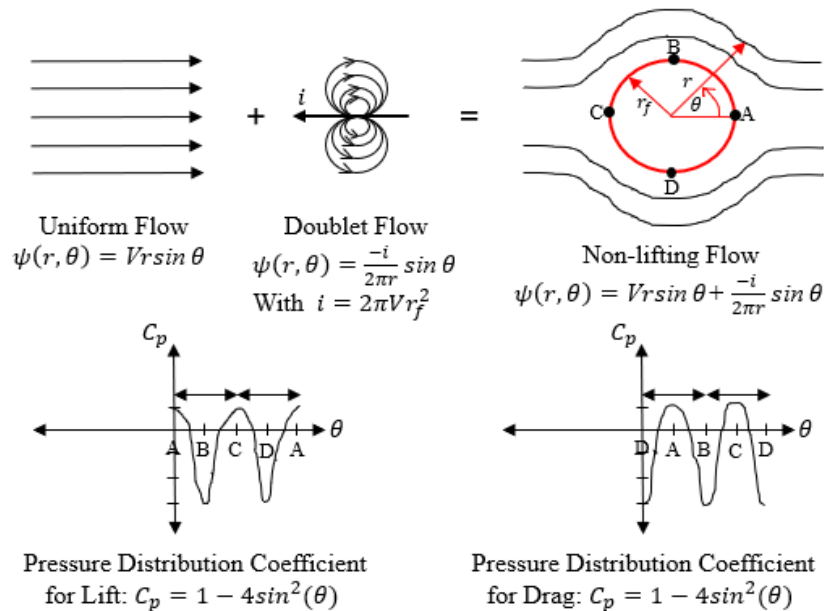
equations explained previously in this section, but they considered the effects of different forces and boundary conditions. Some of the derived particular solutions for the flow field through different cell units, including the assumptions that were made, are explained later in the chapter.

2.3.2.2.1 Isolated Cylindrical Fiber

The flow field through an isolated cylindrical fiber is derived based on the previous flow equations through a cylindrical fiber in an infinite space. This theory agrees with experiments carried out on fibers removed from a filter and gives an acceptable description for the flow field through a granular bed. However, where the inter-fiber distance is very small, like in the case of the fibrous filter, the effects of neighboring fibers should be taken into consideration, and as a consequence, this theory will have flaws in describing the flow field in the fibrous filter.

Lamb (1932) considered the non-lifting potential flow as a solution to represent the flow over a circular cylinder, achieved through the combination of uniform flow and doublet flow. The doublet flow is aligned and positioned such that its axis is parallel to the direction of the uniform flow, exhibiting an intensity denoted as i ($i = 2\pi V r_f^2$), as shown in Figure 2.4.

Figure 2.4. Non-Lifting Flow Illustration



Then the flow field can be written as follows:

$$\begin{aligned}\psi(r, \theta) &= V r \sin \theta \left(1 - \left(\frac{r_f}{r}\right)^2\right) \\ V_r(r, \theta) &= \frac{\partial \psi}{r \partial \theta} = V \cos \theta \left(1 - \left(\frac{r_f}{r}\right)^2\right) \\ V_\theta(r, \theta) &= -\frac{\partial \psi}{\partial r} = -V \sin \theta \left(1 + \left(\frac{r_f}{r}\right)^2\right)\end{aligned}\tag{2.5}$$

The potential flow does not satisfy the velocity boundary condition at the surface of the fiber and does not exert any drag on the fiber. It is a good approximation of the flow far away from the fiber, but the error is significantly close to the fiber. Lamb also derived another solution for the flow field around an isolated fiber by solving the Navier-Stokes equations with the mass conservation equation and neglecting the inertial effects. However, his solution gave a good approximation for $Re_f < 0.1$, $r_f > 0.5 \mu m$ and $r \ll 2r_f^2$ (in the regions close to the fiber surface). The solution has the following form in polar coordinates:

$$\begin{aligned}\psi(r, \theta) &= \frac{V r \sin \theta}{2K_l} \left(2 \ln \left(\frac{r}{r_f}\right) - 1 + \left(\frac{r_f}{r}\right)^2\right) \\ V_r(r, \theta) &= \frac{\partial \psi}{r \partial \theta} = \frac{V \cos \theta}{2K_l} \left(2 \ln \left(\frac{r}{r_f}\right) - 1 + \left(\frac{r_f}{r}\right)^2\right) \\ V_\theta(r, \theta) &= -\frac{\partial \psi}{\partial r} = \frac{V \sin \theta}{2K_l} \left(2 \ln \left(\frac{r}{r_f}\right) + 1 - \left(\frac{r_f}{r}\right)^2\right)\end{aligned}\tag{2.6}$$

where $K_l = 2 - \ln Re_f$ is the Lamb's hydrodynamic factor which is related to the velocity gradient.

More advanced works have been done on this theory, which stays lacking on describing the flow around a single cylindrical fiber in a filter media, since it does not consider its surrounding fibers, which will make the region around the studied fiber not stagnated.

Improvements in this theory lead to the cell unit theory, which will be explained in the next section.

2.3.2.2.2 Cell Unit

This theory studies the flow around a particular fiber extracted from a transverse parallel array of fibers in a direction perpendicular to the flow to represent an average single collector of all other fibers in the array by assuming that the flow is similar through all fibers in the array.

As mentioned before, the airflow in the fiber's vicinity is steady, incompressible, and laminar. Thus, the density remains constant, and the inertial terms in the equation of motions can be neglected in favor of the pressure and viscous forces. Then Equation (2.4a) to Equation (2.4c) can be written in the polar form as well after neglecting the gravity force as:

$$\frac{\partial V_x}{\partial x} + \frac{\partial V_y}{\partial y} = 0 \quad ; \quad \frac{\partial V_r}{\partial r} + \frac{V_r}{r} + \frac{\partial V_\theta}{\partial \theta} = 0 \quad (2.7a)$$

$$V_x = \frac{\partial \psi}{\partial y} \quad ; \quad V_y = -\frac{\partial \psi}{\partial x} \quad (2.7b)$$

$$V_r = \frac{\partial \psi}{r \partial \theta} \quad ; \quad V_\theta = \frac{-\partial \psi}{\partial r}$$

$$\frac{\partial P}{\partial x} = \mu \left(\frac{\partial^2 V_x}{\partial x^2} + \frac{\partial^2 V_x}{\partial y^2} \right) \quad ; \quad \frac{\partial P}{\partial y} = \mu \left(\frac{\partial^2 V_y}{\partial x^2} + \frac{\partial^2 V_y}{\partial y^2} \right) \quad (2.7c)$$

$$\frac{\partial P}{\partial r} = \mu \left(\frac{\partial^2 V_r}{\partial r^2} - \frac{V_r}{r^2} - \frac{2}{r^2} \frac{\partial V_\theta}{\partial \theta} \right) \quad ; \quad \frac{\partial P}{\partial \theta} = \mu \left(\frac{\partial^2 V_\theta}{\partial \theta^2} - \frac{V_\theta}{r^2} + \frac{2}{r^2} \frac{\partial V_r}{\partial \theta} \right)$$

By taking the curl of Equation (2.7c) and substituting the velocity components using Equation (2.7b), Equation (2.7c) will be reduced to the fourth-order scalar biharmonic equation of terms of ψ :

$$\frac{\partial P}{\partial x} \mathbf{i} + \frac{\partial P}{\partial y} \mathbf{j} = \mu \left(\frac{\partial^2 V_x}{\partial x^2} + \frac{\partial^2 V_x}{\partial y^2} \right) \mathbf{i} + \mu \left(\frac{\partial^2 V_y}{\partial x^2} + \frac{\partial^2 V_y}{\partial y^2} \right) \mathbf{j}$$

$$\begin{aligned}
\nabla \times \left(\frac{\partial P}{\partial x} \mathbf{i} + \frac{\partial P}{\partial y} \mathbf{j} \right) &= \mu \nabla \times \left[\left(\frac{\partial^2 V_x}{\partial x^2} + \frac{\partial^2 V_x}{\partial y^2} \right) \mathbf{i} + \left(\frac{\partial^2 V_y}{\partial x^2} + \frac{\partial^2 V_y}{\partial y^2} \right) \mathbf{j} \right] \\
\mathbf{0} &= \mu \left(\frac{\partial}{\partial x} \left(\frac{\partial^2 V_y}{\partial x^2} + \frac{\partial^2 V_y}{\partial y^2} \right) - \frac{\partial}{\partial y} \left(\frac{\partial^2 V_x}{\partial x^2} + \frac{\partial^2 V_x}{\partial y^2} \right) \right) \mathbf{k} \\
\frac{\partial}{\partial x} \left(\frac{-\partial^2 \psi}{\partial x^2 \partial x} + \frac{-\partial^2 \psi}{\partial y^2 \partial x} \right) - \frac{\partial}{\partial y} \left(\frac{\partial^2 \psi}{\partial x^2 \partial y} + \frac{\partial^2 \psi}{\partial y^2 \partial y} \right) \\
&= \frac{\partial^4 \psi}{\partial x^4} + 2 \frac{\partial^4 \psi}{\partial x^2 \partial y^2} + \frac{\partial^4 \psi}{\partial y^4} = 0 \\
\nabla^2 (\nabla^2 \psi) &= \nabla^4 \psi = 0
\end{aligned} \tag{2.8}$$

Equation (2.8) has many solutions possible in the polar form $\varphi = f(r)g(\theta)$, and to satisfy the boundary conditions of the velocity in the θ direction and the continuity equation, the g function should take the form $g(\theta) = \sin\theta$ and the f function $f(r) = r^n$. Thus $\nabla^4 \psi = \nabla^2 (\nabla^2 \psi) = \nabla^2 \left(\frac{\partial^2 \psi}{\partial r^2} + \frac{1}{r} \frac{\partial \psi}{\partial r} + \frac{1}{r^2} \frac{\partial^2 \psi}{\partial \theta^2} \right) = r^{n-4} \sin\theta (n^2 - 1)(n^2 - 4n + 3) = 0$ and then $n = \pm 1, 1, 3$.

Therefore, a general solution for the streamlines function in a system of parallel fibers perpendicular to the flow can be written as:

$$\psi = [c_1 r^{-1} + c_2 r + c_3 r \ln r + c_4 r^3] \sin\theta \tag{2.9}$$

Where: $c_1, \dots, c_4$ are integration constants, and:

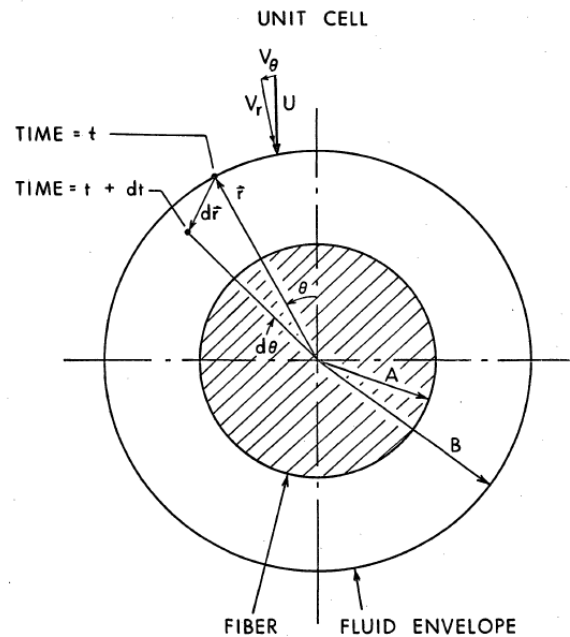
$$V_\theta = -[-c_1 r^{-2} + c_2 + c_3 + c_3 \ln r + 3c_4 r^2] \sin\theta$$

$$V_r = [c_1 r^{-2} + c_2 + c_3 + c_3 \ln r + c_4 r^2] \cos\theta$$

Happel (1959) and Kuwabara (1959) described their average single collector and its environment as two concentric cylinders and assumed boundary conditions at the inner and outer cylinders to derive the constant values in Equation (2.9) and generate a particular solution for the flow around a single collector, including the effects of other neighboring fibers when taking the boundary conditions at the outer surface of the studied fiber and defining the average fiber

fractional volume by the ratio of the singular fiber area to the total area within the boundary of the cell per unit depth. Yeh (1972) indicated that Kuwabara boundary conditions for the cell unit model provide a better representation than Happel, who described the outer surface as a free surface and assumed that the shear stress at that surface is zero. Kuwabara described his unit cell with the same boundary conditions as Happel, except at the outer surface, where he assumed that upper vorticity would cancel the lower vorticity of the cell instead of the zero-shear stress. Figure 2.5 shows a schematic for the Kuwabara cell unit. The first assumption made is that there is no slip condition at the surface of the fiber, which means at $r = r_f$, $V_r = V_\theta = 0$. At the imaginary outer surface, the vorticity is zero ($w = -\nabla^2\psi = \frac{-1}{r}\frac{\partial V_r}{\partial\theta} + \frac{V_\theta}{r} + \frac{\partial V_\theta}{\partial r} = 0$), and the radial velocity can be related to the initial velocity by $V_r = -V\cos\theta$.

Figure 2.5. Kuwabara Unit Cell - Reproduced from Yeh (1972). A Fundamental Study of Aerosol Filtration by Fibrous Filters [Doctoral Thesis, The University of Minnesota]



Then after applying these boundary conditions to Equation 2.9, the particular streamlines equation around the single fiber collector within the unit cell can be obtained and written as follows:

$$\begin{aligned}\psi(r, \theta) &= \frac{Vr \sin \theta}{2Ku} \left(2 \ln \left(\frac{r}{r_f} \right) - 1 + \alpha + \left(\frac{r_f}{r} \right)^2 \left(1 - \frac{\alpha}{2} \right) - \frac{\alpha}{2} \left(\frac{r}{r_f} \right)^2 \right) \\ V_r(r, \theta) &= \frac{V \cos \theta}{2Ku} \left(2 \ln \left(\frac{r}{r_f} \right) - 1 + \alpha + \left(\frac{r_f}{r} \right)^2 \left(1 - \frac{\alpha}{2} \right) - \frac{\alpha}{2} \left(\frac{r}{r_f} \right)^2 \right) \\ V_\theta(r, \theta) &= \frac{V \sin \theta}{2Ku} \left(2 \ln \left(\frac{r}{r_f} \right) + 1 + \alpha - \left(\frac{r_f}{r} \right)^2 \left(1 - \frac{\alpha}{2} \right) - \frac{3\alpha}{2} \left(\frac{r}{r_f} \right)^2 \right)\end{aligned}\quad (2.10)$$

where $Ku = -\frac{1}{2} \ln \alpha - \frac{3}{4} + \alpha - \frac{1}{4} \alpha^2$ the Kuwabara's hydrodynamic factor, which is related to the velocity gradient at the fiber surface, and it is approximated proportionally to the fiber solidity (α) in the filter to compensate for the effect of distortion of the flow field around the fiber. This theory is well accepted for $Re_f < 1$, $\alpha \ll 1$ and $r \ll 2r_f^2$.

It should be noted that advanced works have been performed on cell model theory. Pich (1966) modified Kuwabara's boundary conditions to include slippage at the surface face of the fiber. Lee & Liu (1982) approximated the streamlines function derived by Kuwabara after expanding the natural logarithm term under the assumptions of $\alpha \ll 0$, and $\frac{r}{r_f}$ close to 1 (or $\frac{\delta}{r_f}$ close to 0, where $\delta = r - r_f$). Their result was:

$$\begin{aligned}\psi(r, \theta) &= \frac{V(1 - \alpha) \sin \theta}{Ku(r)} (r - r_f)^2 \\ V_r(r, \theta) &= \frac{V(1 - \alpha) \cos \theta}{Ku} \left(\frac{r - r_f}{r} \right)^2 \\ V_\theta(r, \theta) &= \frac{2V(1 - \alpha) \sin \theta}{Ku} \left(\frac{r - r_f}{r} \right)\end{aligned}\quad (2.11)$$

2.3.2.3 Filter Pressure Drop

Once a flow field is known using the previously explained theories, the corresponding pressure drop using Navier-Stokes equations can be calculated and can be compared with the actual filter pressure drop. It was demonstrated by theoretical and experimental research that there is a linear relationship between the filter pressure drop and flow velocity. Darcy's equation can be used to predict this relationship since porous medium filtration employs low flow velocities for low energy consumption, which allow inertial effects to be disregarded. It is thus possible to express the pressure drop of a filter medium as a function of the air viscosity (μ), filter medium thickness (L), medium permeability (K), and flow face velocity:

$$\frac{\Delta P}{L} = \frac{1}{K} (\mu V) \quad (2.12a)$$

An expression for permeability as a function of fiber diameter and solidity, $f(\alpha)$, was obtained by a series of investigations that started with the theoretical model of Kuwabara (1959) and Happel (1959), who examined the pressure drop across a medium composed of uniformly sized fibers evenly distributed perpendicular to the flow. Following that, the $f(\alpha)$ expression was developed by Davies (1973), Ogorodnikov (1976), Drummond & Tahir (1984), and others. It takes on various forms depending on the theories and models employed. Hosseini & Tafreshi (2010) found that their simulation results for the pressure drops of various filter media with different fiber diameters ranging 0.1–1 μm don't agree with Davies' empirical equation for calculating $f(\alpha)$, which overpredicts $f(\alpha)$ and consequently the pressure drop. This is because Davies' experiments were carried out on microfiber media with fiber diameters ranging 1.6–80 μm and packing density (solidity) less than 30%. On the other hand, their simulation results showed excellent agreement with Ogorodnikov's empirical correlation, which was carried out in the slip and transition flow regime on media with a fiber diameter in the range of 0.2 μm .

$$\frac{\Delta P}{L} = f(\alpha) \frac{\mu V}{d_f^2} \quad (2.12b)$$

$$f(\alpha) = 64\alpha^{\frac{3}{2}}(1 + 56\alpha^3) \quad (\text{Davies, 1973}) \quad (2.12c)$$

$$f(\alpha) = \frac{16\alpha}{-0.5 - 0.5\ln\alpha + 1.15Kn(1 - \alpha)^4} \quad (\text{Ogorodnikov, 1976}) \quad (2.12d)$$

Recent studies by Bian et al. (2018) and Songhui et al. (2023) that account for the impacts of packing density, thickness, face velocity, and fiber size have yielded several empirical correlation equations for predicting the pressure drop across the electrospun nanofiber filters. The first study's theoretical model predicted good agreement with experimental work on nylon electrospun nanofiber filters with a median relative error of less than 4.3%. For various packing densities and face velocities less than 15 cm/s, the theoretical model results from the second study demonstrated excellent agreement with the experimental work of Wang et al. (2007); inaccuracy increases thereafter, reaching a maximum relative error of 15% at a higher velocity of 40 cm/s. However, with a 5.9% packing density, the maximum relative difference between the two models is only about 16.5%; at different packing densities, the difference becomes larger. Although the developed models are limited to extremely thin layers, they may still be applied for a wider size distribution of fibers, such as the conventional fibrous filters. This is because, according to microscopic imaging conducted by Bortolassi et al. (2017) on HEPA H14 and EPM2000 glass fiber sheets, over 60% and 84% of the fibers, respectively, fall within the nanofiber size range ($\leq 0.5 \mu\text{m}$).

$$\frac{\Delta P}{L} = \left(\frac{1.364}{\pi}\right) \left(\frac{\alpha^{0.158}}{1 - \alpha}\right) (Kn^{-0.556}) \frac{\mu V}{d_f^2} \quad (\text{Bian et al., 2018}) \quad (2.12e)$$

$$\Delta P = 18.4955 \frac{\mu \alpha^{1.3821} V}{d_f} Kn^{-0.1262} \left(\frac{L}{d_f}\right)^{1.1128} \quad (\text{Songhui et al., 2023}) \quad (2.12f)$$

2.3.2.4 Diffusion Efficiency

Due to the energy exchange and collision between the particle and air molecule to reach a thermal equilibrium, particles may deviate from airflow streamlines and randomly collide with the fiber surface, resulting in random (Brownian) motion and diffusional deposition on the fiber surface. Particles less than 0.1 μm in diameter exhibit a stronger Brownian effect as they have a higher mobility and will stray from the streamline to deposit onto the fiber surface. If one ignores the effects of vector fields and streamlines, the most basic form of the single fiber diffusion can be written as in Equation (2.13a) using Equation (2.3a) and can be expressed in terms of the mean displacement (δ) of the particle from its original position at the streamline to the fiber surface in the radial direction in a time (t). This displacement expression is related to the particle diffusion coefficient (D) that can be derived from the Stokes-Einstein equation at a known operational testing temperature, T as $D = \mu_p K_B T = \frac{C_c}{3\pi\mu d_p} K_B T$, where μ_p is the particle mechanical mobility, K_B is the Boltzmann's constant number, μ is the dynamic air viscosity, and C_c is the Cunningham slip correction which depends and varies based on the Knudsen number, and particle material and size.

$$E_d = \frac{y_0}{r_f} = \frac{\delta}{r_f} = \frac{\sqrt{2Dt}}{r_f} = \frac{\sqrt{2 \frac{C_c K_B T}{3\pi\mu d_p} t}}{r_f} \quad (2.13a)$$

The Cunningham slip correction factor can be calculated respectively from the semi-empirical equations of (Kim et al., 2005) or (Kowalski et al., 1999) or (Rader, 1990) or (Allen and Raabe, 1985):

$$C_c = 1 + \frac{\lambda}{d_p} \left(2.33 + 0.966e^{-.499\frac{d_p}{\lambda}} \right) \text{ for } 0.5 \leq Kn \leq 83 \quad (2.13b)$$

$$C_c = 1 + \frac{\lambda}{d_p} (2.492 + 0.84e^{-.435\frac{d_p}{\lambda}}) \quad (2.13c)$$

$$C_c = 1 + \frac{\lambda}{d_p} \left(2.418 + 0.882e^{-.39\frac{d_p}{\lambda}} \right) \text{ for } 0.2 \leq Kn \leq 0.95 \quad (2.13d)$$

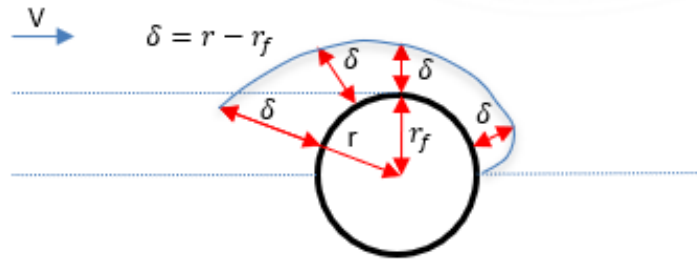
$$C_c = 1 + \frac{\lambda}{d_p} \left(2.284 + 1.116e^{-.5\frac{d_p}{\lambda}} \right) \text{ for } 0.03 \leq Kn \leq 7.2 \quad (2.13e)$$

in which $\lambda = 0.067 \times 10^{-6}m$ (Reist, 1993) is the mean free path of the gas molecule.

If one considers the effects of vector fields and the equation of the streamline explained in the previous section, the mean displacement (δ) can be noticeable from Figure 2.6 that it increases with θ (0 to π) and can be related to θ by $\frac{d\delta}{d\theta} = \frac{r_f \frac{d\delta}{dt}}{\frac{d\theta}{dt}} = \frac{r_f D}{V_\theta \delta} = \frac{r_f D}{\frac{2V\delta}{r_f}} = \frac{Dr_f^2}{2V\delta^2}$ which will lead to $\delta_0 = \left(\frac{3r_f^2 D \pi}{2V} \right)^{1/3} = 2.1123 r_f P_e^{-1/3}$ where ($P_e = \frac{2r_f V}{D} = \frac{d_f V}{D}$) by integrating between $\theta = 0$ to π and $\delta = 0$ to δ_0 . The single fiber diffusion efficiency can be written in advance form now using Equation (2.3b) to form:

$$E_d = \frac{\psi}{V_0 r_f} = \frac{\delta_0^2}{r_f^2} = 4.462 P_e^{-2/3} \quad (2.13f)$$

Figure 2.6. Approximate Mean Trajectory of a Specific Particle Size



Hence the effectiveness of this mechanism is strongly related to the Peclet Number (P_e) which indicates the relative importance of flow-driven transport versus diffusive (random motion) transport of particles, and then E_d can be written in the form of:

$$E_d = c_1 P_e^{c_2} \quad (2.13g)$$

Where c_1 and c_2 are constant obtained analytically from the equation of convective diffusion and can vary based on the model used and boundary conditions. The equations mostly used for single fiber efficiency due diffusional deposition are given theoretically using the Kuwabara flow field by (Lee & Liu, 1982), and (Stechkina & Fuchs, 1966):

$$E_d = 2.58 \left(\frac{1-\alpha}{Ku} \right)^{\frac{1}{3}} P_e^{-\frac{2}{3}} \quad (2.13h)$$

$$E_d = 2.9(Ku)^{-\frac{1}{3}} P_e^{-\frac{2}{3}} + 0.62 P_e^{-1} \quad (2.13i)$$

Where Ku is the Kuwabara factor which is a function of packing density given by Liu & Rubow (1986) and Brown (1993):

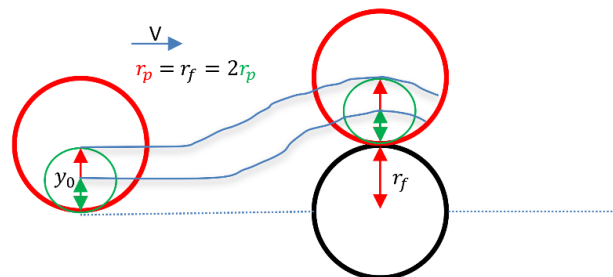
$$Ku = -0.5 \ln \alpha - 0.75 + \alpha - 0.25 \alpha^2 \quad (2.13j)$$

2.3.2.5 Interception Efficiency

Direct interception happens when aerosol particles behave passively in relation to the airflow, meaning they do not divert but follow a streamline. Under such circumstances, as seen in Figure 2.7, particles are anticipated to come into touch with the fiber at its top surface. Then, the very basic form of interception efficiency can be expressed as follows using the preceding definition of the single fiber efficiency ratio:

$$E_r = \frac{y_0}{r_f} = \frac{r_p}{r_f} = \frac{d_p}{d_f} = R \quad (2.14a)$$

Figure 2.7. Aerosol Particles with Different Sizes in Contact with a Fiber



It follows that intercepting particles is directly correlated to the relative size of the particles in relation to the diameter of the fiber, and all particles falling between $y_0 = r_f$ and $y_1 = r_p + r_f$ are likely to be collected by the interception mechanism. By examining the flow field and pattern through an isolated single cylindrical fiber or through a cell unit consisting of staggered parallel cylinders, one can obtain distinct streamline functions and, as a result, various correlations for the equation that calculates interception efficiency. For instance, the Kuwabara cell model of homogeneous cylinders oriented perpendicular to the airflow determined the capture interception efficiency by assuming boundary conditions that the upper vorticity is counteracted by the lower vorticity of the cell and expressed it in terms of the packing density of fibers (α) as well as the above R ratio in the following equation:

$$E_r = \frac{1 + \frac{d_p}{d_f}}{2Ku} \left[2 \ln \left(1 + \frac{d_p}{d_f} \right) - 1 + \alpha + \left(\frac{1}{1 + \frac{d_p}{d_f}} \right)^2 \left(1 - \frac{\alpha}{2} \right) - \frac{\alpha}{2} \left(1 + \frac{d_p}{d_f} \right)^2 \right] \quad (2.14b)$$

Stechkina & Fuchs (1966) derived an equation below identical to the one mentioned above, but they only considered the filter packing density in the Kuwabara factor to calculate the interception efficiency:

$$E_r = \frac{1 + \frac{d_p}{d_f}}{2Ku} \left[2 \ln \left(1 + \frac{d_p}{d_f} \right) - 1 + \left(\frac{1}{1 + \frac{d_p}{d_f}} \right)^2 \right] \quad (2.14c)$$

Additional frequently used interception efficiency expressions, which are empirically adjusted for a specific range of particles, fibers, and/or flow regimes, are provided by Lee & Liu (1982) for $0.01 \text{ m/s} < V < 0.3 \text{ m/s}$ and $0.05 \text{ } \mu\text{m} < d_p < 1.3 \text{ } \mu\text{m}$ and $0.86\% < \alpha < 15\%$ and Liu & Rubow (1986) for $2.9\% < \alpha < 10\%$:

$$E_r = \frac{1}{\varepsilon} \left(\frac{1 - \alpha}{Ku} \right) \left[\frac{\left(\frac{d_p}{d_f} \right)^2}{1 + \frac{d_p}{d_f}} \right] \quad (2.14d)$$

$$E_r = \frac{1}{\varepsilon} \left(\frac{1 - \alpha}{Ku} \right) \left[\frac{\left(\frac{d_p}{d_f} \right)^2}{1 + \frac{d_p}{d_f}} \right] \left(1 + \frac{1.996Kn}{\frac{d_p}{d_f}} \right) \quad (2.14e)$$

Where ε is a corrective empirical value introduced into the equation to account for fiber inhomogeneity in the filter media. According to Raber's (1986) experiments, this empirical number is approximately 1.6 for polyester filters and is a suitable value for glass fiber filters.

2.3.2.6 Impaction Efficiency

Inertial impaction occurs when particles depart from the streamline due to their inertia. This happens for particles larger than 1 μm in diameter size. The motion equation for a spherical particle projected into a stationary medium can be used to explain and derive an expression for this mechanism:

$$m_p \frac{dV_p}{dt} = F_e + F_D \quad (2.15a)$$

Where the inertia force is represented by the term on the left side of the equation, external forces are represented by the first term on the right side of the equation, and the drag (friction) force between the aerosol and air particles is represented by the last term. The above equation can be simplified for a laminar flow, where the relative velocity between the spherical particles and the air is very low, and by removing the external forces to represent it in terms of Stokes number, which describes the behavior of particles suspended in a flow:

$$\rho_p \times \text{Volume of Particle} \times \frac{dV_p}{dt} = \frac{1}{2} \rho C_D \left(\pi \frac{d_p^2}{4} \right) |V - V_p| (V - V_p) \quad (2.15b)$$

With $Re_p = \frac{d_p |V - V_p| \rho}{\mu}$, and $C_D = \frac{24}{Re_p C_c}$

$$\frac{dV_p}{dt} = \frac{1}{\tau_p} (V - V_p)$$

With $\tau_p = \frac{C_c \rho_p d_p^2}{18\mu}$ is the particle response time in Stokes flow

The particle's position at any time, given its initial position, as well as the distance (d_s) it traveled before coming to rest, can be found by converting the above equation to rectangular coordinates and solving it numerically by setting the boundary conditions at the initial position. The impaction efficiency can thus be expressed in terms of Stokes number (St) in a very fundamental manner, building on the previously discussed single fiber ratio theory:

$$E_i \approx f(St) \quad (2.15c)$$

$$\text{Where } St = \frac{d_s}{d_f} = \frac{\left(\frac{C_c \rho_p d_p^2}{18\mu} V \right)}{d_f} = \frac{C_c \rho_p d_p^2 V}{18\mu d_f}$$

Hence, the intensity of the impaction process is controlled by the Stokes number. When $St \ll 1$, the inertia effect will be decreased, and the particles will proceed along the streamline; however, when $St \gg 1$, the particles will diverge from the streamline of the airflow and may be collected by the fiber. Stechkina et al. (1969) provided a standard equation that is commonly used to determine the efficiency contribution by the impaction:

$$E_i = \frac{St \times f}{(2Ku)^2} \quad (2.15d)$$

Where: f is an empirical factor established by Lee & Liu (1982) and Hinds (1999), and valid for $0.4\% < \alpha < 10\%$:

$$\begin{cases} f = \left[(29.6 - 28\alpha^{0.62}) \left(\frac{d_p}{d_f} \right)^2 - 27.5 \left(\frac{d_p}{d_f} \right)^{2.8} \right] & \text{for } \frac{d_p}{d_f} < 0.4 \\ f = 2 & \text{for } \frac{d_p}{d_f} > 0.4 \end{cases}$$

2.3.2.7 Gravitational Settling Efficiency

Particles experience gravitational settling when they pass through fibrous layers and stray from the streamline under the influence of gravity, ultimately depositing on the fiber surface. To understand the basic principles of this mechanism, consider only the gravitational force acting on the particle flowing at a streamline. The particle will subsequently attain its terminal settling velocity, at which point the drag force exerted by the air on the particle is exactly equal and opposite to the gravitational force, with the neglect of the buoyancy force due to the particle's density being significantly greater than that of the air. Hence, the particle settling velocity (V_{se}) can be calculated as explained in the preceding section, and the particle motion equation could be written as follows:

$$F_D = F_g = m_p g = \rho_p \times \text{Volume of Particle} \times g \quad (2.16a)$$

$$V_{se} = \frac{\rho_p g d_p^2}{18\mu} \quad (2.16b)$$

Therefore, the filtration effectiveness of a single fiber due to gravitational deposition can be determined using the single fiber ratio theory, and it can be expressed by the equation provided by Yeh & Liu (1974):

$$E_g = \frac{V_{se}}{V} = \frac{\rho_p g d_p^2}{18\mu V} \quad (2.16c)$$

Further analysis was performed by Stechkina et al. (1969), and the particle-to-fiber diameter ratio was incorporated into the equation for airflow perpendicular to the fiber surface, whether directed downwards or upwards. The equations are presented here, respectively:

$$E_g = (1 + R) \frac{V_{se}}{V} \quad \text{or} \quad E_g = -(1 + R) \frac{V_{se}}{V} \quad (2.16d)$$

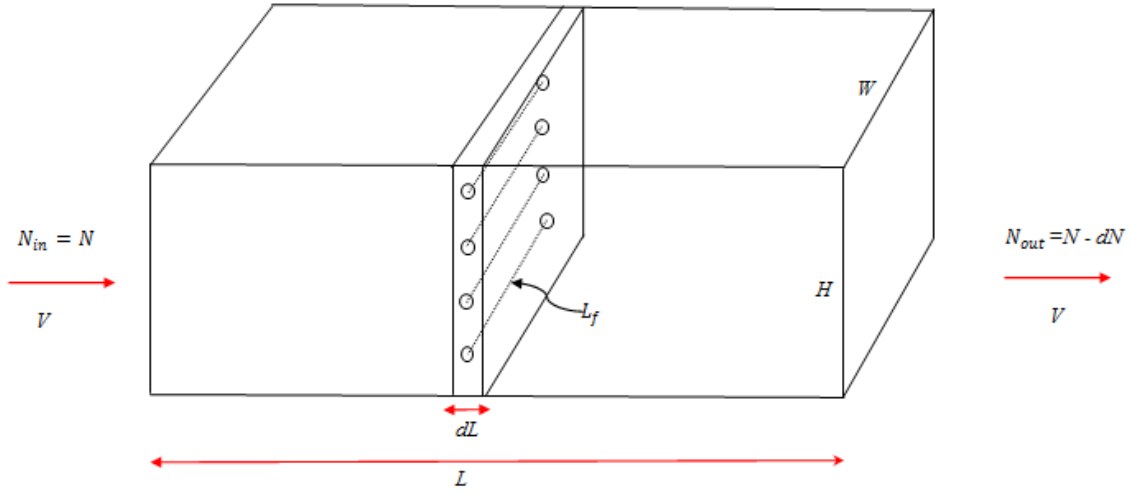
2.3.3 Overall Filter Efficiency

The mechanical particle collection mechanisms explained above occur practically simultaneously and superimpose accordingly, and this is what forms the basis of a filter's efficiency. The efficiency of a filter is generally calculated using the single fiber theory, which takes into consideration the effects of the neighborhood fibers but not their inhomogeneity. Consider a filter sheet of height (H), width (W), and thickness (L), which consists of many fibers that have the same diameter size (d_f) and length (L_f), and assume those fibers are orientated parallel to each other and perpendicular to the air flow direction. The flow velocity at the face of the filter, which is $V = \frac{Q}{H \times W}$, and the air velocity $V_f = \frac{Q}{H \times W \times (1 - \alpha)} = \frac{V}{(1 - \alpha)}$ in the vicinity of the filter, which is a little greater because of the reduced passage area caused by the volume of fibers, are considered uniform over all the area, and the particle concentration in the flow, N , is equally distributed over all the face area of the filter sheet, and the aerosol particles are assumed to be not bounced or re-entraining. This assumption is predicated on the fact that the particle sizes of interest in HEPA filtration are 0.3 μm or smaller, which are less likely to exhibit bounce behavior. The small fiber diameter and spacing in HEPA filter media also contribute to reduced particle bounce. Additionally, the low filtration velocity minimizes the likelihood of particle rebound. As a result, taking a small differential layer of the filter sheet with a thickness of dL , as shown in Figure 2.8, and balancing the particle rates of particles passing through that differential layer, yields the following equation:

$$NVHW = (N - dN)VHW - NHWdL\alpha \left(\frac{1}{\frac{\pi d_f^2}{4} L_f} \right) (2y_0 L_f) \left(\frac{V}{1 - \alpha} \right) \quad (2.17a)$$

Where the left side term is the particle rate entering the filter sheet at velocity V , the first term on the right side is the particle rate of particles passing out the differential layer of the mentioned filter sheet, and the last term from the right side is the particle rate collected on all the fibers that are in the differential layer.

Figure 2.8. Filter Sheet Illustration



The equation can be reduced to:

$$\frac{dN}{N} = \frac{-4\alpha}{\pi d_f(1-\alpha)} E_s dL \quad (2.17b)$$

Then integrating over the thickness, L of the filter sheet gives the total filter efficiency, E_f , as a function of a single fiber efficiency.

$$\begin{aligned} \int_{N_{in}}^{N_{out}} \frac{dN}{N} &= \int_0^L \frac{-4\alpha}{\pi d_f(1-\alpha)} E_s dL \\ \frac{N_{out}}{N_{in}} &= e^{\frac{-4\alpha L E_s}{\pi d_f(1-\alpha)}} \\ E_f &= 1 - \frac{N_{out}}{N_{in}} = 1 - e^{\frac{-4\alpha L E_s}{\pi d_f(1-\alpha)}} \end{aligned} \quad (2.18)$$

2.3.3.1 Correction Factors to the Classical Filtration Efficiency Model

This single fiber model can be extended to a multi-fiber filtration model to fit most of the high-efficiency and HEPA filters, which consist of fiber diameters ranging from 0.4 to 10 μm .

Hence, the overall filter efficiency becomes as follows:

$$E_f = 1 - e^{-\sum E_{si}A_i} = 1 - e^{-\sum E_{si}d_{fi}L_{fi}} = 1 - e^{-\sum E_{si}d_{fi}\frac{4\alpha_i L}{\pi d_{fi}^2}} = 1 - e^{-\sum E_{si}\frac{4\alpha_i L}{\pi d_{fi}}} \quad (2.19)$$

Where E_{si} is the single fiber efficiency for fiber i and A_i is the individual fiber projected area.

The correction factors D_f , L_u , and f are added to the efficiency equation that counts for diffusion and interception to avoid the 100% removal efficiency for small particles and in the upper limit for particles in the 5–10 μm size range and to be used to fit the filter model to the specifications provided by manufacturer. The single fiber collection efficiency will be defined by Kowalski et al. (1999) as:

$$E_f = L_u[1 - e^{-(D_f E_d + f E_r)A_f}] \quad (2.20)$$

Where: $D_f = 1 - (10^{-10})^{(d_p - g_m)^{\frac{3}{4}}}$, $g_m = 0.003 \times 10^{-6} \text{m}$ is the gas molecule size, while L_u and f can be set to optimize the efficiency curve fitting if necessary.

2.4 Experimental Work

2.4.1 Pressure Drop

Wang et al. (2008) investigated the figure of merit (Filter Quality Factor), which is defined as $q_f = -\ln(1 - E)/\Delta P$, for filters consisting of a single layer of nanofibers on a substrate. They conducted experiments using four distinct samples, each with varying fiber solidity, and tested with varied types and sizes of injected particles. The pressure drop was evaluated at six different face velocities, ranging up to 40 cm/s. Their results demonstrated a linear correlation between the pressure drop and the face velocity, which aligns with Darcy's

law. Furthermore, the results indicated that the sample with a greater nanofiber density/solidity exhibited a higher pressure drop but superior efficiency, as anticipated. Conversely, the sample with a moderate fiber solidity of 5.9%, which closely resembles the solidity commonly used for HEPA and other standard fiberglass filter media, exhibited the highest q_f value for particles larger than 0.1 μm and slightly lower q_f values than the media used in HEPA filters for particles smaller than 0.1 μm . Bémer & Callé (2000) constructed a test apparatus with a testing chamber of 150 mm diameter size, capable of holding a 130 mm diameter filter sheet, to conduct experiments on two filter media commonly used in industry. The first was OPA95 media, which has homogeneous fine glass fibers with an average $d_f = 2.8$ μm , $\alpha = 5.3\%$, and a thickness of 0.5 mm. The second was made of large heterogeneous polyester fibers with an average $d_f = 11.7$ μm , $\alpha = 14.55\%$, and a thickness of 2.34 mm. The aim was to examine and model the pressure drop and fractional efficiency of these filter media when subjected to particle loading. When loading, a different monodispersed generator was employed, and changes in the efficiency and the pressure drop in relation to the mass of particles deposited per unit of surface area were observed. The results demonstrated how the media characteristics changed as the loading increased, specifically in relation to the improvement in efficiency induced by the rise in pressure drop resulting from the mass of the deposited particles. This increase in pressure drop was assessed in terms of the initial $\Delta P_0(2\Delta P_0, 4\Delta P_0)$. Huang et al. (2010) studied the effect of fiber orientation on filter quality in cigarette filters where the fibers are practically parallel to the air streamlines, as opposed to most filtration models that assume the air streamlines are perpendicular to the fibers. They created parallel and perpendicular cellulose acetate cigarette filter cubes and placed them in filter holder. Their findings revealed that the pressure drop across orthogonal filters was substantially greater than across parallel filters, where the airflow is

thought to form eddies downstream of the fibers and may have a transition or turbulence flow regime rather than a laminar flow. The turbulent level increased with airflow rate; however, it is important to note that their study was conducted at higher face velocities than typically observed in HEPA filtration, reaching up to 3 m/s. Songhui et al. (2023) developed experimental apparatuses for fabricating polyacrylonitrile electrospun nanofiber media using a syringe pump and spinning drum, as well as a differential pressure measurement apparatus to measure the pressure drop of those produced ultra-thin filter media. The study found that increasing media packing density has a non-linear correlation with pressure drop, similar to the Knudsen number (Kn), and has a greater negative influence (increased values) on pressure drop for smaller fiber diameters. In their study, they also found a linear relationship between pressure drop and media flow face velocity for four different velocities, demonstrating that the permeability function $f(\alpha)$ does not depend on flow velocity in the case of nanofiber filters. In addition, they examined the impact of thickness, ranging up to 100 μm , on the pressure drop of media composed of various mono-fiber sizes of 0.05–0.8 μm at a specific $\alpha = 6\%$. They discovered a direct linear correlation between media thickness and pressure drop, noticing that media with smaller fiber size produces a higher pressure drop. This is due to the higher number of tiny fibers present in comparison to media with larger fiber sizes, where fewer fibers are needed to achieve the same fiber density. Mouret et al. (2009) used a test chamber that resembled a circular sheet with a 6 cm diameter to test three distinct fiberglass filter sheets in order to assess their performance with and without various millimetric pinholes. These filter sheets included a HEPA filter medium in one of them. They measured pressure drops through these media relative to airflow in the 0–100 l/min range and discovered a linear relationship for both intact and pinholed cases.

2.4.2 Fractional Efficiency

A filter's efficiency is described in terms of separation efficiency, often known as fractional efficiency. According to Maus & Umhauer (1996), fractional efficiency is the ratio of the total number or mass of particles of a particular size captured by the filter fibers to the total number or mass of particles of that size upstream of the filter. It can be experimentally measured using the following equation:

$$E(i) = \left[1 - \frac{C(i)}{C_u(i)}\right] \times 100 \quad (2.21)$$

Where i represents the particular particle size, C_u is its concentration in raw air measured upstream the filter, and C is its concentration in clean air measured downstream the filter. These researchers examined the fractional efficiencies in the particle size range from 0.6 μm to 10 μm of polyester and polycarbonate medium and high-efficiency filters, which were evaluated according to the European organization Eurovent. The experiments were conducted using a flow channel with an inner diameter of 5 cm. They confirmed that the highest efficiency was achieved with the higher-class filter. Since the investigation was conducted in the range of particles where impaction is prominent, they noticed that, as would be expected from the impaction mechanism described above, the filter efficiency increases with an increase in velocity. However, for one of the tested filters, the opposite occurred for the larger particle range ($d_f \geq 2.1 \mu\text{m}$). This phenomenon is referred to as filter inefficiency produced by incomplete particle adherence to the filter fibers, resulting in particles bouncing off the fibers and decreasing filter efficiency at higher face velocities for particles with high inertia. It should be noted that these filters are rated for higher velocities ranging 50–250 cm/s and have been tested at 100 cm/s and 125 cm/s, as opposed to HEPA filters, which are typically evaluated with laminar flow. Bémer & Callé (2000) showed that taking polydispersity of the fiber diameter into account in the efficiency calculation

improves filter fractional efficiency to match experimental results. The findings of Huang et al. (2010) demonstrated that orthogonal fibrous filters outperform parallel filters in the overall injected particle size range. From the standpoint of filter quality, the parallel filter may only function better when the particles are smaller than the MPPS and under higher face velocity. As a result, despite the significant difference in air resistance discussed in the previous section, the filter quality factors of parallel and orthogonal fibrous filters were found to be roughly the same. Rivers & Murphy (2000) evaluated various full-size air filters, including pleated air filters, in accordance with the ASHRAE 52.1 for air filter test standard under constant and variable air volume, utilizing a flow that varied in a linear sawtooth pattern from 1000 to 2000 CFM in 60 seconds. Their findings demonstrated, with the exception of the filters with the lowest efficiency, filter performance did not significantly decline under the variable air volume operating conditions. Zhou et al. (2020) concurred with that for particles with sizes near MPPS when testing glass fibrous air filter media under sinusoidal flow conditions. However, they noted a minimal effect on the capture efficiency for particles smaller than $0.1\ \mu\text{m}$ and larger than $1\ \mu\text{m}$. This is where diffusion and impaction mechanisms dominate, and that effect can be attributed to the face velocity included in the equations for those mechanisms explained in preceding sections. A testing rig with a filtration apparatus that fitted $5.3\ \text{cm}^2$ of filter media was set up by Bortolassi et al. (2017) to assess the fiber diameter permeability and efficiency of three different HEPA filter samples. Among those tested, one has a 99.995% efficiency at MPPS and is classified as H14. They started with a series of efficiency tests and measurements for the clean media, and then after an hour and a half of filtration with the aerosol generator turned on, they repeated the measurements for the same media (dirty media). Their findings indicated that fewer particles passed through the filter media during the second series of testing, which is to be expected

because the particles deposited during the first series of testing helped to retain fresh particles by reducing the amount of free space between the fibers. Additionally, they demonstrated that the HEPA filter media sample, which has a smaller average fiber diameter and lower permeability (higher pressure drop), can retain more particles from the air stream. Yoshikawa (1978) and numerous other experimental studies on fibrous filters demonstrated that, even when the layer thickness of the media reaches tens of millimeters, the efficiency or penetration is linearly proportional to the media's layer thickness. Their findings showed that linear relationship for a 16 μm fiber diameter at various face velocities and thickness ranges up to 30 mm.

Regarding the damaged filter media with pinholes or caused by other leaks, there has been a scarcity of research conducted on this matter. Even Li et al. (2022) evaluated the impact of the leakage ratio on the performance of a polyester filter medium experimentally using a leakage regulation valve on a filter medium bypass pipe with an inner diameter of 6 mm rather than a leakage through the medium. They managed to control that valve, allowing them to test a 150 mm diameter and 0.72 mm thick polyester filter medium with two holes measuring 2.64 mm and 4 mm. Their results showed that when there is leakage, the filtration efficiency decreases with time and as the leakage ratio increases. Mouret et al. (2009) used an experimental setup with a testing filter holding chamber of 60 mm diameter to investigate the initial performance (initial filtration state) of three fibrous filter samples, each of which was initially rated with a different efficiency. Their research focused on the initial performance of filter media for particles with sizes ranging 0.004–0.03 μm in both the presence and absence of calibrated diameter holes of 0.4 mm, 1.32 mm, and 2 mm through the filter medium. The results allowed for the distinction between three regimes: leakage, filter bed, and transitional. In a leakage regime, filter efficiency becomes independent of particle size and face velocity; in a filter bed regime, the influence of

leaks can be minimal, and the filter will continue to function as predicted by filtration theory for an intact medium. It was also found that the most efficient filter medium is more vulnerable to leaks, and it was subjected to a leakage regime for every leak that was examined. Lastly, it is worth noting that all of these studies were conducted on large pinholes in millimetric sizes, with Mouret et al. studying smaller particles in the range of $d_f \leq 0.03 \mu\text{m}$ and Li et al. studying particles in the range of $d_f \geq 0.9 \mu\text{m}$.

2.5 Computational Work

2.5.1 2D and 3D Computational modeling of Fibrous Filters

Kang et al. (2019) developed a 2D numerical model of two commercially available fibrous filter media to compute the flow field and particle collection efficiency while accounting for polydisperse fibers. They succeeded in simulating these filters' 0.36 mm and 0.74 mm actual thicknesses. The fiber size was created at a random, maintaining a 0.1 μm gap between adjacent fibers to avoid overlapping, and a fitted log-normal equation was utilized to match the SEM measurements of the fiber size distribution in these media. Fibers were added to the domain until actual solidity was obtained with a particular domain height. Since $Re_f \ll 1$ on the fiber diameter in the actual filtration process, Stokes flow was assumed for the flow field simulation and calculated in ANSYS Fluent using the continuity and momentum equations in a computational domain that extends 150 μm upstream and 30 μm downstream of the filter medium. They created an in-house JAVA code that uses the Langevin equation, which takes into account both frictional and Brownian forces, for particle tracking and modeling. They uniformly inserted 1500 particles at the entrance of the computational domain for each specified size up to a particle size of 0.5 μm . The model was verified using their experimental data for face velocities of 10 cm/s and 15 cm/s, with a maximum discrepancy of less than 7%. According to their results,

fiber polydispersity has a negligible effect on the particle collection efficiency for sizes less than 0.01 μm and greater than 0.1 μm . A 2D fibrous model was also developed by Hosseini & Tafreshi (2010) to compare computational results with the theory of cell models. They did this by creating C++ code that generates random circular homogeneous fibers. However, the distinction in this case compared to the previous model was establishing the inlet and outlet boundary condition of the computational domain at a distance of $20d_f$ and $5d_f$ respectively upstream and downstream of the filter media. Additionally, they used the convective-diffusive equation to simulate the diffusion mechanism and compute the concentration for particles less than 0.5 μm . This is the convective-diffusive equation, where the velocity components are denoted by (U, V) , the particle concentration is represented by n , which is regarded as 1 at the inlet and 0 at the fiber surfaces, $\frac{\partial n}{\partial x} = 0$ at the outlet boundary is applied, and D is the previously described diffusion coefficient:

$$U \frac{\partial n}{\partial x} + V \frac{\partial n}{\partial y} = D \left(\frac{\partial^2 n}{\partial x^2} + \frac{\partial^2 n}{\partial y^2} \right) \quad (2.22)$$

Furthermore, the interception and inertial impaction captures of particles larger than 0.5 μm were accounted for by the Lagrangian method and solving the force balance equations using the Fluent built-in discrete phase model (DPM). The drag and Brownian forces are incorporated into the force balance equation in the first and second terms on the right-hand side of the equation, where K_B is the Boltzmann constant, ρ and ρ_p is the air and particle density, T is the absolute temperature, ν is the kinematic viscosity, ξ_i are zero-mean unit-variance-independent Gaussian random numbers, Δt is the time step, and C_c is the Cunningham correction factor that accounts for non-continuum effects.

$$m_p \frac{dV_p}{dt} = F_D + F_B \quad (2.23a)$$

$$\frac{dU_p}{dt} = 18\mu \left(\frac{U-U_p}{d_p^2 \rho_p C_C} \right) + \sqrt{\frac{216\nu K_B T}{\pi \rho d_p^5 \left(\frac{\rho_p}{\rho}\right)^2 C_C \Delta t}} \xi_i \quad (2.23b)$$

$$\frac{dV_p}{dt} = 18\mu \left(\frac{V-V_p}{d_p^2 \rho_p C_C} \right) + \sqrt{\frac{216\nu K_B T}{\pi \rho d_p^5 \left(\frac{\rho_p}{\rho}\right)^2 C_C \Delta t}} \xi_j \quad (2.23c)$$

Lastly, since the standard Ansys-Fluent DPM treats the particles as mass points and does not compute the capture efficiency due to interception, they developed a C++ code and modified Fluent's standard DPM module to enhance the fiber capture by interception mechanism by continuously monitoring the distance between the particle's center of mass and the fiber's surface during particle trajectory. The results revealed reasonable agreement, particularly when the slip boundary condition at the fiber surfaces was considered, with existing formulations and semi-analytical models of fibrous filter efficiency. Zhou et al. (2020) used the concepts from the previous 2D model to create different 2D structures of fibrous media to study the impact of elliptical fiber configurations on filtration performance. Their findings demonstrated that substituting circular fibers for elliptical fibers in the sparse medium layer improved the fibrous media's quality factor and performance. Conversely, elliptical fibers in the dense layer produced a high-quality factor for filter medium for particles smaller than 0.5 μm but a low-quality factor for larger particles.

Thus far, few studies have been conducted on 3D computational modeling of the filtration process, and the publication by Hosseini & Tafreshi (2010) stands out as the most comprehensive and realistic filter modeling approach to date, as it replicates the microstructure of a fibrous medium. They developed a C++ program to generate 3D random fibrous structures arranged in horizontally stacked layers, each with a preset thickness of $1.4d_f$, fiber diameter size, and solid volume fraction (SVF) (fiber solidity or packing density). In this study, they integrated the methodologies employed in their 2D computational fluid dynamics (CFD) simulations to

account for particle collection resulting from interception and Brownian diffusion, as well as the slip phenomenon occurring at the nanofiber surface. However, fiber interpenetration is allowed here since it does not impact media pressure drop or collection efficiency. In the range of particle size of 0.025–1 μm , they simulated the pressure drop and collection efficiency of nanofibrous media containing uniform fiber size in the range of 0.1–1 μm and SVF of 2.5%, 5%, and 7.5%. They then compared these results with existing analytical and empirical results from classical filtration theories. Their findings revealed that the medium with the smallest fiber size and the highest SVF resulted in higher filter efficiency, and their results for pressure drop and efficiency were in good agreement with existing correlations such as the one for pressure drop by Ogorodnikov (1976) and the one for efficiency by Liu & Rubow (1990). Building on this study, Hou et al. (2019) included an electric field force equivalent to the product of the particle charge and the fiber electric field strength in their 3D simulation of the filtration performance of the electrostatic fibrous filter. Instead of using $20d_f$ distance upstream and $5d_f$ downstream of the filter medium for the computational domain at the inlet and outlet, they demonstrated by calculating non-changing velocity contours that a $7d_f$ distance upstream and downstream the filter medium will work to set the inlet and the outlet boundary conditions of the calculation zone, optimizing computational resources. They examined how the filtration efficiency and pressure drop of fibrous filters were affected by changes in parameters such as the fiber field potential, particle charge to mass ratio, SVF, fiber diameter, and face velocity. Their flow model results also revealed a linear relationship between filter pressure drops and face velocities, and a similar linear relationship between filter pressure drops and SVFs. However, the correlation between pressure drops and face velocities was closer this time to that found by Davies (1973), with some deviation due to the uniform fiber diameter in their model. Additionally, they showed

that the filtration efficiency rises by increasing absolute fiber potential and particle charge, as well as the SVF, but up to a point when the rise becomes negligible. As the fiber diameter increased at a constant SVF, particle charge-to-mass ratio, and potential field, the filter efficiency and pressure drop decreased. Furthermore, they showed that an increase in face velocity had a negative impact on efficiency and also as fiber diameter increased. This supported the expected results from existing experimental studies that a filter medium with a thinner fiber diameter is more efficient and that increasing the face velocity will negatively impact the filter quality factor in two ways (efficiency decrease and pressure drop increase). In conclusion, it is important to highlight that there has been a lack of computational research carried out on a damaged filter medium caused by internal or external leaks such as pinholes or through the gaskets, with research limited, as stated previously, to experimental work and theoretical or mathematical modeling for larger leak sizes.

Chapter 3 – In-Situ Assessment of HEPA Filters in Biological Containment Units

High-efficiency particulate air (HEPA) filters are used in the filtration housings that are installed as the last barrier in the exhaust systems of a National Bio and Agro-Defense Facility (NBAF) and other level 3, 3Ag, and 4 facilities to prevent any environmental contamination. Working with biological infectious agents in the NBAF laboratories calls for the need for checking both the efficiency ratio and the integrity of the HEPA filter elements and housing after installation of the filtration system. The Biosafety in Microbiological and Biomedical Laboratories (BMBL) guidelines also require that all HEPA filters installed in such mentioned facilities must be tested and certified annually for safety aspects and cost-effectiveness. A duct flow loop was constructed for testing and evaluating prototypes of those biological containment units with the associated auto scanning technology and HEPA filters. In the present chapter, two of the available and reputable auto-scanning techniques were used to measure the filter's local and overall efficiencies, and the results were compared with the efficiencies obtained from the traditional penetration test method described in the ASHRAE 52.2 standard. A series of prerequisite tests were also performed to verify the design for challenging the entire face of the filter and the measurement consistency of the injection and sampling probes and to establish the ASHRAE 52.2 requirements for in-place filter testing and rating. The duct flow loop was examined per the ASHRAE 52.2 standard for attaining equal particle distribution on the upstream face of the filter and ensuring that all aerosol particles that penetrate the filter are well mixed and detectable by the downstream sampler. The proficiency of each scanning method for measuring the in-situ filter efficiency was investigated at different flow rates. Results of the penetration of aerosols as a function of aerosol diameter for different face velocities showed an

increase in the aerosol penetration at a higher face velocity for a small particle size range where the diffusion mechanism is dominant, as expected. However, there is less effect for the velocity in the interception regime where the particle size is in the range of $0.1 \mu\text{m} \leq d_p \leq 0.5 \mu\text{m}$. Results using the scanning technique for overall efficiency measurements and the technique described in ASHRAE 52.2 are comparable as far as filter ratings are concerned. The scanning technique is also capable of measuring the local efficiency for detecting any possible leak.

3.1 Introduction

Residents express heightened concerns regarding safety when an existing or new NBAF is proposed for construction in their vicinity. In addition to the facility design criteria outlined in the USDA 242.1- ARS standards and the safety procedures that operators must adhere to when working in high-security facilities, it is crucial to consider the filtration elements integrated into the HVAC systems. These systems are essential for maintaining specific air conditioning within the laboratories and for filtering contaminated air before it is released into the environment.

Evaluation of a filter's performance is conducted by measuring the global (overall) and local efficiencies during the operation of the filtration system. Therefore, a filter is evaluated and classified according to the recognized standards (ASHRAE 52.2, IEST, EN 1822, ISO 29463) in order to facilitate the selection of the filter for the intended use. These standards outline a range of methodologies for testing the in-situ filter efficiencies, such as employing static or movable probes for overall efficiency testing, utilizing a photometer or particle counter, using different upstream concentration and injection aerosol types, and conducting measurements at different most penetrating particle size (MPPS), among others. This work focuses on the use of automated scan technology with a particle counter approach. This method involves moving the inlet of the sampling probe automatically, within a distance of 1 inch from the tested filter's downstream

face at a certain scanning speed. This scanning speed (S_r) is presented in Equation (3.1) and is determined based on a relationship between the concentration of the challenge aerosol upstream (C_u), the maximum allowed leak penetration percentage (L_s), the airflow of the sampling device (F_s), the dimension of the scanning probe (D_p), and the expected particle counts (N_p), which characterizes the designated leak:

$$S_r = \frac{C_u L_s F_s D_p}{60 N_p} \quad (3.1)$$

$$\text{Or: } N_p = C_u L_s F_s \left(\frac{D_p}{60 S_r} \right) = C_u L_s F_s t_r$$

with $t_r \geq \frac{D_p}{60 S_r}$ as the sample acquisition time of the particle counter.

The overall efficiency or total leakage test method outlined in ASHRAE 52.2 determines the global filter efficiency by calculating the ratio of downstream to upstream concentrations, as measured by two stationary sampling probes. These probes are strategically positioned upstream and downstream in the duct at a sufficient distance from the filter to provide adequate aerosol mixing. The leak (scan) test method allows for the measurement of both global and local efficiencies. The global efficiency is determined at a specified particle size and flow rate by the ratio of the overall or average downstream particle concentrations, which are derived from local particle concentrations measured by the scanning probe traversing the downstream face of the filter and taking samples at a designated acquisition time ($\cong 1$ sec), to the overall or the average concentrations measured by an upstream stationary probe. The total particle counts at each sample acquisition time are summed over the test duration to determine the overall upstream and downstream concentrations, while the average concentrations are calculated by averaging these values. The simultaneous upstream-downstream sampling sequence using two particle counter systems with the same sample acquisition time can be more sufficient for measuring the overall

or average upstream and downstream concentrations than the sequential upstream-downstream sampling with one particle counter, which can be acceptable by standards for measuring the overall or average upstream and downstream concentrations. The local efficiencies are determined by taking the ratios of each downstream concentration measured by the scanning probe to its corresponding upstream concentration measured at the same time by the stationary upstream probe, using the simultaneous upstream-downstream sampling sequence. Alternatively, the ratios can be derived from each of those downstream concentrations to only the same one average concentration of the upstream concentrations that are taken for a period of time (50 to 60 seconds) at a certain sample acquisition time, using the sequential upstream-downstream sampling sequence. The local efficiency measurements happen to ensure the detection of smaller leaks that can be missed through the overall or the average concentration calculations of the global efficiency during a scan test. One can decide then whether small leaks exist on an installed filter or not based on those local efficiency values and the acceptable designated leak size percentage. The designated leak size is a matter of agreement between the customer and the supplier, and it is defined in the standards as a multiple (1–10 times) of the integral maximum particle penetration percentage, which is associated with a global efficiency value to rate and classify a filter at the MPPS range. The designated leak percentage is defined as being equal to or higher than the maximum particle penetration percentage by multiple factors to increase the sensitivity of the real leak detection and exclude other leaks that can be due to the particles passage through the filter media pores. For instance, a leakage factor of 5 is applied to H14 HEPA filter media according to EN 1822, yielding a local efficiency value of $\geq 99.975\%$ (penetration $\leq 0.025\%$) at the MPPS for a successful leak test. This value is calculated from the

integral (overall) efficiency value of $\geq 99.995\%$ (penetration $\leq 0.005\%$) for a successful penetration test, multiplied by a factor of 5 ($0.025\% = 5 \times 0.005\%$).

Following installation and prior to conducting in-situ filter testing, the HEPA filters have to undergo a seating or housing pressure test, as well as upstream and downstream aerosol uniformity testing. ASME N510 provides two methods for verifying the leak tightness of filter housing and ducts to demonstrate their ability to meet structural capability pressure (SCP). The constant pressure test technique is commonly utilized for small volume applications in which the pressure supply source is continuously connected to the housing under examination. This method entails pressurizing the housing to its maximum operating pressure and sustaining this pressure until temperature stabilizes within ± 0.5 °F for at least 10 minutes. The flow rate added to the housing, indicative of the leakage rate, is then measured with a flow meter placed in line between the supply pressure source and housing, while maintaining the maximum operating pressure within ± 0.1 IWC. In large volume applications, the pressure decay technique is the one that is often employed. It involves pressurizing the housing to 125% of its maximum operating pressure, but less than the SCP. This pressure is maintained until the temperature stays constant within ± 0.5 °F for at least 10 minutes. Afterwards, all initial pressure, time, and temperature are recorded, along with continuous recordings at one-minute intervals until the pressure decays to 75% or for a minimum duration of 15 minutes, whichever occurs first. Then the leakage rate (Q_{avg}) can be calculated using the following equation in standard CFM:

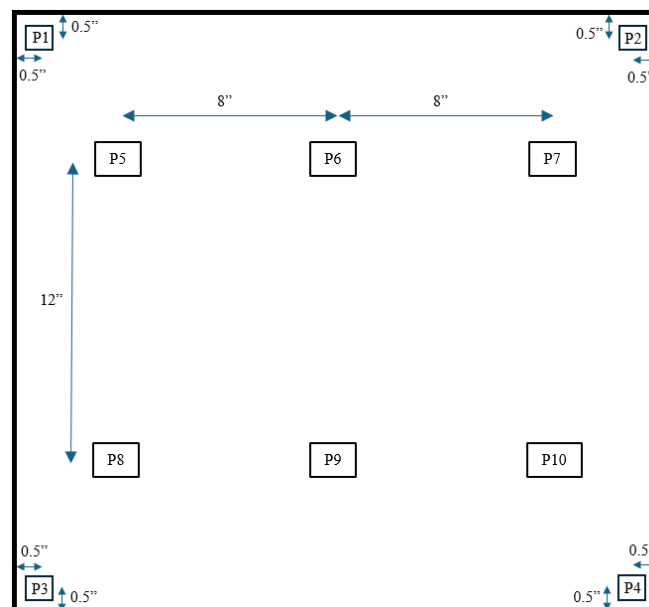
$$Q_{avg} = \left(\frac{p_{in}}{T_{in}} - \frac{p_{fn}}{T_{fn}} \right) \left(\frac{Vol}{\rho R_a (t_{fn} - t_{in})} \right) \quad (3.2)$$

Where p , t , and T represent the measured pressure, time, and temperature, respectively; in denotes the initial state and fn the final state; R_a is the gas constant for air; ρ is the density of air, and Vol is the volume within the test boundary.

The ANSI/ASHRAE 52.2 and IEST-RP-CC034.3 standards outline the procedures for testing aerosol uniformity. The aerosol uniformity testing is conducted by sampling a nine-point traverse within the 24"x24" housing frame immediately upstream of the in-place HEPA filter, in accordance with the ASHRAE 52.2 method. The traverse configuration comprises nine squares with equal area (8"x8"), with sampling points located at the center of each square. Repositioning a single probe or installing nine sample probes of identical curvature, diameter, and inlet nozzle diameter are allowed to be used per the standard. The test is performed at airflow rates of 472, 1970, and 2990 CFM. The sampling probe must maintain isokinetic sampling within 10% of 1970 CFM, and the same probe shall be used at the other airflows. The average concentration of five samples from each point will be presented for assessing the aerosol uniformity testing. The test results will be accepted if the coefficient of variance of the corresponding nine grid point measured particle concentrations is less than 15% in each of the 12 particle counter size ranges. The IEST specifies that the sampling traverse consists of 10 points in addition to the housing sampling port. Four points are positioned at the corners, each within 0.5" of the edges, while the remaining 6 points are located in the center of the rectangles, which measure 8" in width and 12" in height, within a 24"x24" area, located 0.5" upstream of the in-place HEPA filter as shown in Figure 3.1. The test is performed at a preferred airflow rate, and it is acceptable to reposition a single probe for measurements. The average concentration of three samples from each point will be presented for assessing the aerosol uniformity testing. The test results will be accepted if the coefficient of variance (CV) for the measured particle concentrations at corresponding traverses is less than 20%, the standard deviation of any single point is less than 50%, and the ratio of average concentration to mean concentration is between 0.75–1.25 across each of the 12 particle counter size ranges. Regarding the specifications of the stationary upstream injector and

downstream sampler, along with their mixing baffles used for conducting the overall filter test independently, they are outlined in ASHRAE 52.2. Each of the upstream and downstream mixing baffles includes a diffusion plate positioned $6'' \pm 1/8''$ from the orifice plate, with perforations spaced evenly to provide 40% open area for enhanced aerosol mixing. This standard also includes the verification of aerosol uniformity downstream of the HEPA filter to confirm that all particles passing through the filter are detectable by the downstream sampler. The downstream uniformity testing traverse and method are analogous to those described for the upstream uniformity testing. However, the key distinctions are the positioning of the nine-grid traverse to be within 10'' of the HEPA filter downstream face, the sufficiency of triplicate measurements at each of the nine-grid points for assessing the downstream mixing testing, and the requirement to measure downstream aerosol concentration as total aerosol concentration for particles with a diameter of $d_p \geq 0.3 \mu\text{m}$. The test results will be considered acceptable if the CV of the measured particle concentrations at the corresponding points of the traverse is less than 10% for each flow rate.

Figure 3.1. IEST Sampling Grid Points for Aerosol Uniformity Testing



Prior research lacked evaluations of auto-scan technology and typical HEPA filter performance in the context of small leaks. Bergman et al. (1997) conducted in-place testing of HEPA filters utilized in nuclear ventilation systems prior to the advent of scanning technology. The filter efficiency using two distinct laser spectrometers was examined and compared under controlled leaks in the filter, utilizing a 0.025-inch diameter needle, against the traditional filter test given in MIL-STD-282 with a photometer. Their findings indicated a weak correlation between the photometer and laser spectrometer measurements, since the photometer only factored in the average size of the challenge aerosol. Nonetheless, it is good to note that the pressure drop and the MPPS of 0.15 μm remained unchanged for filters with and without 1, 2, 6, 9, 13, 19, 27, and 40 pinholes of 0.025-inch diameter; however, efficiency exhibited substantial declines with an increasing number of pinholes. Their data indicated that after 40 pinholes, the 0.15 μm MPPS penetration increased from around 0.01% to 0.5%, at which point the filter may fail. The impact of a filter bypass (gap) was assessed and modeled by Ward & Siegel (2005). Their analysis of the minimum efficiency reporting value (MERV) 15 rating efficiency revealed a reduction to MERV 14 with a 1 mm gap and to MERV 8 with a 10 mm gap, irrespective of the number of bends through the leak. Arunkumar et al. (2007) developed a standard HEPA filter test stand of 300x300x292-mm dimension for filter performance-related studies, but they employed the traditional method to measure efficiencies and provided no data for efficiency testing in the presence of leaks. Their test stand was designed to assess filter performance under other conditions, including variable aerosol mass loading rate, flow rate, temperature, and humidity. Zhang et al. (2014) designed and evaluated a cylindrical blunt sampling probe for in-situ scanning leak testing of HEPA filters. The width of the probe's slot inlet was established at 1.7 mm to enable isokinetic sampling at an inlet velocity of 0.45 m/s. The cylinder has an inner

diameter of 22 mm and a length of 610 mm, positioned vertically at a distance of 1 inch from the filter face to encompass the entire filter area. It is linked to two branches, each with a diameter of 17 mm, which are subsequently merged to connect to the particle counter. This probe was assessed for its suitability in detecting a pinhole leak, and the results were compared with measurements obtained from the standard thin-walled rectangular inlet sampling probe, which served as a reference. The probe's effectiveness demonstrated the capability to detect a 0.4 mm leak at nine distinct diagonal locations, with a penetration ratio ranging 0.46–1.03 in comparison to the reference probe. It is important to highlight those results for leak sizes of 0.25 mm and 0.35 mm using needles that were reported; however, only the 0.4 mm size exhibited a change in filter penetration or efficiency, leading to its selection as a representative suitable leak. This chapter examines two distinct in-situ auto scan technologies, along with their housings and scanning probes, to assess their capability for detecting leaks of increasingly smaller sizes and to evaluate their integrity in this context, while also comparing testing methodologies and results with the traditional filter penetration testing described in the ASHRAE 52.2 standard. Experimental investigations will be performed at various flow rates, both in the absence and presence of pinholes with defined diameters, to assess the filter performance and determine the magnitude of leakage that will lead to failure. This work will establish a long-term training and research facility for the NBAF filtration prototype systems and units.

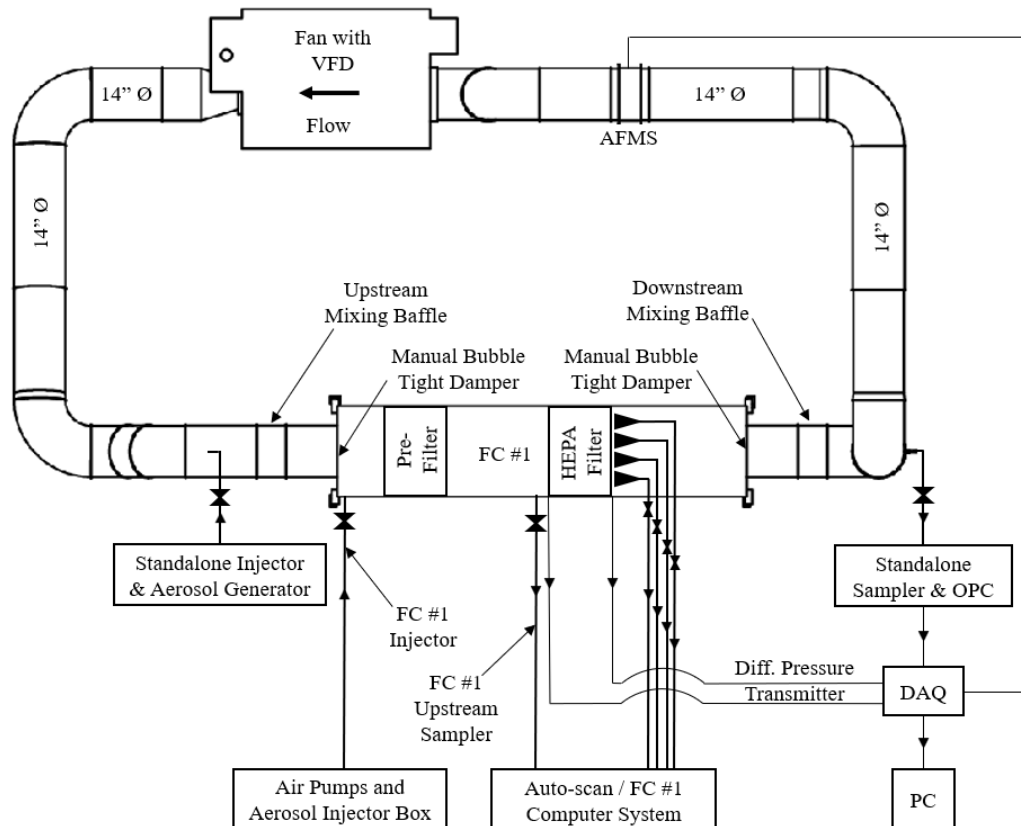
3.2 Experimental Setup

A biofiltration testing center has been designed and constructed, featuring a closed air loop test stand, as illustrated in Figure 3.2. An essential aspect of the duct loop is the filter containment, which comprises the HEPA filter element and an automated scan compartment equipped with its measuring instruments and computer system. The present study employed two

distinct filter containment (FC #1 and FC #2) interchangeably from the leading manufacturers in this industry, with the flexibility for the duct loop to incorporate more if necessary in subsequent investigations. Each containment module has its own design with respect to the aerosol injection port or manifold, as well as the auto-scan technique, filter seat, and filter gasket. FC #1 has a circular ring with tiny holes located at the inline inlet damper of the housing, which serves as the injector of the poly alpha olefin 4 (PAO 4) oil challenge aerosol particles and has another 24"x24" perforated aerosol mixing plate with equally spaced 0.5" diameter holes that can be placed in the prefilter slot. This unit conforms to the IEST criteria in terms of the probe shape, speed, distance from the filter downstream face, and other related parameters for the scanning process. A mechanically operated scanning test section designed to move laterally, using four vertically aligned sampling probes to fully cover the downstream face of the filter and its frame, thereby enabling a systematic scanning procedure. The suction point of each probe features a rectangular cross-section measuring 0.375" in width and 5.22" in height. This transitions to a circular cross-section with an inner diameter of 0.3125" at the hose connection of the particle counter. FC #2 features four parallel tubes that are perforated with very tiny holes oriented in all directions for the di-ethyl-hexyl-sebacat (DEHS) aerosol injection purpose with a perforated plate located before the injection tubes after the pre-filter slot. Additionally, a pointed upstream sampling probe is aligned with the flow near the injection manifold, in contrast to FC #1, which has a flat configuration integrated with the housing frame. The scanning technique employed in FC #2 involves the use of a circular rod positioned close to the filter's downstream side, as shown in Figure 3.3, with perforations on the front side for aerosol sampling. Upon activation of the computer system for scanning, the rod initiates motion and proceeds to scan the downstream face of the filter in a vertical direction from the top to the bottom position. Sampling the

concentration of aerosol particles upstream and downstream the filter is taken simultaneously utilizing two optical particle sizers, as opposed to the FC #1 auto scan system, which only uses one particle sizer. The filter is physically forced into its seat in FC #1 using a sliding bar assembly integrated into the filter seat for a leak-free seal with its gel gasket, whereas FC #2 has a seat sized to accommodate the HEPA filter with an adhesive polyurethane foamed gasket. Both containment units being tested are designed to hold a standard $610 \times 610 \times 292 \text{ mm}^3$ HEPA filter along with a pre-filter compartment. However, this compartment will not be used in our present testing as our primary goal is to test and challenge the HEPA filter. In addition, they contain tight dampers at the inlet and outlet, as well as other ports for decontamination injection, humidity and temperature sensors, and Magnehelic pressure transmitters to measure the pressure drops across the pre-filter, HEPA filter, and housing.

Figure 3.2. Schematic of Test Facility



The remaining components of the duct loop consist of a floor-mounted centrifugal fan with 2400 CFM maximum capacity and a variable volumetric flow controlled by a variable frequency drive (VFD), allowing testing a filter at various flow rates. A duct-mounted air flow measurement station (AFMS) equipped with a differential pressure transmitter, capable of measuring airflow and velocity with an accuracy of $\pm 0.5\%$ for a pressure up to 5 IWC, was set up and linked to a data acquisition (DAQ) system. Additional components developed in-house for ASHRAE 52.2 testing include upstream and downstream mixing baffle sections, as well as their injector and sampler, for independently and isokinetically assessing filter efficiency and authenticating results obtained using auto scan technology. These segments were integrated into the 14-inch stainless-steel tubing by connecting custom-made portions designed to prevent air infiltration and ease filter testing using both housings interchangeably. A stand-alone Laskin nozzle was utilized to generate an artificial PAO-4 into the system at the designed port, and one optical particle counter (OPC) was used to count and size particles in the 0.3 to 10 μm diameter size range per ASHRAE 52.2. The evaluations of the samplers and the uniformity of aerosols both upstream and downstream were conducted with the use of an in-house designed device, as represented in Figure 3.3. The following Table 3.1 and Table 3.2 provide detailed specifications on the filter material being tested, aerosol generator, particle counter, and other used equipment.

Figure 3.3. In-House Designed Injection and Sampling Device

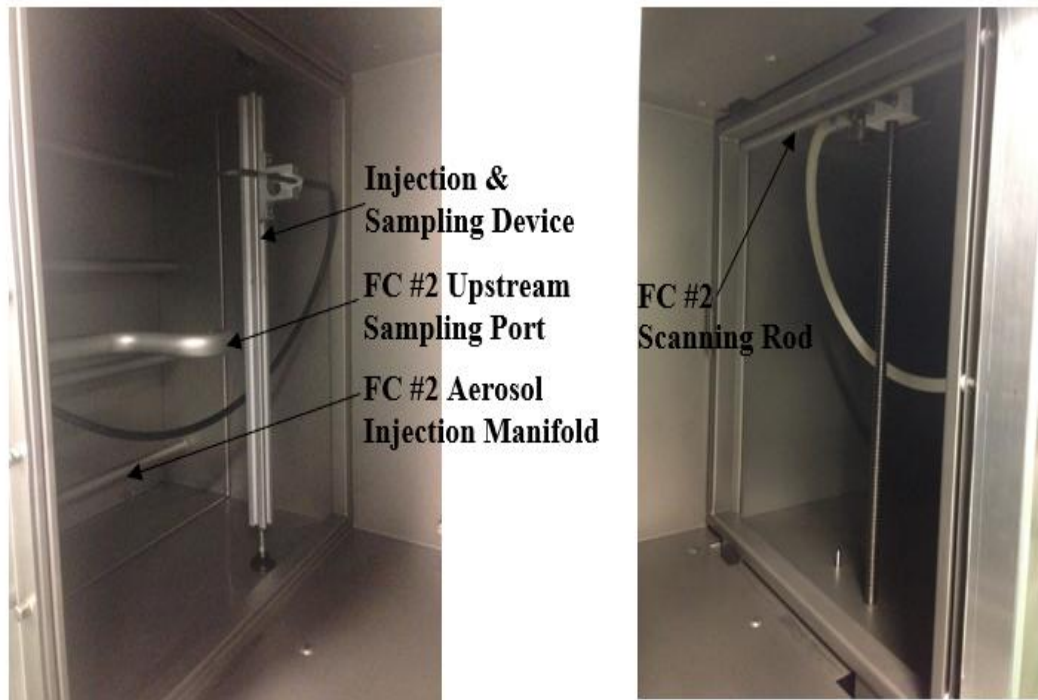


Table 3.1. Filter Characteristics and Needle Used for Leak (Scan) Testing

Filter Characteristics	
Size (mm)	610×610×292 Pleated
Frame	Galvanized Steel
Separator	Corrugated Aluminum with Hemmed Edge
Seal	Gel Gasket PU Foamed Gasket
Efficiency (%)	99.9 @ 0.3 μm (IEST) 99.995 @ MPPS (EN 1822)
Rated Airflow (CFM)	2000 CFM, @1.35" WG P.D.
Media	Micro Glass Fiber
Media Area (FT ²)	301
Media Basis Weight (g/m ²)	78
Media Thickness (mm)	0.4
Media Fiber Solidity, α (%)	7.5
Fiber Density (g/cm ³)	2.6
Needle Diameter Size	
Media Pinhole Created Size (mm)	0.051, 0.159, 0.260, 0.464, 0.514, 0.718, 0.908, and 1.270

Table 3.2. Instrumentation

Instruments	FC #1 Auto-scan System	ASHRAE 52.2 Stand-alone	FC #2 Auto-scan System
Aerosol Generator	ATI TDA-4Blite, 1-3 Laskin Nozzle		TOPAS ATM 230 Model
Aerosol Injection	Concentration Output	100 µg/L @ 405 CFM and 10 µg/L @ 4050 CFM when operated at 23 PSI Aerosol Output = 13500 x # of nozzle in use / CFM	5x10 ¹¹ of 0.2 µm, 4x10 ¹¹ of 0.3-0.5 µm, 2x10 ¹¹ of 0.5-1.0 µm
	Aerosol Material	PAO-4	DEHS
	Particle Size Distribution	Geometric: 0.229 µm Mean and 1.68 nm Std. Dev.	0.2 µm Highest
	Size Range	40 nm - 1 µm	Below 1 µm
	Particle Counter	Lighthouse 3104	Climet .3 Spectro Model Two SOLAIR 1100 LD
Aerosol Sampling	Particle Size Ranges	0.3 µm One Channel	0.3-10 µm 16 Size Channels 0.15-0.20 µm 0.20-0.25 µm 0.25-0.30 µm >0.5 µm
	Sampling Volume Rate	1 CFM	0.1 CFM 1 CFM
	Diluter	Model ADS, @ 1CFM (1:1388 Dilution Factor)	TDA-D100 Model Calibrated, @ 0.1CFM (1:100 Dilution Factor) Two VKL 100 Model (1:100 Dilution Factor)

3.3 Theory

A leak through a filter media can be modeled as an orifice, and the airflow (Q_h) through it can be expressed, according to Ryan (2014), using the following formula derived from Bernoulli's theorem:

$$Q_h = C A_h \sqrt{\frac{2\Delta P}{\rho}} \quad (3.3)$$

Where C represents the coefficient of contraction, which depends on the exact shape of the boundary near the orifice, ranging between 0.5–1. However, for a circular hole punched in a thin

plate, the contraction coefficient was observed to be between 0.61–0.64 by Batchelor (2000). A_h denotes the cross-sectional area of the orifice, ΔP signifies the pressure drop across the filter, and $\rho = 1.2041 \text{ kg/m}^3$ indicates the air density. The calculated leak (pinhole) sizes, obtained from this formula, which will result in the failure of the HEPA filter according to the local leak scan test, are displayed in Table 3.3 at different testing flow rates and standards.

The sampling concentration (C_s) of a stationary leak test involving a pinhole leak and measured by a scanning probe linked to a discrete particle counter, with a sampling flow rate of $F_s = 1 \text{ CFM} = 28.3 \text{ l/min}$, a challenge (upstream) aerosol concentration (C_u), and L_s representing the filter designated leak penetration value (designated leak size fraction of the upstream concentration), can be expressed as follows:

$$C_s = \frac{(F_s - Q_h)C_u L_s + Q_h C_u}{F_s} \quad (3.4)$$

$$\frac{C_s}{C_u} = \frac{(F_s - Q_h)L_s + Q_h}{F_s}$$

Table 3.3. Calculated Pinhole Diameters Leading to HEPA Filter Failure

Guidance	Filter Type	Particle Size	Overall Value		Local Value / Leak (Scan) Test			Pinhole Size Ø (mm)	
			Efficiency (%)	Penetration (%)	Leakage Factor	Efficiency (%)	Penetration (%)	Q=2000CFM ΔP=325Pa	Q=390CFM ΔP=65Pa
EN-1822 ISO-29463 (ISO 45 H)	H14 (HEPA)	MPPS	≥99.995	≤0.005	5	≥99.975	≤0.025	0.101-0.103	0.150-0.154
EN-1822 ISO-29463 (ISO 50 H)	H14 (HEPA)	MPPS	≥99.999	≤0.001	5	≥99.995	≤0.005	0.045-0.046	0.067-0.069
IEST RP- CC001	J (HEPA)	0.1-0.2µm or 0.2-0.3µm	≥99.990	≤0.01	1	≥99.990	≤0.01	0.064-0.065	0.095-0.097
IEST RP- CC001	K (HEPA)	0.1-0.2µm or 0.2-0.3µm	≥99.995	≤0.005	1.6	≥99.992	≤0.008	0.057-0.058	0.085-0.087

Notes:

* Leakage Factors are set in the standards to come up with a designated leak penetration percentage and it is a matter for agreement between the customer and the supplier.

* The pinhole sizes are calculated based on the instruments utilized in our laboratory.

A particle counter having a sampling flow rate of 1 CFM.

* Flow rates of 2000 CFM and 390 CFM and their corresponding filter pressure drops have been derived from testing in our laboratory at initial filtration state.

Then, the overall particle penetration (P) and efficiency (E) across the entire downstream face of the filter can be defined as the product of the flow $(Q_f - Q_h)/Q_f$ and penetration (P_f) fractions through the remaining filter fibers, in addition to the product of the flow (Q_h/Q_f) and penetration (P_h) fractions through the orifice.

$$P = \frac{\sum C_s}{\sum C_u} = \frac{(Q_f - Q_h)P_f + Q_h P_h}{Q_f} \quad (3.5)$$

$$E = 1 - P = 1 - \frac{(Q_f - Q_h)P_f + Q_h P_h}{Q_f} \quad (3.6)$$

The filter penetration (P) will be equal to P_f in the absence of a leak. It can be defined using the single fiber efficiency (E_s) and classical filtration theory, as expressed in Equation (3.7), where L represents the thickness of the filter medium, α denotes the fiber solidity, and d_f indicates the fiber mean diameter. The penetration fraction through the orifice can be modeled using a transport efficiency in a pipe exhibiting laminar flow (Friedlander, 1998). In the case of a thin filter medium measuring 0.4 mm, where particle deposition can be negligible in the pinhole, it can be assumed that P_h approaches one. The flow through the remaining filter bed can be represented by Equation (3.8), which relates to the pressure drop across the filter utilizing Davies' model, or Darcy's equation, or alternative pressure-fitted models. In this context, V denotes the filter face velocity, A_f indicates the area of the filter medium, A_h represents the area of the leak, and μ signifies the air viscosity. The correlation between flow through the orifice and pressure drop can be described in accordance with Clement (1995), analogous to air moving through a capillary. This is based on the flow through the pinhole remaining in a laminar state, which is true to a standard HEPA filter with a large filtration area, as shown in Equation (3.9).

$$P = P_f = e^{\frac{-4\alpha L}{\pi(1-\alpha)d_f} E_s} \quad (3.7)$$

$$\Delta P = f(\alpha, d_f, L)\mu V = f(\alpha, d_f, L)\mu \frac{Q_f - Q_h}{A_f - A_h} \quad (3.8)$$

$$Q_f - Q_h = \frac{(A_f - A_h)}{f(\alpha, d_f, L)\mu} \Delta P$$

$$\Delta P = f(d_h, L)\mu V_h = f(d_h, L)\mu \frac{Q_h}{A_h} = \frac{32L}{d_h^2} \mu \frac{Q_h}{(\frac{\pi d_h^2}{4})} \quad (3.9)$$

$$Q_h = \frac{\pi d_h^4}{128L\mu} \Delta P$$

3.4 Results and Discussion

3.4.1 Housing Pressure Test

The entire FC #1 housing, along with its upstream and downstream bubble-tight isolation dampers, was subjected to pressure decay testing as per ASME-N510, which specifies a maximum leak rate of 0.0005 CFM per cubic foot of housing volume at 10 IWC. All pressure and temperature measurement probes connect directly to the auto-scan system for result outputs. FC #2 HEPA filters were subjected to a seating inspection only after installation to check the tight seat of a HEPA filter element. A standalone leak test device equipped with a hand pump was externally connected to the filter seat test groove via an air pressure line from the filter housing until a test pressure of 2 KPa was reached. The tightness was assessed according to the constant pressure method, facilitating a rapid and straightforward measurement of the device's leakage airflow. Table 3.4 presents examples of detailed pressure decay testing conducted on FC #1 housing, which yielded passing results. Pressure decay testing is characterized by its detailed and sensitive nature in detecting minor leaks; however, it took a significant amount of time for high-pressure assessments. Figures 3.4 and 3.5 show the results of leak scan testing, which was carried out at a flowrate of 2000 CFM. In more than 15 different filter replacement tests, FC #1's

gel-type gasket filter outperformed FC #2 in terms of tightness and sealing, whereas FC #2 experienced minor leaks through the bottom side of the filter. However, the longevity of this aspect was not evaluated.

Table 3.4. Example Results of FC #1 Pressure Decay Testing

Test	Type	P _i (IWC)	P _f (IWC)	T _i (°F)	T _f (°F)	Q _{avg} (CFM)	Result
1	Low Vacuum, @-2 IWC	-1.41	-1.39	71.41	71.17	0.009299	Pass
	High Vacuum, @-10 IWC	-8.82	-8.68	70.44	70.53	0.002467	Pass
	High Pressure, @+10 IWC	9.02	8.64	72.39	72.39	0.014334	Pass
2	Low Vacuum, @-2 IWC	-1.79	-1.79	73.54	73.12	0.011427	Pass
	High Vacuum, @-10 IWC	-3.62	-3.54	73.12	72.88	0.010658	Pass
	High Pressure, @+10 IWC	8.8	8.14	75.56	74.83	0.004421	Pass
Notes: * FC #1 volume is equal to 31ft ³ . * Acceptable leak rate is set to 0.0005 CFM of housing volume (0.0155 CFM).							

Figure 3.4. FC #1 Scan Test

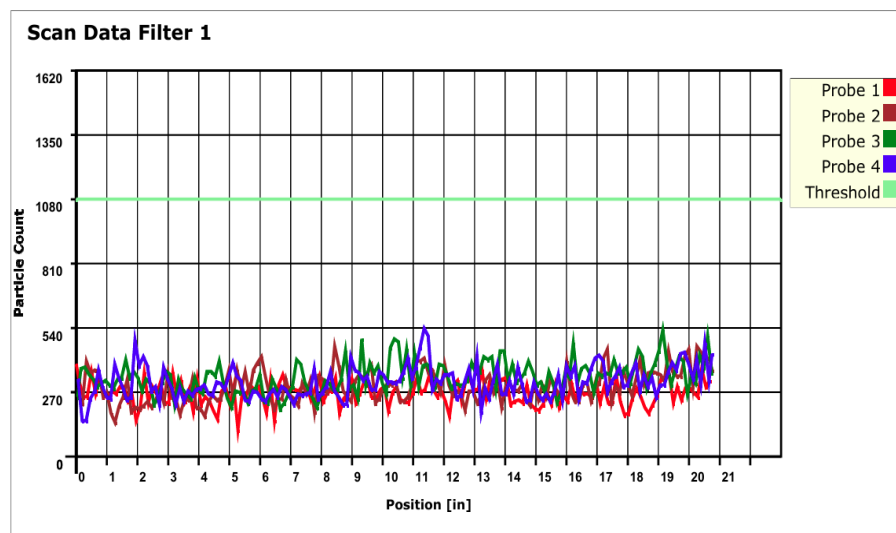
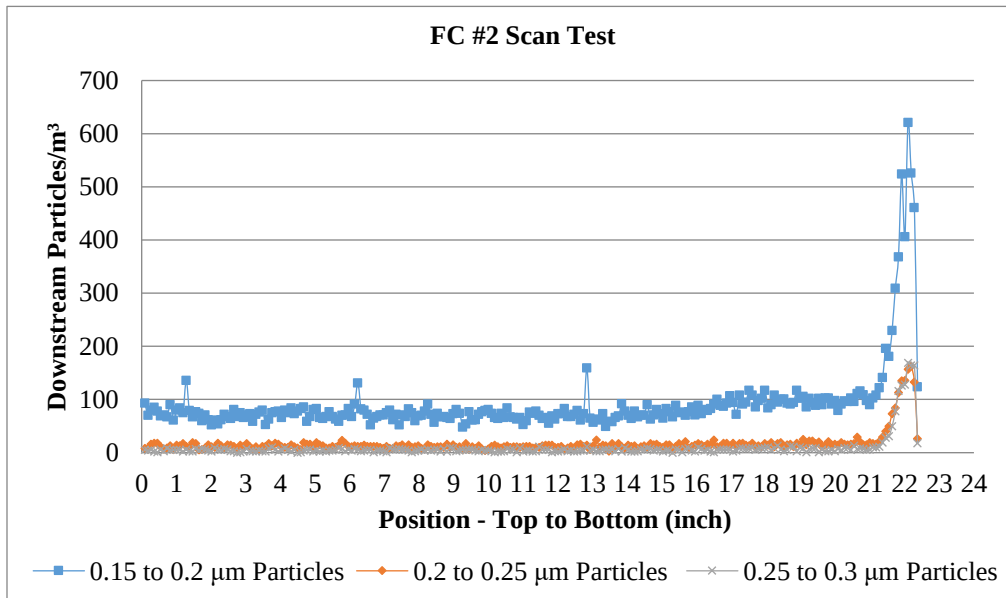


Figure 3.5. FC #2 Scan Test



3.4.2 Upstream Aerosol Uniformity

Upstream aerosol uniformity was validated using airflows of 472 CFM and 1970 CFM, in accordance with the ANSI-ASHRAE 52.2 standard; an additional 390 CFM was incorporated as it is typically used for manual scanning verification purposes. On the other hand, 1970 CFM airflow was used for validation in compliance with the IEST Recommended Practices. This was conducted for FC #1 and FC #2 utilizing our custom sampling device that measures the aerosol concentrations introduced via the designed injection port and/or the housing injection port according to both above standards. The supplied manufacturer sampling instrument with FC #2 was also utilized for performing aerosol uniformity testing in accordance with the ASHRAE 52.2 standard during this validation process.

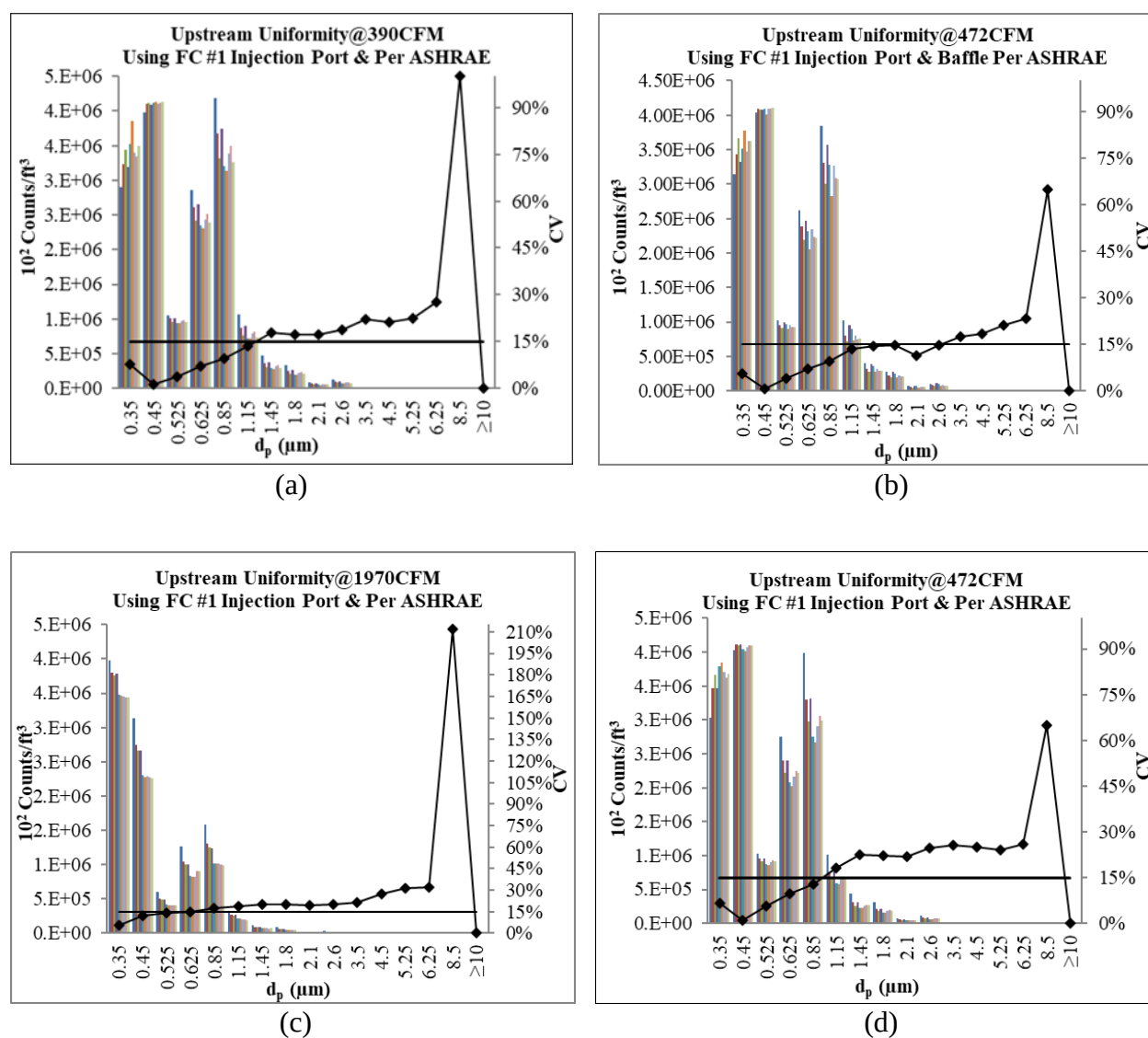
The outcomes of FC #1 upstream injector, depicted in Figure 3.6(a-e), demonstrated superior performance according to ASHRAE standards when utilizing the unit replaceable mixing baffle positioned post-housing injection port and within the pre-filter slot, alongside satisfactory results per IEST as illustrated in Figure 3.8(a). Outliers were identified, rendering the

results unreliable for particles beyond 3 μm due to insufficient concentrations of injected particles in that range. The results obtained from the designed injector, which was equipped with its mixing diffusion plate for the independent assessment of filter overall penetration efficiency, demonstrated satisfactory outcomes in alignment with the ASHRAE 52.2 standard, as illustrated in Figure 3.7(a-d), and the IEST standard, as shown in Figure 3.8(b), with fewer concentration deviations at each position compared to prior results for FC #1. The implementation of the housing mixing baffle in this instance did not make a difference, as shown in Figure 3.7(c) and Figure 3.7(d). The findings indicated that the distal injection port from the HEPA filter, coupled with a diffusion perforated plate positioned subsequently, enhanced the mixing of aerosol particles and facilitated their uniform distribution across the upstream face of the filter.

The results obtained for the FC #2 injection port were consistent when utilizing either our custom sampling device or the FC #2 manufacturer-supplied sampling device for aerosol uniformity testing, in accordance with ASHRAE 52.2, as illustrated in Figure 3.9(a-f). Given that IEST requires validation at additional positions and our designed sampling device is mobile, we used it then for the IEST aerosol uniformity validation. Results at low flow rates of 390 and 472 CFM were adequate for the particle sizes up to 1.3 μm . In contrast, the aerosol uniformity at a higher flow rate of 1970 CFM was only acceptable for the particle size range of 0.3 to 0.4 μm , consistent with IEST results at the same airflow, as illustrated in Figure 3.11(a). This challenge occurred due to the proximity of the housing injection port to the HEPA filter, coupled with the absence of a diffusion plate to facilitate particle mixing and ensure uniform distribution on the upstream side of the filter. The results from the designed injector, illustrated in Figure 3.10(a-f), indicated a significant improvement at the higher flow rate of 1970 CFM, yielding outcomes comparable to IEST as depicted in Figure 3.11(b).

This testing established the requirements outlined in the ANSI-ASHRAE 52.2 standard and the IEST Recommended Practices regarding the use of the designed duct injection port, as well as both housing injection and sampling ports. This is essential for the injection and measurement of upstream aerosol concentrations, necessary for calculating the fraction and overall efficiencies of the HEPA filter.

Figure 3.6(a-e). FC #1 ASHRAE Upstream Uniformity at Varied Flow Rates Using Housing Injection Port



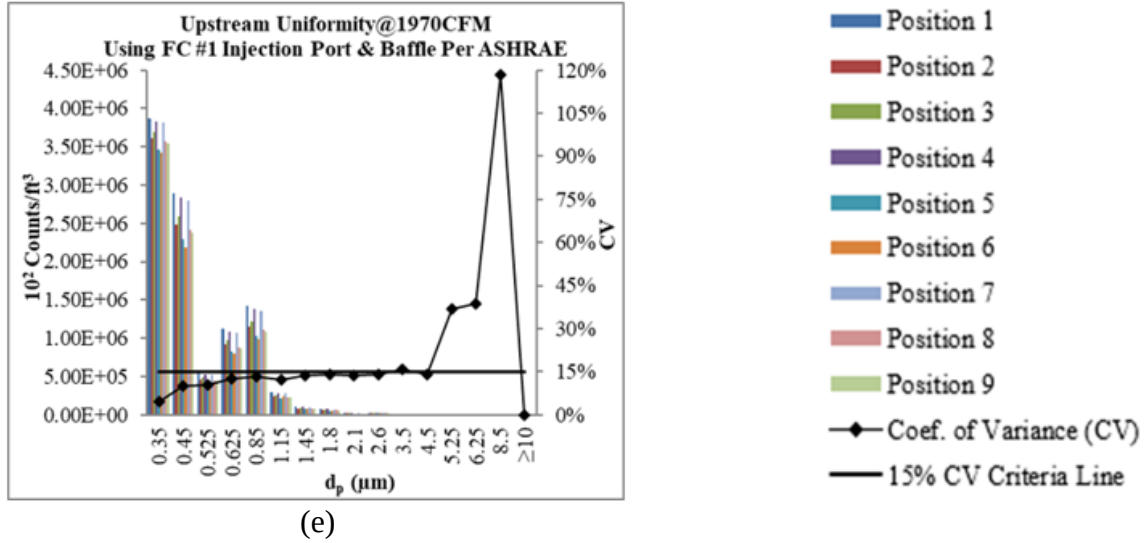


Figure 3.7(a-d). FC #1 ASHRAE Upstream Uniformity at Varied Flow Rates Using Designed Injection Port

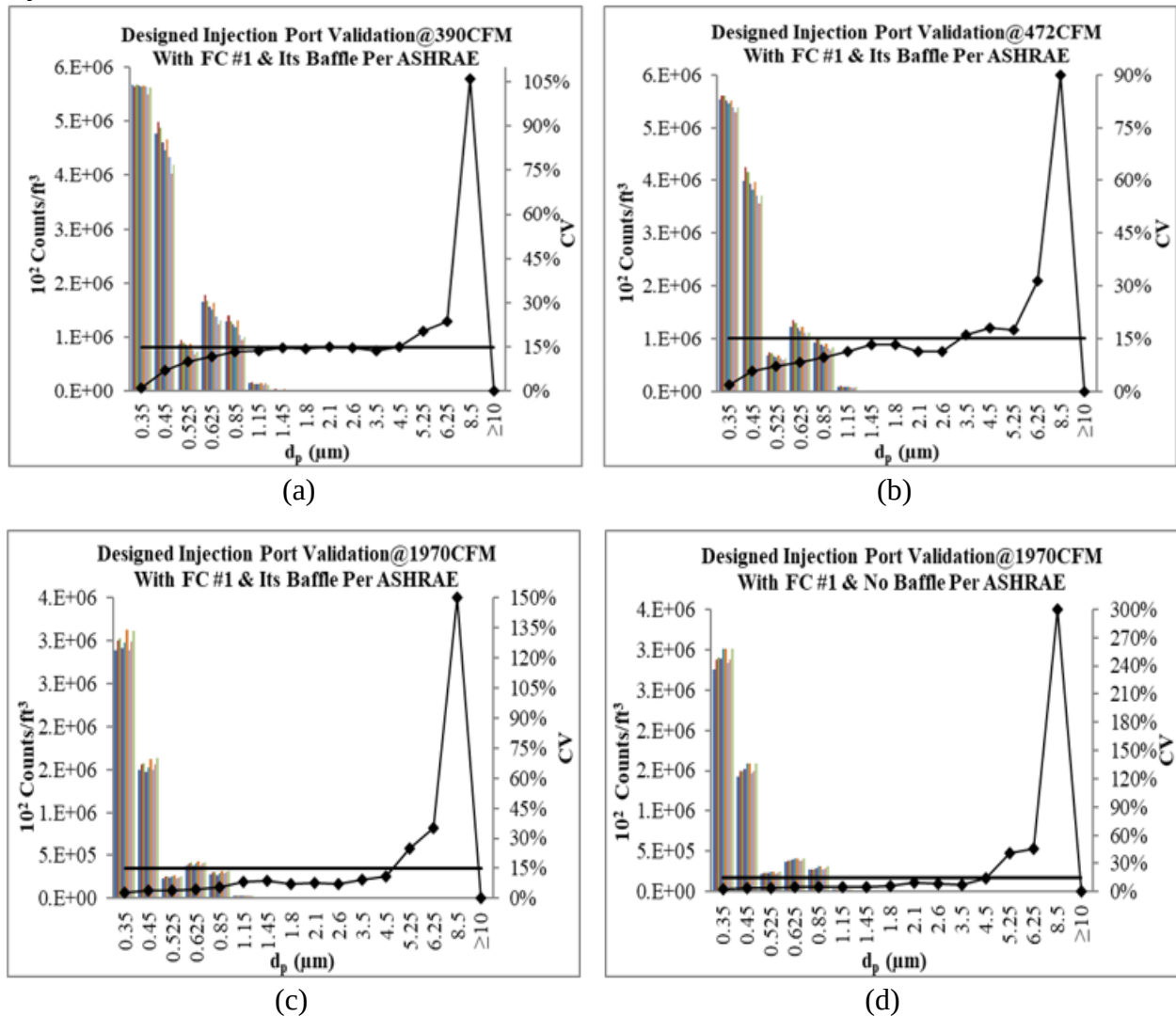


Figure 3.8(a-b). IEST FC #1 Upstream Uniformity Using Housing Injector (a), & Designed Injector (b)

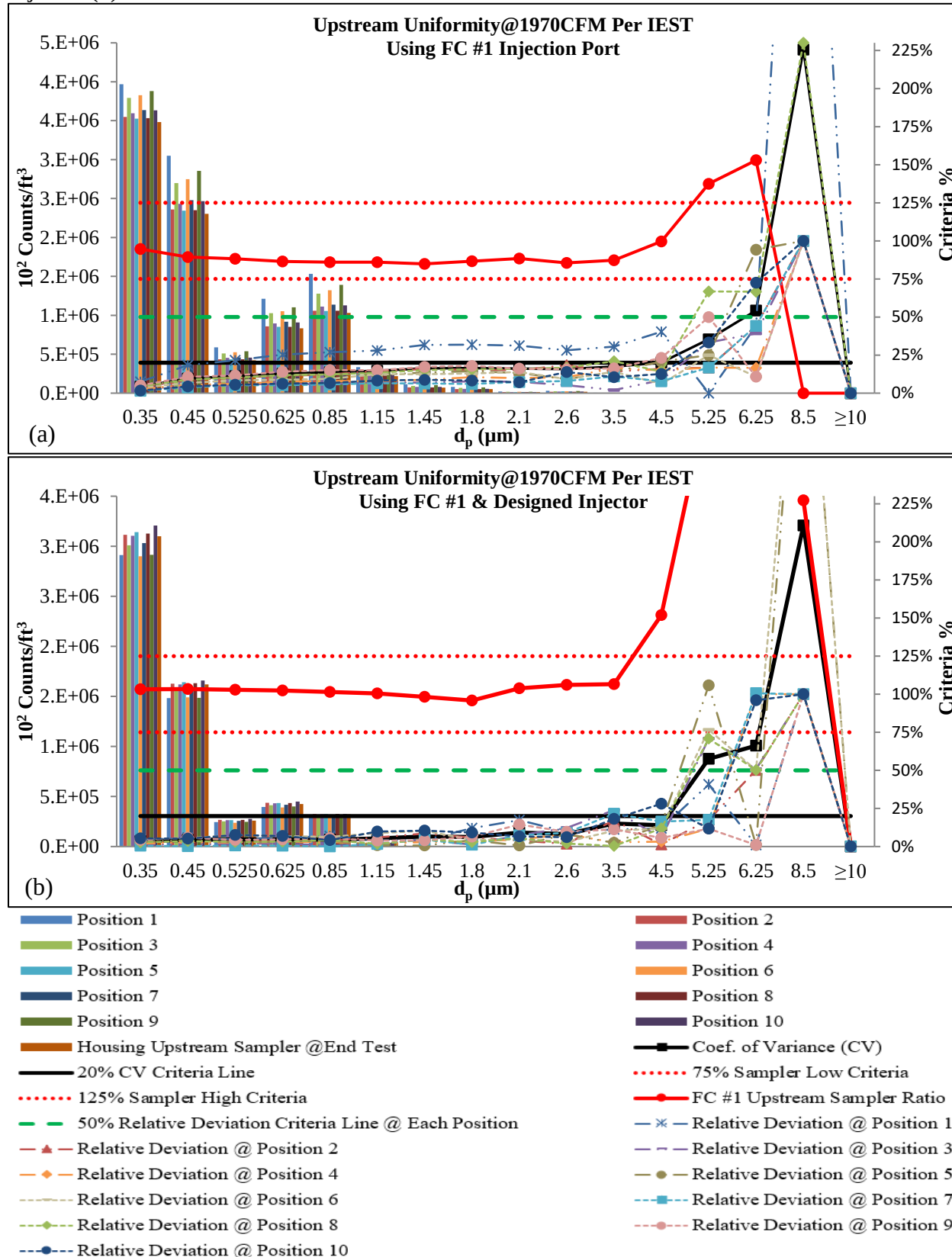
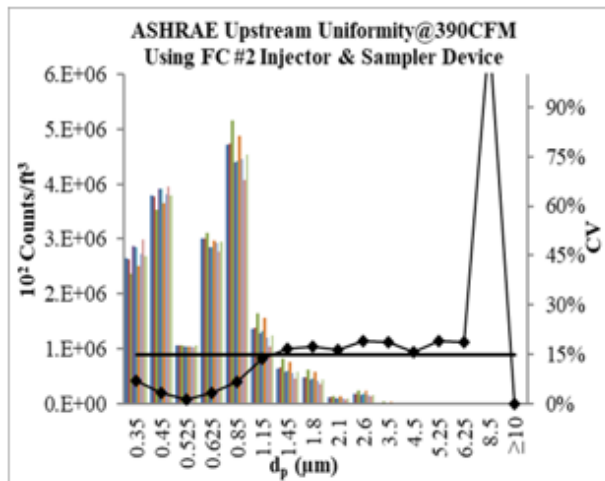
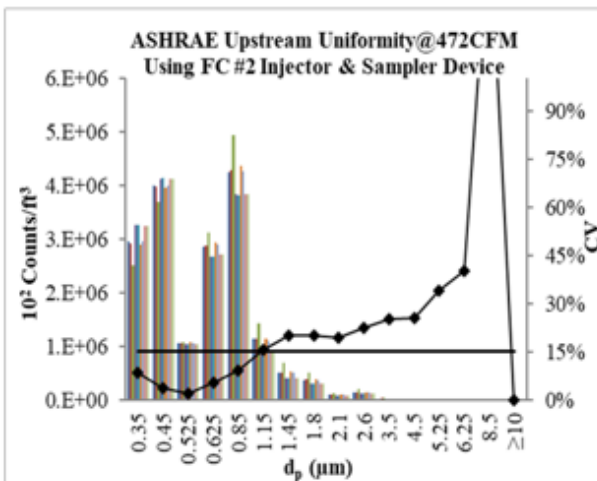


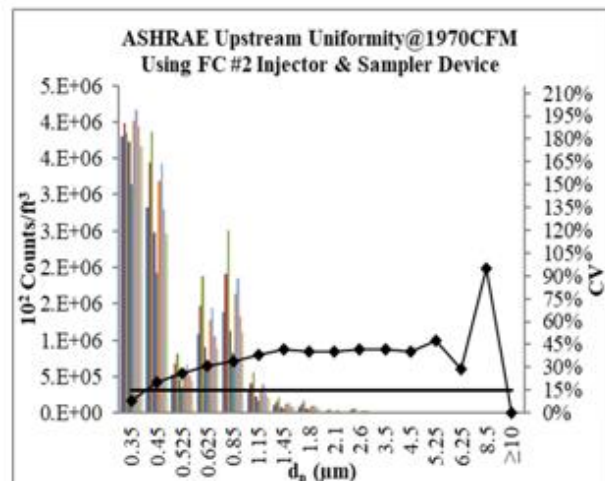
Figure 3.9(a-f). FC #2 ASHRAE Upstream Uniformity at Varied Flow Rates Using Housing Injection Port and Sampler Device



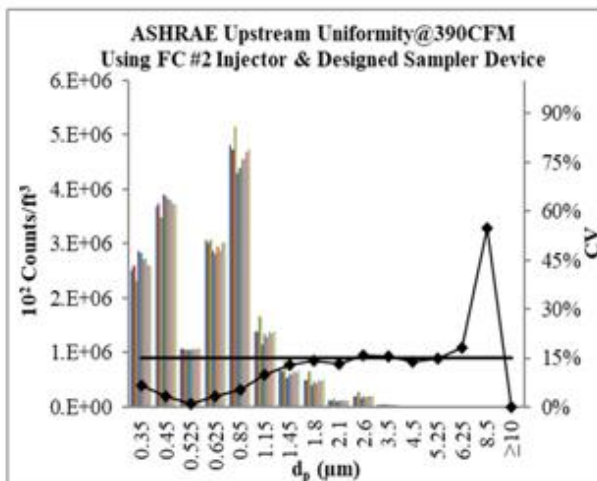
(a)



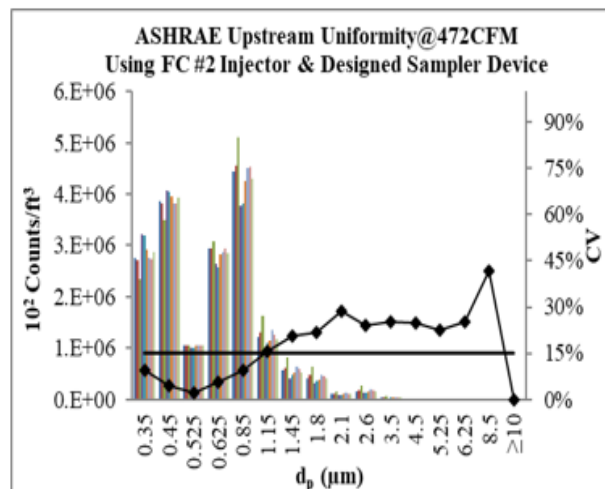
(b)



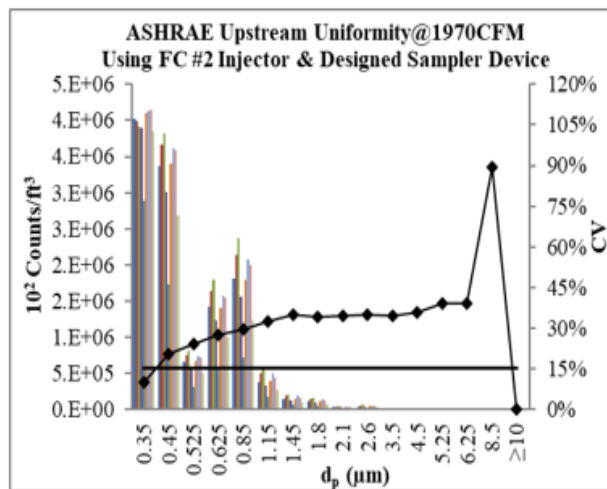
(c)



(d)

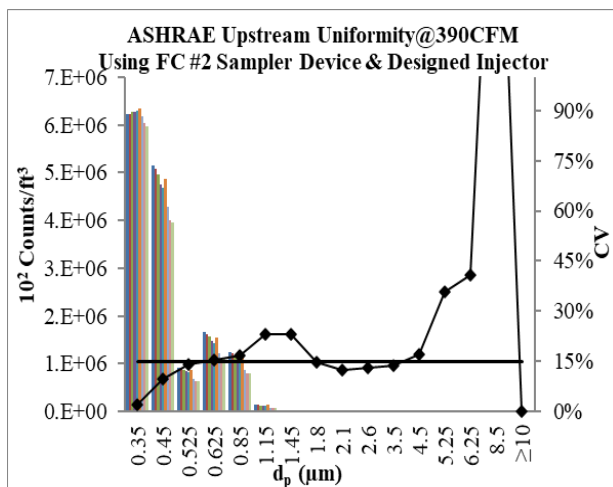


(e)

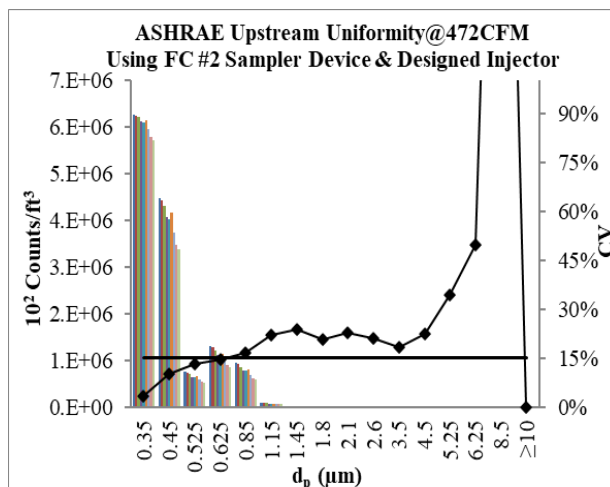


(f)

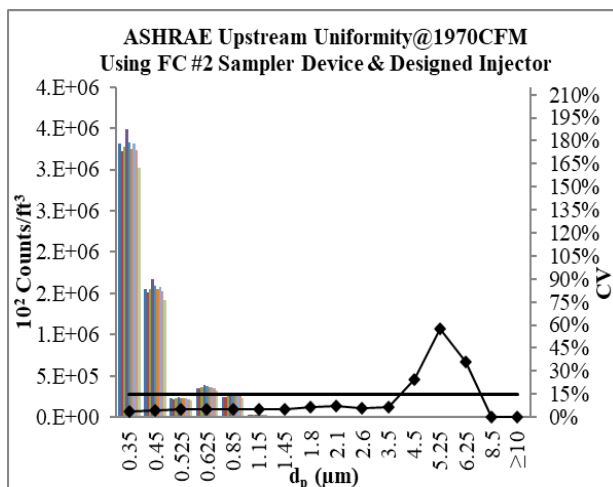
Figure 3.10(a-f). FC #2 ASHRAE Upstream Uniformity at Varied Flow Rates Using Designed Injection Port and Sampler Device



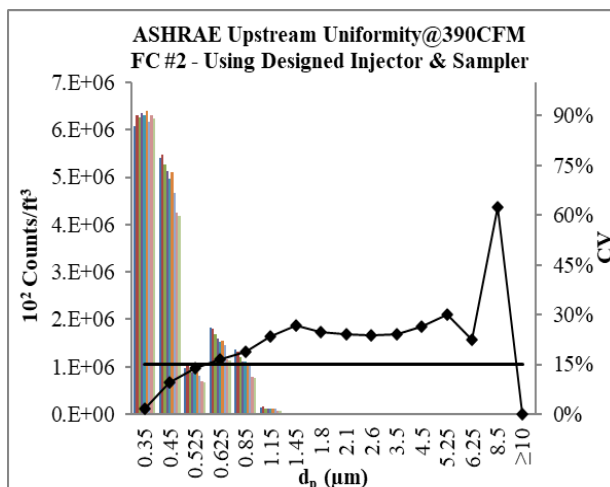
(a)



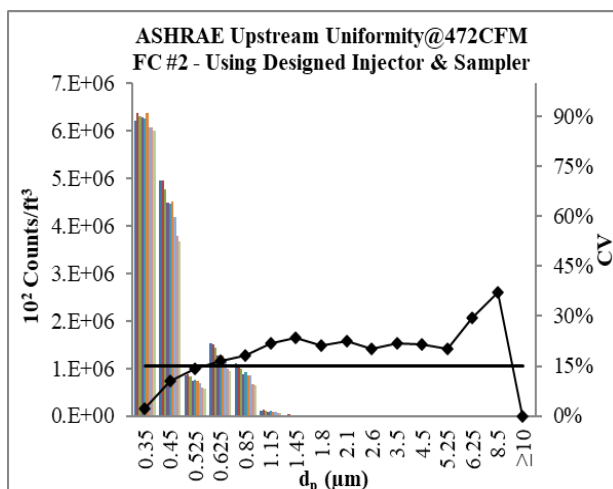
(b)



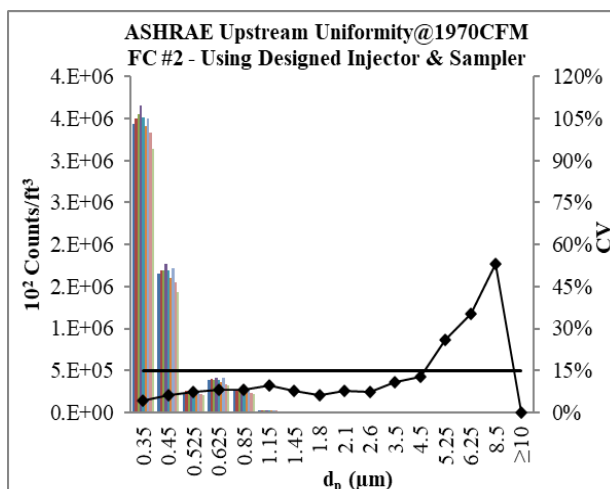
(c)



(d)

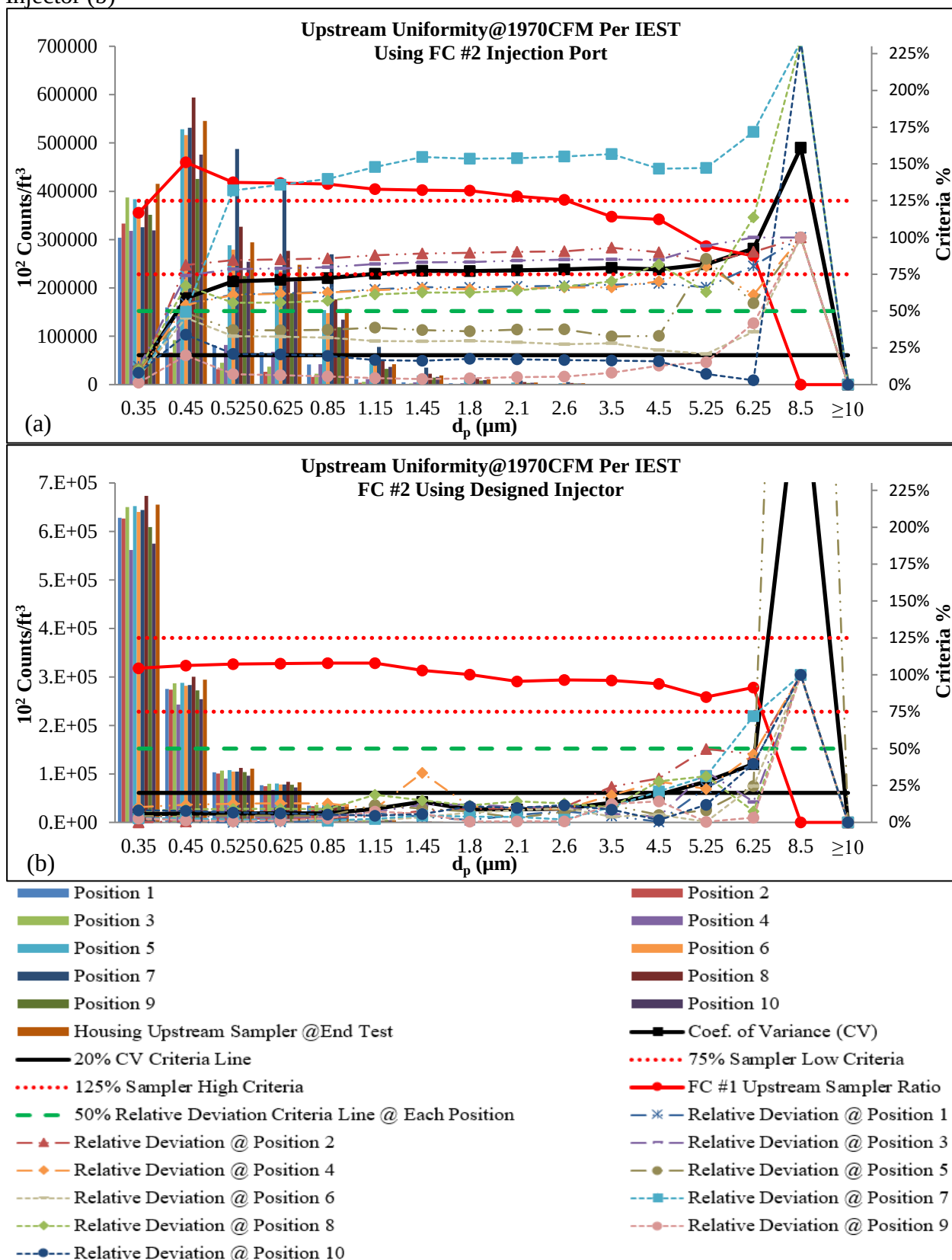


(e)



(f)

Figure 3.11(a-b). IEST FC #2 Upstream Uniformity Using Housing Injector (a), & Designed Injector (b)



3.4.3 Downstream Aerosol Uniformity

The airflow rates employed for the downstream mixing tests were 390, 472, 1250, and 1970 CFM. The downstream total concentrations at different airflows are illustrated against the nine injection grid points downstream of the filter in Figures 3.12(a) and 3.13(a) for each housing, along with the corresponding CV graphs for each airflow shown in Figure 3.12(b) and Figure 3.13(a). The results for FC #1 were achieved by repositioning the downstream duct mixing diffusion plate from a vertical to a horizontal orientation, placing it near the housing along with its associated sampler. This adjustment yielded a reduction of fluctuations in particle concentrations at all nine downstream locations illustrated in Figure 3.12(a), attributed to decreased gravitational deposition. The results yielded CV values that were consistently below the 10% threshold across all flow rates, as shown in Figure 3.12(b). With an increase in flow rate from 390 to 1970 CFM, the CV exhibited a corresponding rise from 0.7% to 5.3%, taking into account the total particle concentrations of all particle counter channels. It is important to note that for particle sizes of 1 μm and greater, the resulting particle concentrations became increasingly unrepresentative as the injected aerosols fell below the necessary threshold for sampling, owing to the limitation of the aerosol generator used. The results obtained with FC #2 demonstrated consistency and satisfaction, as illustrated in Figure 3.13(a) and Figure 3.13(b). A modest increase was observed in CV values, rising from 1% to 1.6% when compared to prior findings using FC #1. At a flow rate of 1970 CFM, the CV value exhibited minimal variation, which can be attributed to isokinetic sampling conducted at this specific flow rate. This established the reliability and dependability of the in-house-designed duct sampler for measuring downstream concentrations of particles that may pass through the filter from any location. It can subsequently be used for evaluating a HEPA filter and assessing its fractional efficiencies across

various flow ranges, in accordance with the ASHRAE 52.2 requirements for in-place HEPA filter testing and rating.

Figure 3.12(a-b). ASHRAE Duct (Designed) Sampler Validation Using FC #1

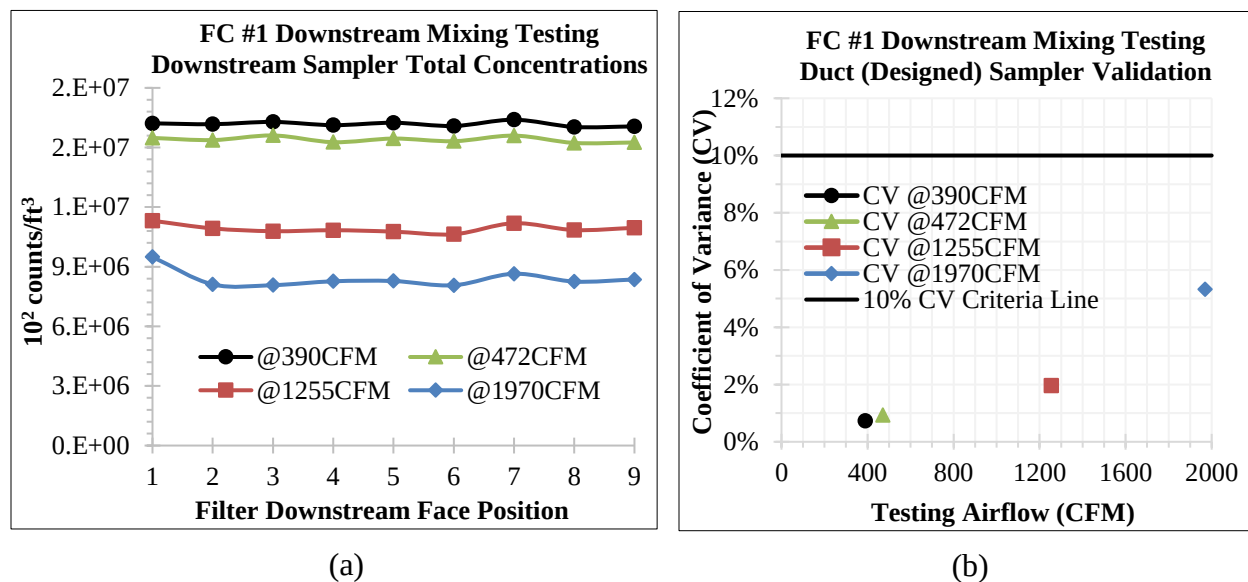
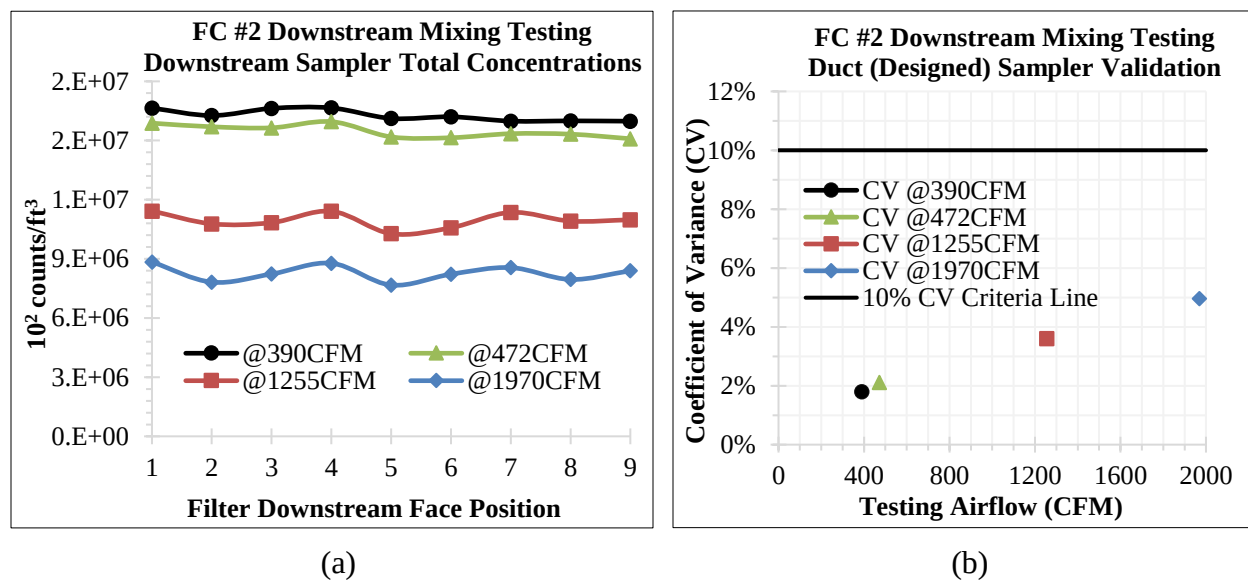


Figure 3.13(a-b). ASHRAE Duct (Designed) Sampler Validation Using FC #2

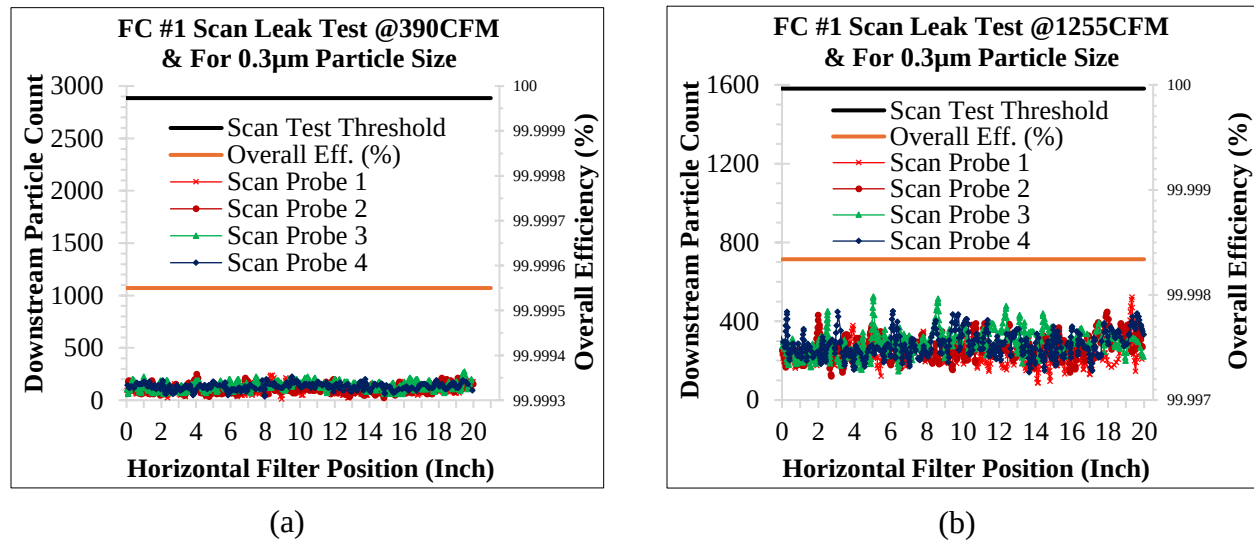


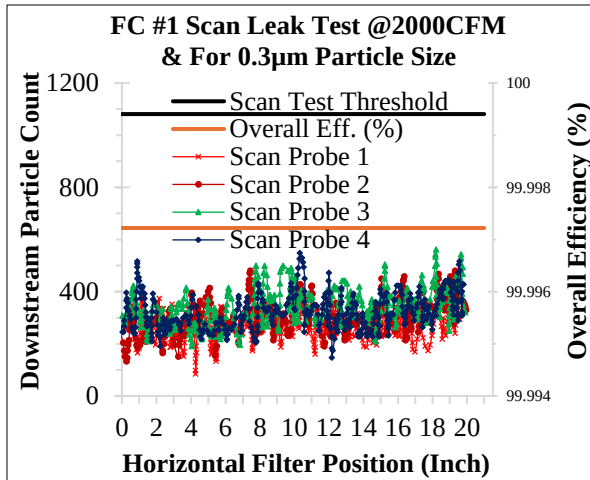
3.4.4 Filtration Efficiency

The examined filters were applied to the initial filtration condition, disregarding the impact of particle deposition on the filter medium. The outcomes of an intact filter scan leak and penetration testing utilizing FC #1 and its automated scanning apparatus, as illustrated in Figure 3.14(a-c), demonstrated a passing rating for the filter and leak-free results at various flow rates for a 0.3 μm particle size. However, as the flow rate increased, the downstream particle counts increased as well, which led to a decrease in overall efficiency. A significant and distinct linear correlation between overall efficiency and airflow for a 0.3 μm particle size was discovered, indicating the influence of the diffusion filtration mechanism as it continues to have an impact at this particle size. The filter penetration tests conducted using standalone equipment according to ASHRAE 52.2 are illustrated in Figure 3.14(d). Utilizing the same housing, these tests successfully achieved a filter rating, demonstrating expected results for particle sizes $\geq 0.52 \mu\text{m}$, where the overall efficiency of a HEPA filter is 100% for particles outside the MPPS range. The impact of airflows on overall filter efficiency is less evident here; however, for particles sized between 0.3 and 0.4 μm , the results were consistent with previous findings at 2000 CFM airflow for the 0.3 μm . Using FC #2 and its automated equipment, the filter scan test findings displayed in Figure 3.15(a-d) allowed for the investigation of four distinct particle size ranges encompassing all potential MPPS for a HEPA filter, which may somewhat fluctuate based on the tested airflow and other testing parameters. The downstream concentrations of particles were elevated for smaller particles within the range of 0.15–0.2 (averaging 0.175 μm), exhibiting some spikes and an increase correlated with airflow, although remaining far below the scan test threshold for leak-free conditions. This led to a lower overall efficiency for that particular particle range. Figure 3.15(e) clearly illustrated the influence of airflow on overall filter

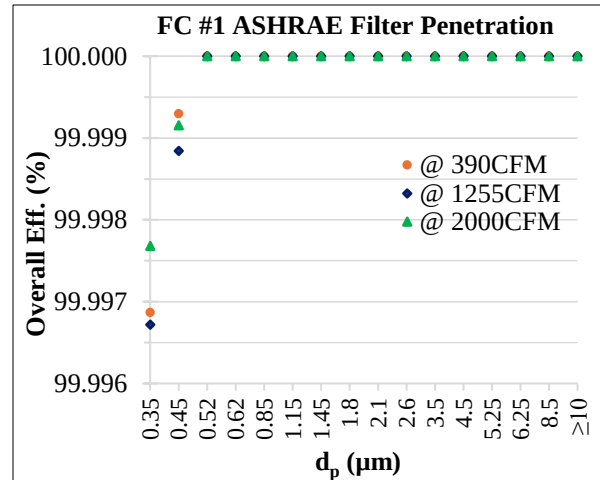
efficiency, indicating that efficiencies increased with particle size until they became less reliant on airflow variations for particles sized $\geq 0.5 \mu\text{m}$. Furthermore, reduced airflow enhanced filter efficiency for particles smaller than $0.5 \mu\text{m}$ until the MPPS diminished, resulting in a 100% efficient HEPA filter across all particle sizes. These observations align with filtration theory, which posits that aerosol penetration increases at higher face velocities for smaller particles due to the predominance of the diffusion mechanism, while the velocity's impact in the interception regime remains independent of airflow velocity for particles sized $\geq 0.5 \mu\text{m}$. The filter penetration tests conducted in accordance with ASHRAE 52.2 utilizing this housing demonstrated reliability in filter rating, as illustrated in Figure 3.15(d), with the MPPS range extended to an average particle size of $1.15 \mu\text{m}$, compared to $0.45 \mu\text{m}$ with FC #1, while maintaining equivalent clarity in illustrating the impact of airflow on the overall filter efficiency.

Figure 3.14(a-d). Intact Filter Scan Leak & Penetration Testing Using FC #1



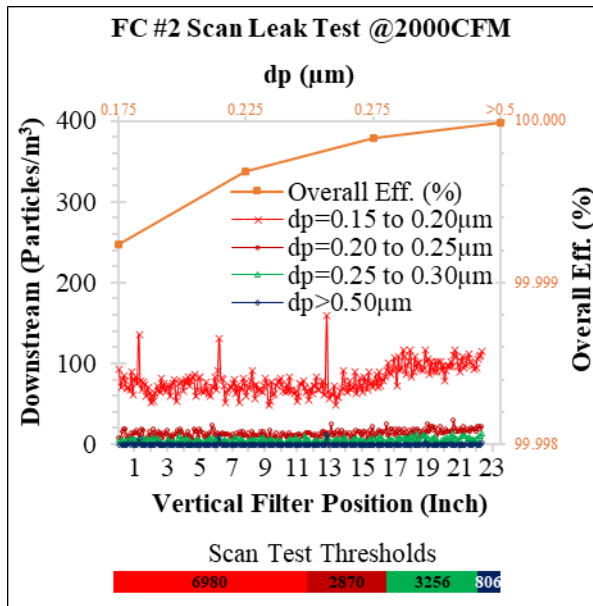


(c)

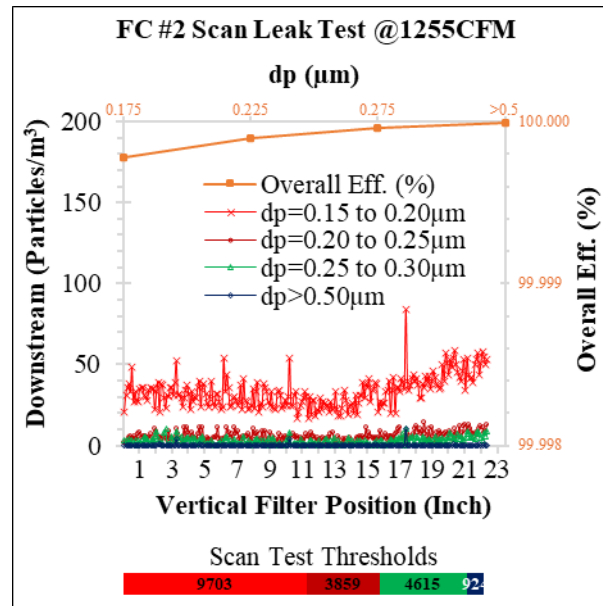


(d)

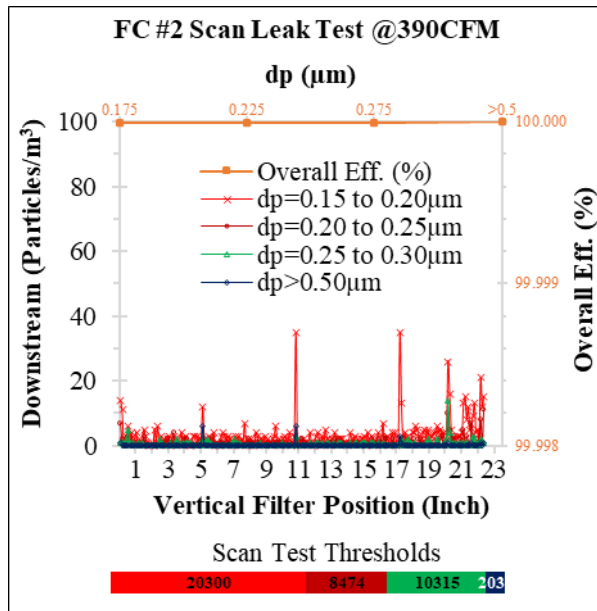
Figure 3.15(a-f). Intact Filter Scan Leak & Penetration Testing Using FC #2



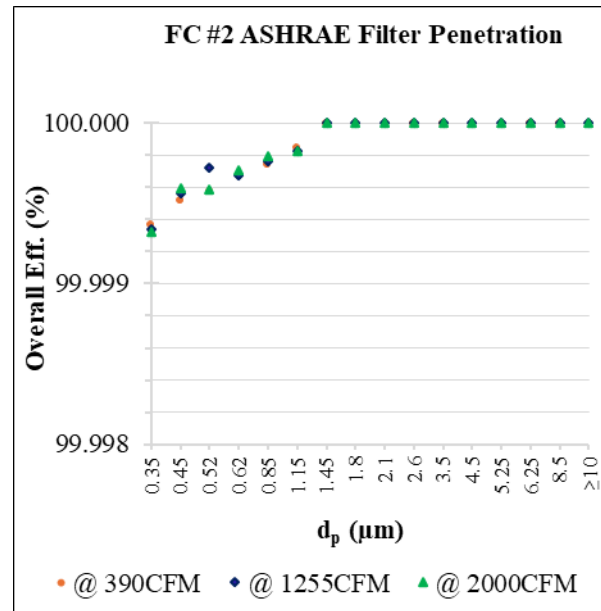
(a)



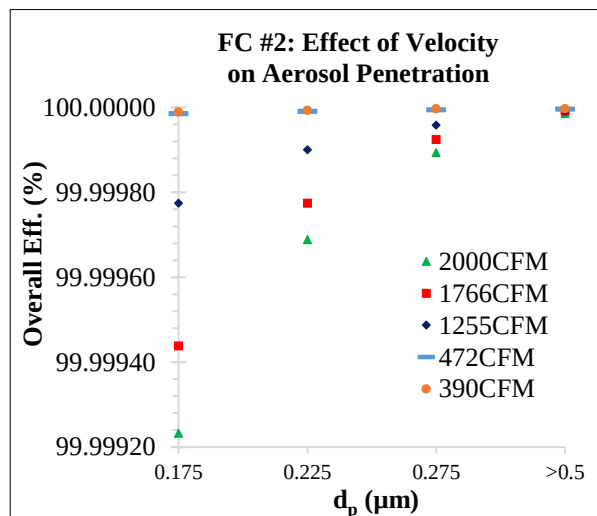
(b)



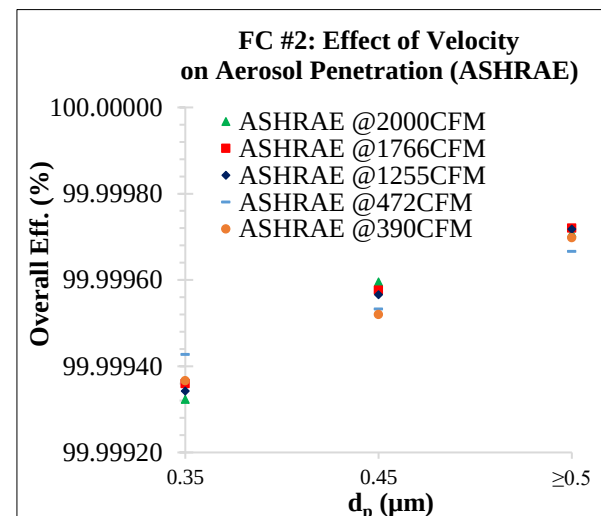
(c)



(d)



(e)



(f)

Figure 3.16(a-c) presents results from an additional series of tests conducted with a fresh filter, demonstrating the efficacy of the automated scan of FC #1 in identifying a pinhole leak through the filter media. As anticipated from Table 3.3 regarding the scan leak test, a leak with a diameter of ≥ 0.26 mm at a low airflow of 390 CFM was distinctly identified, and the downstream particle counts through it exceeded the threshold value for filter failure for local efficiency. A notable rise (spike), while below the threshold value, in recorded particle counts

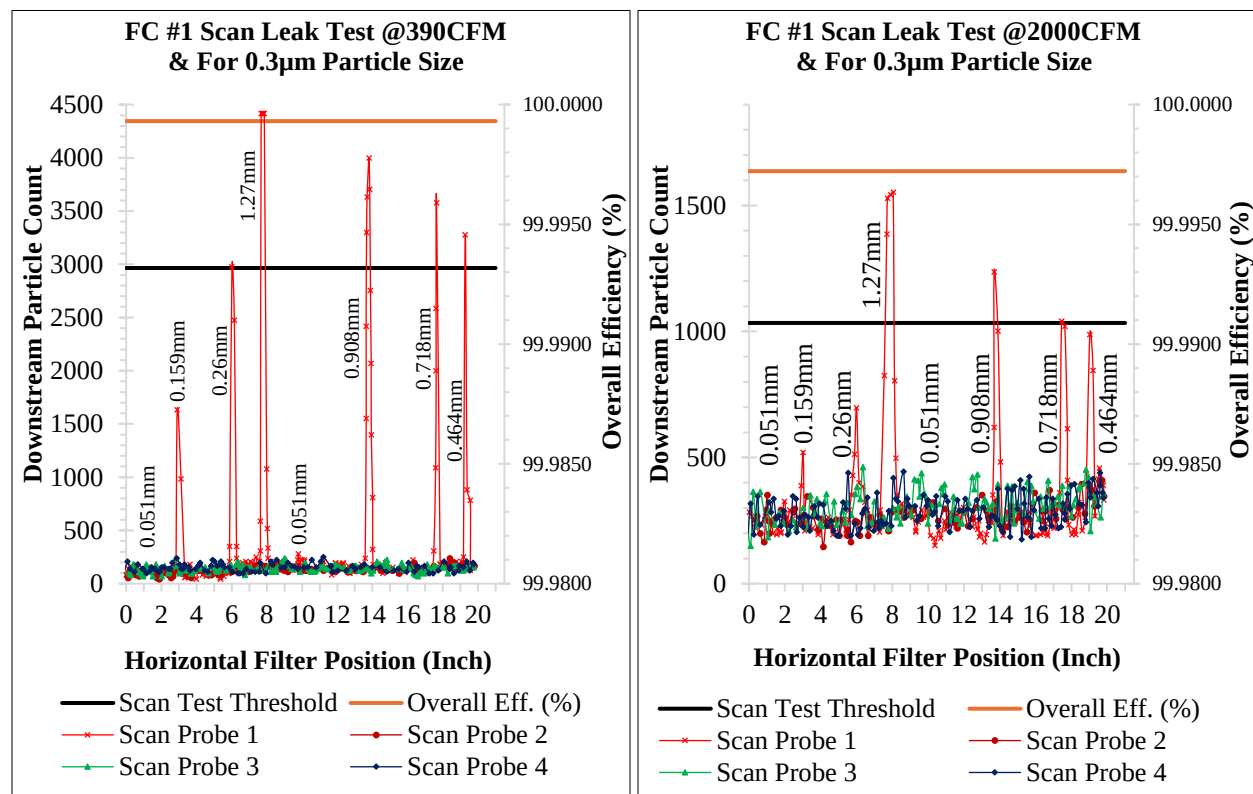
downstream of the filter indicated a potential leak at the location where we perforated the filter medium with a 0.159 mm pinhole. A stationary scan feature using this housing equipment was conducted over the leak to verify and confirm a leak of this magnitude. Nevertheless, tests failed to detect a very small pinhole leak with a diameter of 0.051 mm at both low and high airflows. Discrepancies were noted for leaks of 0.464 and 0.26 mm tested at an elevated airflow of 2000 CFM in Figure 3.16(b), identified by spikes yet remained beneath the threshold value (potential leaks). This may be attributed to non-isokinetic measurements at that airflow velocity, as the design, dimensions, and scanning speed of the probe accommodate an inlet velocity of approximately 230 ft/min (800 CFM). When the face velocity of the filter exceeds the probe's inlet velocity, particles may escape the probe and not be fully captured. Accurate isokinetic measurements became more critical here for detecting minute pinhole leaks of size ≤ 0.26 mm; otherwise, adjustments to the equipment settings and probe scan speed, as per Equation (3.1), are necessary to ensure reliable isokinetic samplings. Figure 3.16(c) illustrates the findings from testing another new filter, with pinholes positioned at predetermined positions both upstream and downstream. The results demonstrated the effectiveness and consistency of FC #1 in detecting leaks of identical size but varying locations, whether upstream of the filter or downstream near the scanning probe. The downstream particle counts remained consistent for the same leak size, irrespective of its occurrence upstream or downstream of the filter medium, demonstrating that the location of the internal pinhole had no impact. The penetration test findings illustrated in Figure 3.16(d) demonstrated a lower overall efficiency size between 0.3 and 0.4 μm (averaging 0.35 μm), while remaining equivalent to outcomes achieved with FC #1 equipment for 0.3 μm at 2000 CFM, with a variation of 0.0024%. Testing conducted with FC #1 and standalone

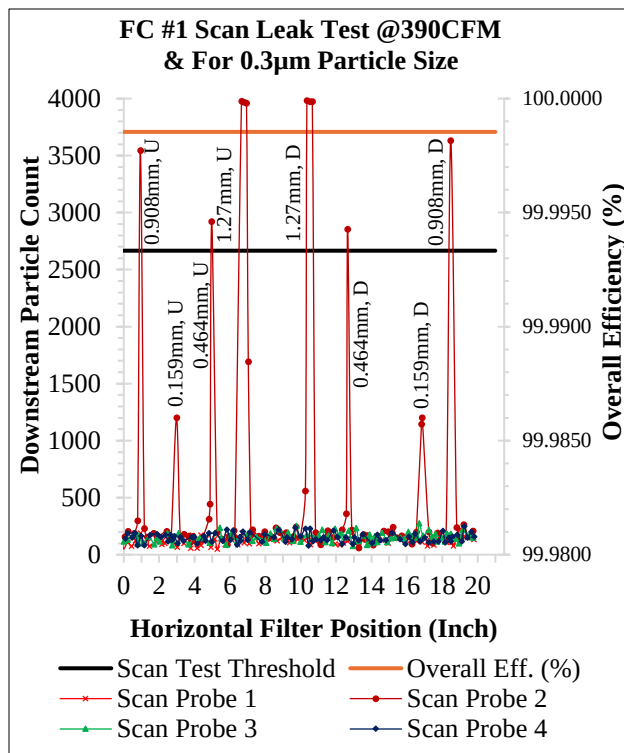
equipment demonstrated successful filter performance in terms of overall efficiency, despite the presence of multiple known pinhole leaks.

Figure 3.17(a-d) illustrates the outcomes of a further series of tests conducted on a new HEPA filter, which was subjected to a larger bypass leak through the gasket (external leak), in an attempt to marginally compromise the filter in order to assess the reliability of each testing method in identifying filter failure via penetration and scan leak testing. Four cuts near each corner of the filter frame were made through the gel gasket, measuring 0.5"×0.75" ×0.75", to marginally fail the filter during 390 CFM airflow testing, achieving an overall efficiency of 99.98994% and 99.98745% at 2000 CFM for the 0.3 µm particle size, against a passing rate of 99.99%. The scanning technique recorded particle penetrations through probes 1 and 4 at the bypass locations with almost identical maximum threshold values. However, for the two bypasses situated at the commencement of the scan, particles were detected for an extended duration and over greater distances, specifically approximately 6 inches from the filter frame side with probe 1 and 4 inches with probe 4. Conversely, at the bypasses located at the conclusion of the scanning distance, particles were captured and leaks identified, but the detection spanned a shorter distance, ceasing at the opposite side of the filter. This may have resulted in an overestimation of the particle count used in calculating overall efficiency. Nonetheless, leaks were distinctly discovered, demonstrating the superiority of this automated scanning technique in this matter. The penetration filter testing employing the ASHRAE 52.2 method yielded more definitive failure results, demonstrating an efficiency of 99.58216% at 390 CFM and 99.88288% at 2000 CFM for particles ranging 0.3–0.4 µm (averaging 0.35 µm), as shown in Figure 3.17(c). This method exhibited superior overall effectiveness compared to others, attributable to the effective mixing of aerosol particles and the positioning of the sampling probe. The findings of

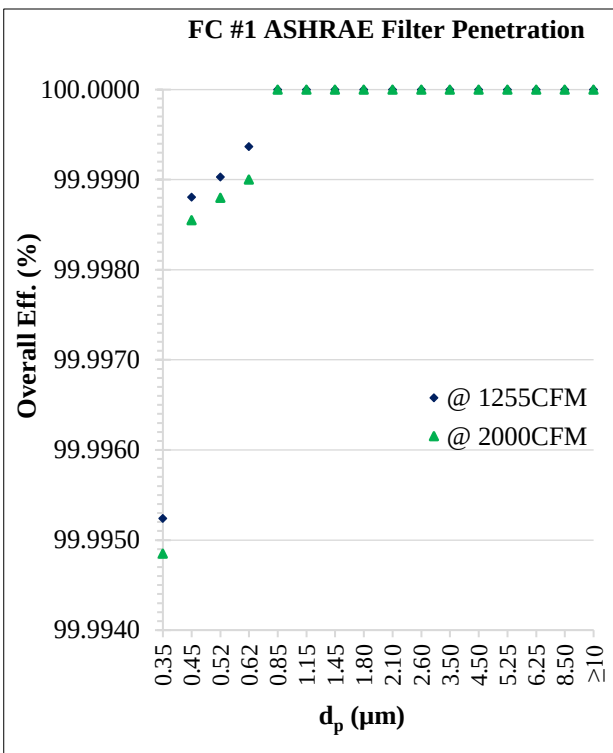
this testing method indicated that larger particles (up to 1.45 μm) penetrated bypasses in a logarithmic correlation with both particle size and airflow rate for the most particle sizes, as illustrated in Figure 3.17(c-d). Furthermore, an increase in efficiency was noted at a higher flow rate, which contradicted the results presented in Figure 3.16(c). This phenomenon can be attributed to the leaky filter medium and the slight reduction in pressure drop across the filter, as opposed to the negligible pressure drop variation observed with the pinholed filter, which improved particle capture within the filter bed.

Figure 3.16(a-d). Pinholed Filter Scan Leak & Penetration Testing Using FC #1



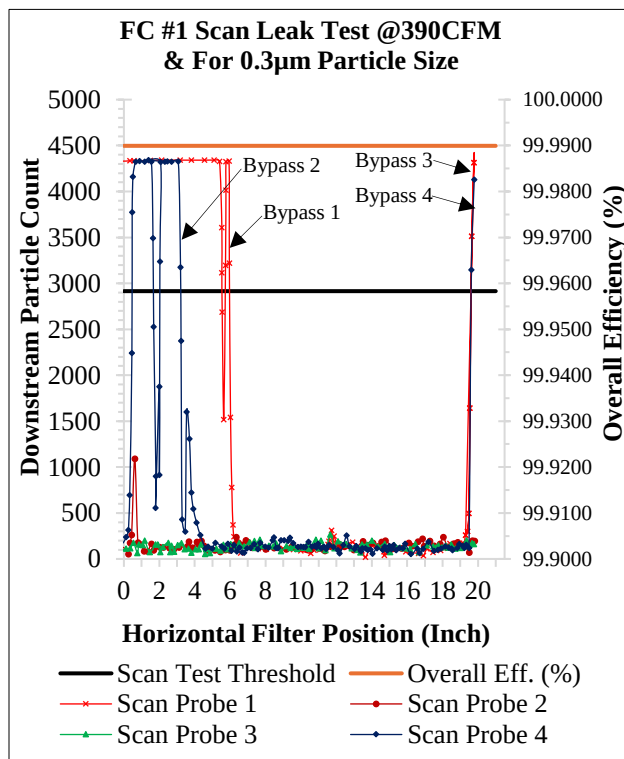


(c)

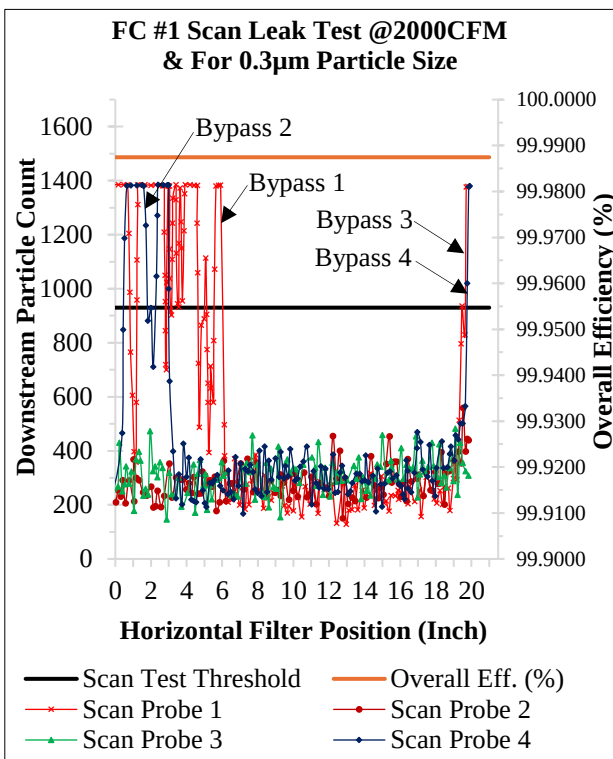


(d)

Figure 3.17(a-d). Leaky Filter Scan Leak & Penetration Testing Using FC #1



(a)



(b)

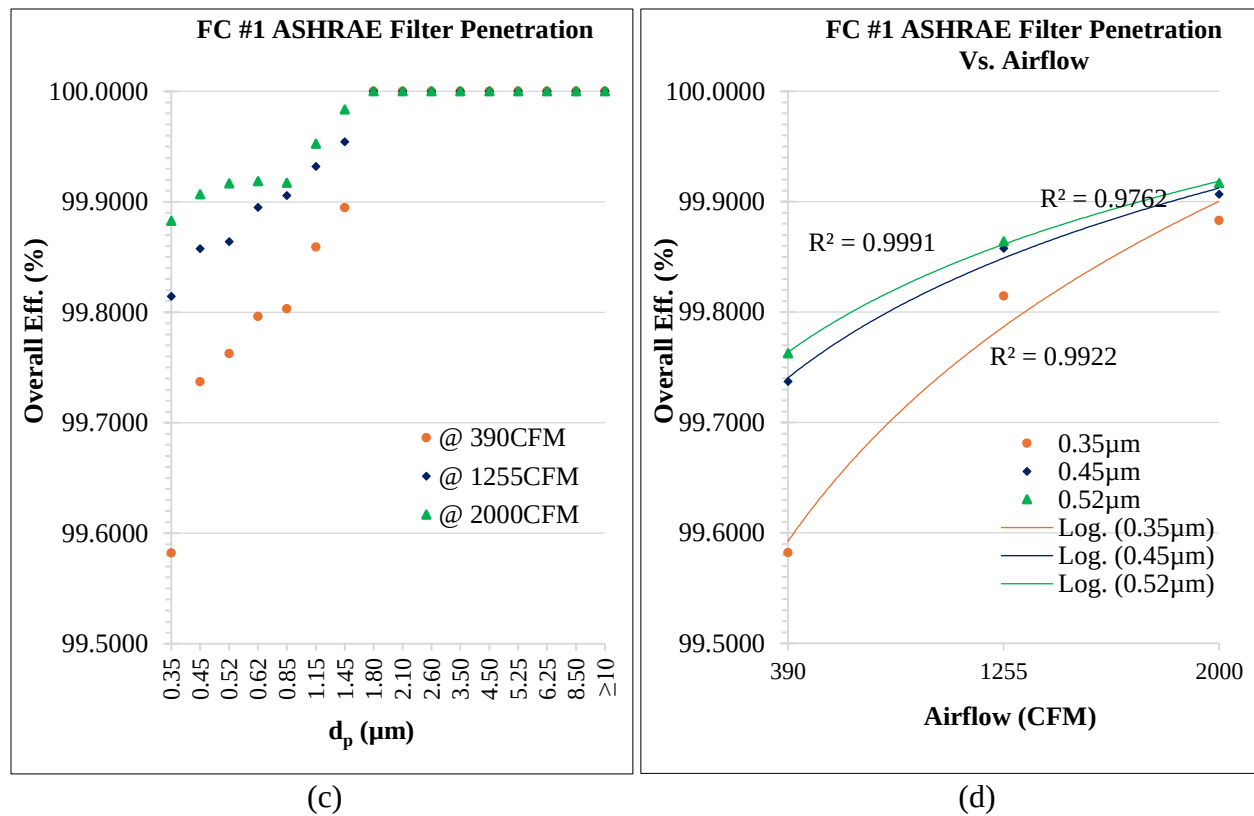


Figure 3.18(a-b) presents the results of a series of tests conducted on a filter utilizing FC #2, with pinholes of the smallest leak sizes achievable in our laboratory (0.051 mm and 0.159 mm) positioned upstream and downstream at specified locations. As estimated by theoretical analysis in Table 3.3, the results of a 0.051 mm leak size did not reveal a filter leak at all testing airflow rates. Detecting a 0.159 mm leak size at an airflow of 2000 CFM posed challenges, potentially attributable to the non-isokinetic measurements of the automated scanning probe. At an airflow of 390 CFM, the leak size was identified at the predefined locations with increased sensitivity. However, this did not lead to a failure of the filter according to local efficiency or overall efficiency calculations as per IEST standards and ratings. The overall efficiency improved with increasing particle sizes, consistent with typical observations for an intact filter. However, when leaks were identified at 390 CFM, the variations in overall efficiencies for the tested particle sizes were reduced due to a greater number of particles passing through the leaks.

Failing a filter took additional testing on a fresh filter with somewhat bigger leak sizes of 0.26, 0.464, and 1.27 mm (10 pinholes with different sizes at different locations), as opposed to FC #1, where a bigger bypass leak was introduced but with a 99.99% passing efficiency rather than 99.995%. Figure 3.19(a) and Figure 3.19(b) present the scan leak testing results at varying flow rates, indicating the failure of the filter. The filter's overall efficiency was found to be nearly independent of particle size and air volume (filtration velocity) within the MPPS range, consistent with the results on nanoparticles reported by Mouret et al. (2009). The overall filter efficiency values at the higher flow rate of 2000 CFM were improved relative to those at the lower flow rate of 390 CFM, aligning with the penetration testing results according to ASHRAE, as illustrated in Figure 3.19(c) and Figure 3.19(d). The increase in overall efficiency at higher filtration velocities can be linked to the inverse relationship between particle penetration of a pinholed filter and filtration velocity while maintaining the same pinhole leaks at both flow rates, as explained and also observed in the work of Bach & Schmidt (2007). The overall efficiencies obtained from the penetration ASHRAE testing shown in Figure 3.19(c) and Figure 3.19(d) were clearly reliable in demonstrating filter failure even for particles outside the MPPS range.

Figure 3.18(a-b). Pinholed Filter Scan Leak & Penetration Testing Using FC #2

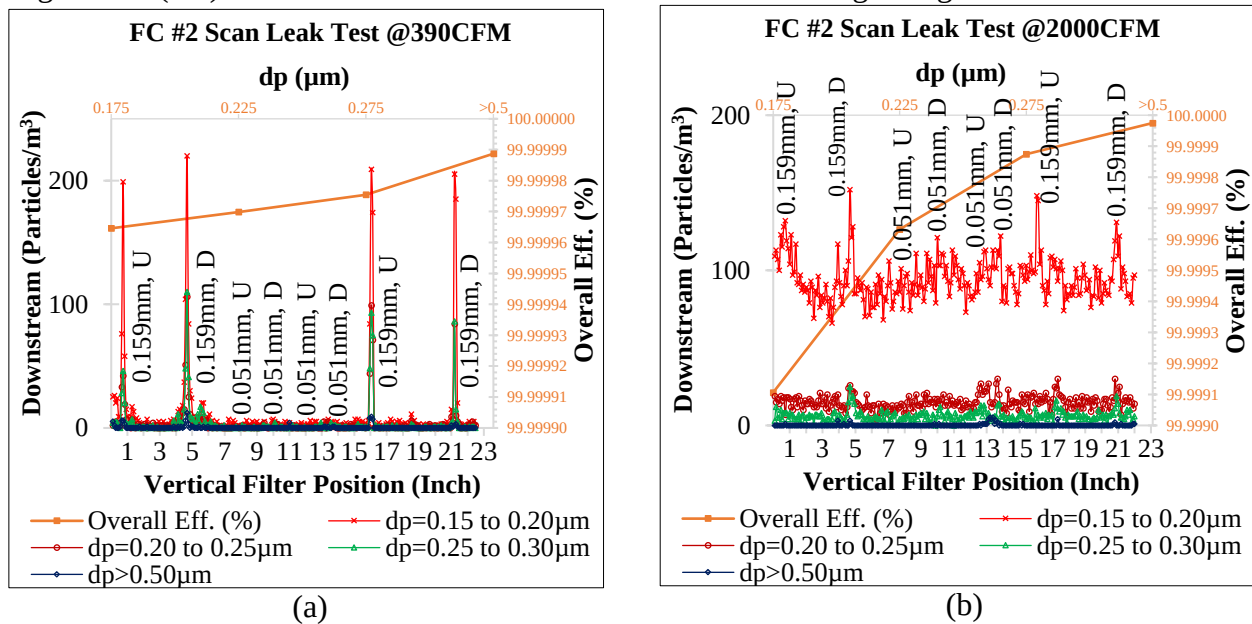
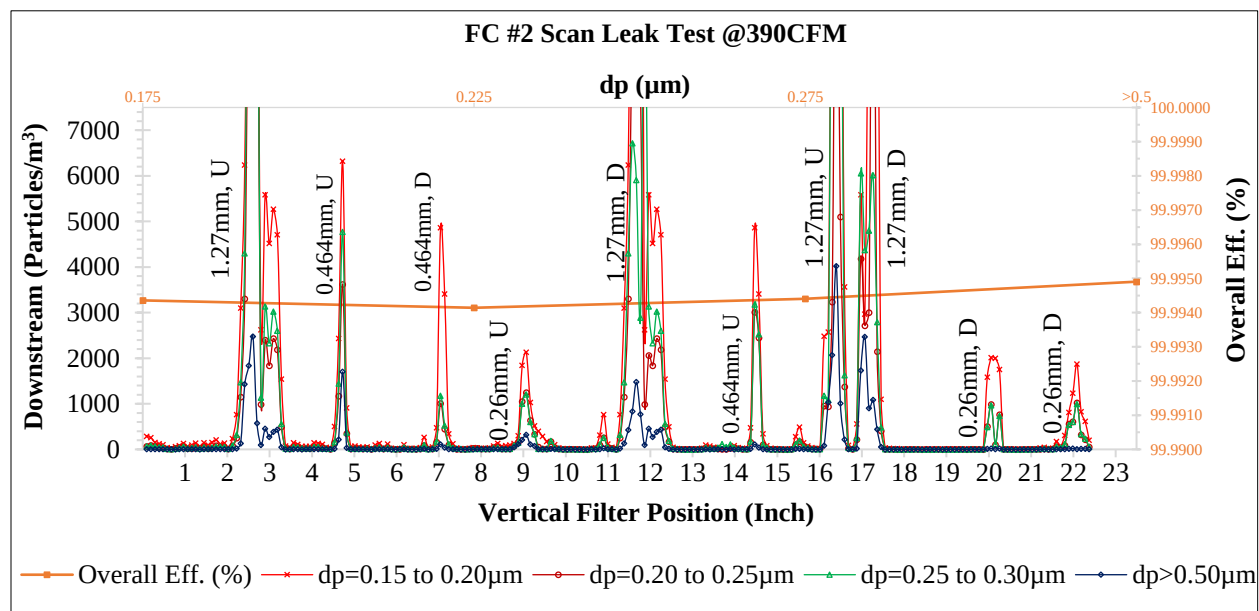
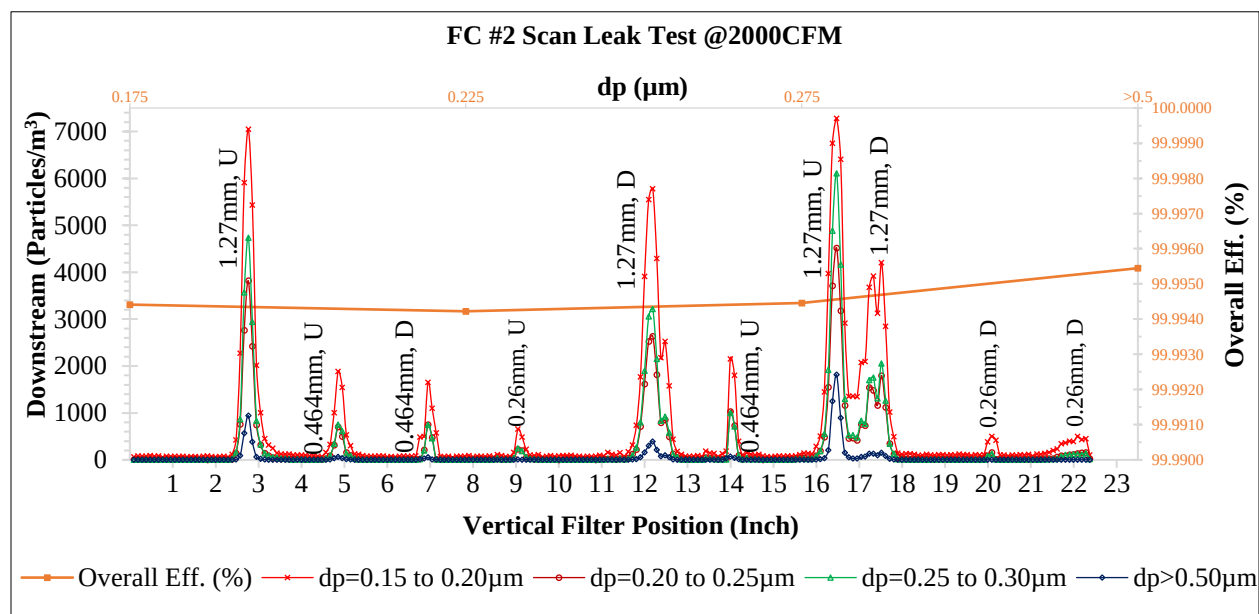


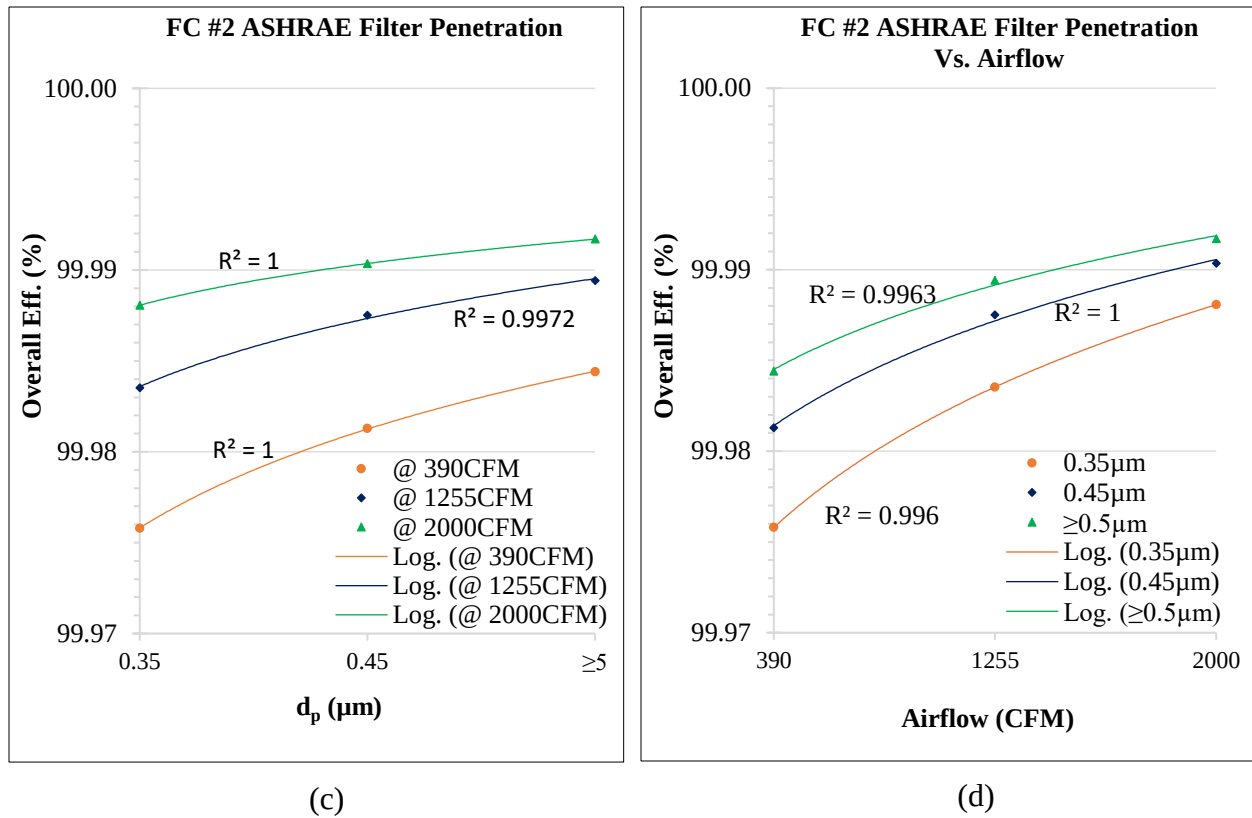
Figure 3.19(a-d). Leaky Filter Scan Leak & Penetration Testing Using FC #2



(a)



(b)



The results obtained using the scanning technique for overall efficiency measurements were comparable to those derived from the method outlined in ASHRAE 52.2 concerning filter ratings. The scanning technology is also specialized in measuring local efficiency for the detection of any potential leaks. This is crucial in the context of pinhole leaks, as global efficiencies can become unpredictable for such leak sizes and may not adequately indicate or reflect filter failures.

3.5 Conclusion

A test stand was successfully designed and constructed to facilitate objective testing and evaluation of HEPA filter performance and housing used in NBAF, as well as to support long-term training and education modules for these NBAF prototype systems. We conducted comprehensive testing of HEPA filters, and their housing integrated with associated auto-scan technologies. This included preliminary testing, filtration penetration, and leak tests, following

the guidelines specified in the ASHRAE 52.2 and IEST standards. Although the filter penetration tests performed according to ASHRAE 52.2 were reliable for certifying and classifying intact filters and produced results comparable to those obtained with auto-scan technology in that regard, it fell short in detecting a minor leak in the full-scale filter. On the other hand, automated scanning measuring equipment demonstrated a high level of reliability in detecting leaks. Nevertheless, the accuracy and reliability of automated scanning instruments in detecting leaks in the full-scale filter media began to be compromised when a 34-gauge needle with its nominal outside diameter of 0.159 mm was used to create a small leak, and particularly with its inside diameter when the leak was 0.051 mm (51 μm). This necessitates modeling the microstructure of the HEPA filter medium and conducting additional experiments on small-scale filter media. This methodology will allow for more in-depth research into the effect of those small leaks on the filter performance. The application of the filter medium microstructure model, alongside simulation data and results, will enable the enhancement of the criteria and parameters within the standards and adapt scanning device designs to identify leaks smaller than 160 μm and 51 μm .

Chapter 4 – Modeling the Performance of HEPA Filter Media With & Without Internal Leaks and Assessing the Likelihood of a Successful Filtration Leak Test

An affordable microscale modeling analysis of high-efficiency air particulate (HEPA) filter medium is presented in this chapter. Both leak-free and leaking media with known leak sizes are the subjects of this analysis. In contrast to earlier research, a three-dimensional fibrous model with non-homogenous fiber diameter sizes ranging from 0.2 to 2 μm and a packing density of 7.5% was developed to replicate the actual microstructure of a HEPA filter sheet (H14). The objective is to simulate and analyze the pressure drop and collection efficiency of nanofibrous media when challenged with aerosol particles of $\leq 0.5 \mu\text{m}$ size range. The results were compared to prior experimental and theoretical models and exhibited a significant level of concurrence with pressure drop and efficiency predictions. We successfully determined the pinhole size at which the collection efficiency of a damaged filter medium is influenced by collection through the fiber bed, as well as the size at which efficiency is controlled by collection through the pinhole (leakage regime). We also determined the smallest pinhole size at which a noticeable change in filter media efficiency begins to occur. The established computational model and predicted outcomes will be extremely useful in the development and improvement of related standards and scanning testing machines used in the testing and certification of HEPA and ultra-low particulate air (ULPA) filters.

4.1 Introduction

Leaks can be found in every filter unit due to the manufacturer's defect or damage to the media during installation, handling, and operation. The presence of leaks in filter media may

yield, depending on their sizes, to a particle penetration greater than 0.03%, which means a failure of the filter to meet the qualification and quality assurance tests described in the standards such as ANSI/ASME N510 and MIL-STD-282. This requires a patching of leaks or even an entire replacement of the filter to avoid subsequent failure and any dead spots that create local points of high resistance and velocity reduction. Thus, it is important to assess and understand the effect of internal leaks on the filter media performance for assuring health and environmental protection and safety.

The filter penetration values in the intact media regime for a wide range of operating conditions should follow predictions of filtration theory shown in Figure 4.1 and Figure 4.2, as the diffusion, interception, inertial impaction, and sedimentation (gravitational deposition) mechanisms determine the shape of the overall single-fiber and total filter efficiencies. In the range of particle sizes studied in this chapter, the two principal filtration mechanisms that dominate are Brownian diffusion and interception (Lee & Liu, 1982). Particle collection through a filter fiber due to both diffusion and interception is based on the air streamlines, particle size, and fiber/media properties. The former is a result of an energy exchange between the particle and gas molecule to reach a thermal equilibrium, which may cause particles to depart from streamlines and random collisions with the fiber surface and therefore deposition on the fiber surface. Particle capture due to diffusion tends to increase when the particles are smaller, and that is due to their higher mobility. The effectiveness of this mechanism is strongly related to the Peclet number,

$$P_e = \frac{d_f V_f}{D} \quad (4.1a)$$

Where d_f is the fiber diameter, V_f is the filter face velocity, and D is the particle diffusion coefficient, which can be calculated from the Stokes-Einstein expression at the known

operational or testing temperature, T , as $D = \mu_p K_B T$, where μ_p is the particle mechanical mobility, and K_B is the Boltzmann's constant number; and the single fiber diffusion collection efficiency has the following form:

$$E_D = c_1 P_e^{c_2} \quad (4.1b)$$

Where c_1 and c_2 are constant obtained analytically from the equation of convective diffusion and can vary based on the model used and boundary conditions. The latter mechanism occurs when the passive (massless) particles are in contact with the fiber surface by following the air streamlines around the fiber (collector), and this is only dominant for particle sizes within the size of the fiber. Therefore, collection efficiency due to interception depends primarily on the interception parameter (R), which is defined as the ratio of particle diameter to fiber diameter:

$$R = \frac{d_p}{d_f} \quad (4.2a)$$

Interception has more effect on the total media efficiency as the interception parameter and the fiber packing density or solid volume fraction (SVF) increase (Zhang, 2004), and thus the single fiber interception collection efficiency can have the following simple form:

$$E_R \approx \alpha R \quad (4.2b)$$

The overall single-fiber efficiency curve can then be determined by summing the values of the four primary mechanism efficiencies previously mentioned. Figure 4.1 presents a calculation of the single-fiber efficiency of a filter media characterized by an average fiber diameter of $0.59 \mu\text{m}$ and an SVF of 0.075, under a face velocity of 5 cm/s. This calculation utilized the established relationships for diffusion and interception as outlined by Liu & Rubow (1990), the inertial impaction relationship proposed by Stechkina et al. (1969), and the gravitational deposition relationship from Yeh & Liu (1974). By employing assumptions about the distribution and orientation of fibers with a diameter size of d_f , aligned perpendicularly to the airflow and

parallel to one another within a filter media, the total filter media efficiency can be calculated from the single-fiber efficiency. This is achieved by considering a differential layer of the filter medium with a thickness of (L) and balancing the particles rate (N) that traverses this differential layer. This will yield the total intact media efficiency (E_f) or penetration (P_f) as a function of a single fiber efficiency (E_s) and its corresponding curve shown in Figure 4.2:

$$E_f = 1 - \frac{N_{out}}{N_{in}} = 1 - e^{\frac{-4\alpha L E_s}{\pi d_f (1-\alpha)}} \quad (4.3a)$$

$$P_f = 1 - E_f = e^{\frac{-4\alpha L E_s}{\pi d_f (1-\alpha)}} \quad (4.3b)$$

Figure 4.1. Overall Single-Fiber Efficiency Curve

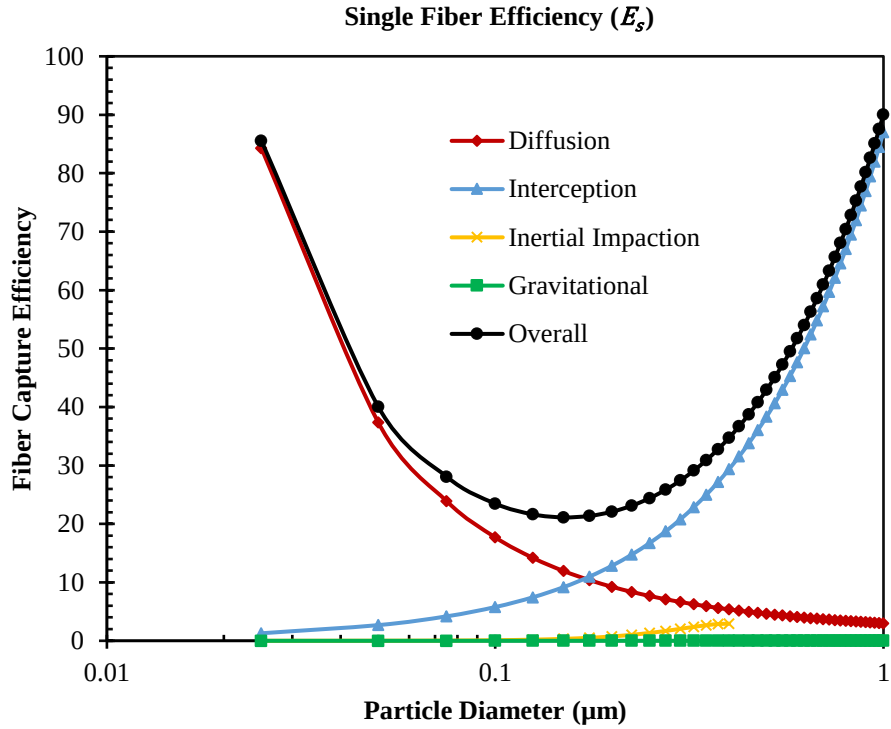
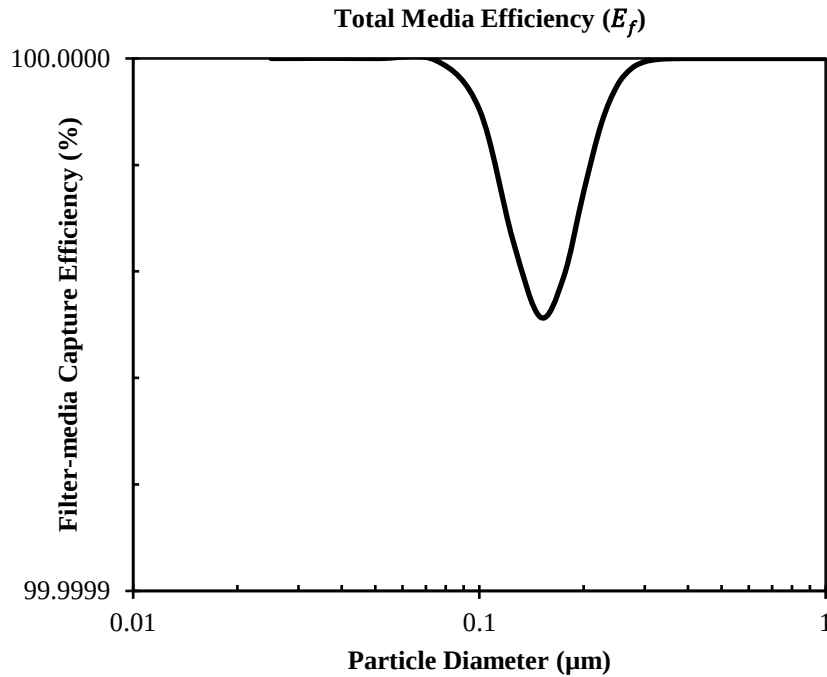


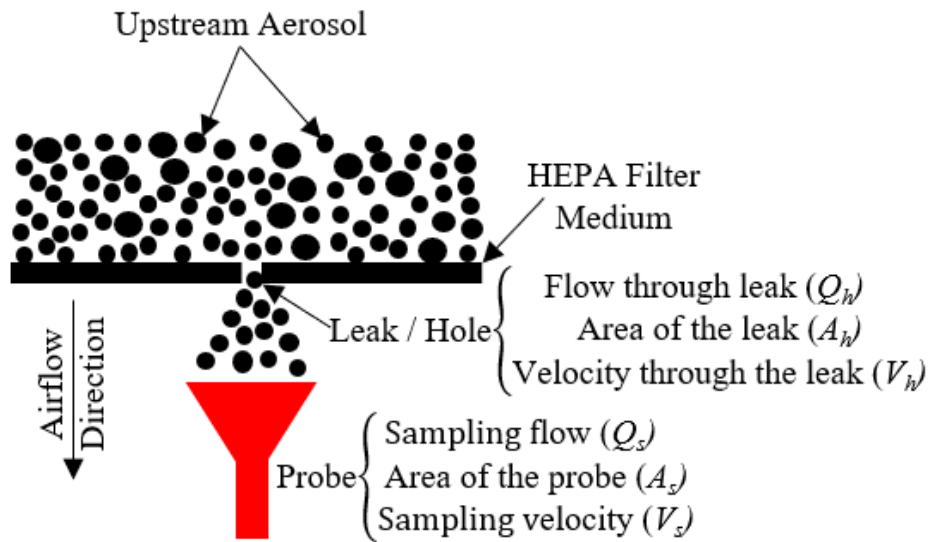
Figure 4.2. Total Filter-Media Efficiency With Thickness of 0.4 mm



The purpose of this chapter is to study the performance of a HEPA filter media with different pinhole sizes and investigate the applicability of the classical filtration theory to predict that. Any small pinhole has a drastically negative effect on the efficiency of the HEPA filter in contrast with the other MERV filters, and that will lead to penetration values not following predictions of filtration theory since micro-sized particles can pass through the media without resistance and directly into the downstream of the filter. The method and procedure for testing and classifying filters are explained in standards and guidance such as ASHRAE 52.2, European EN 1822, International Organization for Standardization (ISO)-29463, and Institute of Environmental Sciences & Technology (IEST) Recommended Practices, which define aerosol generation method, aerosol type, particle size for testing, penetration test, leak (scan) test, designated leak penetration, etc. The leak test is the most commonly used in nuclear and biolab facilities, which involves the use of a scanning probe connected to a photometer or aerosol

particle sizer with a sampling flow rate (Q_s) to detect downstream particle concentrations passing through the filter medium. This allows for the classification of filters and the measurement of their efficiency. A leak is identified based on a designated leak penetration percentage for each filter type (L_s), which is the leak threshold limit of the upstream concentration (C_u) allowable downstream. The sampling concentration (C_s) measured by the probe in the presence of a leak, where the particles passing through a HEPA filter medium can be considered negligible compared to those passing freely through the hole (as illustrated in Figure 4.3, which indicates a leak regime dominance), can be calculated using the following equations:

Figure 4.3. Illustration of a Leak



$$C_s = \frac{Q_h}{Q_s} C_u \quad \text{or} \quad \frac{C_s}{C_u} = \frac{Q_h}{Q_s} \quad (4.4a)$$

$$\frac{C_s}{C_u} = \frac{V_h \times A_h}{V_s \times A_s} \quad (4.4b)$$

By setting the sampling to the upstream concentrations ratio equal to L_s , Ryan (2014) calculated the smallest leak diameter size detectable during a scan test to be 365.29 μm using the scanning

probe area (Equation (4.4b)) under the assumption of $V_h = V_s$ with an isokinetic sampling, and to be 82 μm using a more realistic approach (Equation (4.4a)) based on Bernoulli's theorem for flow through a flat plate orifice area (Q_h). His analysis was based on a common and standard probe area size of 0.0113 ft^2 , a 1 CFM sampling flow rate, a 125 Pascal pressure drop across the filter, and a designated leak penetration of 0.01%, which corresponds to the HEPA H13 filter type. The flow rate through the hole used in the analysis is given by (Q_h):

$$Q_h = C \times A_h \times \sqrt{\frac{2\Delta P}{\rho}} \quad (4.5)$$

Where $C = 0.61$ is given by Batchelor (2000) as a dimensionless contraction coefficient for a flat plate orifice rate or a circular hole punched in a thin plate, A_h is the area of the orifice, ΔP is the pressure drop across the filter, and ρ is the density of air. The efficiency of a damaged filter due to an internal leak can be correlated with classical filtration theory using a model equation developed by Mouret et al. (2009). The initial step involved balancing the upstream volumetric air flow to match the downstream air flow through the filter medium while accounting for the presence of a leak, as specified in Equation (4.6a). This led to a model that predicts the efficiency of a filter medium with an internal leak of a defined millimetric diameter for nanoparticle sizes where $d_p \leq 30 \text{ nm}$, in which diffusion is the primary filtration mechanism as indicated in Equation (4.6b).

$$Q_f P_{f,o} = Q_h P_h + Q_b P_b$$

$$P_{f,o} = \frac{Q_h P_h}{Q_f} + \frac{Q_b P_b}{Q_f} \quad (4.6a)$$

$$P_f = 1 - \frac{A_b K'}{A_f K} \left(1 - \exp \left[-\frac{4\alpha L}{\pi(1-\alpha)d_f} \times 0.84 \left(\frac{K'}{K} P_e \right)^{-0.43} \right] \right) \quad (4.6b)$$

Using $\eta_s = 0.84(P_e)^{-0.43}$ for diffusion by Wang et al. (2006)

Where $P_{f,o}$ is the penetration fraction of the damaged filter. Q_f , A_f and K represent the flow rate, surface area, and flow resistance of the intact filter, respectively. Q_b , A_b , K' , and P_b correspond to the flow rate, surface area, flow resistance, and penetration through the remaining fiber bed following medium perforation, respectively. By dividing the first term by the second term on the right side of Equation (4.6a), a dimensionless parameter was defined as ($\emptyset = \frac{Q_h P_h}{Q_b P_b}$) to differentiate between two regimes: a leakage regime where $\emptyset > 10$ indicates that $Q_h P_h \gg Q_b P_b$ and aerosol penetration through the leak is dominant, and a fiber bed regime where $\emptyset < 0.1$ indicates that $Q_h P_h \ll Q_b P_b$ and aerosol penetration remains influenced by the filter fibers exhibiting the filtration efficiency curve and behavior of an intact filter medium. However, this raises concerns about predicting the performance of filter media under these regimes for micro-sized particles where the filter is typically rated at the most penetrating particle size (MPPS) range, as well as how to identify the pinhole cut-off that separates where each regime is dominant, particularly for the HEPA filter medium. Furthermore, it becomes increasingly challenging to experimentally predict the efficiency of a filter medium with micro-sized internal leaks in the vicinity of the smallest detectable leak by a scanning machine, which is a critical factor in assessing the reliability of these scanning devices and enhancing the standards by more stringent criteria for the maximum allowable leak rates for classifying and rating different types of filters. Therefore, a computational model is necessary for simulating the filtration process of fibrous filter media to evaluate the impact of micro-sized pinholes on the performance of the filter media for particles with $d_p \leq 0.5 \mu\text{m}$ and broaden research efforts.

4.2 Modeling Approaches

Kolakaluri (2013) explained two approaches for the computational fluid dynamics (CFD) simulation of the filtration process. The first one is macroscopic; it depicts the filter and the

particles as interpenetrating continuums (Euler-Euler model) and is based on theoretical and semi-empirical filtration laws. The concentration transport model for the particles and the porous media model for the filter material, which is defined as the sink of the particles per unit volume of the filter, are the two CFD models employed for this purpose. The interaction of the particles with the flow is simulated with the consideration of the convection transfer, diffusion, and the external volumetric forces (gravity, Saffman force, thermophoretic force, etc.). This approach assumes that the filter's thickness and fiber packing density will be adequate to establish the filter as a continuous solid medium with a predetermined permeability value for the flow, and it allows for solving the problem of particles penetrating a larger scale filter using relatively small resources. The macroscopic approach can provide a cost-effective method for modeling large-scale porous filter media, both with and without leaks, by utilizing results obtained from microscopic analysis and experimental results. However, it fails to yield any insights or comprehension into the nature or mechanism of the filtration process.

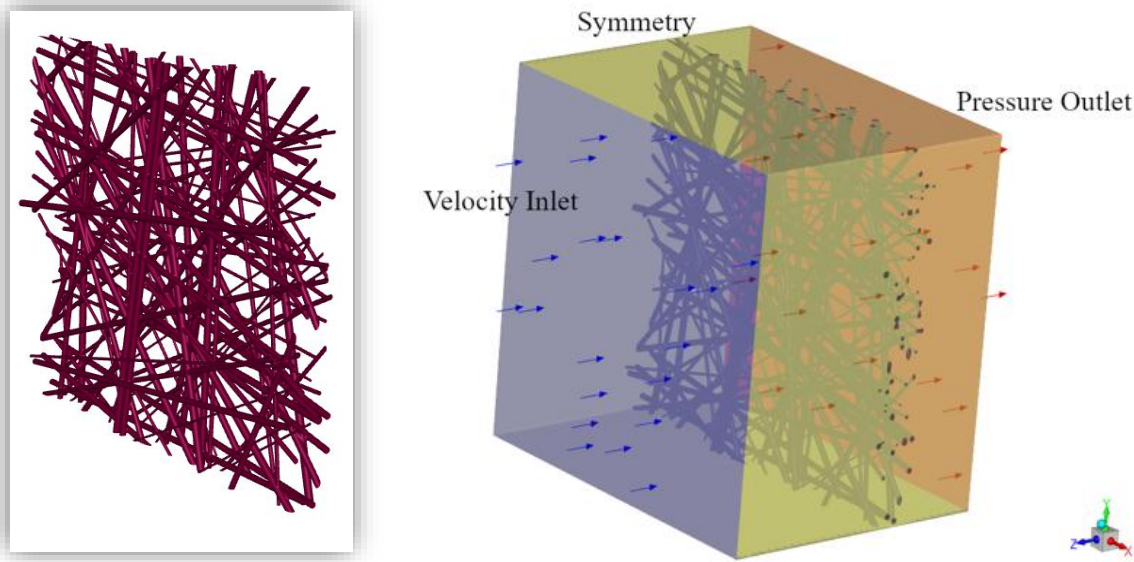
The second approach, which is the one we use in our work, is microscopic and involves direct computational simulation of each particle slipping through the filter fibers. This approach considers each particle separately and requires strict imposition of the filter fibers' geometry. The microscopic approach allows describing the filtration process based on the equation of motion for particles and the minimum quantity of the particle-particle and particle-fiber interaction laws. This is an apparent advantage and allows understanding the physics of the filtration process. Nevertheless, the microscopic method becomes extremely resource-consuming as the number of particles and medium fibers increases and thus can only be applied to small-scale filter medium applications. Since there have been no prior computational modeling studies on the leaky filter medium, it is imperative to use a microscopic approach in order to

comprehend the high-efficiency intact and leaky filter performance and provide insights that could be integrated into a macroscopic simulation of a larger scale porous filter medium in the future.

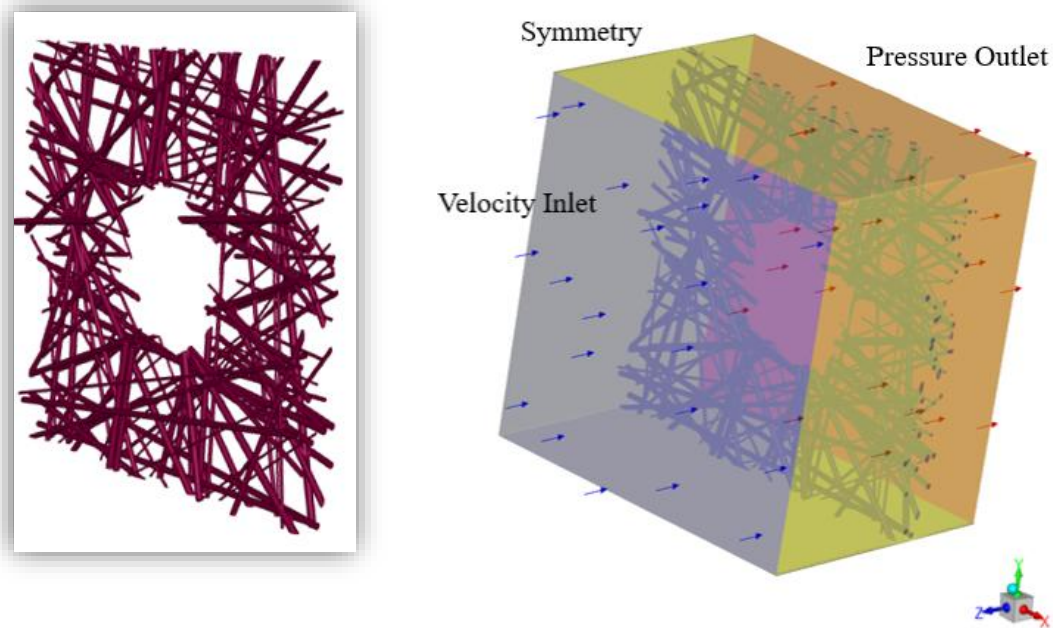
4.2.1 Fiber Model and Geometry

As shown in Figure 4.4(a), a realistic 3D virtual model of an H14 HEPA filter medium was developed, containing random and non-homogenous cylindrical fibers with an SVF of 7.5% and a mean diameter of 0.59 μm . Fibers were generated randomly using a Python script and incorporated into the medium domain, with 90% of fibers measuring $\leq 1 \mu\text{m}$, 9.7% in the range of $]1-1.68] \mu\text{m}$, 0.3% in the range of $]1.68-2] \mu\text{m}$, and an average fiber diameter defined as 0.59 μm . This reproduced the scanning electron microscope (SEM) image analysis and the experimental results regarding the accumulated fraction of fiber diameter (fiber distribution) in a HEPA glass fiber filter sheet classified as H14, as reported by Bortolassi et al. (2017). The pinhole in the center of the model shown in Figure 4.4(b) was created as an actual geometrical object in Ansys SpaceClaim by utilizing the pull tool. To generate the 3D model, we developed a Python script that utilizes different pre-existing libraries in Python. The script's objective is to replicate a fibrous network in a specific domain while also characterizing the shape and spatial distribution of fibers according to user-defined parameters. Figure 4.5 explains the algorithm used to generate fibrous stacks. Once the model is generated, the geometry is exported to Ansys SpaceClaim to create the computational domain and set up the boundary conditions. The structure is then meshed for finite volume calculations using the Fluent solver with the poly-hexcore mesh and a mesh grid of > 15 to provide independent airflow pressure drop results, as explained in Hosseini & Tafreshi (2010).

Figure 4.4(a-b). 3D Random and Non-Homogeneous Fiber Model (With SVF of 7.5%, thickness of 7 μm and mean fiber diameter of 0.59 μm) (a), and With 20 μm Pinhole in the Center (b)

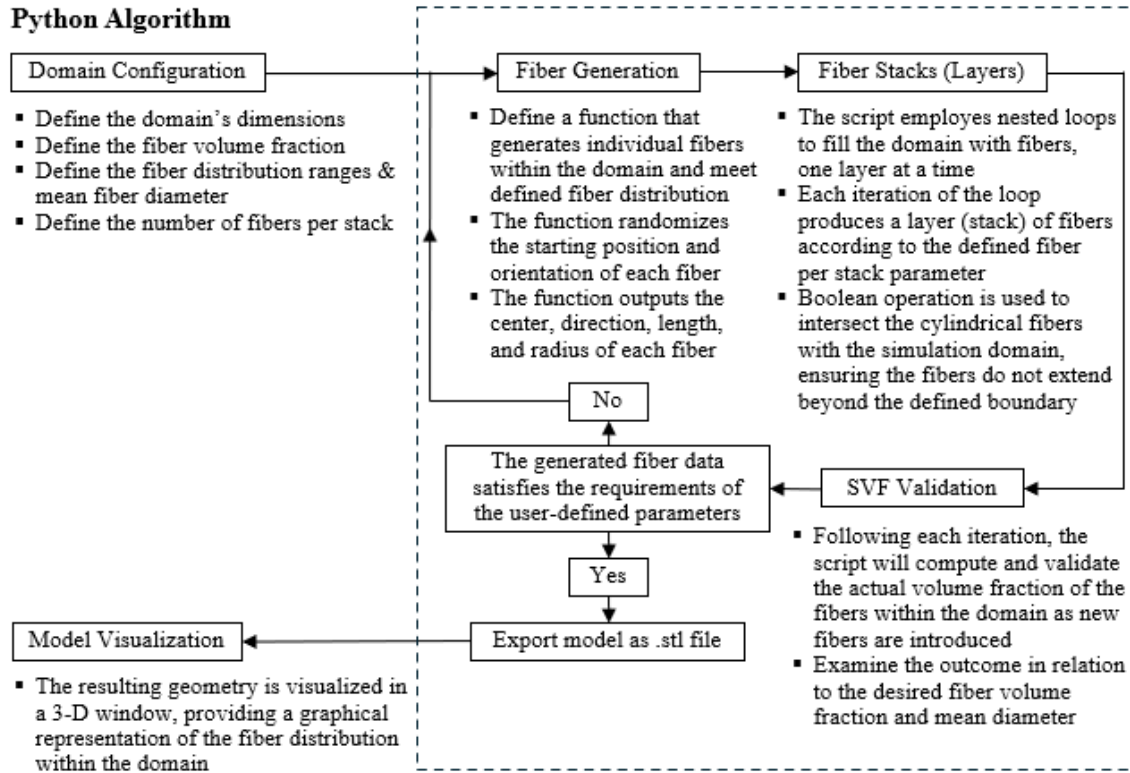


(a)



(b)

Figure 4.5. Model Code Algorithm



4.2.2 Boundary Conditions

The filter fibers are treated as walls with a trap boundary condition to properly simulate particle capture. Particles that come into contact with the fiber surface are trapped, imitating their physical interaction and accurately representing the filtration process. Assuming that the computational domain's lateral size is large enough to ensure that the flow remains primarily in the thorough-plane direction, symmetry boundary constraints can be imposed on the domains' sides, eliminating the impact of lateral borders on the core simulation results. The air filtration simulation is run with a velocity inlet located upstream of the filter medium and a pressure outlet located downstream. We extend the domain $20d_f$ (d_f = Maximum d_f in the range) upstream and $10d_f$ downstream of the fibrous medium to ensure that the airflow is fully developed when it enters the filter medium via the velocity inlet and then stabilizes and fully develops before

exiting through the pressure outlet boundary. This setup aims to minimize the entry and boundary effects on flow measurements and simulation accuracy, and it is considered the most rigorous in comparison to the ones used in other literatures, as Hosseini & Tafreshi (2010) used $20d_f$ and $5d_f$, Rabiee et al. (2018) used $7d_f$ and $5d_f$, and Hou et al. (2019) used $7d_f$ and $7d_f$ upstream and downstream the filter medium, respectively. In addition, we applied a slip boundary condition at the walls to accurately simulate the airflow-filter fibers interaction and account for the slip velocity at the fiber surfaces, since airflow around the nanofibers that constitute the filter medium structure is typically in the slip or transition regime. This condition is applied using the low-pressure boundary slip laminar model in Ansys-Fluent, which has the following mathematical expression:

$$u_w = \frac{2-\sigma_v}{\sigma_v} \lambda \left. \frac{\partial u}{\partial n} \right|_w \quad (4.7)$$

where u_w is the slip velocity at the wall, σ_v is the tangential momentum accommodation coefficient, λ is the mean free path of air molecules, and $\frac{\partial u}{\partial n}$ is the normal derivative of the velocity at the wall.

4.2.3 Airflow Model

Generally, the velocity of the flow at the filtration face (medium) falls between the range of 2 cm/s to 5 cm/s, resulting in a low Reynolds number of less than unity and a laminar flow through the nanofiber filter medium structure. Experimental and theoretical investigations have both demonstrated a linear relationship between the pressure drop across a filter and the velocity of the airflow. This enables us to focus solely on the impact of viscous force while disregarding the influence of the inertial force. Therefore, the finite volume method in Ansys-Fluent can be employed to simulate the flow velocity components (u , v , w) in each direction and analyze the dynamics of the airflow particles within the fibrous medium in great detail by solving the

continuity and steady-state Navier-Stokes equations with only the viscous term. Here μ and p represent the air viscosity and pressure, respectively.

- Continuity Equation (Mass Conservation):

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = 0 \quad (4.8)$$

- Momentum Equations (Navier-Stokes for laminar flow):

$$\frac{\partial p}{\partial x} = \mu \left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} + \frac{\partial^2 u}{\partial z^2} \right) \quad (4.9a)$$

$$\frac{\partial p}{\partial y} = \mu \left(\frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2} + \frac{\partial^2 v}{\partial z^2} \right) \quad (4.9b)$$

$$\frac{\partial p}{\partial z} = \mu \left(\frac{\partial^2 w}{\partial x^2} + \frac{\partial^2 w}{\partial y^2} + \frac{\partial^2 w}{\partial z^2} \right) \quad (4.9c)$$

4.2.4 Particle Model

The Eulerian and Lagrangian approaches are widely used to describe and simulate the particle motion and behavior in a fluid in the context of gas-solid two-phase flow dynamics. To simplify the filtration process and particle capture mechanisms caused by diffusion, interception, and inertial impaction, we opted to use the Lagrangian technique to simulate the air-particle mixture passing through a fibrous medium. Hou et al. (2019) and Hosseini & Tafreshi (2010) used this technique, which monitors individual particle positions without accounting for particle interaction with the continuum phase (air), and their results revealed good particle simulation. Using the Ansys-Fluent discrete phase model (DPM), one can solve the force balance equation of a particle in the Lagrangian technique to find its position:

$$m_p \frac{dV_p}{dt} = F_D + F_B \quad (4.10a)$$

$$\frac{dV_p}{dt} = 18\mu \left(\frac{V - V_p}{d_p^2 \rho_p C_C} \right) + \sqrt{\frac{216\nu K_B T}{\pi \rho d_p^5 \left(\frac{\rho_p}{\rho} \right)^2 C_C \Delta t}} \xi_i \quad (4.10b)$$

Here, F_D stands for the drag force resulting from the particle's velocity relative to the fluid and affected by the surrounding airflow, F_B represents the Brownian force that explains the random

motion of particles due to collisions with air molecules, V_p is the particle velocity, K_B is the Boltzmann constant, ρ and ρ_p is the air and particle density, T is the absolute temperature, ν is the kinematic viscosity, ξ_i are zero-mean unit-variance-independent Gaussian random numbers, Δt is the time step, and C_C is the Cunningham correction factor that accounts for non-continuum effects and can be calculated via Allen & Raabe (1985) correlation for the particle size under this study whose Knudsen number (Kn) falls with the given range:

$$C_c = 1 + \frac{\lambda}{d_p} \left(2.284 + 1.116e^{-5.5\frac{d_p}{\lambda}} \right) \text{ for } 0.03 \leq Kn = \frac{\lambda}{d_p} \leq 7.2 \quad (4.11)$$

To appropriately simulate the particle motion and behavior in the domain within the DPM model, the inlet and outlet boundaries are set as “escape”, allowing particles to leave the domain once they reach these boundaries. The symmetry boundary conditions ensure that particle behavior is mirrored across symmetrical borders. The “trap” setting on the fiber surface collects particles that come into contact with the fibers. Due to the fact that the standard Ansys-Fluent DPM treats the particles as mass points and does not compute the capture efficiency due to interception, we developed a new user-defined function (UDF) to enhance the intercepting particle capture mechanism and augment the trap boundary condition placed at the filter fiber surface. The UDF continuously keeps track of the distance between the particle center and the fiber surface. The particle is deemed intercepted and removed from the domain if the distance is smaller than or equal to the particle radius.

4.2.5 Model Validation

A single-layer fiber model was constructed with a fiber solidity of 5.9% and a uniform diameter of 150 nm, as illustrated in Figure 4.6. This model was tested by comparing our findings to the experimental results of Wang et al. (2008), who investigated the pressure drop and filtration efficiency of a nanofiber filter made of a single layer of nanofibers on a substrate.

Our model and methodology were demonstrated to be legitimate by comparing our results to those of Wang et al. (2008) sample ID C, who measured in one of their tests the pressure drop and filtration efficiency of nano-sized particles of $0.78\ \mu\text{m}$ polystyrene (PSL) with a density of $1050\ \text{kg/cm}^3$ at a face velocity of $0.1\ \text{m/s}$. The results are presented in Table 4.1, where the absolute errors for pressure drop and efficiency are 1.29 Pascal and 6.52%, respectively.

Figure 4.6. Single Layer Fiber Model with $d_f = 150\ \text{nm}$

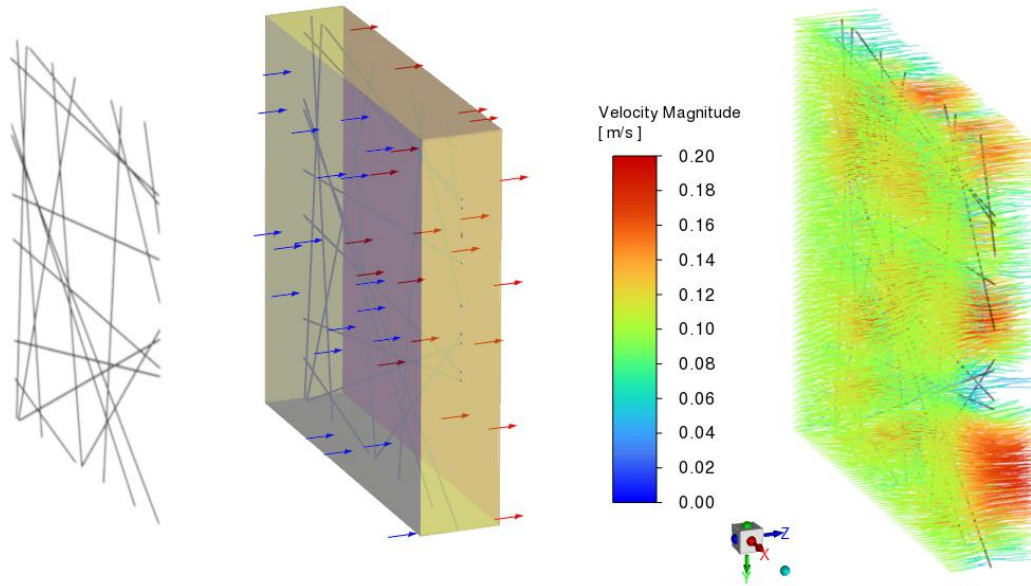


Table 4.1. Model Validation Using the Experiments of Wang et al. (2008)

From Wang et al. (2008) experiments				Model Validation	
Sample ID	C	Substrate	Net for Sample C	Our Simulation	Absolute Error
Nanofiber Solidity, α (%)	5.9	0	5.9	5.9	
Pressure Drop (Pas)	7.7	2.2	5.5	4.21	1.29
Efficiency (%)	38.4	4.28	34.12	27.60	6.52

The variations in pressure drop and particle capture efficiency can be attributed to the single-layered structure of the fibers and the random orientation and length of the fibers.

Therefore, we validated our computational model with other semi-empirical models and

correlation equations for predicting pressure drop across electrospun nanofiber filters developed by Bian et al. (2018) and Lee et al. (2023), as well as with the classical filtration theory. The results of pressure drop at various velocities for the above single-layer fiber model are presented in Figure 4.7. This is succeeded by Figure 4.8, which illustrates a complete model with a thickness of 7 μm , developed to replicate the H14 HEPA filter sheet characterized by a fiber solidity of 7.5% and non-homogenous fibers with a mean diameter of 0.59 μm . Our results are in excellent agreement with the Lee et al. (2023) model for the single-layer model and when the filtration velocity is ≤ 10 cm/s (the common filtration face velocity). As the velocity increases, our pressure drop values remain valid since they fall between the experimental values acquired from Wang et al. (2008) and the values obtained from Bian et al. (2018) and Lee et al. (2023) on the opposite side. It is worth noting that the pressure drop predicted by the Bian et al. (2018) model has a median relative error of 4.3%, whereas the Lee et al. (2023) model has a maximum relative error of less than 15%. On the other hand, our H14 filter medium model results were highly consistent with the Bian et al. (2018) model throughout the whole velocity range.

Figure 4.7. Pressure Drop Vs. Face Velocity for the Single Layer Filter with $d_f = 150$ nm

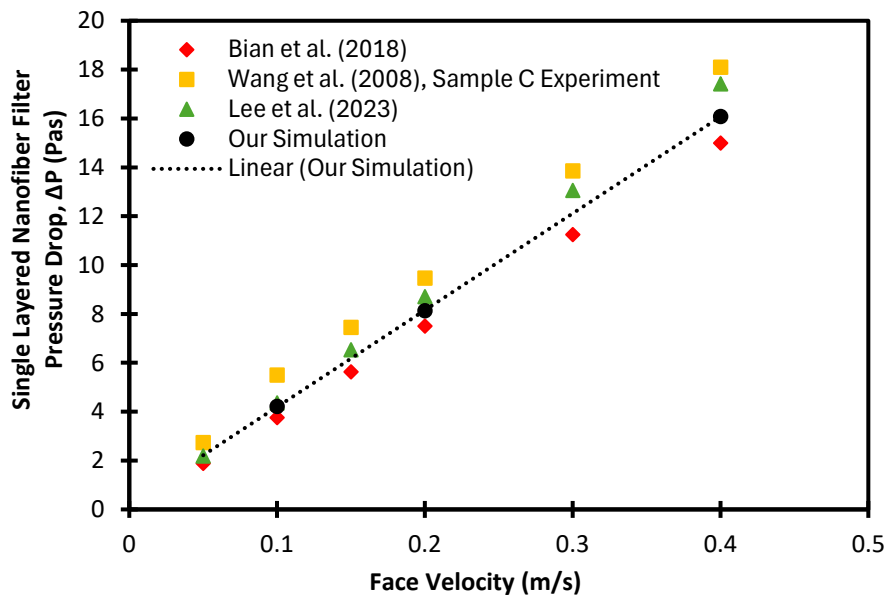
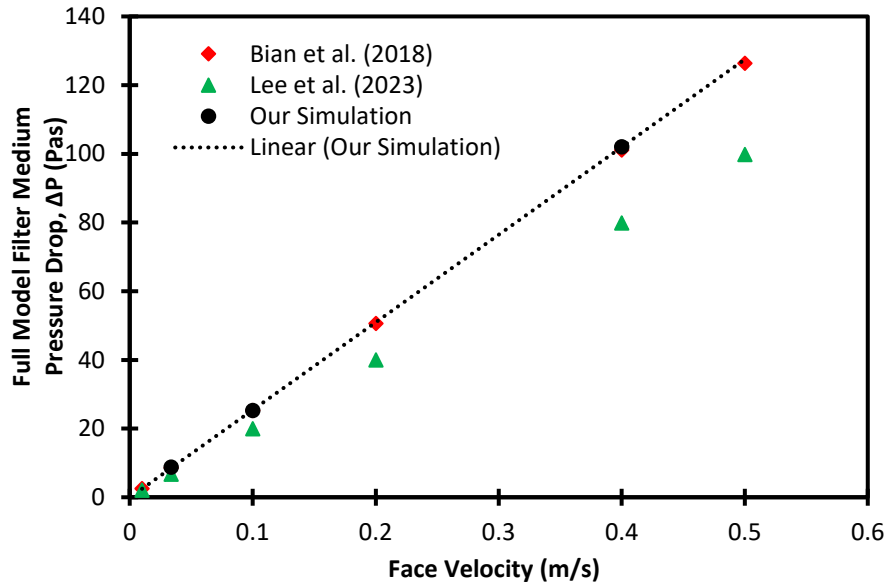


Figure 4.8. Pressure Drop Vs. Face Velocity for the H14 HEPA Filter with 7 μm Thickness



We conducted additional validation of our efficiency results for the full model at a face velocity of 0.1 m/s, as depicted in Figure 4.9. Additionally, Figure 4.10(a-b) displays the trajectories of 0.1 μm and 0.5 μm particles passing through the simulated H14 HEPA filter medium. This validation was carried out in comparison with the semi-empirical and classical filtration theoretical models proposed by Lee & Liu (1982) and Liu & Rubow (1990) for diffusion and interception efficiencies, as well as a combination of the diffusion model proposed by Payet et al. (1992) and the interception model proposed by Lee & Gieseke (1980). Our efficiency results demonstrate a very good agreement with the Payet et al. (1992) model for particles with diameters $\leq 0.1 \mu\text{m}$, where the major filtration mechanism is diffusion. Our results were more in line with the Lee & Liu (1982) model in the MPPS range, and as the particle size increases, our values start to resemble the Liu & Rubow (1990) model.

Figure 4.9. Efficiency Validation Using Classical Filtration Theory

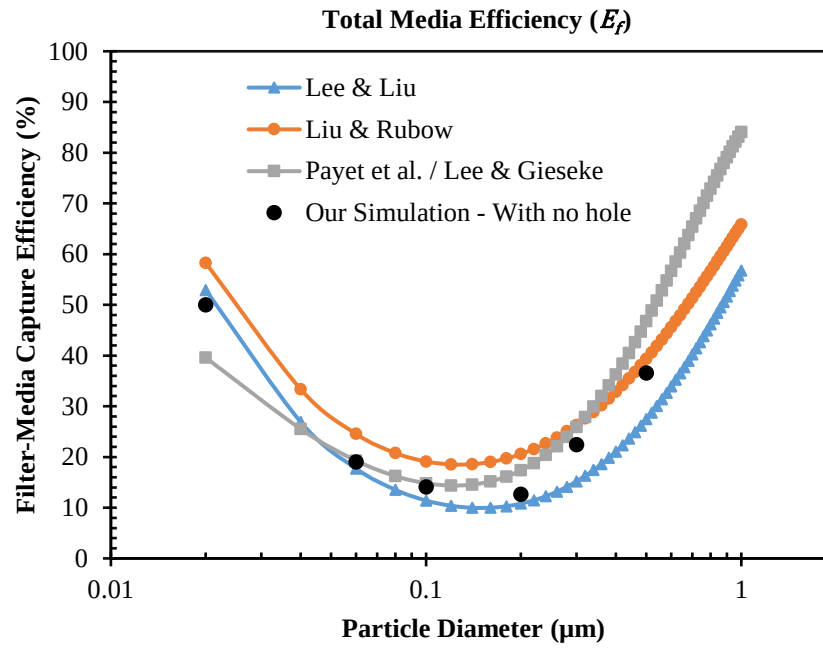
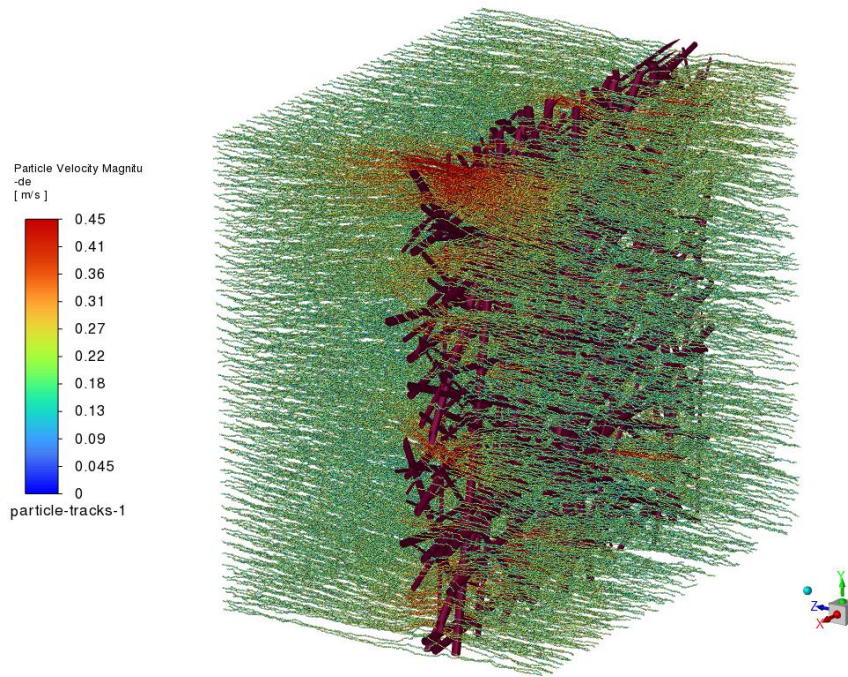
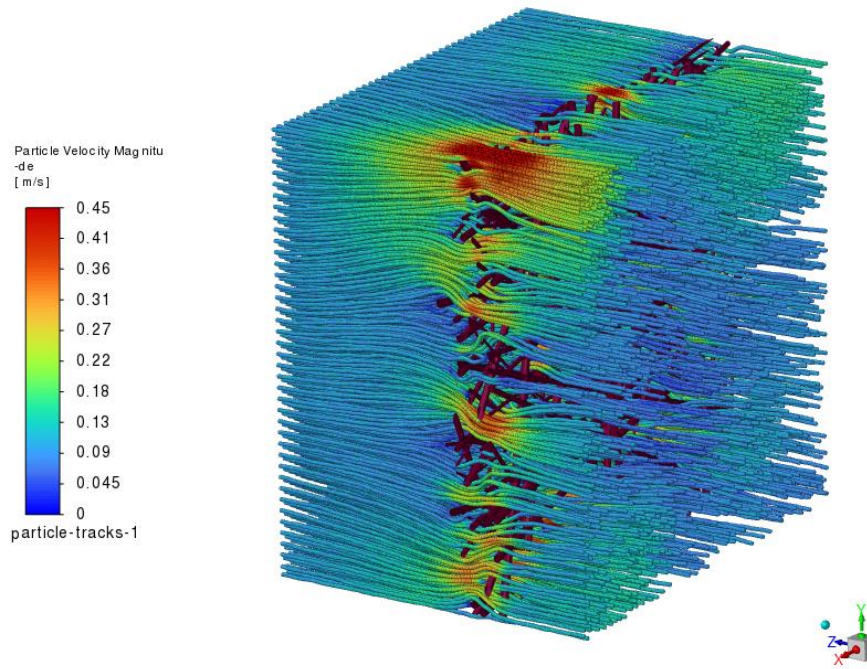


Figure 4.10(a-b). Trajectory of Particle Passing Through a 7 μm Thick H14 Filter Medium: $d_p = 0.1 \mu\text{m}$ (a), $d_p = 0.5 \mu\text{m}$ (b)



(a)



(b)

4.3 Results and Discussions

This study employed our validated model that replicates the H14 HEPA filter medium, characterized by a thickness of $7\text{ }\mu\text{m}$, a fiber solidity of 7.5%, and non-homogeneous fibers with an average diameter of $0.59\text{ }\mu\text{m}$, to run aerosol particle simulations at various flow rates. Simulations were performed under intact medium conditions and in scenarios with centrally located pinholes of different diameters within the filter medium. We evaluated the impact of different pinhole sizes on filter media efficiencies and pressure drops. Our goal is to determine the smallest pinhole size that initiates this impact, as well as the pinhole size at which the filter medium begins to leak significantly, causing the efficiency to become independent of particle sizes and face velocity but dependent on the hole owing to leaky regime domination. In our subsequent analysis, we employed the Lee & Liu model for diffusion and the Liu & Rubow model for interception to predict the efficiency of an intact filter medium, as they demonstrated

the highest level of agreement with our simulation results, with average differences of 2.67% and 2.75% for filtration face velocities of 0.1 m/s and 0.05 m/s respectively. The findings regarding the efficiencies are presented in Figure 4.11 and Figure 4.12 for flow rates of 10 cm/s and 5 cm/s respectively, along with Figure 4.13(a-b), which illustrates the trajectory of a 0.5 μm particle through the simulated H14 HEPA filter medium in the presence of a 20 μm pinhole leak at 10 cm/s and 5 cm/s. The smallest microhole size with negligible leak influence was found to have a diameter of roughly 10 μm , with average efficiency differences of 2.02% and 2.54%, respectively, for 0.1 m/s and 0.05 m/s velocities. This is where the filter medium remained to function in accordance with the filter bed regime, with no changes to the shape of the efficiency curve or MPPS range. Additionally, it was discovered that the effects of a leak began to dominate the efficiency of the filter medium at a pinhole size of 20 μm , except for smaller particle sizes of 0.02 μm and greater dominance of larger particle sizes of 0.5 μm , where the filter bed regime continues to have an effect. At a pinhole size of 32 μm , the particle penetration was completely controlled by the leak regime, at which point the filter medium efficiency became independent of both particle sizes and filtration face velocity. Under conditions of leakage, the efficiency values experience a substantial decrease, with an average difference of 23.66% at a lower velocity of 0.05 m/s and 18.4% at a higher velocity of 0.1 m/s, in comparison to the intact filter model. However, the efficiency values eventually converge to a uniform and constant value for every particle size and velocity. Based on our findings for the microhole size at which the leak regime begins to occur and the fact that the efficiency of fibrous filters is linearly proportional to the layer thickness of the filter medium for each particle size (as demonstrated experimentally by Humphrey & Gaden, 1955), this suggests that the observed trends in the efficiency graphs presented in Figure 4.11 and Figure 4.12 will remain valid for a

thicker filter medium. Consequently, and according to the conditions and calculations outlined in Equation (4.4) and Equation (4.5), we recommend adopting a more stringent designated leak penetration value of 0.0015% (calculated based on the 32 μm leak size that signifies the onset of the leakage regime) in place of the 0.005% utilized in the EN-1822 H14 filter classifications (which corresponds to a detected leak size of 58.45 μm). Moreover, our findings suggest that IEST-RP should establish guidelines for testing at the 0.2 μm MPPS instead of at a particle size of 0.3 μm or ranges of 0.1–0.2 or 0.2–0.3 μm , as our computational efficiency results for intact filter media and during the transition from a filter fiber regime to a leakage regime revealed the lowest efficiency value at $d_p = 0.2 \mu\text{m}$. Our results were found to be more compatible with the ISO-29463 Class ISO 50 H guidelines, which suggest testing and classifying H14 HEPA filters at an integral value of 0.001% for penetration at MPPS.

Figure 4.11. Efficiency of a Replicated Intact and Pinholed H14 Filter Medium with 7 μm Thickness at 0.1 m/s

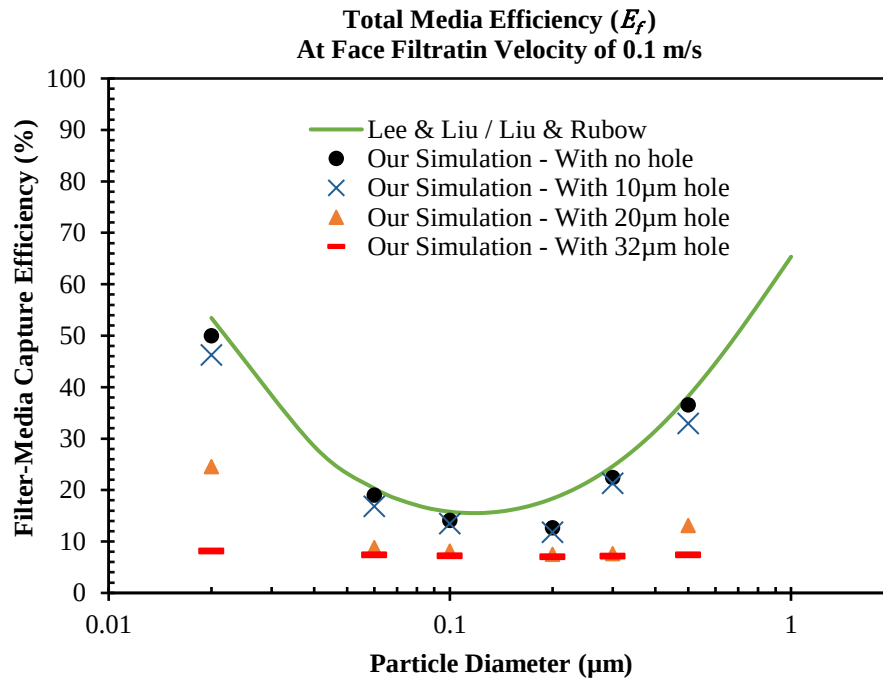


Figure 4.12. Efficiency of a Replicated Intact and Pinholed H14 Filter Medium with 7 μm Thickness at 0.05 m/s

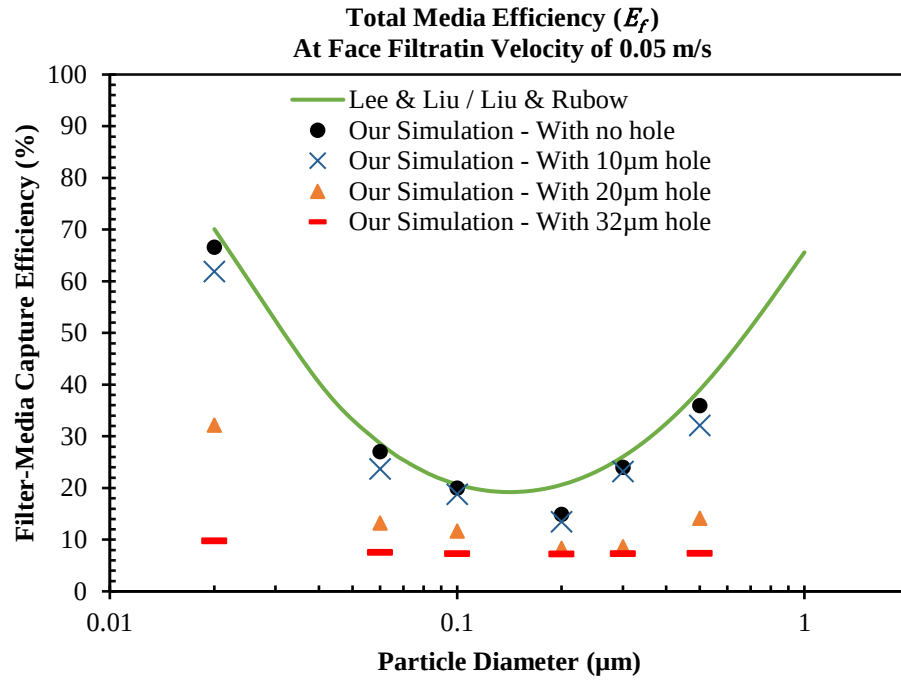
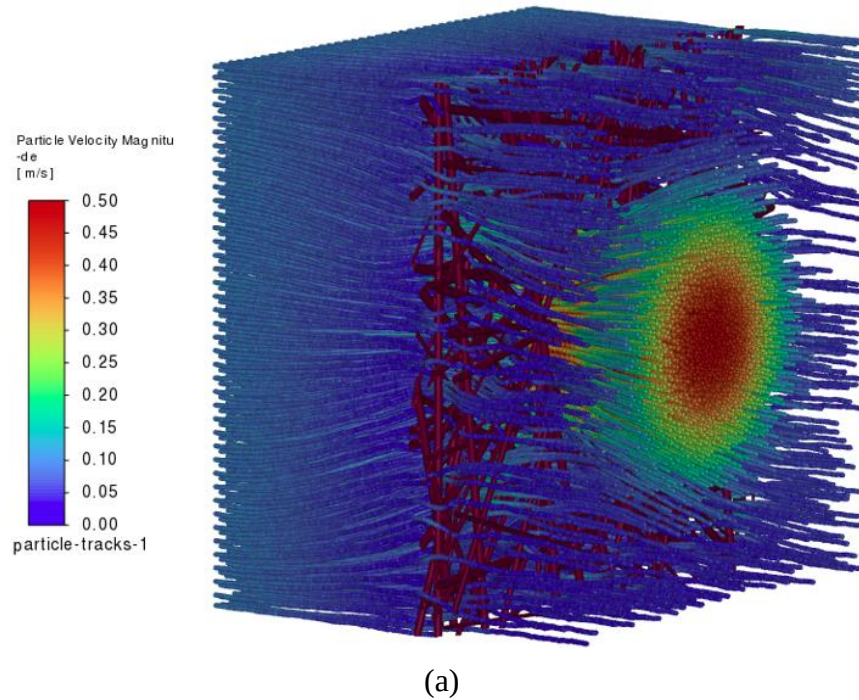
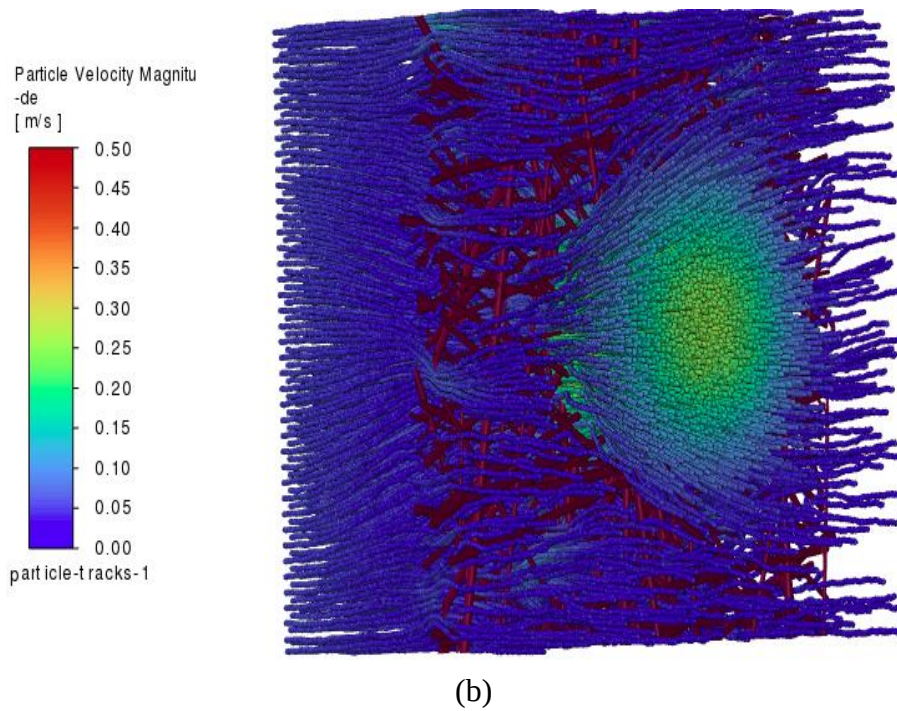


Figure 4.13(a-b). Trajectory of $d_p = 0.5 \mu\text{m}$ Passing Through a Pinholed H14 HEPA Filter Medium with 20 μm Centered Hole: at 10 cm/s (a), at 5 cm/s (b)





Lastly, It is important to acknowledge that our computational model was constrained to a fibrous filter media thickness of $7\text{ }\mu\text{m}$, considerably less than the actual and typical thickness of H14 media, which is about $400\text{ }\mu\text{m} \pm 30\text{ }\mu\text{m}$. The analysis focused solely on the initial filtration state, which is essential for the testing and classification of the filter post-installation. Capturing and modeling the true 3D thickness of H14 filter media requires substantial computational resources. The significant increase in the number of fibers complicates the generation of fibers with all associated properties, as well as the preprocessing and acquisition of simulation results. The model with thickness of $7\text{ }\mu\text{m}$ was identified as an optimal compromise between the standard thickness of an H14 and achieving satisfactory performance results for that filter media. Additionally, previous studies have demonstrated that the efficiency of fibrous filters increases linearly with media thickness for each particle size. In the event of a leak through the media and once the leakage regime is established, thickness becomes less critical, particularly for larger pinhole sizes. The presence of these pinholes enables the internal bypass of particles through the

filter media, making its performance more dependent on the flow regime than on the physical characteristics of the filter media.

4.4 Conclusion

Computational filter media consisting of non-homogeneous nanofiber layers, similar to those found in the H14 HEPA filter medium, were developed and verified to determine the pressure drop and efficiency of both intact and pinholed media. The outcomes of our numerical simulations showed a strong agreement with existing experimental findings and correlations for filter efficiency and filter pressure drop. As expected, filtration face velocity has a greater effect on efficiency for smaller particle sizes. We tested our model with various microleak sizes to discover the leak size at which the filter efficiency is still impacted by the filter bed regime, as well as the leak size that initiates the leak regime, and to assess the likelihood of a successful filtration leak test using commercially available scanning devices. This provided us with crucial information to determine the designated leak penetration value utilized in the standards and guidelines for conducting a successful leak test and for testing and classifying HEPA and ULPA filters. The results of our study indicate that the designated leak penetration value should be adjusted to 0.0015% instead of the currently recommended value of 0.005% according to the EN 1822 standard for a successful leak test of the H14 HEPA filter. This adjustment becomes very important, particularly in applications where there are strict conditions and when prefiltration is not utilized. Additionally, we propose that the MPPS for the EN 1822 and ISO-29462 standards should be set at 0.2 μm , rather than the range of 0.1–0.2 or 0.2–0.3 μm as suggested by the IEST-RP guidance. The established model and research findings will offer essential insights for future analysis and investigations to establish a correlation between the efficiencies of damaged and intact filters. Furthermore, the established model and results will aid in the design and

development of scanning equipment employed in filter testing, as well as in establishing designated leak penetration levels for conducting successful leak tests and classifying other HEPA and ULPA filters.

Chapter 5 – Investigation of Thru-Leak Affecting Performance of Highly Efficient Air Particulate Filter Media

In this study, high-efficiency air particulate (HEPA) filter media without and with leaks of known sizes were tested to investigate the effects of those leaks on the filter media's effectiveness in removing fine particles from the air. Experiments were carried out in the laminar flow regime on fiberglass filter media, and a scanning mobility particle sizer spectrometer (SMPS) system was used to measure the particle penetration of 0.5 μm and smaller particle diameter sizes. The results showed less effect of particle size and airflow velocity on the particle penetration in the existence of small leaks, which consequently vanished the most penetration particle size (MPPS) range. This illustrated the dominance of the leaky regime, wherein a minor leak considerably impacts the efficiency of a HEPA filter media.

5.1 Introduction

Despite ULPA and HEPA filters being recognized as the most efficient fibrous filters and widely utilized in NBAF, even a minor leak occurring during delivery, installation, or operation of the filter can considerably impact filtration performance and collection efficiency. This differs from MERV filters, which exhibit an inverse behavior and reduced sensitivity to small leaks in terms of efficiency. Mouret et al. (2009) established a dimensionless parameter ($\emptyset$) for nanoparticle sizes below 0.03 μm , defined as a ratio of the product of the flow rate and penetration fraction through the pinhole ($Q_h P_h$) to the product of the flow rate and penetration fraction through the remaining fiber bed ($Q_b P_b$) of the filter media, in order to differentiate between regimes that govern the total penetration of the filter media. A leakage regime characterized by $\emptyset > 10$ signifies that $Q_h P_h \gg Q_b P_b$, with aerosol penetration through the leak being the primary factor. Conversely, a fiber bed regime characterized by $\emptyset < 0.1$ indicates that

$Q_h P_h \ll Q_b P_b$, where the filter fibers continue to govern aerosol penetration or efficiency, thereby illustrating the filtration efficiency curve and behavior of an intact filter medium. This simply explains why filter media may exhibit unexpected efficiencies and unpredictable values from the filtration theory when it is controlled by collection through the leakage or intermediate regime, but it raises concerns about predicting the performance of HEPA filter media under these conditions for micro-sized particles, where the MPPS of ULPA or HEPA filters is concerned. A minor pinhole significantly impairs the efficiency of the HEPA filter, unlike other MERV filters, resulting in penetration values that deviate from the predictions of filtration theory, as micro-sized particles can traverse the media unimpeded and enter the downstream side of the filter. Li et al. (2022) validated this notion, indicating that a higher accuracy (rated efficiency) of the filter medium correlates with increased sensitivity of the filtration efficiency to a leakage ratio of 0.23% or higher. However, their work did not demonstrate a correlation of that with particle sizes. This work aims to examine the efficiency of HEPA filter media with varying pinhole sizes (smaller leakage ratio) and to investigate the relevance of the classical filtration theory in making predictions regarding this efficiency in the range of the MPPS of HEPA filter media.

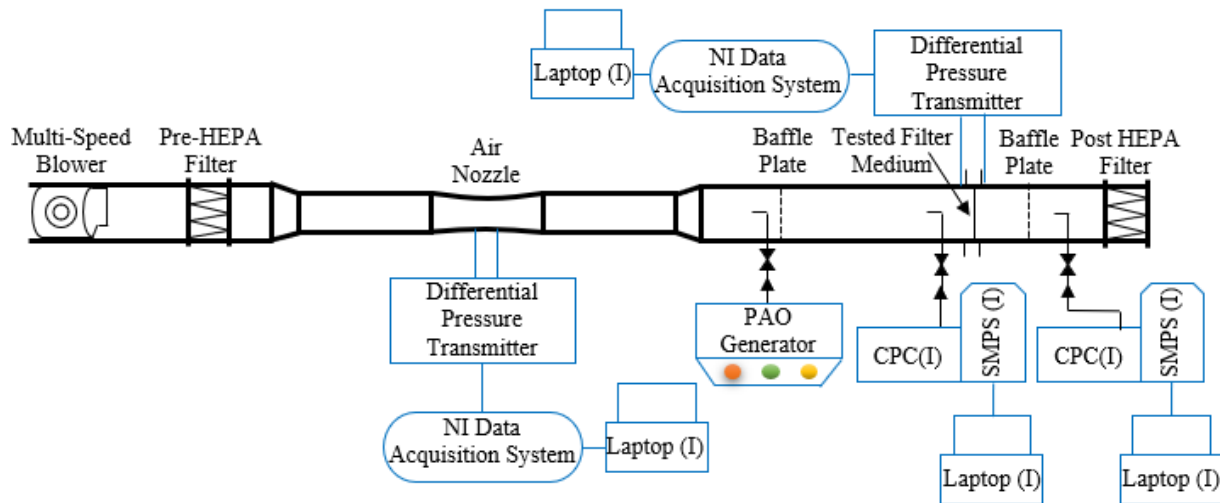
5.2 Materials and Methods

5.2.1 Testing System

The performance of the filter media was checked based on the method described in ASHRAE 52.2, using a test stand of 3.5"x3.5" duct size in which the isokinetic setup had been achieved to measure the particle concentration before and after the filter media and consequently the media efficiencies. The other major components of the test stand are: the blower, the pre and post filter to enclose the tested filter media and insure a clean test chamber, the poly alpha olefin (PAO) generator that introduces the poly-disperse aerosol to the chamber through a regulating

splitter valve to prevent the high generated aerosol concentrations which can clog the filter very rapidly, the differential pressure transmitters to measure the airflow and the pressure across the tested filter medium, and the TSI SMPS with a condensation particle counter (CPC) to analyse the number concentration for different size particles with diameter smaller than $0.5\ \mu\text{m}$ over 120 seconds for each sampling scan and 15 seconds for retrace time. For each penetration test, a new filter medium was used, and three samplings were taken upstream and then downstream sequentially and inversely to diminish the effects of particles that are collected by the medium from a test to others and avoid any downstream sampling delay that can block the small leak created through the filter media. A schematic of the test system is illustrated in Figure 5.1.

Figure 5.1. Schematic of the Test Apparatus



5.2.2 Filter Media

The physical characteristics of the tested filter media with their corresponding pinhole sizes are tabulated in Table 5.1. All tested media are glass fibers used in the commercial HEPA filter, and they have almost the same properties. These media were perforated at the center with different-sized calibrated needles as shown in Figure 5.2(a-b). The fiber solidity was determined for these filter media based on the manufacturer's information for the basis weight and fiber

density. The effective mean fiber diameter was calculated before loading the media from the empirical relationship of Davies (1973), which is also confirmed by visual inspection with microscopic pictures as illustrated in Figure 5.3(a-b). The pressure drop value across the filter sheet was obtained before and after loading the media with the aerosol and throughout the whole testing.

Table 5.1. Filter Media Characteristics and Needle Sizes Used

Filter Media Characteristics	
Size (Inch x Inch)	3.5 x 3.5
Thickness (mm)	0.4
Basis Weight, m_{basis} (g/m ²)	78
Fiber Density, ρ_f (g/cm ³)	2.6
Media	Micro Glass Fiber
Media Fiber Solidity, α (%)	7.5
Effective or Davies Fiber Diameter, d_f (μm) at average velocity	1.9
Rated Efficiency (%)	99.99 @ 0.3 μm (IEST)
Rated Airflow (CFM)	2000 @ $\Delta P = 1.35$ IWC
Needle Diameter Size	
Media Pinhole Created Size (mm)	0.133, 0.26, 0.33, 0.5, 0.8, 1.27, 1.270, 3, 5

Figure 5.2(a-b). Pinholed Filter Medium: With 0.25 mm Diameter Pinhole (a), With 0.5 mm Diameter Pinhole (b)

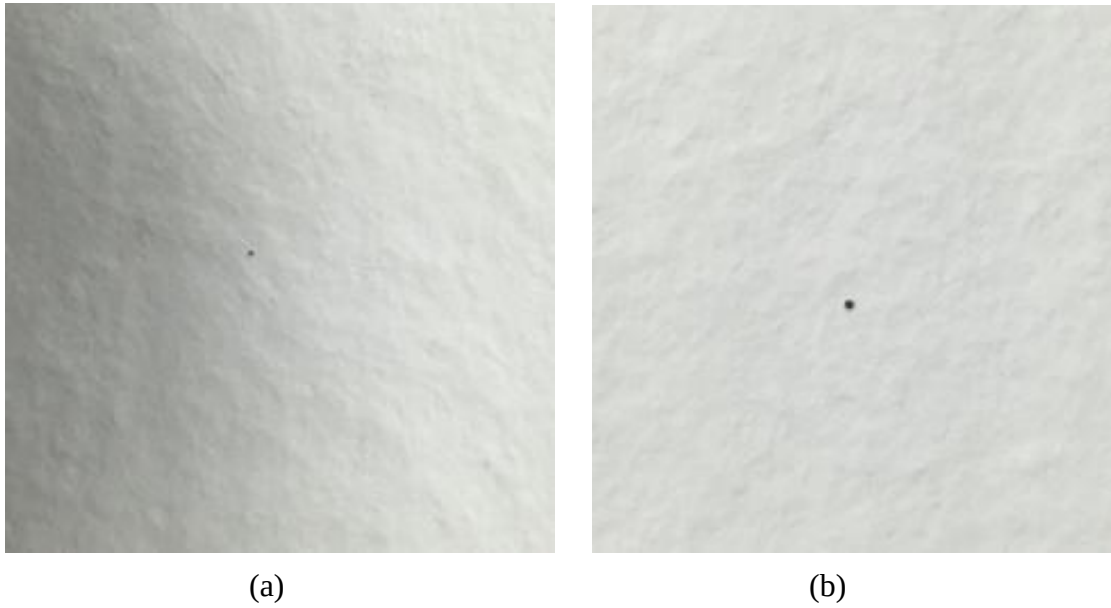
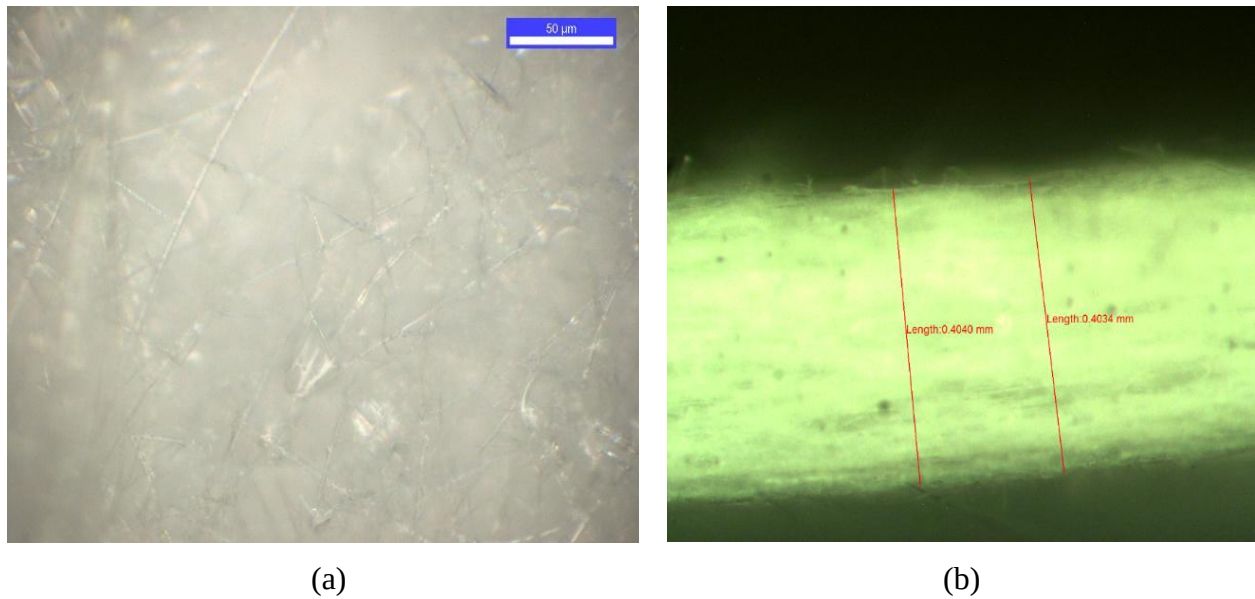


Figure 5.3(a-b). SEM Image of Tested Fiberglass Media (a), SEM Image of Media Thickness (b)



5.2.3 Testing Methods

The upstream number concentrations for aerosol measuring $\leq 0.5 \mu\text{m}$ were analyzed and illustrated in Figure 5.4 to provide a sufficient aerosol challenge for evaluating filter media efficiency, in accordance with IEST-RP filter integrity testing standards, which necessitate

aerosol challenge concentrations ranging from 2 to 30 million particles/ft³, equivalent to 71 to 1060 particles /cm³. Five samples were collected at each test using the SMPS, and the average was plotted as illustrated. We regulated the injection flow rate using two SMC (AS3002F) valves, each with 10 turns, placed to partition and manage the flow straight from the aerosol generator. A stark oil and water separator device was installed in the line going outside. We opted for a half-turn valve open to ensure adequate particle flow and reliable measurement for particles measuring $\geq 0.1 \mu\text{m}$ while maintaining levels above the IEST recommended threshold of 1060 particles/cm³.

To eliminate the influence of filter media clogging, preliminary tests were conducted to monitor variations in pressure drop across the filter media while it was loaded with aerosol upstream at the maximum flow rate. The results for pressure drop are depicted in Figure 5.5 over a duration of approximately two hours. The data indicated no increase in pressure drop, allowing for the assumption that clogging of the media can be disregarded. This timeframe was adequate to encompass the measurements for each filter media, which involved three samples taken upstream and three samples taken downstream for both the intact case and then the pinholed case, with a total measurement time of 26 minutes. The pressure drop across a clean and intact filter media was assessed at various flow rates, as illustrated in Figure 5.6. The results demonstrated a linear relationship with flow, consistent with findings from prior experimental studies and theoretical models.

Figure 5.4. Controlling Upstream Concentrations of Aerosol

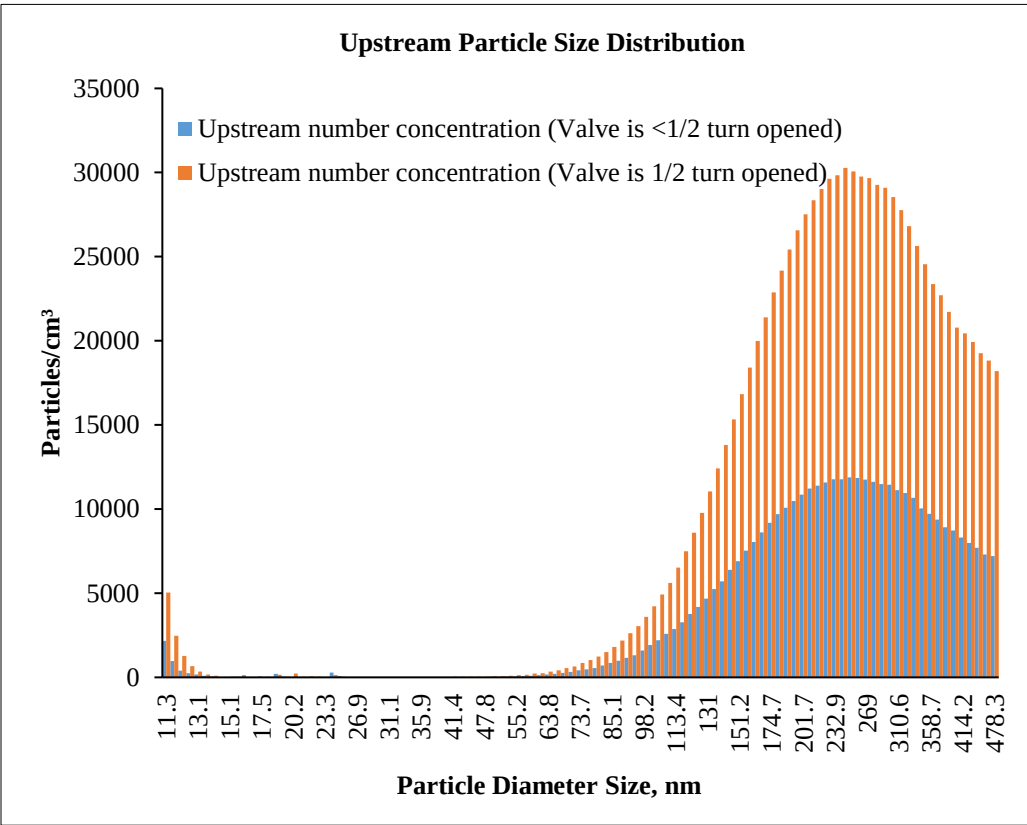


Figure 5.5. Filter Media Loading and Clogging

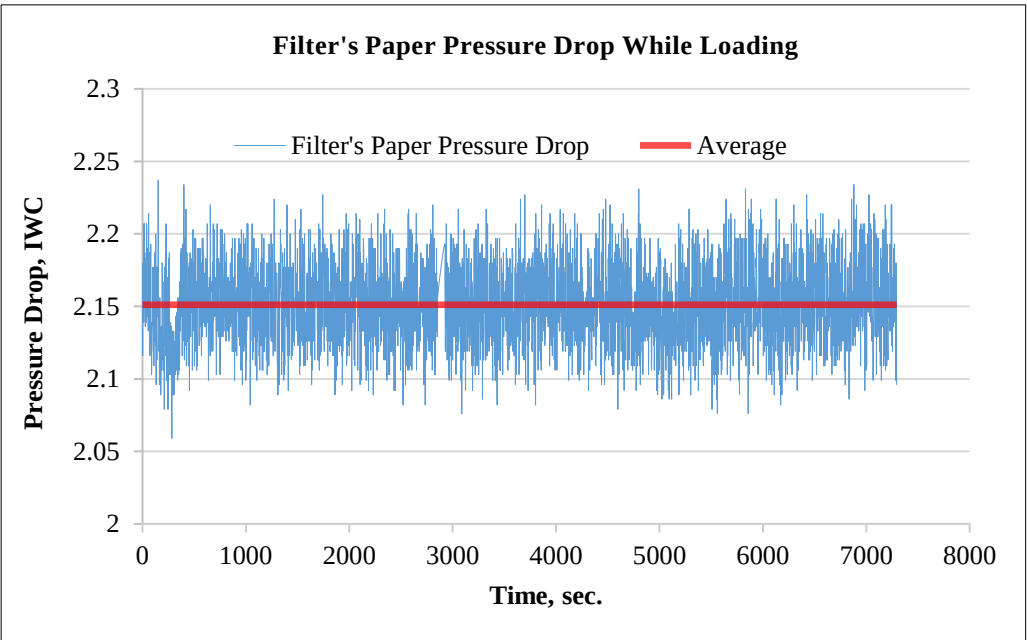
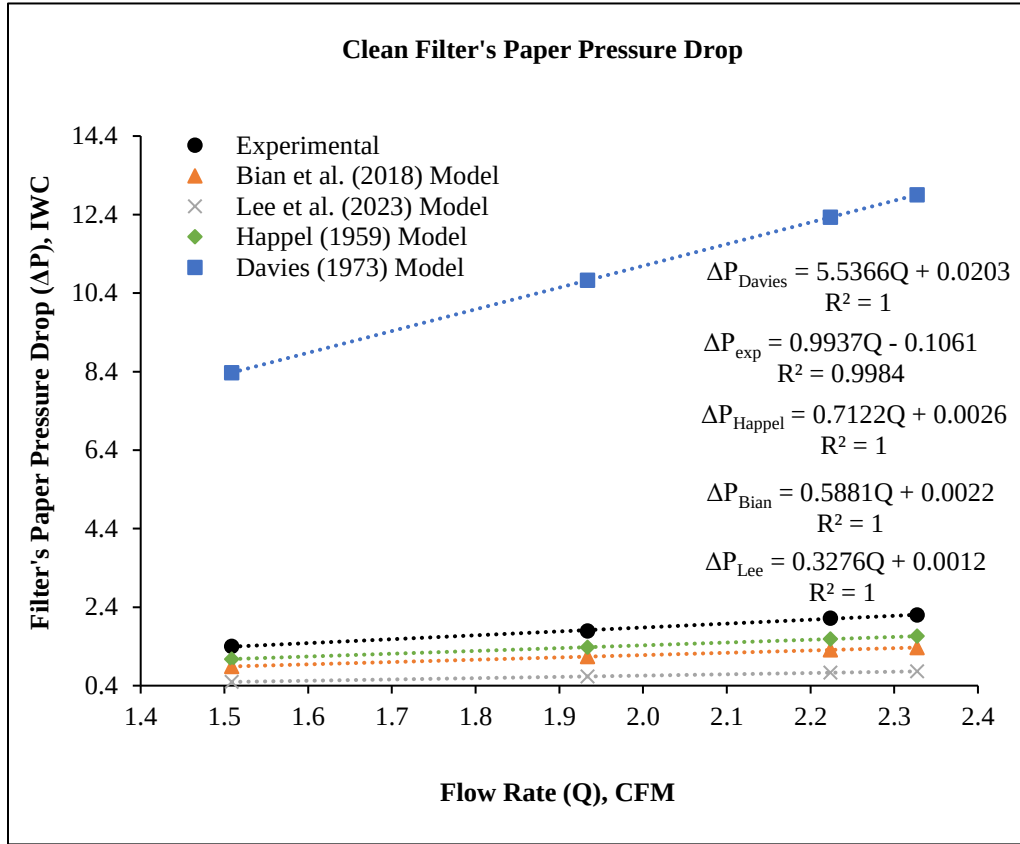


Figure 5.6. Filter Media Pressure Drop



5.3 Test Results and Discussion

The results of pinholed filter media penetrations indicated the failure of HEPA H14 filter media, even with the smallest experimentally possible hole size of 0.26 mm, as illustrated in Figure 5.7(a-b). This explained the susceptibility of HEPA filter efficiency to minor leaks, which can compromise the highly rated filter's performance. The average difference between aerosol penetration through a pinholed filter medium with the smallest hole size and an intact filter medium was around 0.17%, while the difference for the pinholed filter media with the largest hole size examined was about 0.39% compared to an intact filter medium. It was also observed that the penetration through the leaky filter media was solely governed by the leak regime, independent of the remaining medium fibers, as the penetration for all particle sizes within the

studied range of $\leq 0.5 \mu\text{m}$ was nearly uniform, indicating that all particles in that range traversed the leak freely. This explains the linear and strong correlation between the penetration of leaky filter media (P_f) and the ratio of the hole area to the filter medium area, as shown in Figure 5.8(a-b). This can be represented in the following simplified airflow balance equation:

$$P_f Q_f = P_b Q_b + P_h Q_h \quad (5.1)$$

Where P denotes the penetration, Q signifies flow rate, with the subscript f representing the filter, b indicating the residual fibers bed, and h referring to the hole. In this scenario, where the leakage regime is dominant, the first term on the right side of the equation for the penetration through the residual filter bed can be disregarded with $P_b = 0$. Given that all particles traversed the leak freely, P_h can be considered equivalent to one, thereby allowing the above equation to be simplified as follows:

$$P_f = \frac{Q_h}{Q_f} = \frac{A_h \times V_h}{A_f \times V_f} = \frac{A_h}{A_f} \times \frac{V_h}{V_f} \quad (5.2)$$

Further testing of pinholed filter media with different hole sizes at varying flow rates was conducted, focusing on a higher flow rate of 15 cm/s and a lower flow rate of 10 cm/s, to evaluate the effects of velocity variations on the penetration of the pinholed filter media. The data presented in Figure 5.9(a-b), corresponding to two distinct hole sizes of 0.26 mm and 0.5 mm, demonstrated that the filter media penetrations in the presence of a leak were unaffected by variations in velocity, exhibiting less than 0.002% difference at the two testing velocities. This contrasts with intact filter media, where filtration velocity does have an impact. This observation is consistent with the findings reported by Mouret et al. (2009) and Li et al. (2022), despite the differences in leakage ratios addressed.

The results of the pressure drop for the tested filter media prior to perforation are presented in Figure 5.6 of the preceding section. The data obtained aligns more closely with the

models proposed by Happel (1959) and Bian et al. (2018). The inhomogeneity factor was determined, respectively as follows:

$$\varepsilon = 0.76 = \frac{\Delta P_{Happel\ Model}}{\Delta P_{Our\ experimental}} \quad (5.3)$$

$$\varepsilon = 0.625 = \frac{\Delta P_{Bian\ Model}}{\Delta P_{Our\ experimental}} \quad (5.4)$$

The inhomogeneity factor of fibers for the tested filter media, determined by correlating our experimental data with the model proposed by Bian et al. (2018), was found to be equivalent to the findings of Stechkina et al. (1969) and Lee & Liu (1982). Given that the pinhole through the filter medium can affect the arrangement and distribution of fibers within the filter medium, this factor may also be linked to the correlation shown in Figure 5.8(b) between the penetration percent of the pinholed filter's media ($P_f(\%)$) and the leakage ratio ($\frac{A_h}{A_f}$) as follows:

$$P_f(\%) = 1.6 \frac{A_h}{A_f} = \frac{1}{\varepsilon} \frac{A_h}{A_f} = \frac{\Delta P_{Experimental}}{\Delta P_{Theory}} \frac{A_h}{A_f} \quad (5.5)$$

One can use this correlation to find out the threshold pinhole size that leads to the failure of the filter medium under the IEST rating conditions for a HEPA H14 filter, which has an efficiency of 99.99%. The filter media size utilized in this study indicated that a pinhole diameter of 0.0793 mm (80 μ m) represents the minimum size capable of causing filter medium failure. Any leaks smaller than this threshold do not compromise the filter's media efficiency below the rated efficiency of the H14 media in question. The identification of this size can present challenges in experimental settings and may also pose difficulties for advanced scanning apparatus in detecting such a small leak. This situation necessitates further research into computational modeling for enhanced analysis.

Figure 5.7(a-b). Pinholed Filter Media Penetration (a), Continuation (b)

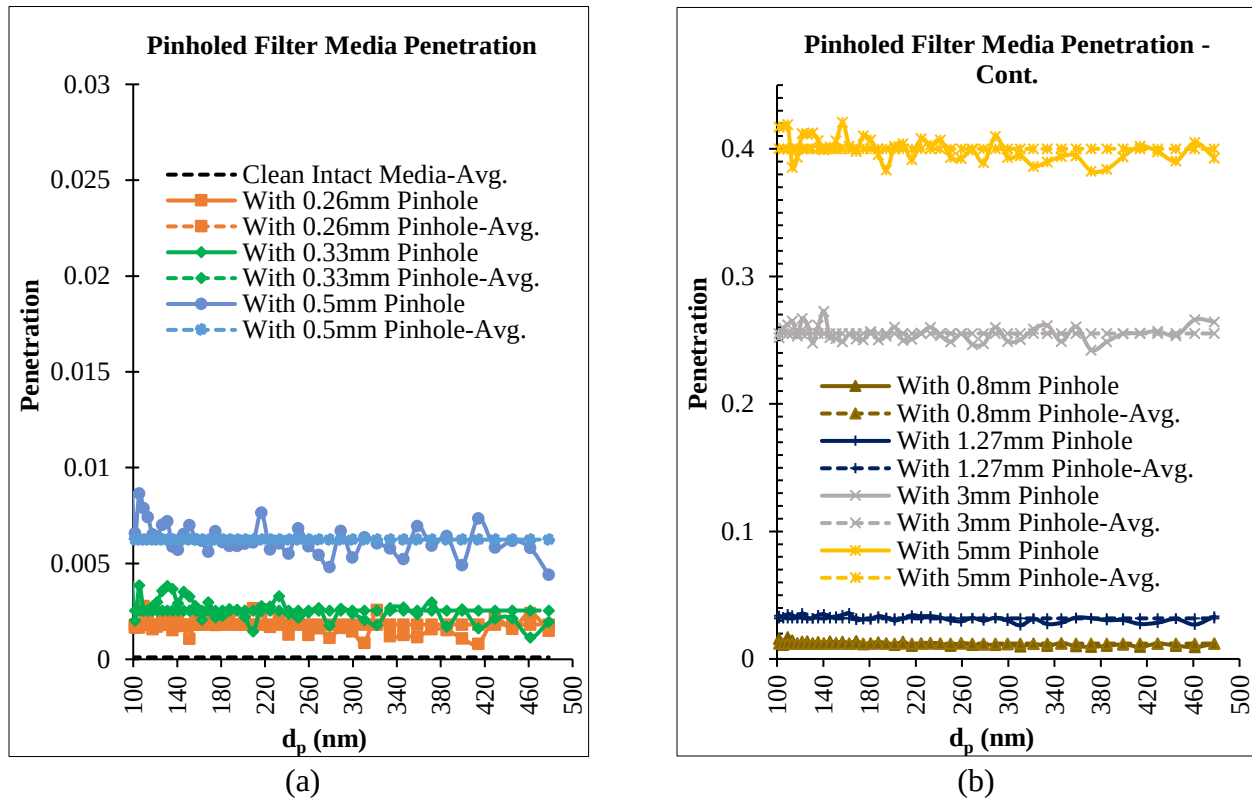


Figure 5.8(a-b). Penetration of Pinholed Filter Media Correlation (a), Refined Correlation (b)

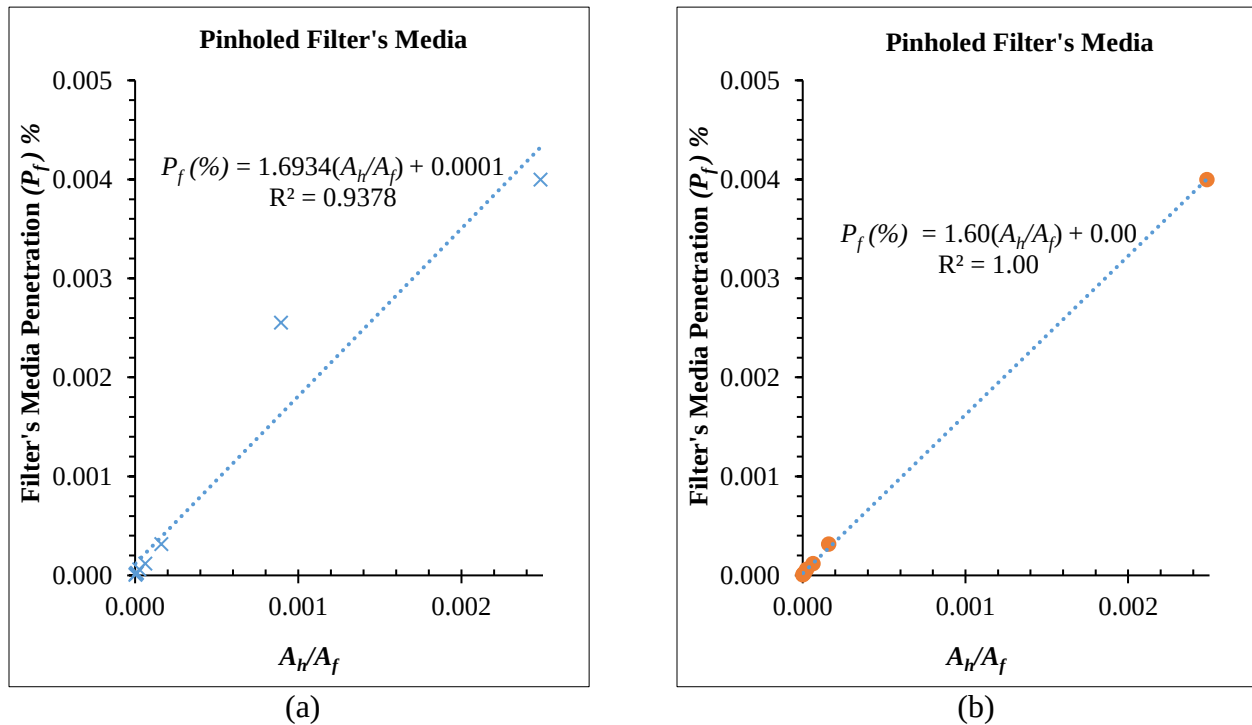
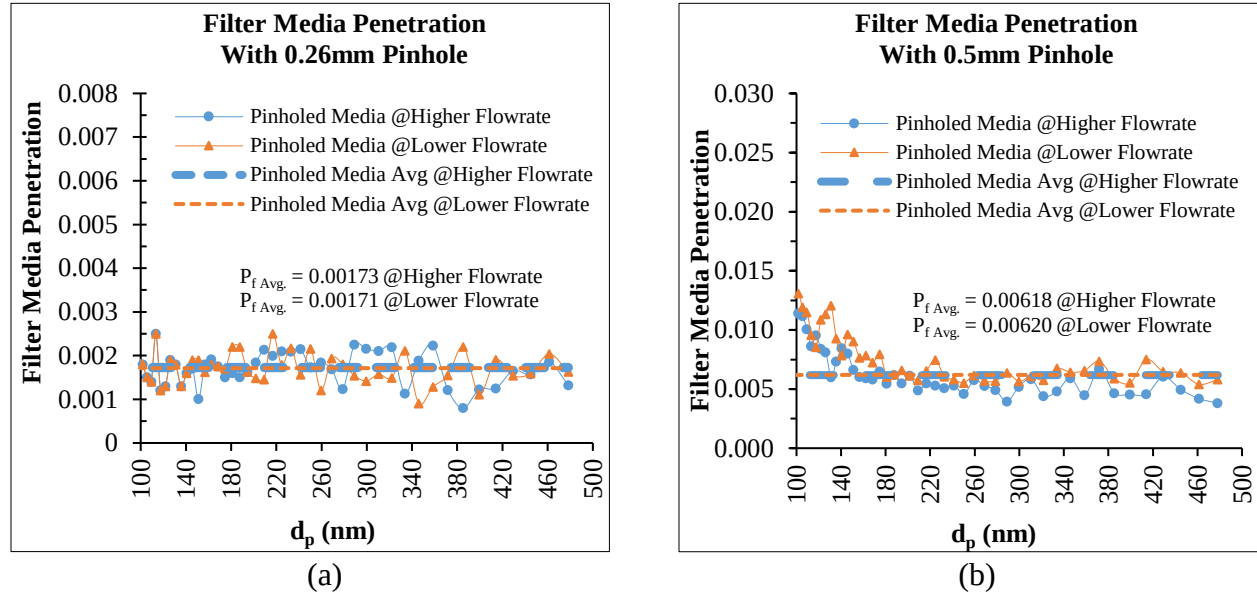


Figure 5.9(a-b). Flow Rate Effect on Pinholed Filter Media Penetration With 0.26 mm Pinhole (a), With 0.5 mm Pinhole (b)



5.4 Conclusion

This study examined the variation in particle penetration and collection efficiency within the MPPS range of fiberglass HEPA filter media. The focus was on perforated filter media with pinholes of varying sizes, and performance was evaluated at two different flow rates. The analysis indicated a notable correlation between filter media penetration (P_f) and pinhole diameter size, illustrating a linear relationship with the leakage ratio ($\frac{A_h}{A_f}$). The penetration results for all attainable pinholes were observed within the leakage regime, as demonstrated by the graphs being unaffected by d_p across the entire range of $d_p \leq 0.5 \mu\text{m}$. The filtration process here was governed by the hole rather than the filter media bed, enabling particles of varying sizes to pass through the hole, resulting in uniform penetration across all particle sizes. The findings warrant further investigation and comparison with the computational model developed in the previous chapter, given that the 3D model effectively identified the leakage regime under minor

leak conditions. The model can also be converted from 3D to 2D to reduce computational time and can be adjusted to correspond with the actual thickness of the filter media, which is 0.4 mm.

Chapter 6 – Conclusions & Recommendations for Future Research

We successfully designed and built a test stand setup to analyze the performance of standard-sized HEPA filters used in NBAF. In this part, we performed comprehensive testing, starting with preliminary assessments such as pressure decay testing and aerosol uniformity testing both upstream and downstream, and progressing to evaluations of HEPA filter efficiency and the effectiveness of auto-scanning technologies in detecting leaks through various methods and standards. Our findings indicated that the methodology outlined in ASHRAE 52.2 remains effective for conducting penetration tests to evaluate the fractional efficiency of filters and filter failure when subjected to eight pinholes of millimetric size or more. Auto-scan leak testing demonstrated greater reliability; however, it encountered challenges with a leak size of 159 μm and became increasingly unreliable for smaller leaks, ultimately becoming undetectable at 51 μm . The established laboratory will facilitate long-term training and educational programs for the NBAF prototype systems, as well as future research on HEPA or ULPA filters and their housings, including filter longevity testing, decontamination efficacy testing, humid environment filter integrity testing, and wet media testing, among others.

In the second part of this research, existing SEM imaging was employed to model the microstructure of H14 HEPA filter media commonly used in NBAF, facilitating a detailed investigation into the effects of those small leaks on filter performance. This 3D computational model enabled the examination of filter efficiency when subjected to micro-sized pinholes that are not feasible for experimental replication in the first part (smaller than 51 μm). We modeled micro-scaled media with a thickness of 7 μm . The efficiency of both intact and leaky (pinholed) H14 filter media was simulated, and the results were compared with previous studies and theoretical filtration models. The outcomes observed for an intact medium aligned with

established filtration theory; however, there is a lack of experimental research performed on the leaky medium featuring micro pinhole sizes smaller than 51 μm . In the case of the pinholed medium, we successfully identified the transitional and leakage regimes that will occur in the event of a minor leak. A pinhole size of 32 μm was identified to be the critical threshold for the examined model size, delineating the leakage regime from the transitional regime, wherein particle penetration through the filter medium becomes independent of particle size and is solely dependent on the pinhole size rather than the remaining fiber bed in the medium. Our results suggest a proposed designated leak penetration value of 0.0015%, which is stricter than the 0.005% value set forth in the EN 1822 H14 filter classifications. The proposed value is in alignment with the ISO-29463 Class ISO 50 H guidelines, which recommend the testing and classification of H14 HEPA filters at an integral value of 0.001% at the MPPS. The 3D computational model we have developed serves as a resource for future research aimed at understanding the influence of other physical and operational parameters on the performance of H14 filter media. This model will assist in the design and development of filtration scanning devices and serve as a tool for standards to establish and enhance criteria for successful filter leak (scan) testing.

Lastly, additional investigations on the H14 HEPA filter media were conducted utilizing a mini-scaled testing rig, which allowed us to have a more economical and practical method for the replacement and testing of HEPA filter media in comparison to full-sized HEPA filters. The results revealed a linear correlation between the percentage of filter media penetration ($P_f(\%)$) and the leakage ratio ($\frac{A_h}{A_f}$) when a pinhole leak was present, resulting in the filtration operating within the leakage regime. The analysis demonstrated that a threshold pinhole size of 80 μm will lead to the failure of the examined 3.5-inch x 3.5-inch x 0.4 mm filter medium under the IEST

rating conditions for a HEPA H14 filter. However, further computational analysis using our developed model would be advantageous for confirming these findings. This will pave the way for future research by converting our developed 3D computational model into a 2D model, allowing for the acquisition of the entire 0.4 mm H14 medium thickness, with the goal of reducing simulation time and facilitating analysis and comparison with these experimental results.

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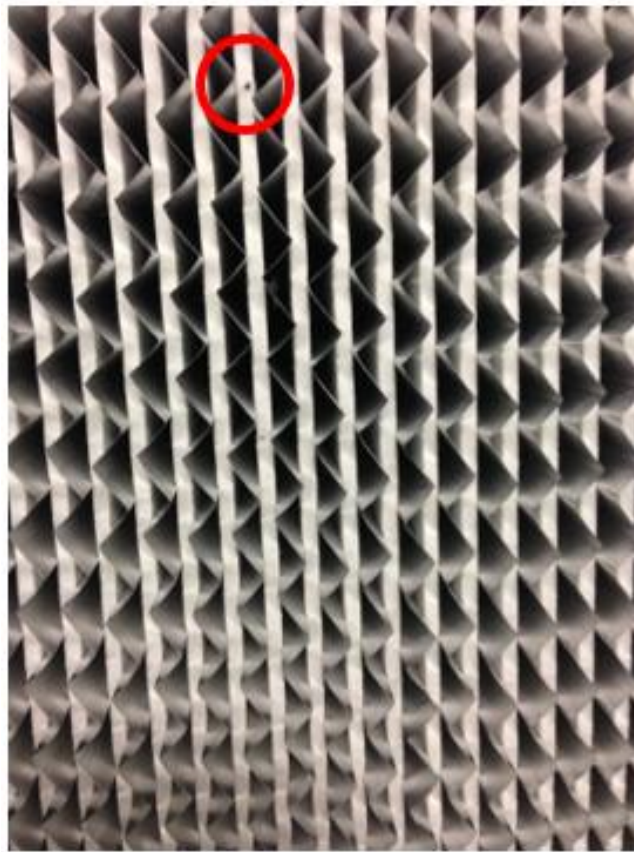
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Appendix A – Photos from BRI Experimental Work

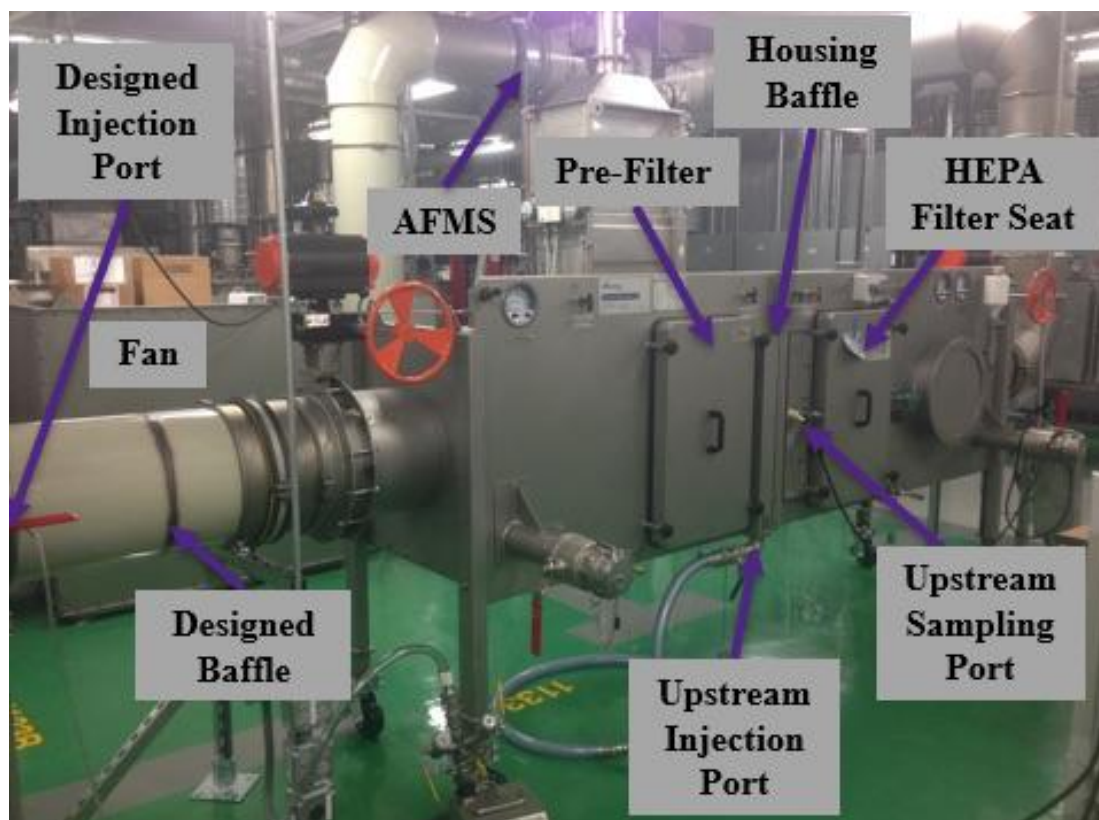
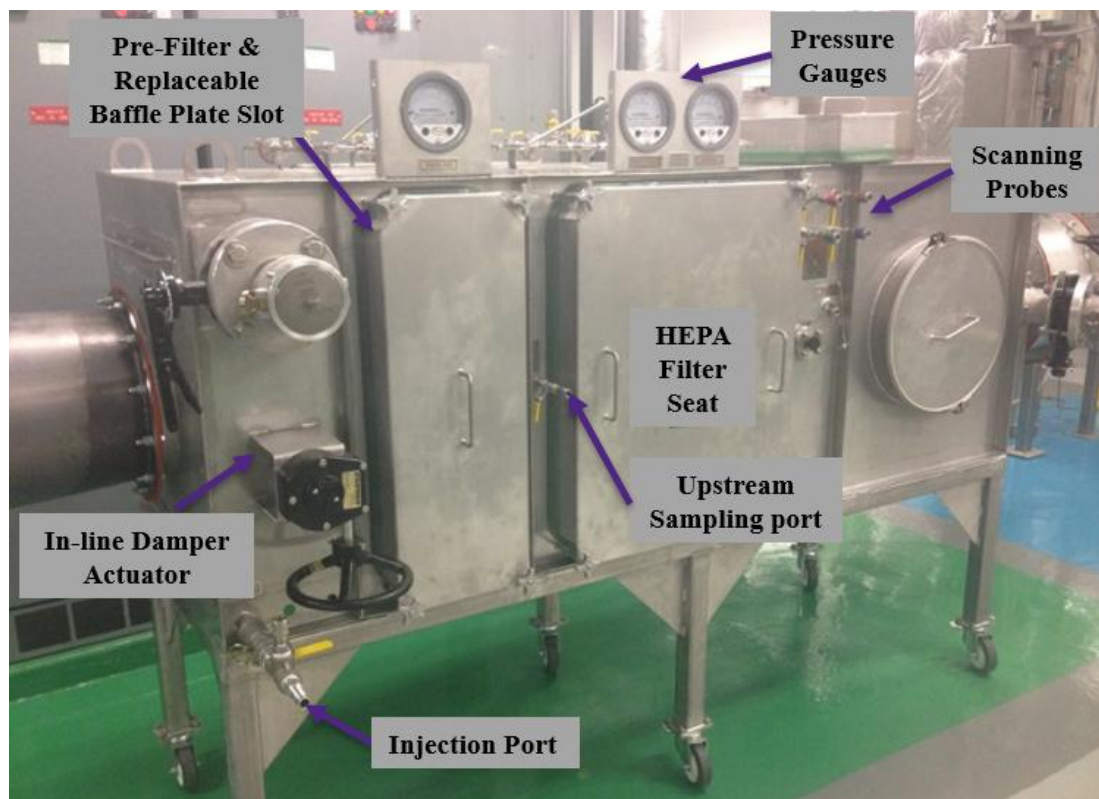
Appendix Figure A.1. Pinhole through a large-scale pleated HEPA filter



Appendix Figure A.2. Our testing device for Aerosol distribution upstream & downstream filter



Appendix Figure A.3. NBAF Filtration Housing Prototypes (FC #1 and FC #2)



Appendix B – Codes

Appendix Figure B.1. Interception UDF code

```
#include "udf.h"
#include "dpm.h"
#include "sg.h"
#include "math.h"

#define WALL_THREAD_ID 27 // Replace with your actual wall thread ID
#define TOLERANCE 3e-6
// Define the bounds of the cube
#define X_MIN 5e-8 // minimum X coordinate of the cube
#define X_MAX 5.5e-5 // maximum X coordinate of the cube
#define Y_MIN 5e-8 // minimum Y coordinate of the cube
#define Y_MAX 5.5e-5 // maximum Y coordinate of the cube
#define Z_MIN -2e-6 // minimum Z coordinate of the cube
#define Z_MAX 9e-6 // maximum Z coordinate of the cube

DEFINE_DPM_SCALAR_UPDATE(particle_wall_distance_check1, cell, thread, initialize, p)
{
    Domain* d = Get_Domain(1);
    Thread* wall_thread = Lookup_Thread(d, WALL_THREAD_ID);
    cell_t p_cell = P_CELL(p);
    Thread* p_thread = P_CELL_THREAD(p);
    real p_cell_centroid[ND_ND];
    C_CENTROID(p_cell_centroid, p_cell, p_thread);
    // Check if the particle's centroid is within the defined cube
    if (p_cell_centroid[0] >= X_MIN && p_cell_centroid[0] <= X_MAX &&
        p_cell_centroid[1] >= Y_MIN && p_cell_centroid[1] <= Y_MAX &&
        p_cell_centroid[2] >= Z_MIN && p_cell_centroid[2] <= Z_MAX)
    {
```

```

real f_centroid[ND_ND], ds;
real min_ds = HUGE_VAL;
real particle_radius = P_DIAM(p) / 2.0;
real xF_min = p_cell_centroid[0] - TOLERANCE;
real xF_max = p_cell_centroid[0] + TOLERANCE;
real yF_min = p_cell_centroid[1] - TOLERANCE;
real yF_max = p_cell_centroid[1] + TOLERANCE;
face_t f;
begin_f_loop(f, wall_thread)
{
    F_CENTROID(f_centroid, f, wall_thread);
    // Check if the face's centroid is within the dynamically defined bounds
    if (f_centroid[0] >= xF_min && f_centroid[0] <= xF_max &&
        f_centroid[1] >= yF_min && f_centroid[1] <= yF_max)
    {
        ds = sqrt(pow(f_centroid[0] - p_cell_centroid[0], 2) +
            pow(f_centroid[1] - p_cell_centroid[1], 2) +
            pow(f_centroid[2] - p_cell_centroid[2], 2));
        min_ds = fmin(min_ds, ds);
    }
}
end_f_loop(f, wall_thread)

// If the minimum distance is less than or equal to the particle radius, mark the particle for
removal
if (min_ds <= particle_radius)
{
    p->stream_index = -1; // Mark the particle for removal
}
}}

```

Appendix Figure B.2. Code for generating fibers

```
import numpy as np
import pyvista as pv
import pandas as pd
import random

p = pv.Plotter()
com = pv.MultiBlock()

domain_x = 50
domain_y = 50
domain_z = 7
volume_fraction = 0.075
stack_distance = .5

domain_x_center = domain_x/2
domain_y_center = domain_y/2
domain_z_center = domain_z/2

domain_size = (domain_x,domain_y)

total_volume = domain_x * domain_y * domain_z

total_fiber_volume = total_volume * (volume_fraction/100)

fiber_distribution = np.array([[.2],[.3],[.4],[.5],[.6],[.7],[.8],[.9],[1],[2]])

data = pd.DataFrame(fiber_distribution, columns=['Fiber_diamter'])

def fiber_gen(domain_size):
    domain_x, domain_y = domain_size

    x = random.randint(0+(domain_x*.1),domain_x-(domain_x*.1))
    y = random.randint(0+(domain_y*.1),domain_y-(domain_y*.1))

    center = np.array([x,y,0])
    dir = ([ 3.00000000e+00, -1.83697020e-16,0],
           [ 2.97634410e+00,  3.75999701e-01,0],
           [ 2.90574948e+00,  7.46069661e-01,0],
           [ 2.78932946e+00,  1.10437366e+00,0],
           [ 2.62892004e+00,  1.44526102e+00,0],
           [ 2.42705098e+00,  1.76335576e+00,0],
           [ 2.18690588e+00,  2.05364132e+00,0],
           [ 1.91227197e+00,  2.31153973e+00,0],
           [ 1.60748038e+00,  2.53298378e+00,0],
```

```

[ 1.27733787e+00, 2.71448116e+00,0],
[ 9.27050983e-01, 2.85316955e+00,0],
[ 5.62143944e-01, 2.94686175e+00,0],
[ 1.88371559e-01, 2.99408019e+00,0],
[-1.88371559e-01, 2.99408019e+00,0],
[-5.62143944e-01, 2.94686175e+00,0],
[-9.27050983e-01, 2.85316955e+00,0],
[-1.27733787e+00, 2.71448116e+00,0],
[-1.60748038e+00, 2.53298378e+00,0],
[-1.91227197e+00, 2.31153973e+00,0],
[-2.18690588e+00, 2.05364132e+00,0],
[-2.42705098e+00, 1.76335576e+00,0],
[-2.62892004e+00, 1.44526102e+00,0],
[-2.78932946e+00, 1.10437366e+00,0],
[-2.90574948e+00, 7.46069661e-01,0],
[-2.97634410e+00, 3.75999701e-01,0])

direction = random.choice(dir)

length = max(domain_x,domain_y)*2.5

radius = 1

return center, direction, length, radius

model_num = 0

fraction_volume_num = 0

stack_center = 0
step_count = 0

y = 0

diameter_array = []

for _ in range(100):
    try:
        for _ in range(3):
            cen, dir, len, rad = fiber_gen(domain_size)
            domain = pv.Cube((domain_x_center,domain_y_center,cen[-
1]+stack_center),domain_x,domain_y,4).triangulate()
            one_row_data = data.sample()
            one_row_data_numpy = one_row_data.to_numpy()
            fiber_dia = one_row_data_numpy[0][0]
            fiber_radius = fiber_dia / 2

```

```

cen = np.array([cen[0],cen[1],cen[-1]+stack_center])

cyl = pv.Cylinder(cen,dir,fiber_radius,len).triangulate() #fiber_radius
boolean = domain.boolean_intersection(cyl)
#com.append(cyl) #
p.add_mesh(boolean) #boolean
volume = boolean.volume
fraction_volume_num += volume
fraction_volume_per = (fraction_volume_num / total_volume) * 100
print("SVF factor :", fraction_volume_per)
print(stack_center,"\n")
boolean.save(f'C:\\Users\\DA\\Desktop\\Model\\fiber_{model_num}.stl')
model_num += 1
y += 1
print(y)
diameter_array.append(fiber_dia)

if fraction_volume_per > volume_fraction:
    break

stack_center += data['Fiber_diamter'].mean()
#stack_center += .8

if stack_center > domain_z:
    break

except ValueError:
    pass

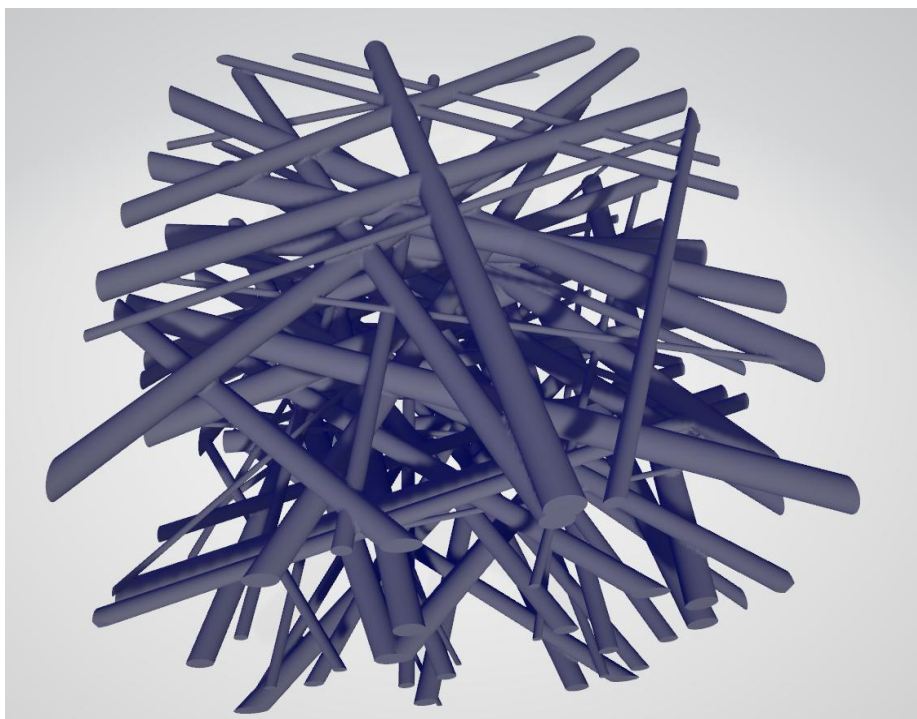
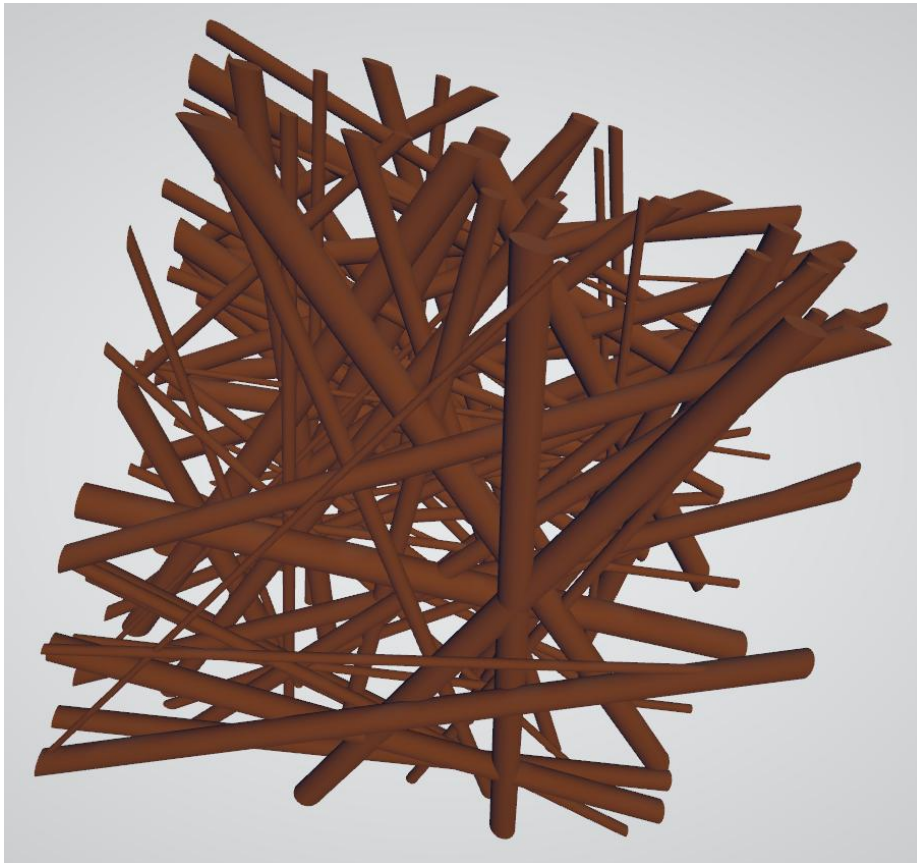
#main_doamin =
pv.Cube((domain_x_center,domain_y_center,domain_z_center),domain_x,domain_y,(domain_z
*2))

#main_doamin.save('C:\\me\\dv\\26_08_23_fiber\\mesh\\main_domain.stl')
#com.save(file_save)

sum_t = np.sum(diameter_array)
print("SVF factor :", fraction_volume_per)
print("Average fiber diameter: ",sum_t/y)
p.show_bounds(grid='back')
p.show()
#print(round(domain.volume)*0.075)
#domain.plot()

```

Appendix Figure B.3. Visualization of generated fibers using ParaView



Appendix C – Permission from Allimand Interweb, Inc. to

Reproduce Figure 2.1

Outlook

RE: Permission to Reproduce Wet-lay Process Figure

From: Riggi Jeff <riggij@allimandinterweb.com>
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To: Daniel Abraham <danabraham@ksu.edu>
Cc: Valadez Roberto <ValadezR@allimandinterweb.com>

This email originated from outside of K-State.

Hi Daniel,

You have the permission of Allimand Interweb, Inc. to use the wet lay process schematic shown below for your dissertation.

Best regards,

Jeff Riggi
VP-Sales
Allimand Interweb
riggij@allimandinterweb.com

Office: 518-793-6102
Direct: 518-791-0819
Cell: 518-798-8401



From: Daniel Abraham <danabraham@ksu.edu>
Sent: Thursday, March 20, 2025 2:35 PM
To: Riggi Jeff <riggij@allimandinterweb.com>
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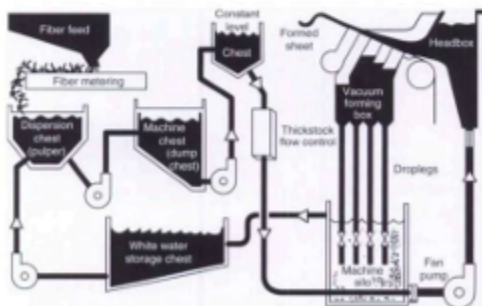
Cet e-mail provient d'une personne externe à votre organisation. Ne cliquez pas sur les liens ou n'ouvrez pas sur les pièces jointes si vous ne connaissez pas l'expéditeur et que vous n'êtes pas certain que le contenu soit sûr.
This email is from someone outside your organization. Do not click on links or open attachments if you do not know the sender and are not sure whether the content is safe.

Hello,

My name is Daniel Abraham, and I am a PhD candidate at Kansas State University (KSU). I would greatly appreciate your permission to reference the figure below in my dissertation.

I understand that Glens Falls Interweb, Inc. (GFI) has transitioned to a new structure named ALLIMAND INTERWEB. I would appreciate your guidance on how to reference the figure (with old Vs. new name), and if you happen to have a more recent picture of the Wet-lay process for making fibers, that would be wonderful. Thank you very much!

Figure 2.1. Inclined Wire Wet-lay Process (Reproduced from Glens Falls Interweb-Allimand Interweb, Inc. Glens Falls, NY, USA)

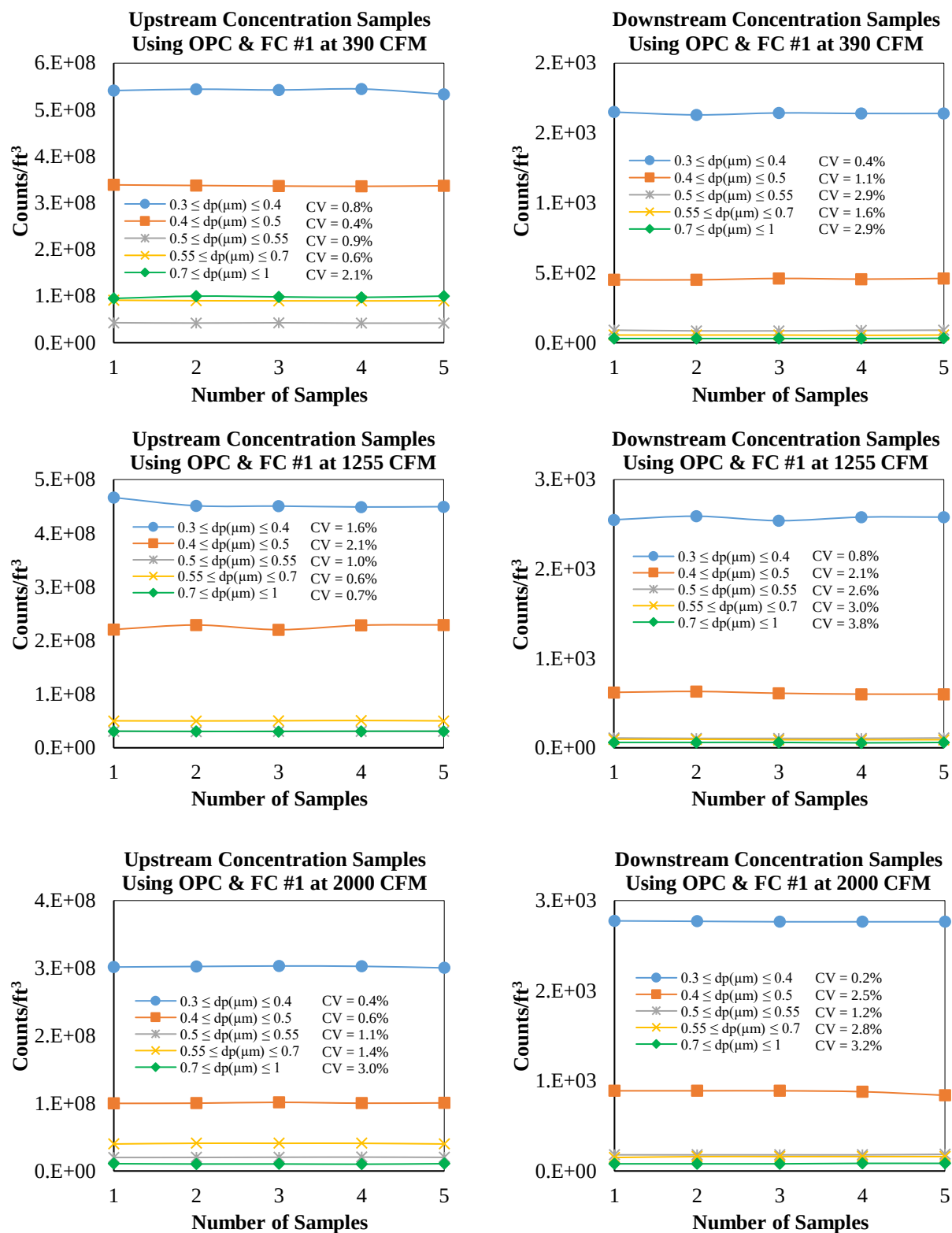


V/R

Daniel M. Abraham

Appendix D – Measurement Repeatability

Appendix Figure D.1. Concentration measurements using OPC & FC #1 at various airflow rates



Appendix Figure D.2. Concentration measurements using OPC & FC #2 at various airflow rates

