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The Development and Validation of an Isokinetic Calibration System for Multiple Aerosol Instruments

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THE DEVELOPMENT AND VALIDATION OF AN ISOKINETIC CALIBRATION SYSTEM FOR MULTIPLE AEROSOL INSTRUMENTS

by

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Abstract

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Utah State University, 2014

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A multi-port calibration fixture for the cross calibration of aerosol point sensors has been developed. The system was designed for comparative calibrations of instruments using differing measurement methods such as optical particle counters, aerodynamic impactors, etc. Four isokinetic sampling ports are attached to a laminar flow plenum such that all four sampling ports sample identical aerosol concentrations under identical flow conditions. Correlation and correction factors are applied to each instrument creating a standard method. This standard method can be applied to inter-compare and calibrate aerosol sensing instrumentation and/or to characterize the microphysical properties of a test aerosol. The performance of this fixture has been demonstrated with a TSI 3321 APS, a GRIMM 1.109 and a MetOne OPC.

(111 pages)

Purpose of this manual

This manual is designed to give the reader a thorough explanation of design and implementation of the development of an isokinetic calibration system for aerosol instruments. Throughout this manual, various parts of the system will be described in detail as well as the methods for validating the system. This manual also contains a user's guide for running the completed system, based on the prototype. The items purchased for this project are not necessarily endorsed by Utah State University, USU Research Foundation Space Dynamics Laboratory, or Dugway Proving Ground. Though using this system does provide an in-house option for calibration, it is recommended to send a laboratory standard to the manufacturer for yearly calibration.

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Chapter 1

Introduction

Ambient air contains particulate matter (PM) which is a mixture of solid particles and liquid droplets. An aerosol is the gaseous suspension of solid and liquid particles. Throughout this paper, PM and aerosol are used interchangeably. PM comes in many sizes which have varying effects on human health and the environment. These concerns include adverse respiratory problems, changes in heart rhythms, heart malfunctions, reduced visibility, and climate changes [2, 7, 8]. These effects may cause harm and are, therefore, of interest to scientists, regulators, and the general public. Currently, there are many different instruments that can measure different characteristics of particles. Some measure the physical diameter of particles (d_p or d_g), some the aerodynamic diameter (d_a), some the chemical constituents, some the mass concentrations. The physical diameter is the actual diameter of the particle and is also referred to as the geometric or optical diameter. The aerodynamic diameter is the diameter of a sphere with unit density that will settle in still air at the same rate as the particle in question [9]. The differences and correlations between these measurements can provide more information on the aerosols being tested, including information on the aerosol density, which can lead to more knowledge on the human health issues that arise due to aerosols.

While there are many types of instruments, one typical procedure for calibrating the systems are to send them back to the manufacturer, which can take significant time away from operations. Because this takes time and money, those who use the instruments in the field are interested in a low cost, "at home" calibration method. By building a system to co-calibrate multiple instruments simultaneously, the time it takes to perform calibrations can be reduced. This reduces the need, and therefore cost, for manufacture calibrations on all instruments. This allows the instruments to be used in the field more without the

downtime of yearly external calibration.

Dugway Proving Ground (DPG) seeks an alternative to sending their instruments back to the manufacturer for calibrations. DPG has a number of instruments, including many duplicates, which require time for characterization and calibration. DPG has provided funding to Utah State University Research Foundation Space Dynamics Laboratory (USURF SDL) and Utah State University (USU) to develop a laboratory-based system to allow them to calibrate their instruments in-house in a time efficient and cross-correlating manner. A transfer standard system has been developed and the design and testing is explained in this manual. This calibration system also has dual use as an aid for finding correlations between instruments that characterize PM under differing methodologies. As well as a general operational outline for cross-correlating different instruments.

1.1 Particulate Matter

PM is typically categorized by size. According to the US Environmental Protection Agency (EPA), "inhalable coarse particles" with aerodynamic diameters larger than 2.5 micrometers (μm) and smaller than 10 μm and "fine particles" are smaller than 2.5 μm. The sum of the inhalable coarse and fine particles are called PM_{10} and the fine particles alone are called $PM_{2.5}$ [2]. These particles are very small and difficult to see with the unaided eye. Figure 1.1 shows relative sizes of PM_{10} and $PM_{2.5}$ to that of a typical human hair and fine beach sand. $PM_{2.5}$ is of special concern due to its ability to penetrate the pulmonary alveolus.

PM occurs both naturally (biogenic) and from man-made (anthropogenic) sources. Biogenic emissions can include gaseous sulfur from volcanoes or decaying vegetation. Anthropogenic sources include coal and oil acids, heavy metals, and elemental carbon [8]. In the trends study done by the US EPA in 2012, fuel combustion, not including fuel combustion for electrical utility or industrial sources, was the leading cause of $PM_{2.5}$ from anthropogenic sources, followed by other unspecified industrial processes, fuel combustion for industrial, highway vehicles, and fuel combustion for electrical utilities [10]. Combustion processes are a significant source of $PM_{2.5}$.

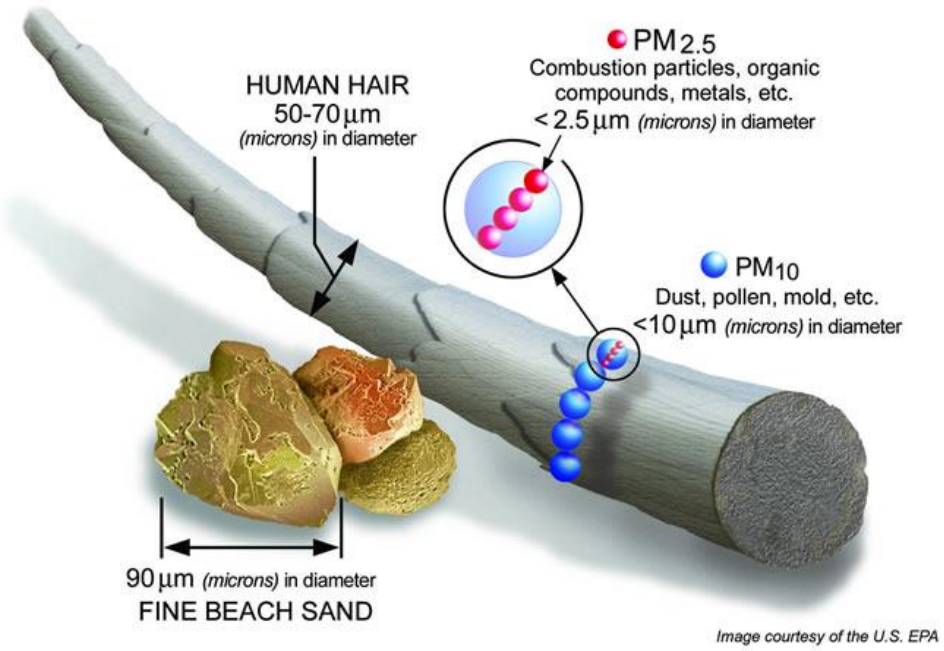


Fig. 1.1: Scale of Particles Sizes Compared to Human Hair and Fine Sand. [2]

People are exposed to PM on a continual basis; these small particles have many associated health effects. For example, $PM_{2.5}$ can become trapped deep in the lungs, contributing to respiratory problems, and may migrate or cross into the blood stream contributing to cardiovascular morbidity and mortality [7]. Other illnesses associated with PM can include changes in heart rhythms, heart malfunctions and heart attacks. Some other health related effects include increased absence from school and work, as well as an increase in hospital admissions [8].

In addition to the adverse health effects, particulate pollution results in visibility reduction, environmental damage, and aesthetic damage [2]. Visibility in clean, dry air can be as far as 200 kilometers or more, whereas in polluted air, visibility can be reduced to less than a kilometer [8]. Some visibility issues can also contribute to climate change via direct physical effects (scattering and absorption of solar radiation) which promote cooling and warming effects, respectively. Indirectly, cloud cover is effected by the amount of PM,

also leading to a net cooling effect [8].

In the US, primary and secondary standards are set for air quality by the EPA. The primary standards are designed for public health protection, especially the young, the elderly, and members of the populace with compromised respiratory systems. The secondary standards provide public welfare protection, including damage to animals, vegetation and buildings, as well as protection against decreased visibility. These standards can be seen in Table 1.1. These concentrations are recorded by local agencies and submitted to the EPA, as well as concentrations for other pollutants designated by the EPA [1].

Table 1.1: EPA Air Quality Standards for PM [1].

Pollutant	Standard	Averaging Time	Level	Reported Form
$PM_{2.5}$	Primary	Annual	12 $\mu g/m^3$	Annual mean, averaged over 3 years
$PM_{2.5}$	Secondary	Annual	15 $\mu g/m^3$	Annual mean, averaged over 3 years
$PM_{2.5}$	Primary and Secondary	24-hour	35 $\mu g/m^3$	98th percentile, averaged over 3 years
PM_{10}	Primary and Secondary	24-hour	150 $\mu g/m^3$	Not to be exceeded more than once per year on average over 3 years

1.2 Experimental Objective

The objective of this project was to develop a calibration/comparison system for multiple, diverse PM samplers. This development was accomplished by the following tasks.

1. Designing and constructing a flow-through sampling chamber,

2. Demonstrating that the calibration system provides a controlled, uniform, unbiased measurement environment, and

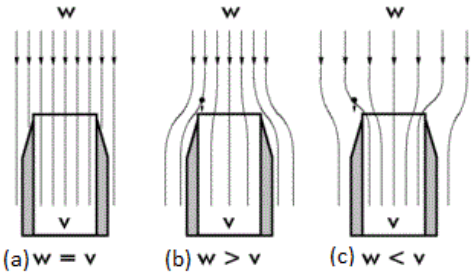


Fig. 1.2: An example of isokinetic sampling (a) versus anisokinetic sampling (b and c) [3].

3. Demonstrating the ability to compare multiple instruments simultaneously.

1.3 Isokinetic Sampling

Isokinetic sampling is a strategy to get a representative sample of aerosol when sampling from a moving stream. Sampling is considered isokinetic when the inlet axis of the sample is parallel to the flowing stream and when the velocity entering the sample is equal to the flowing stream [11,12]. There should be no distortion of the streamlines just upstream of the inlet nor particle loss at the inlet. Isokinetic sampling ensures that the concentrations and size distributions of the aerosol entering the tube are the same as the aerosol in the flowing stream. Failing to sample isokinetically can result in a distortion of the size distribution on the large end, meaning there may be an excess or deficiency of large particles. There is no way to determine the true concentration without sampling isokinetically unless the size distribution is already known or can be estimated [12].

The following equation can be used to determine flow rates and/or diameters of ducts or probes for isokinetic sampling.

$$\frac{Q_S}{Q_0} = \left(\frac{D_S}{D_0}\right)^2 \tag{1.1}$$

Q_s is the sampling flow rate, Q_0 is the flow rate of the duct, D_S is the diameter of the sampling probe, and D_0 is the diameter of the duct, assumed circular [12]. In the plenum design, this equation is used to determine what the D_S should be given Q_S, Q_0, and D_0.

A visual explanation of isokinetic sampling can be seen in Figure 1.2. The first image

(a) shows isokinetic sampling, where both the velocities are equal (w = v) where w is Q_0 and v is Q_S. The other images show anisokinetic sampling. Image (b) shows sub-isokinetic conditions when w > v; and image (c) shows super-isokinetic conditions when w < v. Both (b) and (c) result in too many large particles or too few large particles, respectively, being collected.

1.4 Method

The purpose of this project is to develop a standard method for in-house calibration of multiple aerosol instruments that also provides the opportunity to correlate various instruments. This was to be accomplished using bench scale instruments to measure particle size distributions and concentrations of ambient and controlled particle releases and to correlate the instruments. The protocols developed herein may then be applied to other particulate measurement technologies as desired.

A major factor in developing a consistent correlation between different instruments or measurement techniques is to find the specific gravity of particles with respect to d_a and d_g. The theoretical correlation is

$$d_a = d_g \sqrt{\frac{\text{s.g.}}{\chi}} \tag{1.2}$$

where s.g. is the specific gravity of the particle and χ is the shape factor to account for the effect of the shape on particles in motion. The specific gravity is the ratio of the density of the substance to the density of water. The shape factor is defined as a ratio of the actual resistance force of the nonspherical particle to the resistance force of a sphere of the same volume and velocity; the range is typically between 1 and 2 [12].

1.4.1 Targeted Instruments

The instruments that were used to measure airborne particles in this study included the Aerodynamic Particle Sizer Spectrometer by TSI Incorporated, the Grimm Portable Dust Monitor Series 1.109 by Grimm Aerosol, and the Aerosol Profiler by Met One Instruments

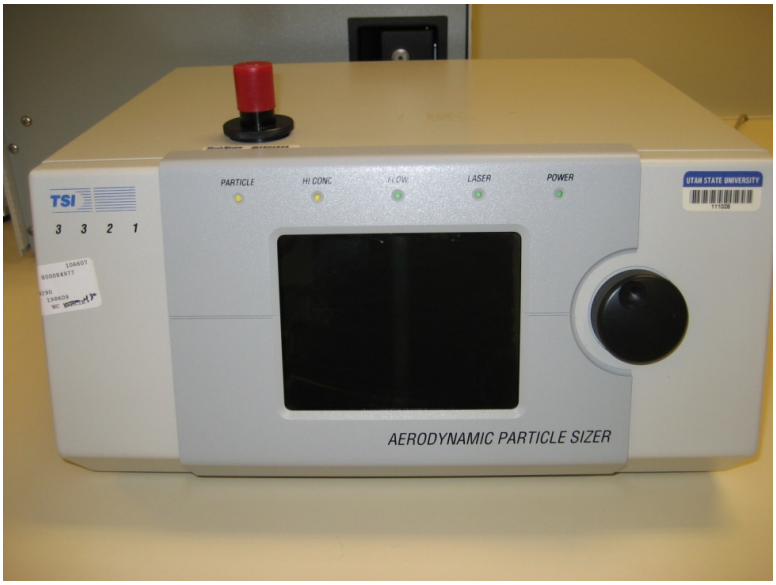


Fig. 1.3: Aerosol Particle Sizer, TSI Inc.

Incorporated. These instruments were to be used to measure both controlled (laboratory) and ambient system aerosol.

Aerodynamic Particle Sizer 3210

The APS is a general-purpose particle spectrometer that measures both aerodynamic diameter and light-scattering intensity; it has been documented widely in peer-reviewed articles and journals. It provides count size distributions of aerodynamic diameters from 0.5 to 20 μm and the light-scattering intensity from 0.3 to 20 μm; it separates these into 52 channels. It uses the time-of-flight method, which uses the acceleration of the particles in response to the accelerated flow. The particles that are smaller will move faster than the larger particles due to inertia. The APS requires a flow rate of 1 liter per minute (L/min) for aerosols and about 4 L/min for sheath air [4]. The APS can be seen in Figure 1.3.

A schematic of the APS can be seen in Figure 1.4. In the APS, particles are confined to the center line of an accelerating flow by the sheath air. Then they pass through two laser beams, scattering light in the process. Side-scattered light is collected by an elliptical mirror that focuses the collected light onto a solid-state photodetector. The photodetector then converts the light pulses into electrical pulses; the velocity can be calculated for each particle

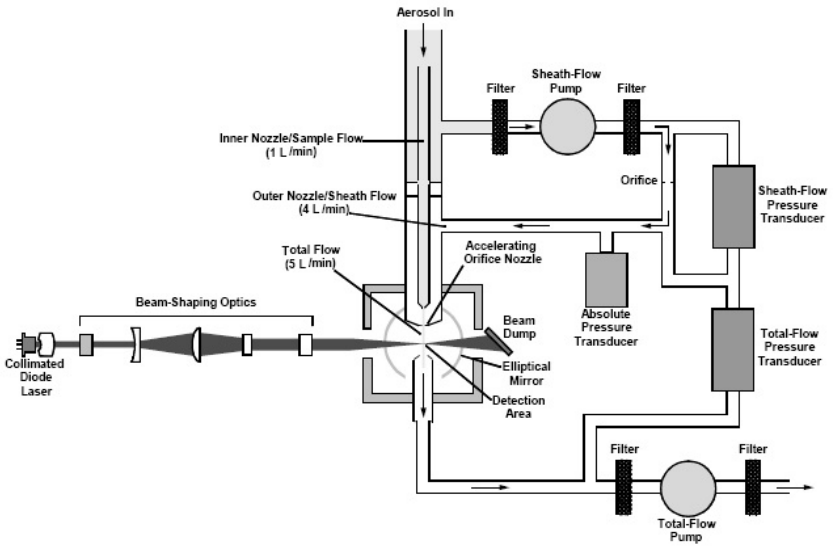


Fig. 1.4: Aerosol Particle Sizer schematic [4].

individually by the timing between the pulse peaks. The APS then takes the velocities and converts them to aerodynamic particle diameters. Measurements can be set from one to 64,800 seconds in summed mode and one to 300 seconds in average mode, the default is set to 20 seconds [4].

Typically, most components of the APS require no maintenance. Some user maintenance operations include cleaning the inner and outer nozzles and replacing the air filters. While one can perform their own calibration, TSI recommends sending the instrument in for a check and/or update the calibration with the manufacturer after 5000 hours of continuous operation. All of these procedures are included in the user's manual [4].

Portable Aerosol Spectrometer Model 1.109

The Grimm is a small portable unit used for continuous measurement of aerosols using light-scattering technology. It is an optical particle counter that can optically size and count airborne particles. It provides particle concentrations (counts/L) or mass concentration, assuming particle density, in micrograms per cubic meters ($\mu g/m^3$) for 32 channels ranging from 0.25 to 32 μm. A 683 nm semiconductor-laser serves as the light-source. The signal is scattered from the particles passing through the beam and is collected on a detector via

Fig. 1.5: Portable Aerosol Spectrometer 1.109, Grimm.

a mirror at approximately 90 degrees. The signal is then transferred to a channel classifier. The data are recorded on a data storage card and can be transferred to a computer [5]. The system requires a flow rate of 1.2 L/min for the sample pump. The Grimm can be seen in Figure 1.5.

A schematic of the Grimm can be seen in Figure 1.6. At the beginning of each measurement, the instrument initiates a self-test, approximately 30 seconds, and then the actual measurement begins. The self-test rinses through the measurement cell and checks several different internal measurements. It produces results every six seconds and averages the results every minute. The data is saved internally every minute. Measurements can be made every six to 60 seconds. The ambient air is drawn into the system and the sample passes through a sample cell then it is collected on a 47-mm polytetrafluoroethylene (PTFE) filter. In the sample cell, the particles pass through the laser beam detector and produce signals via the diodes. These signals are then sent to a multi-channel size classifer which transmits the pulses into corresponding data. The PTFE filter can be analyzed gravimetrically for verification of the reported aerosol's mass. There is also a particle free airflow that ensures no dust contamination comes in contact with the laser-optic assembly and is used for a reference-zero test during the self-test [5].

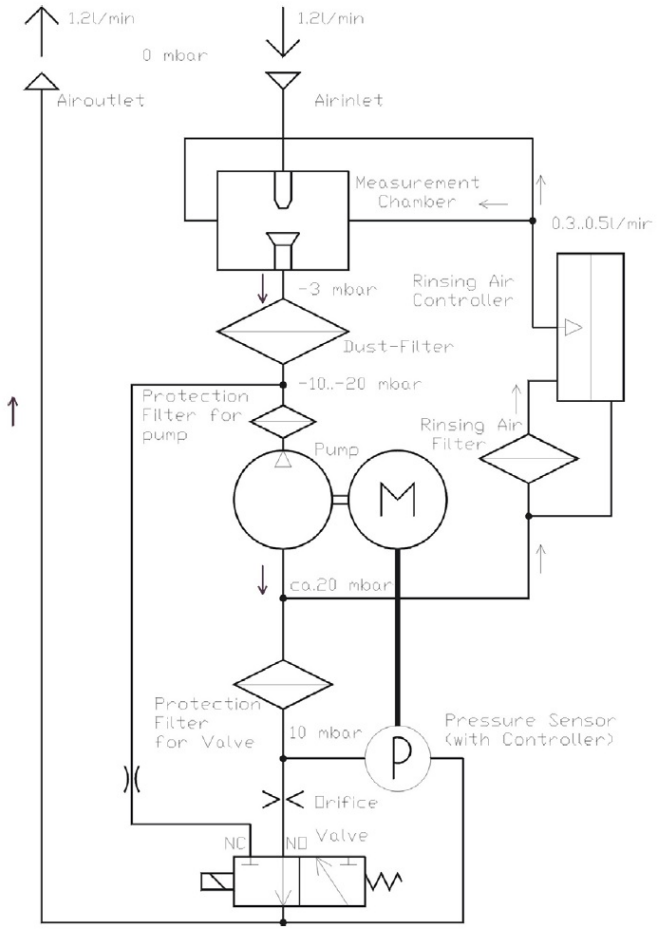


Fig. 1.6: Schematic of the Portable Aerosol Spectrometer 1.109, Grimm [5].

Fig. 1.7: Internal components of the Aerosol Profiler, Met One.

Grimm recommends that the unit be checked annually for the calibration conditions, for which it must be sent to the manufacturer. A reference unit and calibration tower can be obtained from Grimm, if necessary, though a person must be trained by the manufacturer and the reference unit still needs to be sent in annually for evaluation [5].

Aerosol Profiler Model 9722

The Aerosol Profiler is a portable particle counter that can optically size and count airborne particles. The particles are sized and then counted into one of eight channels. It provides particulate concentrations in particles per cubic foot (particles/ft^3) with a range of 0.3 μm to 10 μm. It has a flow rate that is approximately 1 L/min for this project [6]. The MetOne OPC can be seen in Figure 1.7.

A schematic of the MetOne OPC can be seen in Figure 1.8. Similar to the Grimm, the MetOne OPC uses light scattering technology to measure and count particles. A 650 nm laser diode produces light parallel to the sample to illuminate the particles, which scatter the light. The MetOne OPC uses elliptical mirrors to collect the scattered light. The light is converted into voltage pulses which are used to determine the size binwill segregate the sizes and send them to their associated counters. The MetOne OPC systems used in this

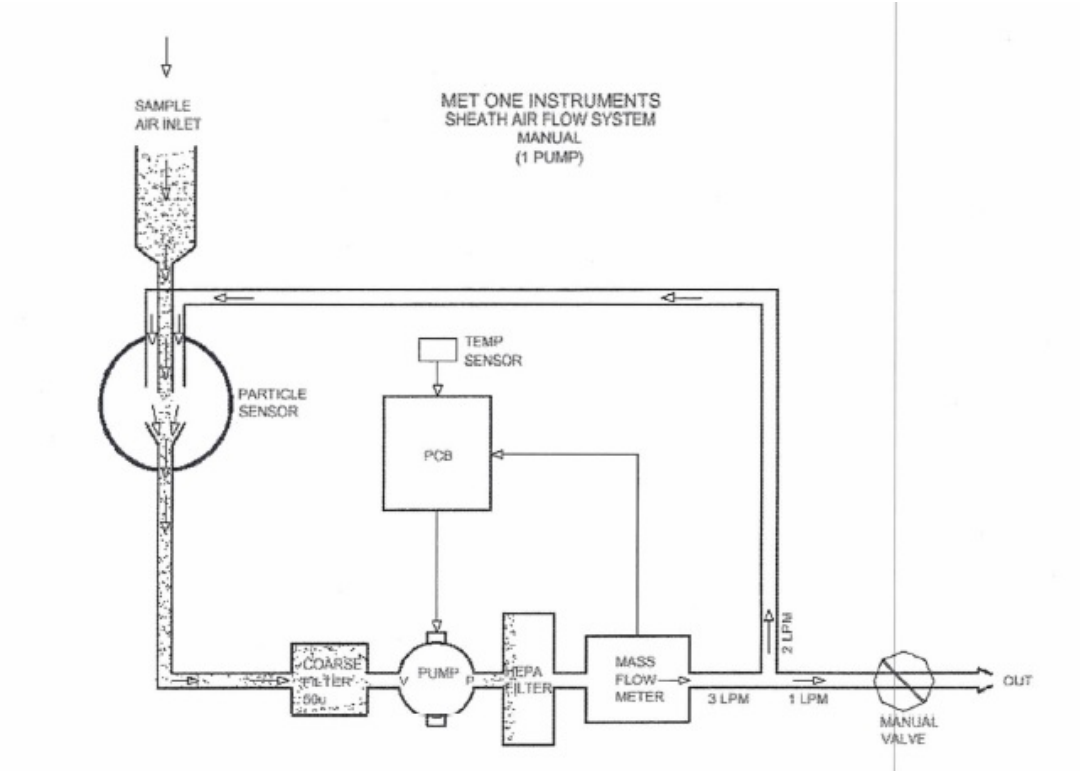


Fig. 1.8: Schematic of the Aerosol Profiler, Met One [6].

study record data to an attached datalogger every 60 seconds, from which the data can be extracted later [6].

Typically a MetOne OPC is calibrated using polystyrene latex (PSL) beads and provides a standard traceable reference as well as reproducibility. However, it can only be calibrated or serviced by factory-authorized personnel and should be calibrated on a yearly basis [6].

1.4.2 Laboratory Controlled Aerosol Generation

The controlled aerosol generation was primarily accomplished using two methods: the Small-Scale Powder Disperser (SSPD) Model 3433 and the Vibrating Orifice Aerosol Generator Model 3450 (VOAG), both by TSI Incorporated. Standardized particles of known size distribution, such as Arizona road dust or PSL beads, were planned to be used throughout the laboratory measurements. By controlling the particle sizes and densities, correlations can be developed between the instruments. These, in turn, can be used to test the hypothesis

Fig. 1.9: Picture of internal pieces of the Small-Scale Powder Disperser (SSPD), TSI Inc.

of correlating the instruments in ambient systems.

Small Scaled Powder Disperser Model 3433

The small-scale powder disperser, see Figure 1.9, is designed to distribute dry powder in the diameter range of 1 to 50 μm. Compressed air with a flow rate of 25 L/min at 20 psi is required to properly operate the system; this air must be dried and filtered. The output flow of air laden with particles is 5 L/min, but 18.5 L/min is required to aspirate the particles [13].

Using the SSPD begins with powder being loaded onto the turntable. This is done by gently brushing it over the surface of a ring of abrasive paper, see Figure 1.10. There are three rings of abrasive paper attached to the turntable. The turntable is placed underneath the capillary delivery tube where the powder is removed via the venturi aspirator and capillary tube, much like a vacuum. Any agglomerates are broken up in the venturi throat due to shear forces in the capillary tube. The particle-ladened air is then sent out the top and into the system as desired. The capillary flow, air, and rotation speed of the turntable are all adjustable [13].

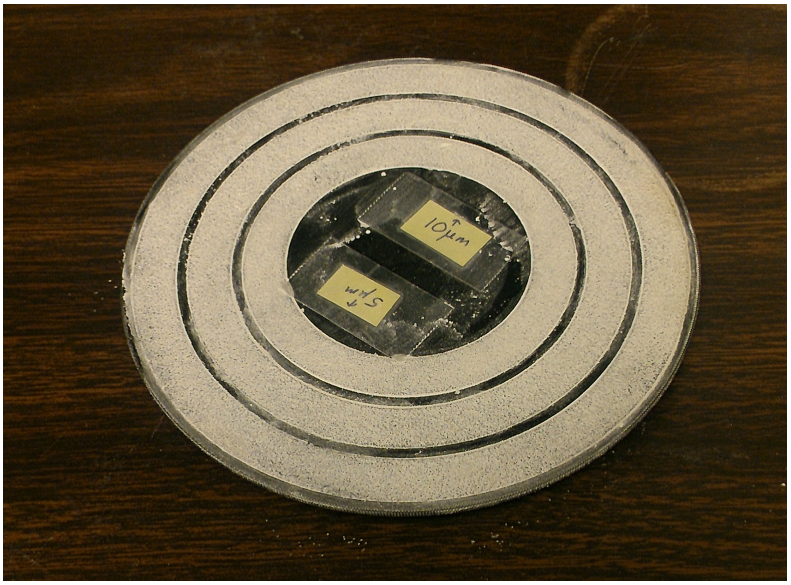


Fig. 1.10: SSPD turntable used to add particles into the system.

Vibrating Orifice Aerosol Generator Model 3450

The VOAG was used to generate particles in the laboratory samples as well, see Figure 1.11. According to the Operations and Service Manual the aerosol generator is based on the instability and break up of a cylindrical liquid jet. These droplets tend to break up in non-uniform ways. However, by periodically applying a disturbance at an appropriate acoustic frequency uniform droplets can be formed. A volume can be precisely calculated from both the acoustic frequency of disturbance and feed rate of the liquid [14]. By using various concentrations with specific sizes, various distributions can be created.

To use the VOAG, one must first determine the desired particle size, then use the corresponding tables for frequency and orifice diameters settings. Once the liquid solution is prepared, made by mixing isopropyl alcohol and olive oil in suggested ratios, is prepared and the orifice is clean, the solution is placed in a syringe and attached to the syringe pump. The syringe pump is then started and the liquid jet flow should become visible. When the liquid jet has stabilized, usually after five minutes, the signal generator can be set to the proper operating frequency. After the VOAG is set to the correct frequency, the aerosol neutralizer is installed and can then be connected to the plenum system. Adjustments can be made as needed after the system is going [14].

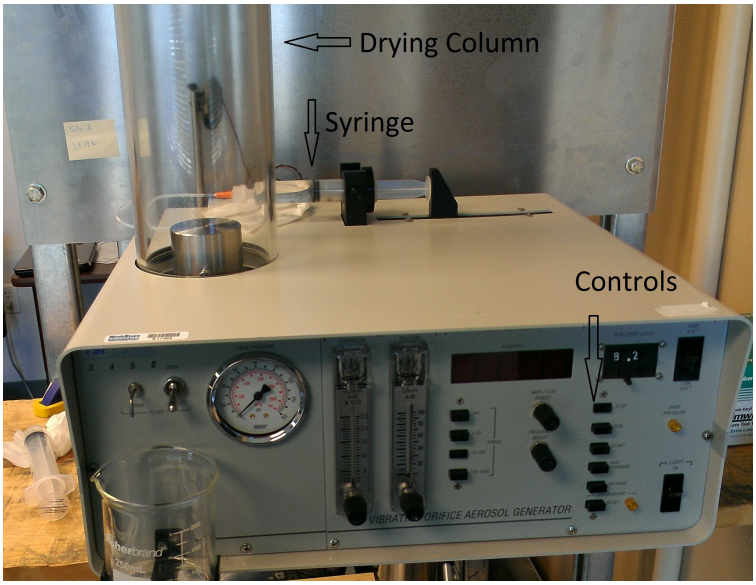


Fig. 1.11: Vibrating Orifice Aerosol Generator (VOAG), TSI Inc.

1.4.3 Plenum

The plenum is a vertical sampling chamber that a set of particles are dispersed into and then sampled downstream in the chamber. It was made from stainless steel tubing and filtered to prevent outside particles from entering in the clean air supply and introduced particles from exiting the chamber. The design of this custom plenum was a significant portion of this project and will be further discussed in Chapter 2.

1.4.4 Ambient Measurements

Any ambient measurements needed were taken using out-of-doors. Samples were taken in accordance with specific methods as necessary. These measurements are used for any pre-calibrations needed for an instrument and as a validation of the calibration system.

1.5 Existing Instrumentation and Previous Comparative Studies

Particle mass concentration is the most commonly desired measurement of aerosols; however, particle size, including size distributions, and shape can provide additional information. Aerosol sampling systems generally contain a sample inlet, a pumping system, and a sample storage volume to fulfill any additional sampling needs. They are also designed to

record a representative sample of the aerosols in the original environment [11]. A key aspect to aerosol sampling is ensuring the sample is not collected in a biased manner. This generally requires isokinetic sampling. This concern was discussed in greater detail in Section 1.3. Particles can generally be classified by to two diameter types, d_a and d_g. A way to determine physical diameters is using light scattering technology, which categorizes based on size, refractive index, and shape. Particle sizing based on this principle has been used for over 50 years with technology continually being developed to improve the system [11].

There are many commercially available instruments that measure PM. Some instruments that characterize the d_a of particles use inertial separation, such as impactors or cyclones. Common examples include the Andersen RAAS Filter Sampler and time-of-flight systems like the Aerodynamic Particle Sizer (APS) by TSI Inc. Systems that characterize the d_g include samplers like the Portable Aerosol Spectrometer by Grimm and Aerosol Profilers by Met One Instruments Inc., which are also referred to as optical particle counters (OPCs), and Airborne Particle Counters by TSI Inc.

A study of the Grimm 1.108 and 1.109 Portable Aerosol Spectrometers (Grimm) and the TSI 3321 APS was performed by Peters, et al. [15]. Their objective was to compare the performances of the Grimms and APS, which were evaluated in both sizing and counting for monodisperse, meaning single-sized aerosols, and polydisperse solid aerosols.The APS has been shown capable of accurately sizing and has high counting efficiencies (85-100%) for solid particles between 0.8 and 10 μm [16]. Therefore, it was concluded that the APS could be used as a reference to evaluate other real-time instruments performances.

Peter et al. would introduce aerosols into a 1 m^3 vertical flow, clean air chamber with a 6 in box fan. They maintained a flow rate throughout the chamber below 0.19 m^3/min, which is considered very slow moving air. The three instruments were placed in the center of the chamber on the same sampling plane. Aerosols were added via a nebulizer operated at 10 psig. The monodisperse tests were conducted with three sizes of fluorescently tagged, green PSL beads at 0.83, 1, and 3 μm and again with white PSL beads at 1 μm. The polydisperse tests were done with Arizona test dust (ISO Medium, 12103-1, A3). The

system was operated to maintain total particle number concentrations between 500 and 1,000 particles/cm^3. The instruments were set to report a size distribution every 6 seconds for a total of 10 minutes.

Peter et al. found across all instruments that the 1 μm PSL beads were actually slightly smaller (0.9 μm) than the manufacturer-reported diameters, but measured the same across the different instruments. The other PSL sizes were measured smaller with the Grimm instruments (0.68 and 2.5 μm) than with the APS (0.78 and 2.8 μm) and, therefore, further from the manufacturer-reported diameter (0.83 and 3.0 μm). The Grimm 1.109 and the APS both had increased size resolutions which helped them distinguish the 0.83 μm from the 1 μm beads. The Grimm 1.109 measured larger number concentrations that both the 1.108 and the APS.

With the polydisperse samples, both of the Grimm instruments found number concentration measured substantially less than that measured with the APS for particles between 0.7 and 2 μm. Conversely, the number concentrations measured by the Grimms were greater than the number concentrations found by the APS for particles larger than 2.5 μm. Furthermore, Grimms mass concentration distributions (total concentration by mass 1.98 $\pm$ 0.56 mg/$m^3$and 1.35 $\pm$ 0.40 mg/m^3) were shifted to slightly larger sizes than the APS (0.99 $\pm$ 0.26 mg/m^3). The Grimms were capable of detecting smaller particles than the APS, showing more accurate concentrations between 0.3 and 0.7 μm [15].

Another study compared the Grimm 1.109 and a Palas Model WELAS 2100 to a custom optical particle counter using an efficient multimodal calibration method; this study was performed by Heim, et al. [17]. Their objective was to show that they had an efficient multimodal calibration procedure that could be tested on multiple OPCs. The Palas WELAS 2100 is an optical system using side scattering. It has a T-shaped cross-section designed to eliminate false signals and are are designed to be portable systems.

The Heim, et al. method performed common calibration using monodisperse PSL beads as well as the multimodal calibration procedure. The multimodal procedure was to generate several monodisperse droplets of different sizes using a collision nebulizer followed by

neutralization in a bipolar Krypton-85 (Kr^{85}) charger. The Kr^{85} neutralizer emits beta radiation to generate positive and negative ions through ionization and provides a reproducible equilibrium charge distribution. This would create up to eight well-defined peaks across the spectrum. Each system was calibrated using single size PSL beads before using the multimodal calibration.

The Grimm's sizing accuracy decreased around 0.8 μm up to approximately 2 μm, but this was "probably due to the occurrence of the said undulations in the calibration curve." The WELAS had high degree of accuracy in the measured range up to about 1 μm. The WELAS results corresponded to the theoretical response of the calibration curve. The WELAS had a greater than 100% counting efficiency for all particles larger than 0.5 μm. The Grimm had a greater than 90% counting efficiency for all sizes greater than 0.25 μm. The multimodal method was found the be superior to the PSL calibration. The Grimm was not able to resolve more than a maximum of three peaks, but still responded well to the multimodal method. The calibration curves for both methods were obtained. The Grimm was found to have a lower limit of 0.305 μm but to have an efficiency within 10% of an ideal 100% [17].

1.6 Engineering Significance

It has been shown that PM in the air can be a hazard to one's health. When the Clean Air Act set standards, it was to protect human health and the environment. "Particulate pollutants and ground-level ozone are the most widespread health threats" [18]. By developing innovative ways to improve measurements of particulate, it will provide more opportunities to improve the air quality.

The design, testing, and validation of a plenum system that delivers uniform particle loadings and flow across the sampling plane, as well as isokinetic sampling ports, assists in further development of measurement techniques. This verified system allows for comparison and calibration checks between instruments of the same type, e.g. OPC, both within and between their make or model. It also allows for comparisons and correlations between systems measuring different particle properties, e.g. d_g or d_a.

Chapter 2

Plenum Design

The plenum is a vertical sampling chamber into which a homogenized set of particles are dispersed into and then sampled by multiple instruments downstream in the chamber. It is made from stainless steel tubing and is filtered to control outside particles from entering the system with High-Efficiency Particulate Air (HEPA) filters. Particles are dispersed into the system near the top and pulled downward with a vacuum pump.

At the sampling site, the instruments remove their required flow rates through use of isokinetic nozzles. These nozzles ensure the inlet velocities match the system velocity and are designed for the specific instruments based on their flow rate requirements. The nozzles are made out of 6061 aluminum and have a smooth internal transition from the nozzle to the sampling tubing.

At the bottom of the plenum is an exhaust filter assembly and vacuum pump. The filter eliminates particles from entering the pumping system and the local ambient air. The system flow rate is controlled by a variable speed vacuum system. For a simple drawing of the plenum, see Figure 2.1. The complete set of all drawings, including all purchased parts, for the plenum can be found in Appendix A.1

2.1 Sizing of Plenum

Before determining the materials used for the sampling chamber, the size and shape were determined. It was desired that no more than ten percent of the Q_0 in the system be removed for sampling. It was also desired that the system be large enough to fit four different sampling tubes without interfering with one another. Known instrument Q_S for the APS, Grimm, and MetOne OPC were 1 L/min, 1.2 L/min, and 1 L/min, respectively. (The 4 L/min sheath air flow for the APS was pulled from the room air rather than from

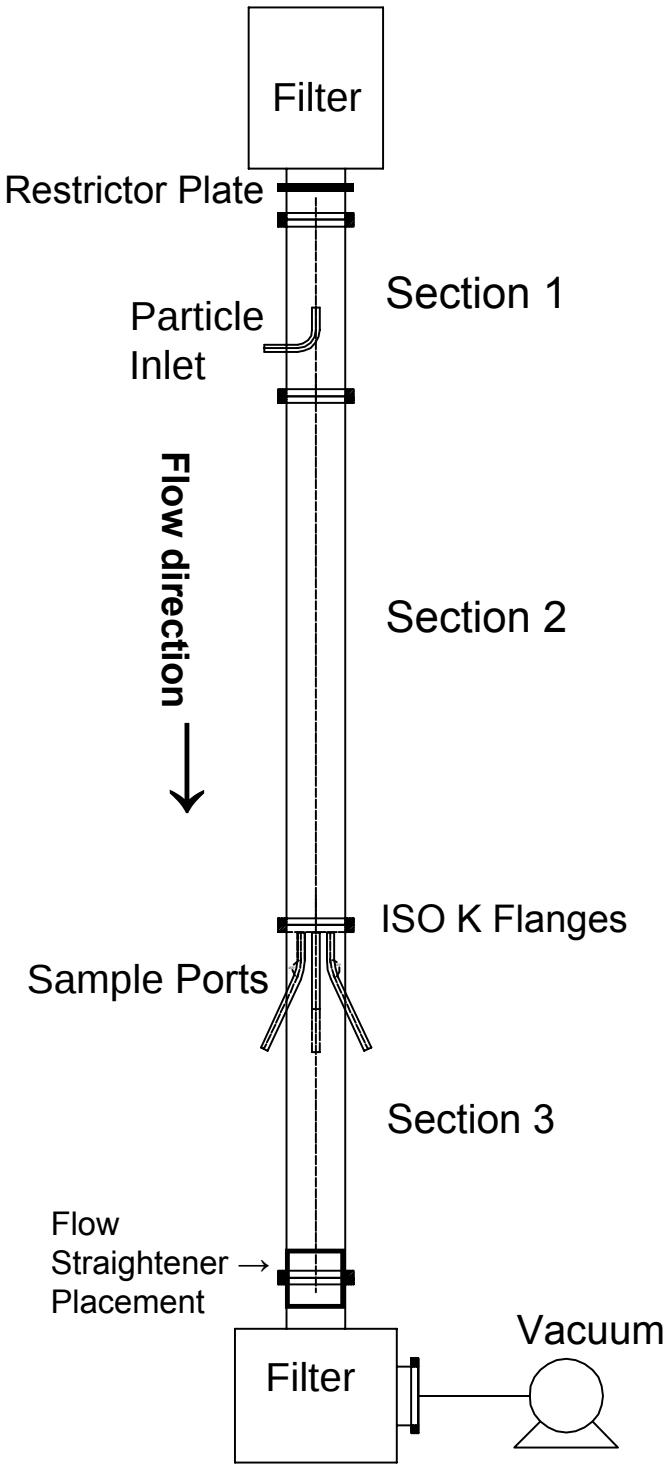


Fig. 2.1: Basic drawing of the plenum system.

Table 2.1: Required plenum diameter sizing based on flow rates of various instruments.

Plenum Diameter (in)	Plenum Velocity (m/s)	Reynolds Number	APS Required Nozzle D_S (in) (Q_S= 1 L/min)	Grimm Required Nozzle D_S (in) (Q_S= 1.2 L/min)	MetOne OPC Required Nozzle D_S (in) (Q_S= 1 L/min)	Other Required Nozzle D_S (in) (Q_S= 5 L/min)
3	0.37	1856	0.30	0.33	0.30	0.67
3.5	0.27	1591	0.35	0.38	0.35	0.78
3.83	0.22	1454	0.38	0.42	0.38	0.86
4	0.21	1392	0.40	0.44	0.40	0.89
4.5	0.16	1237	0.45	0.49	0.45	1.01
5	0.13	1114	0.50	0.55	0.50	1.12
5.5	0.11	1012	0.55	0.60	0.55	1.23
6	0.09	928	0.60	0.66	0.60	1.34
6.5	0.08	857	0.65	0.71	0.65	1.45

the plenum.) Having the ability to sample up to 5 L/min for any unknown instrument was preferred. Due to these restrictions, it was desired that Q_0 be at a minimum 90 L/min; therefore, 100 L/min was chosen as the design Q_0.

Using the desired 100 L/min flow rate for the plenum and the known flow rates of the various instruments, Equation 1.1 was used to determine the size of the system. Table 2.1 shows the plenum diameter in inches, the corresponding velocity with a 100 L/min flow rate, the Reynolds number (Re), and the corresponding isokinetic sampling diameters for each instrument. A Reynolds number of Re$<$2000 is required for laminar flow [12]. While all sizes meet the requirements for Re, the 4 in diameter size was selected due to its reasonable size and availability.

Requirements set for the internal surfaces of the plenum, the portions in contact with the system flow, were that it be smooth, non-corrosive and nonreactive. Also, according to Method 201A, found in Title 40 of the U.S. Code of Federal Regulations Part 60 (40 CFR 60), for determining PM_{10} and $PM_{2.5}$ emissions from stationary sources, it is required that 316 stainless steel or fluoropolymer-coated sizing devices and nozzles be used [19]. Therefore, it was decided that seamless, stainless steel tubing would provide the smooth surface and would limit any reactions that might occur. Because a 4 in diameter pipe does not actually

have an inside diameter of 4 in, the corresponding 3.83 in was also included in the table to make sure that it still provided all the necessary requirements.

Stack sampling Method 1 [20] was used as a guideline for the length of the system and where sampling ports and injection sites should be placed. According to this method, samplings sites should be located at least eight diameters (D_0) downstream and two diameters upstream from any flow disturbances to provide sufficient space for fully developed laminar flow. This meant that the plenum's sampling site needed to be at least 8 in above the pumping system and a minimum of 32 in spacing between the injection site and the sampling site [20]. This provided the length requirements of the system.

To provide access to each portion of the plenum, it is separated into three sections, excluding filters and pumping system. These sections are able to seal together without leaking with o-rings and clamps. ISO K flanges were attached to each section of the tube to provide this sealing.

The first section is the top portion and contains the aerosol injection point. This section is 12 in long to provide sufficient space for the injection site. The injection point is a 0.5 in stainless steel tube welded through the system wall and directed upstream. A drawing of this section can be seen in Figure 2.2. As shown in this drawing, the injection port is located halfway down the pipe. This is designed to inject the particulates against the flow, enhancing disperse over the system's cross-section. A finished prototype of the injection point can be seen in Figure 2.3; it should be noted that a flow throttle is shown in this picture, which will be further discussed in Section 3.1. If a larger sized pipe was chosen, this section needs to remain long enough to add the injection site.

The second section of the plenum provides uninterrupted flow to allow the establishment of laminar flow. This section is 36 in long and has smooth transitions between both the first section and the third section. This section exceeds the minimum 32 in length. A drawing of this section can be seen as part of Figure 2.1; no further details are shown in a drawing for this section alone.

The third, and final, section of the plenum includes the sampling ports. This section

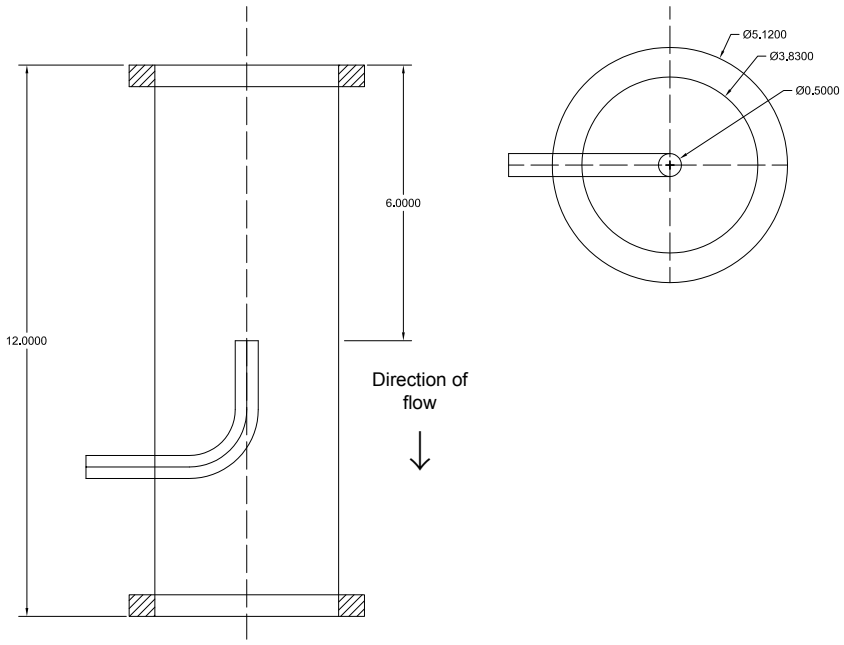


Fig. 2.2: Drawing of the injection site of the plenum.

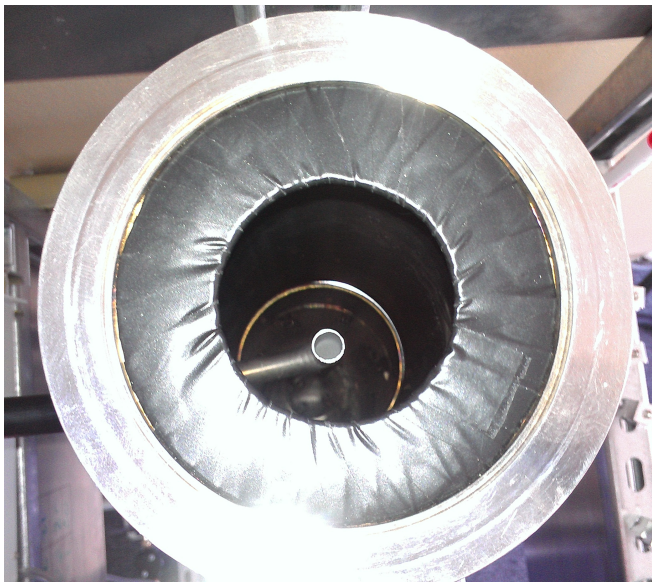


Fig. 2.3: Picture of prototype injection port with flow throttle attached from above.

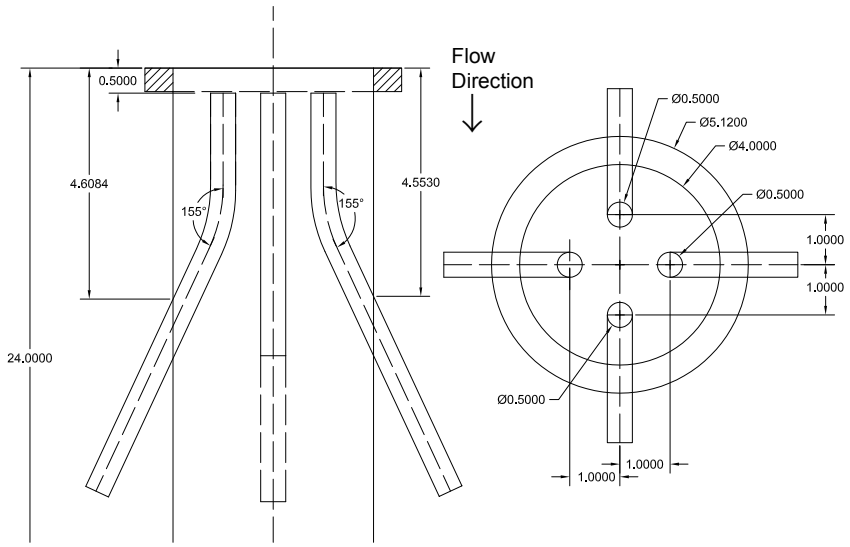


Fig. 2.4: Drawing of the sampling ports in the plenum.

is 24 in long and contains four 0.5 in thin walled, stainless steel tubes for the sampling ports. Each sampling port is placed one inch inward from the side wall and one inch apart from any other tube. The tops of the sampling ports are located 0.5 in down into the pipe. This is to allow the nozzles to be placed on top of the sampling ports and have the sampling plane above the flanged section of the pipe. The design of the nozzles will be further explained in Section 2.3. The angle of curvature of the sampling ports is $< 30^{\circ}$ to meet the sampling probe requirements in Method 5 to minimize particle loss due to settling and inertia [21]. This section also provides the two system diameter lengths (8 in) after the sampling plane before significant flow disruptions. The sampling tubes exit the plenum tube $<$8 in downstream, but the effect on the laminar flow is assumed to be negligible [20]. Since there is plenty of space available, this section could actually be reduced to 15-18 in, however if a larger diameter pipe was used, it would need to have enough space to meet the two diameter requirement. Figure 2.4 shows the drawing of the sampling ports in the pipe as described and Figure 2.5 shows the actual prototype from above with the flow conditioner inserted at the bottom, which will be explained in Section 3.1.

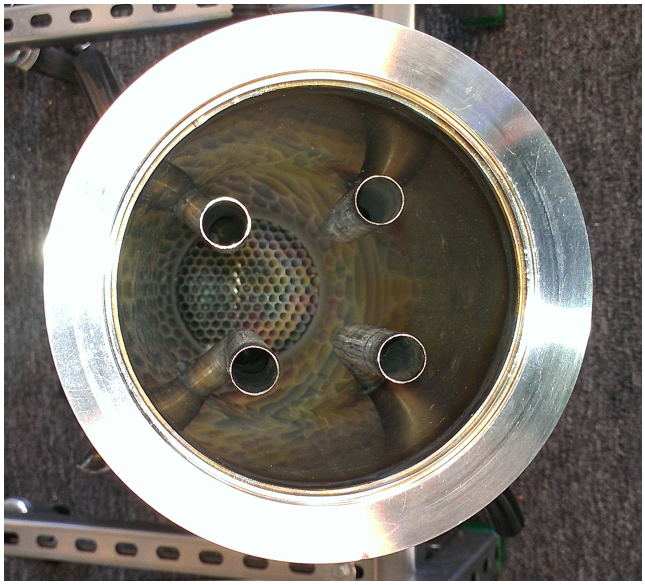


Fig. 2.5: Image of the sampling ports in the plenum looking down with view of flow conditioner at bottom.

2.2 Filters

HEPA filters were placed on both ends of the plenum to ensure that the system had clean supply air and did not expel test particles into the laboratory air. Use of HEPA filters ensured that 99.9% of particles down to 0.3 μm were removed.

The filter assembly located on the top of the system is designed to provide clean air to the system. This assembly is an off-the-shelf filter. It was necessary to adapt the flange of the filter assembly to the ISO flanges of the plenum. The original flange was removed and a flange adapter was welded to the filter. A drawing of this custom flange can be seen in Figure 2.6; this flange was made out of mild steel. Figure 2.7 shows the completed filter with the new flange attached.

A filter was installed downstream of the sample section and before the main pump. The filter was needed to make sure the pumping system was not exposed to excessive particulates. An off the shelf filter housing from the Kurt J. Lesker Company was chosen. This filter and housing can be seen in Figure 2.8.

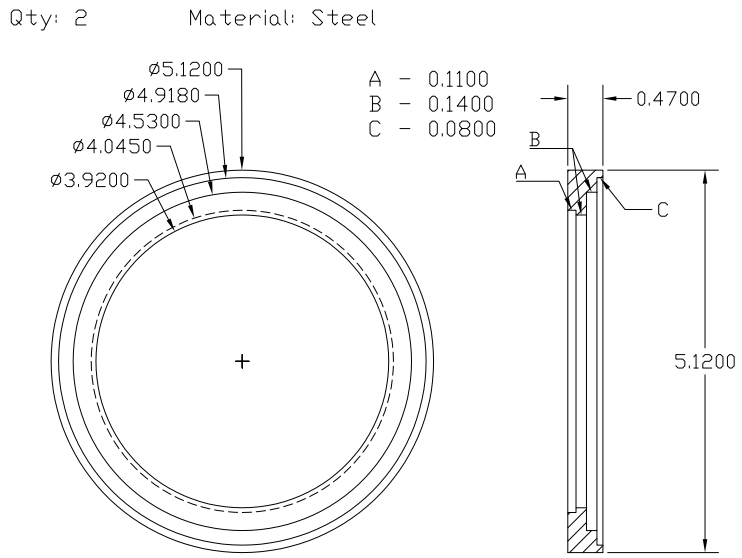


Fig. 2.6: Flange to convert top filter to connect seamlessly to pipe.

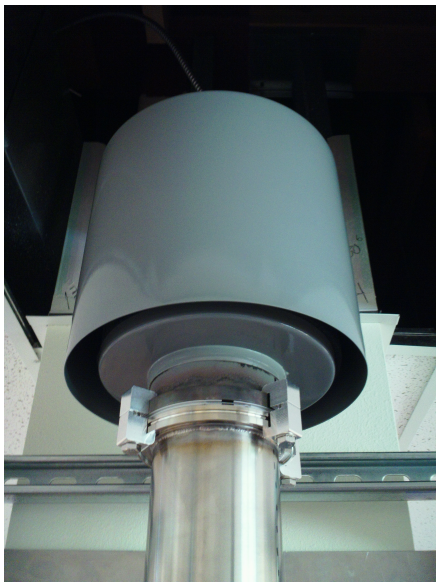


Fig. 2.7: A picture of the top filter with new flange as attached to the plenum.

Fig. 2.8: Bottom filter that connects seamlessly to pipe.

2.3 Nozzle Design

The nozzles were designed to achieve isokinetic sampling, as discussed in Sections 1.3 and 2.1. Since each instrument had a different flow rate, the nozzles were designed specifically for each flow rate. Using the D_S sizes for the 3.83 in plenum diameter, as seen in Table 2.1, nozzles were designed to fit onto the 0.5 in diameter sampling ports in the third section of the plenum. Nozzles were designed and built for four flow rates (0.9, 1.0, 1.2, and 5.0 L/min) and one blank. Examples of these machined nozzles are seen in Figure 2.9.

The following figures are the basic design drawings; larger, more complete drawings are available in Appendix A.1. All the nozzles were designed with a groove in the bottom internal section for a 014 o-ring to ensure a snug fit on the tubing. The o-ring fittings were designed using the Parker O-ring Handbook [22]. The nozzles have sharp, clean edges at the mouth for isokinetic sampling as well as a slight taper to provide smooth transitions to the 0.5 in sampling tube. Aluminum 6061 was used to build the nozzles because it was easily machinable and available. Figure 2.10 shows the nozzle design for an instrument with a flow rate of 1.0 L/min (0.383 in D_S) which was used for the APS as well as two MetOne OPCs. The other nozzles for flow rates 0.9 and 1.2 L/min (0.363 and 0.42 in D_S), respectively, are designed in a similar fashion to the 1.0 L/min nozzle.

Fig. 2.9: Plenum nozzles for various flow rates.

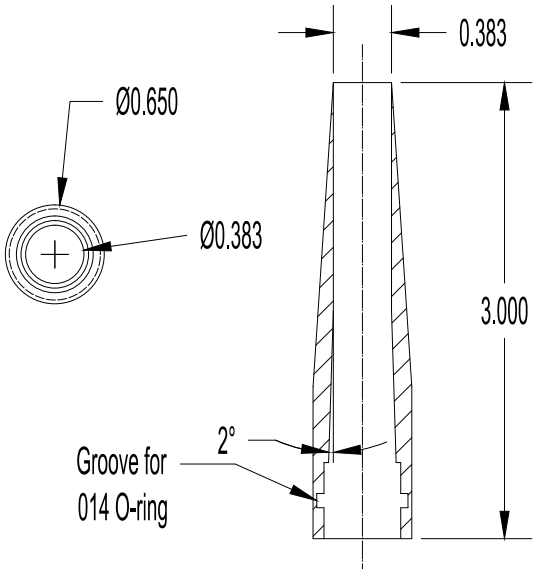


Fig. 2.10: Plenum nozzles for 1.0 L/min flow rate instruments, APS and MetOne OPC. All units are in inches.

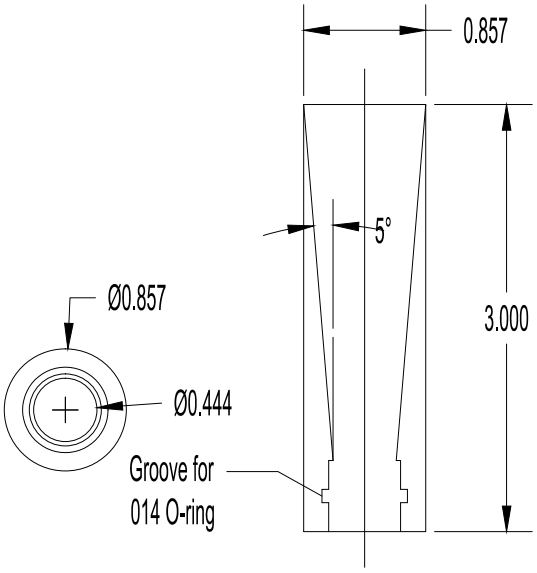


Fig. 2.11: Plenum nozzles for 5 L/min flow rate. All units are in inches.

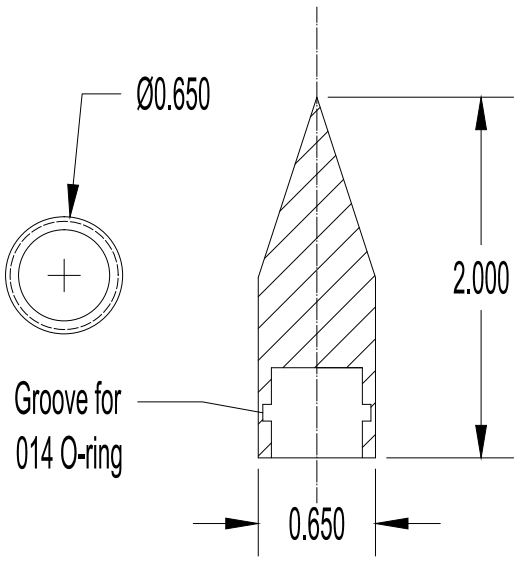


Fig. 2.12: Blank plenum nozzles. All units are in inches.

Fig. 2.13: Shop vacuum used as the pump for the plenum.

Figure 2.11 shows the isokinetic nozzle for a Q_S of 5 L/min; however, a larger body diameter is required for the mouth of the nozzle (0.857 in) than for Q_S ~1.2 L/min. The interior channel narrows down to fit onto the sampling tube (0.5 in). Designing all isokinetic nozzles to fit on the 0.5 in tube provides the ability to place any nozzle on any sampling port. Figure 2.12 is a blank nozzle that has a sharp end and is one inch shorter than the other nozzles. This nozzle is designed to close off a sampling port without effecting the flow. This provides the ability to sample without using all four ports.

2.4 Vacuum System

While any system that can provide a flow rate of 100 L/min could be used with this system, it was desirable to use an option that was readily available. One such system was a small shop vacuum (Shop-Vac Bucket Max). This vacuum provided the right magnitude of velocity through the system with only minor adjustments. This vacuum can be seen in Figure 2.13.

One of the minor adjustments made to the system was to restrict the flow coming through the vacuum. This was done using a cardboard disk with a centered, 1/4 in diameter hole to cover the vacuum's hose inlet, acting as a throttle. Figure 2.14 shows the cardboard

Fig. 2.14: Cardboard throttle plate to restrict the flow on the vacuum system.

throttle.

The other minor adjustment made to the system was to connect it to a variable transformer. Therefore, the user is able to adjust the voltage going to the system, which directly relates to vacuum flow. Adjusting the power going to the vacuum allows the user to modify the Q_0 according to their needs without needing different vacuum systems.

2.5 Structural Support

The system was mounted vertically. The prototype was mounted using 1-5/8 in steel strut channels (uni-strut) and parallel strut-mount clamps. Due to the weight of the system, it is beneficial to have either a wall for support or extra weight at the base to ensure the system does not tip over when heavy components are attached. It is also recommended that metal plates be used to provide support for the frame. An image of the free standing structure, with very few components added, can be seen in Figure 2.15. The support structure has wheels attached at the base to provide mobility, but the final mounting with all components is supported via a wall brace.

Each instrument was mounted to the structural support through various means. The particle generators have their own shelf mounted to the sides of the structural support

system. The SSPD's shelf is 18 in by 24 in with steel strut channels providing the support and a metal plate across the top. The SSPD is mounted approximately 66 in from the ground. The VOAG's shelf is built like the SSPD's, but mounted approximately 42 in from the ground. The MetOne OPCs were either mounted or placed on the ground next to the structure; when mounted, they were mounted on a 1-1/2 in pipe located 24 in above the ground via strut channels and strut-mounts. An additional shelf was mounted across the strut channel, in front of the plenum pipe, for the Grimm and APS to sit.

The major components of the system are described in the previous sections and, when combined with the structural support, form a functional plenum system. For a view of the completed plenum, see Figure 2.16. The total height of the structure with the plenum and filters installed is 8-1/2 ft. The footprint of the structural support is 24 in X 28 in X 96 in, without the shelves. With all the shelves, mounting pipes, and complete plenum attached, the overall footprint is 72 in X 28 in X 105 in. The structural support weighs approximately 75 - 100 lb, depending on how many shelves are installed.

Fig. 2.15: Structural support for the calibration system.

Fig. 2.16: Complete assembled calibration system.

Chapter 3

System Validation

The calibration system was evaluated to determine if it provided a controlled, uniform, unbiased measurement environment. This evaluation involved characterizing the flow, checking the particle dispersion, and demonstrating that samples could be collected.

3.1 Flow Evaluation

A hot wire anemometer was used to evaluate the flow through the system. This device was small enough to not disrupt the flow in the system. A hot wire anemometer by Kanomax with a straight probe 0.24 in diameter and a range of 0.01 to 20.0 m/s was used, Figure 3.1.

Since the hot wire anemometer required access to the inside of the plenum, holes just large enough for the anemometer (0.242 in) were drilled into the second and third sections of the system. The holes were drilled at three locations on the second tube section, as seen in Figure 3.2: just above the sampling site, middle of the second section, and near the top of the second section. These locations were 15 in vertically apart. Each location had two holes perpendicular to each other to allow for cross evaluations of flow. A fourth location, just above the bottom filter was also used to evaluate the flow. Each location also had a small cork stopper to plug the hole when not being used for flow evaluation. At each site, measurements were taken at five different transverse locations between 1 in inside the plenum to 3 in, increasing in 0.5 in increments. Figure 3.2 shows the measurement grid for the flow measurements.

3.1.1 Initial Conditions

The original set up in the plenum system had no flow conditioners applied; the system had all the components put together including the two filters in place, there were no nozzles

Fig. 3.1: Hot wire anemometer by Kanomax.

Table 3.1: Average measurements of the initial flow in the plenum.

Location/Distance	1	2	3	4	5	6
1 in	0.16	0.16	0.06	0.18	0.09	0.20
1.5 in	0.17	0.23	0.16	0.22	0.15	0.26
2 in	0.21	0.21	0.20	0.23	0.20	0.23
2.5 in	0.21	0.21	0.23	0.22	0.24	0.27
3 in	0.24	0.20	0.26	0.25	0.27	0.27
Average	0.20	0.20	0.18	0.22	0.19	0.25
Standard Deviation	0.03	0.02	0.08	0.02	0.07	0.03

on the sampling ports but all the external 0.5 in tube ends were plugged with rubber stoppers. When the flow measurement ports were not in use, they were plugged with a cork stopper. The vacuum was turned on and allowed a few minutes for flow stabilization, then the vacuum speed was adjusted to obtain a 0.22 m/s velocity at intersection of flow ports 5 and 6. Triplicate flow measurements were recorded for each location with the anemometer and the averages can be seen in Table 3.1.

Contour maps of the flow pattern at each test height were calculated using the kriging interpolation. Common across all the plots in Figure 3.3, there is a velocity gradient across the plenum. Of particular concern were locations 5 and 6; with a step change across the profile. This flow profile would cause PM to distribute unevenly throughout the plenum and

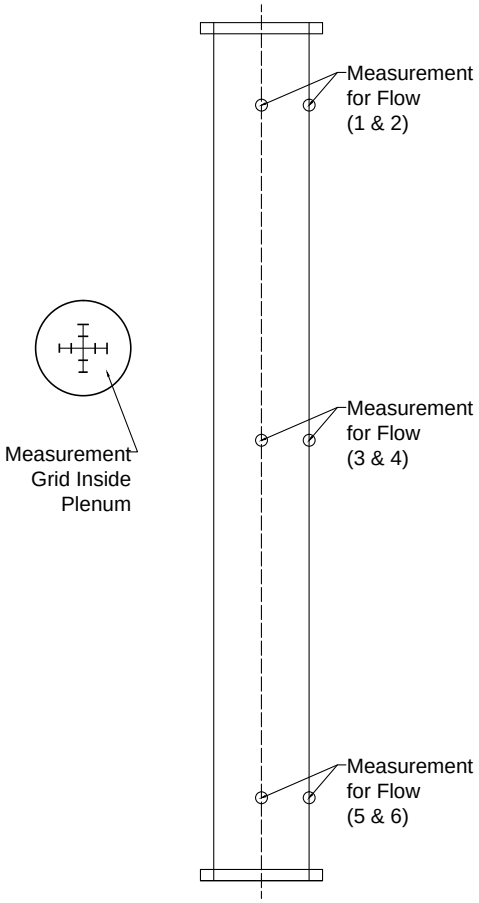
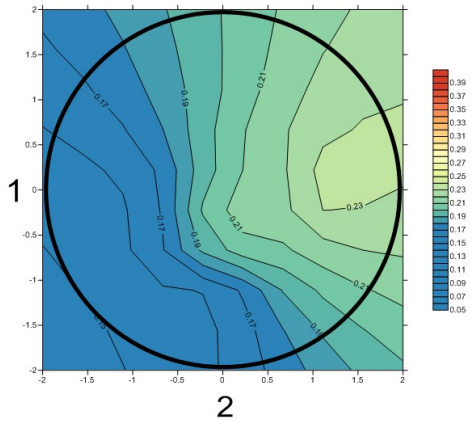
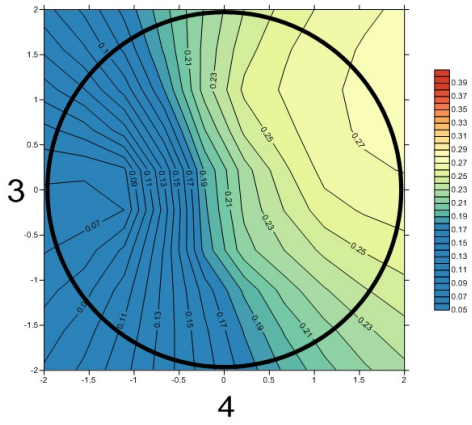


Fig. 3.2: Measurement locations and measurement grid on section 2 of the plenum.

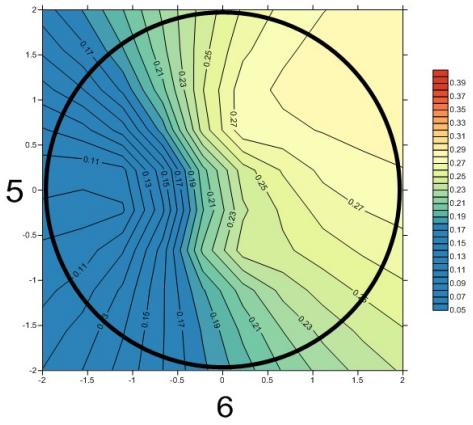
cause measurement bias based on location.



(a) Location 1 and 2 contour flows.



(b) Location 3 and 4 contour flows.



(c) Location 5 and 6 contour flows.

Fig. 3.3: Conditions of flow inside plenum at initial testing.

3.1.2 Flow Solutions Investigation

A flow conditioner was used to smooth out the air flow. The purpose of the flow conditioner was to provide the optimum flow pattern within the plenum through use of flow straightener and/or flow throttle plates. After a few initial tests, it was determined that a flow throttle at the top of the system would aid in the flow conditioning. The flow throttle design was an annular restricting plate, or choke, made of corrugated cardboard wrapped in

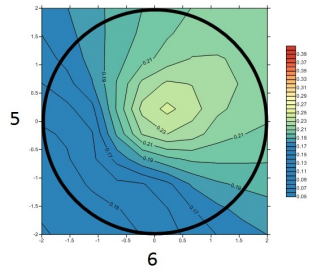
Table 3.2: Flow Conditioner Options Test.

Straw Length (in)	Location of Straw Pack	Throttle in place
7	Top	No
7	Bottom	Yes
7	Bottom	No
6	Top	Yes
6	Top	No
6	Bottom	Yes
6	Bottom	No
5	Top	Yes
5	Top	No
5	Bottom	Yes
5	Bottom	No
3	Top	Yes
3	Top	No
3	Bottom	Yes
3	Bottom	No

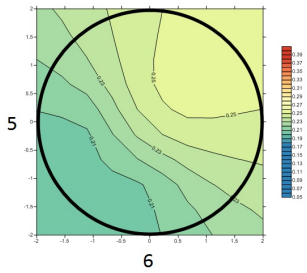
electrical tape for smooth edges. This would constrict the flow before entering the system. This piece was placed above the plenum directly below the top filter at the connection point between section 1 and the filter.

A flow straightener was constructed of Mainstays straws. It was built in a honeycomb fashion and fit tightly into the four inch diameter pipe at one of two locations. The top location was located in section 1 below the injection site and the bottom location was placed at the bottom of section 3 directly above the connection to the filter. Various straw lengths were tested to find the optimum length of straws. These lengths were in inches: 3, 5, 6, 7, 8.25. Table 3.2 shows the test matrix used for evaluation.

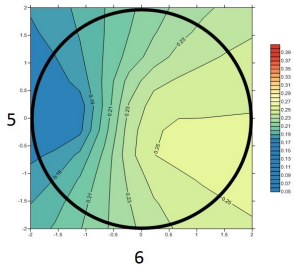
Each configuration was evaluated using the same method as for the initial conditions described above. The results were then compared to determine the five most effective methods for adjusting the flow. The top five methods were: 6 in straws at bottom with choke in, 5 in straws at top without choke, 5 in straws at bottom with choke in, 3 in straws at bottom with choke in and 3 in straws at top with choke in. These five methods were then reevaluated to determine the optimal solution.



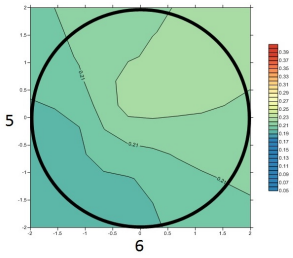
(a) 3 in straw length located at top with throttle plate.



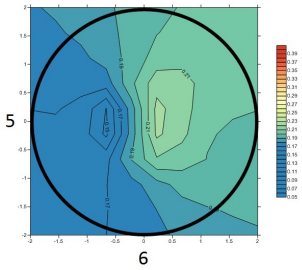
(b) 3 in straw length located at bottom with throttle plate.



(c) 5 in straw length located at top without throttle plate.



(d) 5 in straw length located at bottom with throttle plate.



(e) 6 in straw length located at bottom with throttle plate.

Fig. 3.4: Contour images of the flow inside of the plenum with the 5 top optimum flow conditioner treatments at locations 5 and 6.

3.1.3 Final Flow Evaluation

The three flow straightener lengths were recreated with new straws before the revaluation of the five most effective methods. For each method, measurements were taken in triplicate at the optimum velocity (0.22 m/s), as well as at half of that velocity and twice that velocity. The results of these tests were evaluated statistically and can be seen in Appendix A.2. The average values for each trial were used to graph contour plots, as seen in Figure 3.4.

The most effective flow conditioner was the 5 in straw at the bottom of the system with the choke in place. The results from the data can be seen in Table 3.3 for sample ports 5

Table 3.3: Measurements from the flow conditioner of 5 in straws at bottom of the system with the 2 in choke located on the top. Also includes the statistical averages for each location and the standard deviation.

Locations	1 in	1.5 in	2 in	2.5 in	3 in
5	0.20	0.22	0.22	0.22	0.22
6	0.19	0.20	0.22	0.22	0.22
5	0.20	0.21	0.21	0.21	0.21
6	0.19	0.21	0.21	0.22	0.21
5	0.21	0.22	0.24	0.24	0.24
6	0.22	0.23	0.24	0.25	0.24
Average	0.20	0.22	0.22	0.23	0.22
Std. Dev.	0.012	0.01	0.014	0.015	0.014

(a) Measurements from the flow conditioner.

	Avg (site 5)	Std. Dev (site 5)	Avg (site 6)	Std. Dev (site 6)
1 in	0.20	0.006	0.20	0.017
1.5 in	0.22	0.006	0.21	0.015
2 in	0.22	0.015	0.22	0.015
2.5 in	0.22	0.015	0.23	0.017
3 in	0.22	0.015	0.22	0.015

(b) Statistical averages and standard deviations for each location.

and 6. The first table shows the measured results at all the transverse locations; the second table shows the average and standard deviation for all locations. The overall average of the system at the desired velocity (0.22 m/s) was 0.218 m/s with a standard deviation of 0.015. A larger contour image at location 5 and 6 for the optimum flow conditioner treatment can be seen in Figure 3.5. This is a vast improvement to the original flows inside of the plenum, see Figure 3.3. The flow rate was at the desired velocity and was more evenly distributed throughout the pipe cross section. The visual changes between the initial and final flow conditions show significant improvements. While this flow is not perfectly homogeneous, it is within acceptable variability for the system.

This final flow conditioner can be seen again in Figure 3.6. This was placed into the system at the bottom of the plenum and checked again for consistent results and became the standard implementation for the flow conditioner of the system. It should be noted that the flow rates can change from day to day and therefore must be checked before every

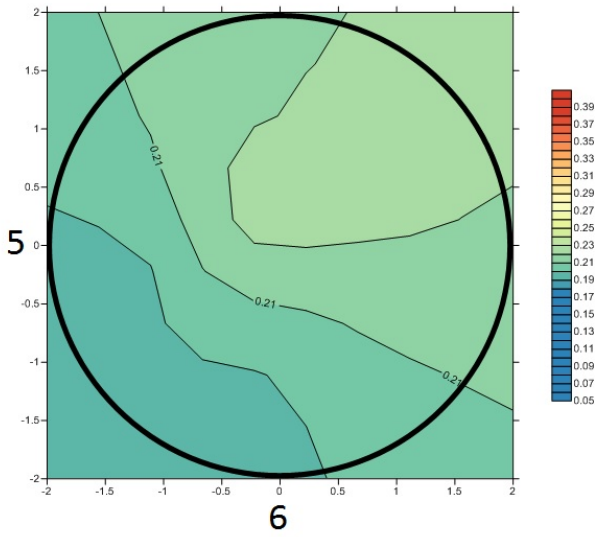


Fig. 3.5: Contour image of the flow inside of the plenum with the optimum flow conditioner treatment at locations 5 and 6.

experiment to ensure that the flow is reasonably within the desired rates.

3.2 Particulate Validation

Following validation of the flow field, particles were introduced to the system. To ensure that the particles were being dispersed evenly throughout the system, a method of determining the conditions inside of the plenum was needed. Four MetOne OPCs were used to validate the PM concentrations.

3.2.1 Particulate Validation Setup

Using MetOne OPCs on the plenum system required nozzles specific to each instrument; measurements have shown that the OPCs have variable, but consistent, flow rates. While the flows are stated as being 1.0 L/min, measured average flow rates deviate from 1.0 L/min by up to 20%. Therefore, knowing the flow rates of individual OPCs were critical. A Gilibrator Air Flow Calibrator was used to determine the flow rate for each of the MetOne OPCs. Each OPC was designated by site number using the index one through four. Table 3.4 shows the flow rate for each OPC, as well as nozzle size and how close it was to isokinetic

Fig. 3.6: Image of the final flow conditioner as placed in the system.

Table 3.4: Flow rates and nozzle sizes for each MetOne OPC instrument.

MetOne OPC	Average Flow Rate	Nozzle Size	Isokinetic Percentage
MetOne OPC 1	1.1537 L/min	1.2 L/min	3.86%
MetOne OPC 2	1.1095 L/min	1.2 L/min	7.54%
MetOne OPC 3	1.0798 L/min	1.0 L/min	7.98%
MetOne OPC 4	1.0196 L/min	1.0 L/min	1.96%

sampling. Nozzle dimensions were not always perfectly matched to the exact size for the flow rates, therefore it is important to confirm that each MetOne OPC was still within 10% of the isokinetic criteria [21]. All are within the ten percent.

The MetOne OPC instruments were connected to the system via 0.5 in diameter conductive silicone tubing. Each OPC had the same length of tubing and was placed in such a way that no section of tubing was bent beyond an angle of thirty degrees.

Sampling port were labeled A-D as shown in Figure 3.7. Nozzles with flow rates of 1.0 L/min were placed on ports A and B and nozzles with flow rates of 1.2 L/min were placed on ports C and D. For the ease of naming convention throughout the data, each MetOne OPC was named with their respective number (1-4), what port it was connected to, and at what degree the port was located with the wall being zero degrees and increasing clockwise, e.g. Site 1(D,45).

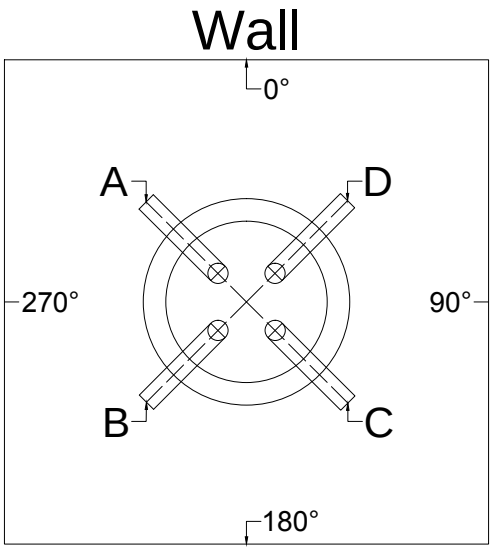


Fig. 3.7: Drawing of the sample ports, as labeled, in their initial locations.

Table 3.5: Measurement schedule for determining aerosol distribution across system.

	Port	Location	Flow Rate
Initial	A	315	1
90 deg turn	A	225	1
180 deg turn	A	135	1
210 deg turn	A	105	1
240 deg turn	A	75	1
270 deg turn	A	45	1

It was necessary to evaluate the aerosol distribution across the sampling ports, therefore a permutational (rotational) procedure was employed. A condensed table showing the location of Port A for all sampling locations can be seen in Table 3.5; a more complete list of the table can be seen in Appendix A.3.

The aerosol generator used to validate the particulate dispersion was the SSPD. The powder used was store purchased baby powder, which provided a polydisperse PM. The baby powder was placed in a fine layer across the turntable before being added to the system. The amount of PM introduced into the system varied every sampling period because the mass consistency on the turntable is hard to control.

3.2.2 Counting Correction Factor

Before any data was collected in the system, an ambient collocated sample was collected with all four MetOne OPCs to calculate a counting correction factor (CCF) [23]. They ran for approximately 23 hours with all system inlets at approximately the same location. The data was then checked for outliers using an EPA statistical method [24]. With regard to the CCFs, the cells in which an outlier was located were tossed out for the calculations (1.6% of the data set). The average particle number concentration from all of the MetOne OPCs were used to compare to each specific MetOne OPC. The data was then graphed and both linear and scalar equations were used to compute the CCF. Both methods were evaluated and it was determined that a linear fit provided a more accurate CCF for this data set. The CCFs for all the instruments can be seen in Table 3.6. It should be noted that MetOne OPC 2 does not record data for channel 8 and, therefore, the CCF is set to zero to ensure any misread data are not counted. Once the CCF was determined, any data recorded would then be adjusted for the CCF, as well as the flow rates because the recorded data assumed a flow rate of 1 L/min.

3.2.3 Results from MetOne OPC Validations

The results for all eight channels are presented in a log-normal distribution shown as D versus dN/dlogD graph, which is a typical visualization for aerosol data. The x-axis is the geometric mean diameter of the particles, this axis is also on a logarithmic scale. The y-axis is comprised of the particle concentration over the logarithmic difference of the upper and lower bounds of the each channel, respectively ($\#/m^3/\mu m$) [12].

The data are from single, twenty minute periods with stabilized particle generations, as shown by the OPC data. Due to the variable rate at which SSPD added PM to the plenum, it was difficult to compare each discrete experimental geometry. Therefore, the criteria of "uniformly distributed" was defined as only periods with stabilized particle generation, which were used to assess the well mixed and uniform condition within the plenum.

The resulting data from the initial setup, as described in Table 3.5, can be seen in Figure 3.8. The error bars are one standard deviation around the averages. The data showed similar

Table 3.6: Linear fit Counting Correction Factor for all four MetOne OPC instruments. (y=mx+b)

	MetOne1 m	MetOne1 b	MetOne2 m	MetOne2 b	MetOne3 m	MetOne3 b	MetOne4 m	MetOne4 b
Ch. 1	1.046	377.55	0.902	-344.19	1.0446	635.14	0.9744	2155.3
Ch. 2	1.0991	2.229	0.9689	100.38	1.1471	-73.714	0.807	257.44
Ch. 3	1.1028	17.723	1.2452	62.881	1.0268	-12.192	0.6912	92.247
Ch. 4	1.0256	24.382	1.2989	88.633	1.1073	7.4841	0.6055	36.451
Ch. 5	1.0468	12.75	1.1216	28.883	0.9057	2.6309	0.8235	-8.095
Ch. 6	1.0319	7.0423	1.0519	15.496	0.8287	-1.0806	0.9567	-0.9188
Ch. 7	1.0563	3.6214	0.9702	2.5178	0.829	0.893	0.8092	0.1182
Ch. 8	0.7741	1.0018	–[1]	–	0.6107	0.6737	0.7019	0.4507

[1]Site 2 does not record data for channel 8

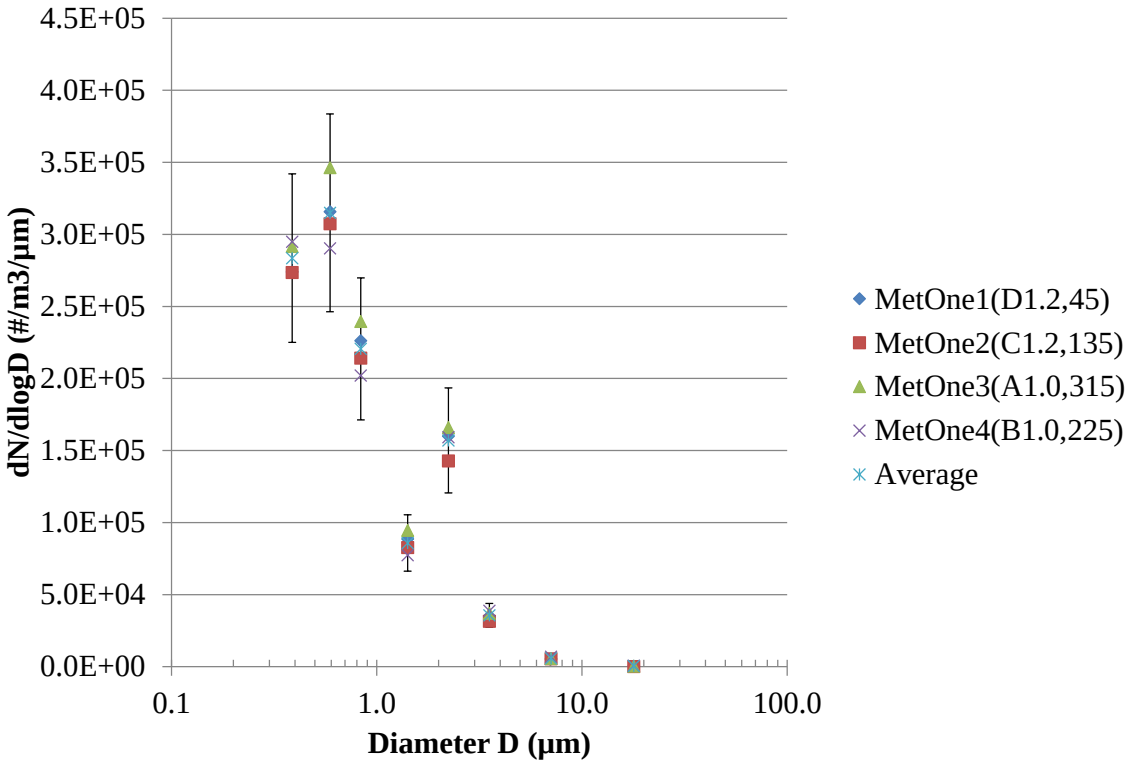


Fig. 3.8: Graph of dN/dlogD for a single measurement data set at the initial locations.

results between all OPC instruments but they have fairly large standard deviations at the smaller diameter PM.

After rotating section 3 of the plenum ninety degrees counter-clockwise, aerosols were again injected into the system and data recorded. The resulting measurements with one standard deviation error bars can be seen in Figure 3.9. Note the y-axis is scaled larger than the previous figure, an example of the inconsistent aerosol generation rate mentioned above. OPC 2 counts were lower than the other instruments, this was more noticeable at the 2.5 μm range. OPC 3 had higher counts than the others, specifically at 0.6 μm but at other diameters as well. One explanation could be that both OPC 2 and 3 were further away from isokinetic sampling than the other instruments, but still within the 10% range of sampling isokinetically; OPC 2 was close to sampling sub-isokinetically and OPC 3 was close to sampling super-isokinetically. This could have caused the instruments to collect less and more small particles than normal, respectively.

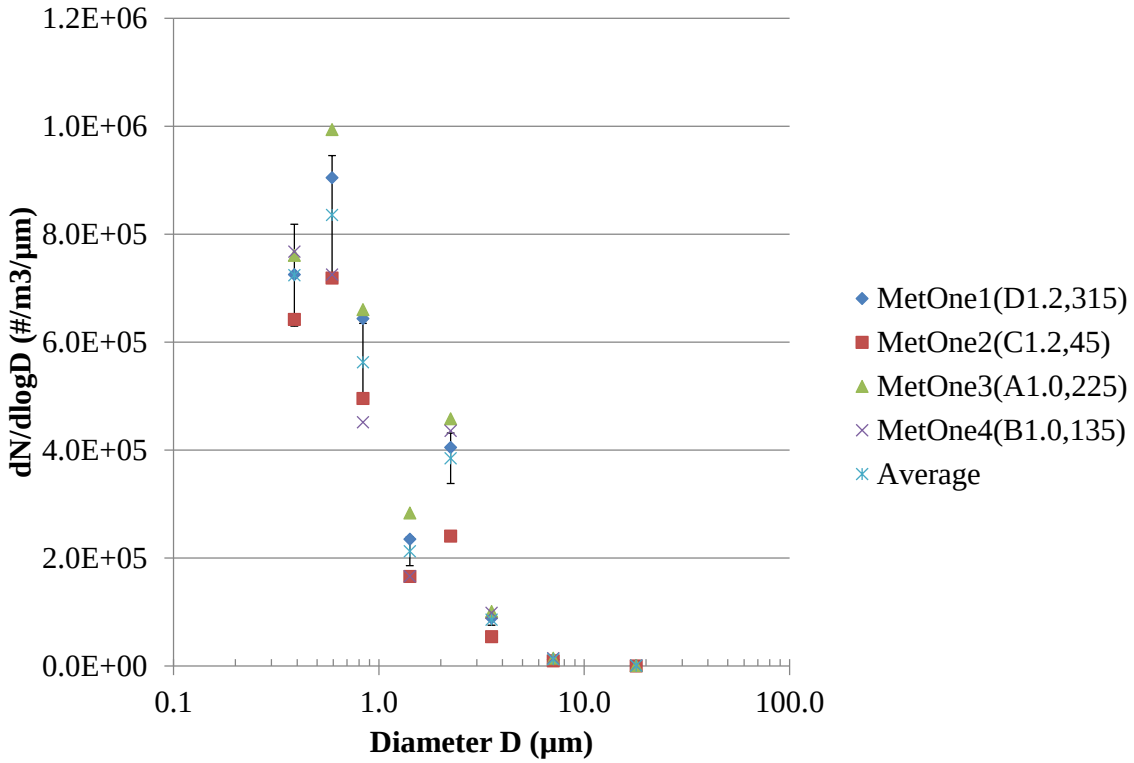


Fig. 3.9: Graph of dN/dlogD for a single measurement data set at 90 degree rotation.

The resulting data from the rotation of section 3 counter-clockwise 180 degrees can be seen in Figure 3.10. During this sampling period, OPC 1 and 2 traded sampling ports with one another, as well as OPC 3 and 4. In this configuration, OPC 2 was located 180 degrees from its location in the previous figure, Figure 3.9. Once again, OPC 2 had lower counts compared to those of the other OPCs, specifically at 2.5 μm. The similarities between these two figures seems to show consistencies within the instruments, independent of location.

Figure 3.12 shows the data from the final rotation, 270 degrees counter-clockwise from the initial location. While the instruments were located at same angle change as Figure 3.10, there were some differences between them. The 270 degree rotation data was very noisy comparatively, as seen in the large standard deviations. This noise was likely due to unsteady aerosol concentrations injected via the SSPD throughout the sampling period, which led to large spikes and drops in the data. These large spikes and drops can be seen in Figure 3.11.

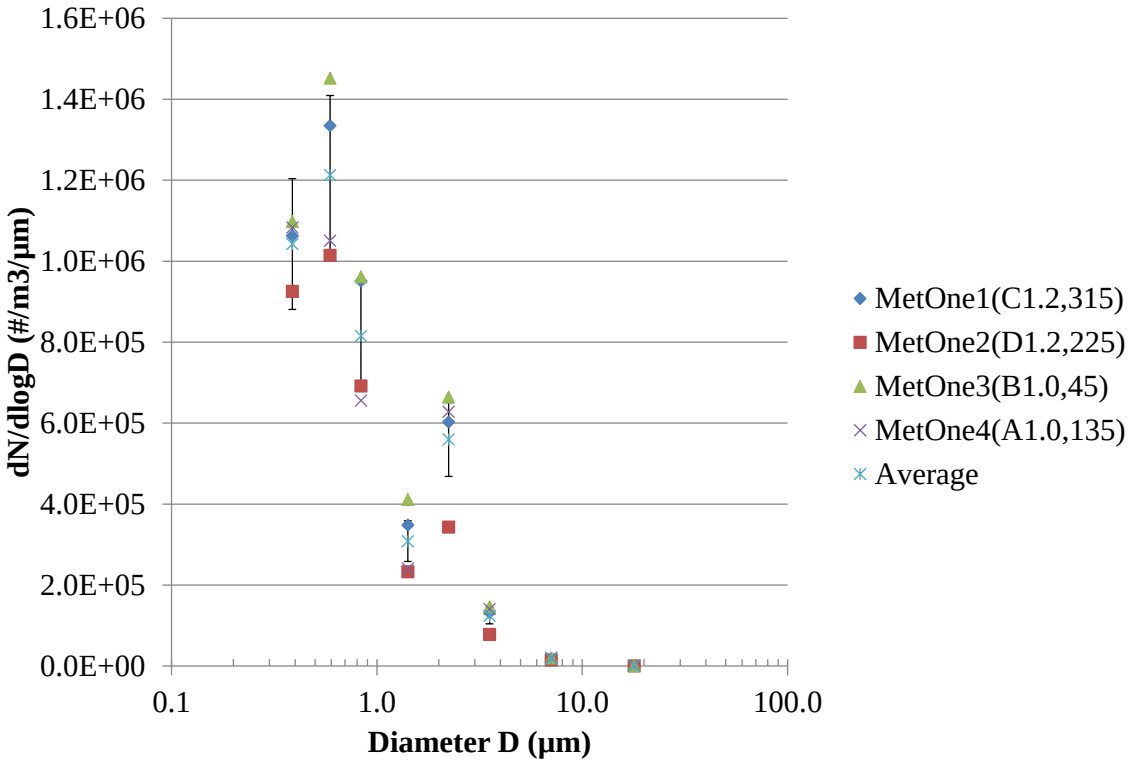


Fig. 3.10: Graph of dN/dlogD for a single measurement data set at 180 degree rotation.

The next two figures shown, Figures 3.13 and 3.14, are for rotations 210 and 240 degrees counter-clockwise, respectively. These rotations were performed to determine if there were any inconsistencies in between the typical locations of the sampling ports. Figure 3.13 had similar data trends as those previously mentioned, OPC 2 and 3 were lower and higher than the average, respectively. This continued to show that, regardless of location within the plenum, the instruments were consistent in their trends. Figure 3.14 had more variance within the data, leading to larger standard deviations. With the exception of diameters 0.8 and 1.4 μm, the data points were located within one standard deviation. This sampling period had similar data issues as the 270 degree rotation data, including large unsteady aerosol concentrations throughout the sampling period. Beyond the noise of the data, the data appeared to be consistent with the data from the typical locations of the sampling ports.

The data from the various rotations seemed to show that regardless of location, OPC 3

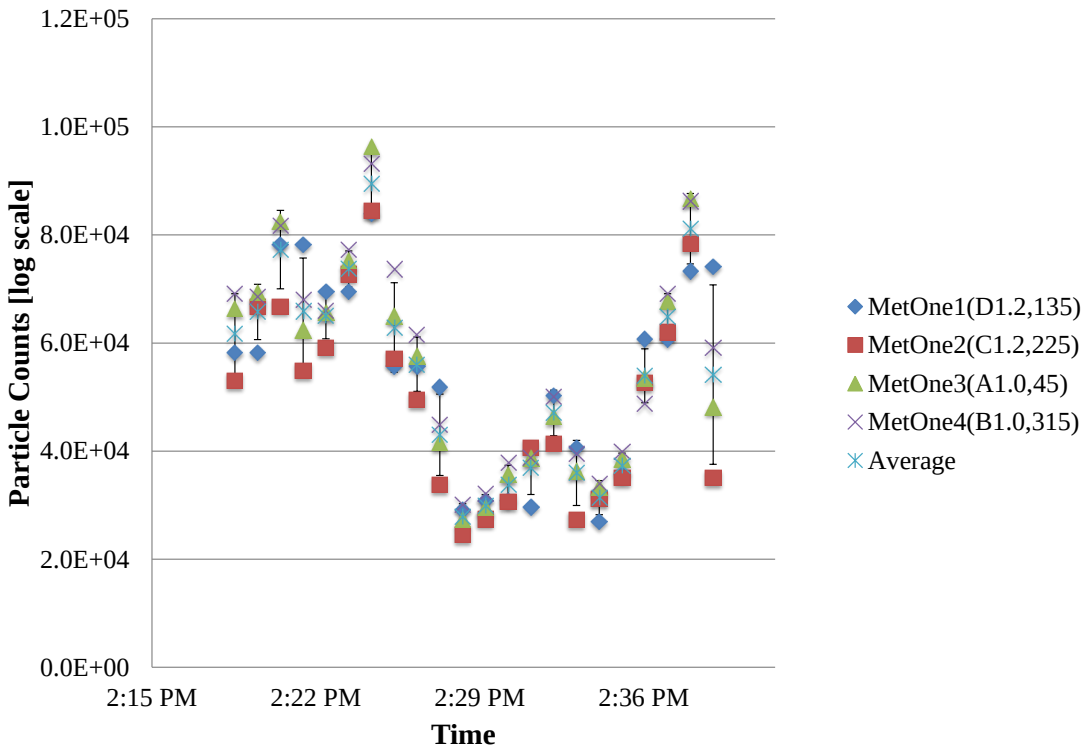


Fig. 3.11: Time series of the channel 1 data set for 270 degree rotation.

had the highest counts and OPC 2 generally had the lowest counts, with the exception being the 240 and 270 degree rotations. At the 240 and 270 degree rotations, the data sets had much greater noise but still followed the general trend of the data. If there would have been a location that was consistently low or high, regardless of what instrument was sampling there, the data would indicate a bias at that location. Since there is no apparent bias, it was determined that the system has a fairly uniform, unbiased dispersion.

One improvement that would be beneficial is using a more consistent aerosol generator. Because of the fluctuation in aerosols generated, it was difficult to determine what was the origin of uncertainty and, therefore, evaluate the overall quality of the data. If further evaluation of the system desired, a more controlled aerosol generator is recommended. Another improvement would be to have the instrument flow rates within 5% of isokinetic flow instead of 10%. This would give the instruments an advantage of accuracy within the data sets. Also, having the instruments freshly calibrated or systems that are more in agreement with

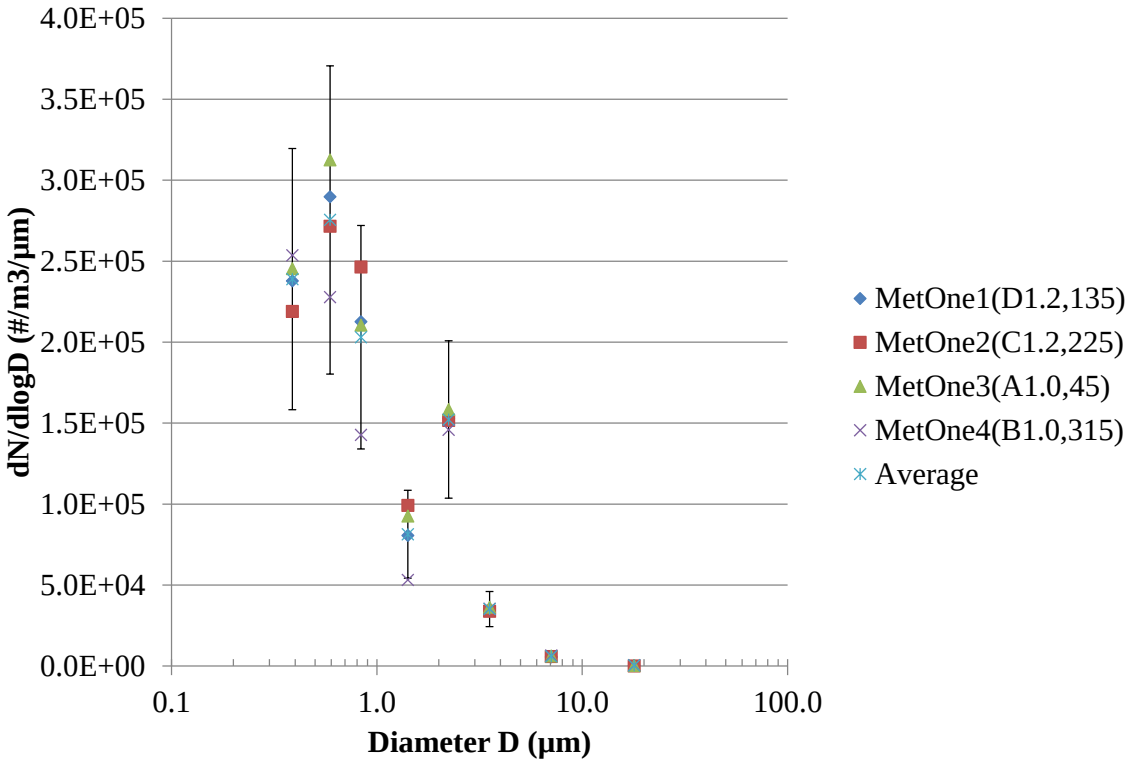


Fig. 3.12: Graph of dN/dlogD for a single measurement data set at 270 degree rotation.

one another could be favorable. It might be desirable to collect data again for data sets with large variance.

3.3 Various Instrument Capability

This system was designed to be used with various instruments; therefore, inter-instrument compatibility is important. The first compatibility test was to show that other instruments besides the MetOne OPCs could be used on the system. For this test, the APS and the Grimm were used alongside two MetOne OPC instruments, OPC 1 and 4. OPC 1 and 4 were chosen because of their flow rates being closer to the designed nozzles. The second compatibility test used the VOAG as an aerosol generator to demonstrate the system's ability to use other aerosol generators. The setup and results of these tests are discussed below.

3.3.1 Aerosol Measurement Instruments

The APS and the Grimm have different sampling port geometries than the MetOne

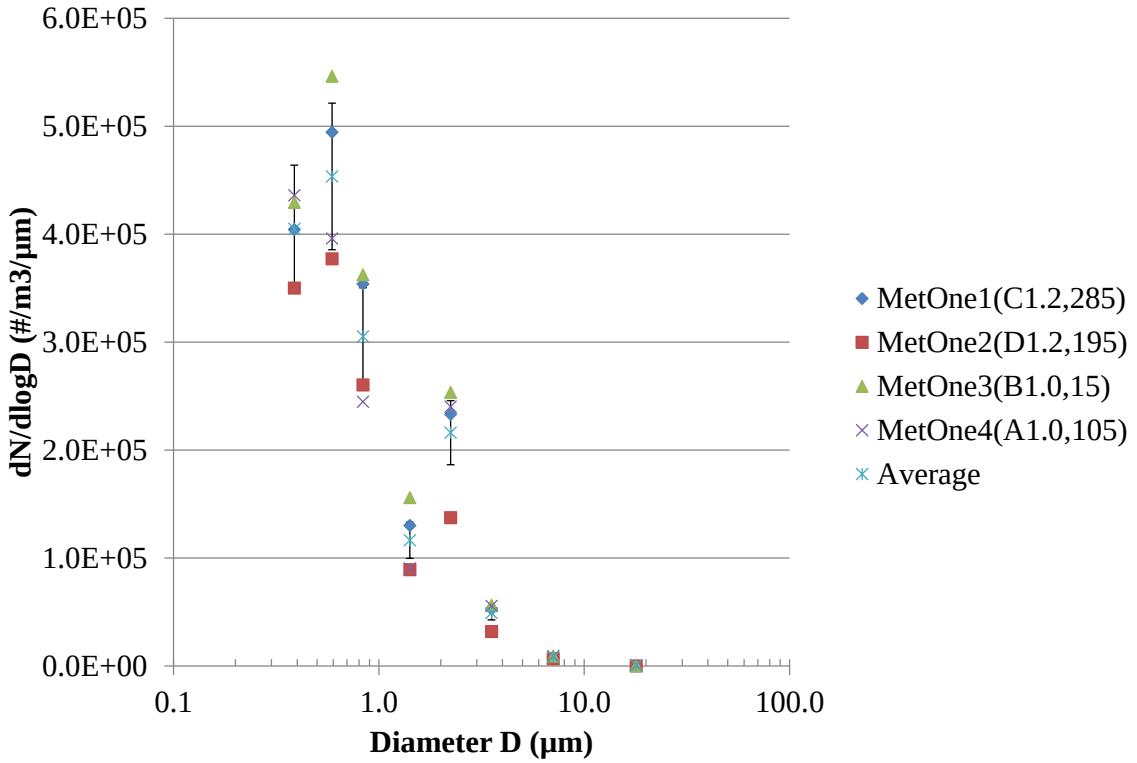


Fig. 3.13: Graph of dN/dlogD for a single measurement data set at 210 degree rotation.

OPCs so different connectors were needed between the system and the instruments. For the APS, the inner inlet nozzle of the instrument has a port slightly larger than a 4 mm diameter tube. The Grimm also has a port slight larger than a 4 mm tube. A Swagelok Ultra Torr reducing union (0.5 in to 0.125 in) along with female NPT hose connectors (0.5 in barb to 0.5 in) were used to transition from the 0.5 in tubing to the instrument sampling ports. The clearance hole in the unions were enlarged to ~0.159 in for the Grimm and APS. The barbs were placed inside of sections of the same conductive silicone tubing used for the OPCs; the barb was the connected to the Ultra Torr reducing union and connected to the applicable instrument. This connection created a smooth transition from the 0.5 in sampling port tubing to the instrument sampling nozzle. The transition from the sample ports on the plenum to the end of the Ultra Torr can be seen in Figure 3.15.

The setup for using the various instruments was the following: OPC1 on port A (315 degrees), Grimm on port B (225 degrees), APS on port C (135 degrees), and OPC 4 on

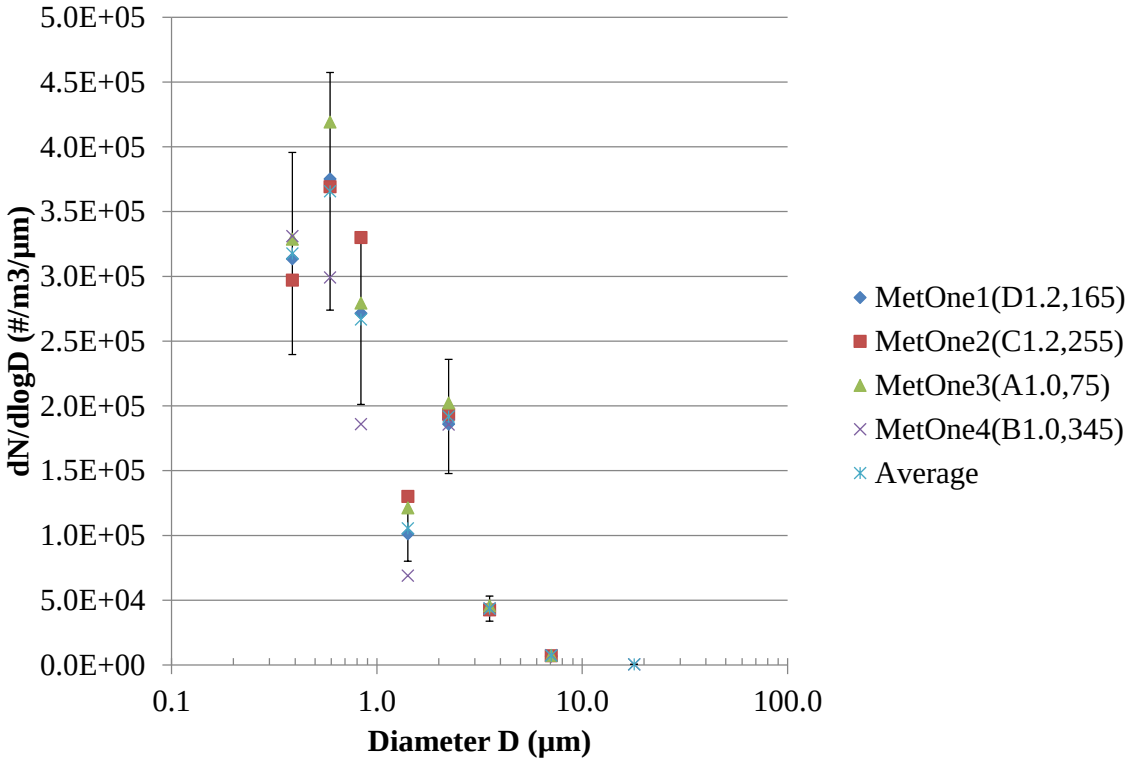


Fig. 3.14: Graph of dN/dlogD for a single measurement data set at 240 degree rotation.

Fig. 3.15: Conductive tubing connections from the sampling ports to the instruments.

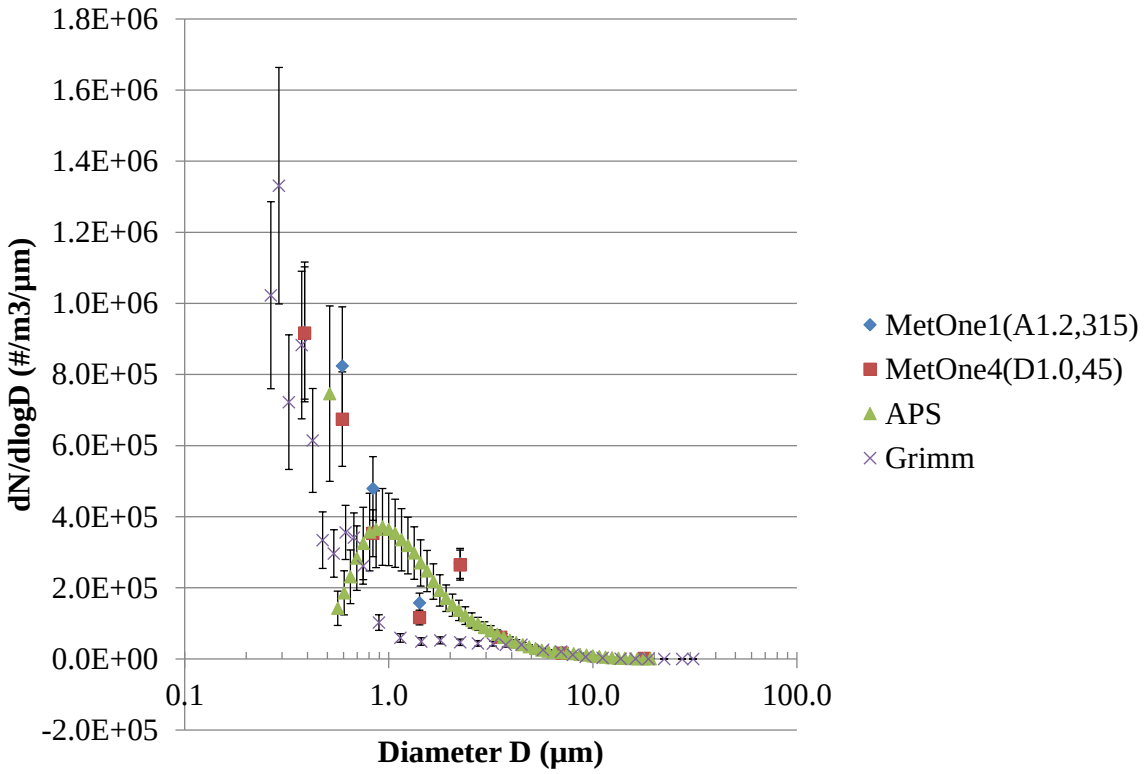


Fig. 3.16: Graph of dN/dlogD for APS, Grimm, OPC 1, and OPC 4.

port D (45 degrees). The aerosol generator used for these experiments was the SSPD, using either talcum powder or quartz dust. Figure 3.16 shows the D versus dN/dlogD graph for the four instruments. The APS and the Grimm measure smaller diameter particles than do the OPC instruments. The Grimm has the largest range, from 0.27 to 31 μm, whereas the APS has more channels within a smaller range than the Grimm, 52 channels from 0.5 to 20.5 μm. Both of these instruments have more size channels than the MetOne OPC. No analysis of the correlation between the instruments have been done but the ability to sample with other instruments has been demonstrated.

3.3.2 Aerosol Generators

Many aerosol generators have the ability to connect to this system. Ideally, the aerosol generator would need to have a pumping system to force the air into the plenum. As demonstrated above, the SSPD was capable of providing PM into the system. To demonstrate that

more than one type of aerosol generator could be used in the system, the VOAG was also used.

Both the SSPD and the VOAG have larger outlet diameters, 1 and 1.2 in, respectively, which requires a transition down to fit the injection port, since the existing injection port was a 0.5 in diameter tube. To accomplish this transition, Swagelok Ultra Torr unions were again used. Figure 3.17 shows the VOAG connected to the plenum. To demonstrate the VOAG in the system, the MetOne OPC instruments were used in the following configuration: OPC 1 on port A, OPC 2 on port B, OPC 3 on port C, and OPC 4 on port D.

The VOAG produced a polydispersed distribution which can be seen in Figure 3.18. In the 0.5 and 2.5 μm particle diameters, there are large discrepancies between the OPCs. Through most of the sample period, OPC4 recorded lower particle counts than the other OPCs. OPC2 was usually on the high end of counts. While the data was more smooth throughout the sample period, the VOAG was difficult to operate and may not have been fully operational. However, the connection to the plenum system and the particle dispersion show the compatibility with other aerosol generators.

Fig. 3.17: Conductive tubing connections from the VOAG to the plenum.

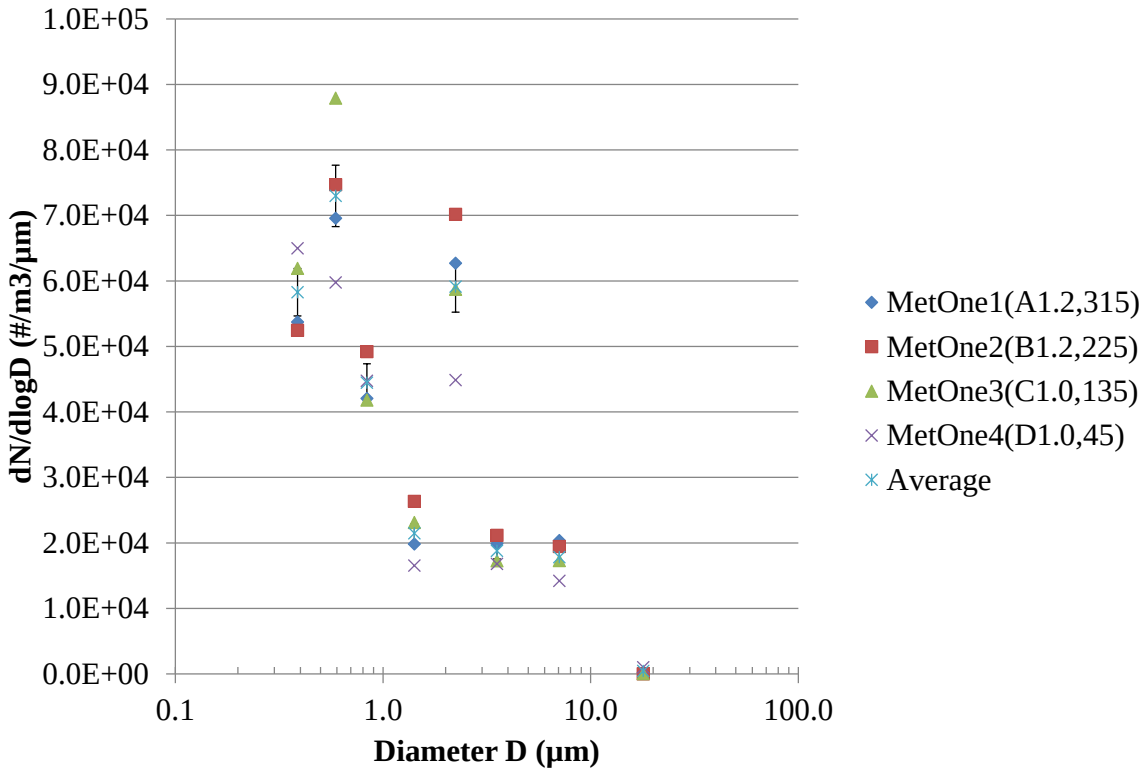


Fig. 3.18: Graph of dN/dlogD for the OPC instruments using the VOAG.

Chapter 4

System Configuration

This calibration system has multiple sizing options based on system requirements and desired capabilities, as seen in Section 2.1. As previously described, this system was designed for a consistent flow of 100 L/min with 4 isokinetic sampling ports, 1 universal particle generator injection port, and filtering systems. This chapter describes the prototype components, the cost of materials, assembly instructions, recommended procedures, and recommended improvements. Potential improvements to the existing prototype have been identified through testing and validation.

4.1 System Components and Considerations

A list of the components for the prototype described previously can be seen in Table 4.1. HEPA filters are used on both ends of the plenum to provide clean air to the system and remove test particles prior to venting. The inlet filter needs to provide the system with air as clean as required by the instruments being tested, below the instruments range. Two important aspects of the flow-through sampling chamber are that it can accommodate all desired sampling ports and it follows the flow disturbance length guidelines described in Section 2.1. It should be noted that the sampling chamber is not required to be round but should be made out of a noncorrosive material with smooth surfaces. A sample injection site to insert aerosols into the system as well as sampling ports are also required. To achieve isokinetic sampling, known diameters that correspond to flow rates are required. The vacuum system must be able to pull the system at the specified velocity, as temporally uniform as possible. A structural support of some sort provides the frame for the system. This support can be designed in a way that allows one to suspend various instruments on it as well.

Table 4.1: List of components used in the designed flow-through sampling chamber.

Components	Qty	Services
Stainless Steel Tubing (304L), 3 lengths, 1ft, 2ft, 3ft	1	Yes
ISO-K Weld Flanges (304L SS)	8	Yes
Double Clamps for "K" Flanges	25	No
Centering Ring for "K" Flanges	4	No
Type 316 SS Smooth-Bore Seamless Tubing, 1/2in, length 3ft	1	Yes
Conductive Silicon Tubing, 1/2in FTG, length 25ft	1	No
Steel Strut Channel Slotted, 1-5/8in X 1-5/8in, Zinc-Plated, 2ft Length	12	No
Steel Strut Channel Slotted, 1-5/8in X 1-5/8in, Zinc-Plated, 8ft Length	7	No
Parallel Strut-Mount Clamp for 4in OD, 3-1/2in Pipe/Rigid Conduit, Zinc Pltd STL	3	No
Strut Channel Accessory 90 Degree Angle Bracket, 2-hole, Zinc-Plated Steel	30	No
Grade 8 Alloy Steel Head Cap Screw, 3/8in - 16 Thrd, 1in L, Fully Thrd	50	No
Grade 8 Alloy Steel Head Cap Screw, 3/8in - 16 Thrd, 1-1/2in L, Fully Thrd	50	No
Steel Flat Washer SAE, 3/8in Screw Size, 13/16in OD, 0.05in - 0.08in Thick	50	No
Nut for Strut Channel Zinc-Plated STL, for 1-5/8 in Wide Strut, 3/8in - 16 Thrd	75	No
Outlet Vacuum Filter with HEPA Filter	1	No
Air Intake Filter with HEPA Filter	1	Yes
Ultra Torr Reducing Union 1in X 3/4in Ultra Torr	2	No
Ultra Torr Reducing Union 1/2in X 1/4in Ultra Torr	2	No
Ultra Torr Reducing Union 1/2in X 1/8in Ultra Torr	2	Yes
Hose connecting barb for 1/2in	2	No
Variable Transformer	1	No
Hot-wire Anemometer	1	No
Vacuum	1	No
Aerosol Generator	1	No
Nozzles for specific flow rates	4+	Yes
Blank nozzles	4	Yes

(a) Required components.

Components	Qty	Services
Cover for 1-5/8 in Single Strut, Green Plastic	10	No
Caster for Strut Channel W/Side Wheel Brake, Swivel, 3 in X 1-1/4 in, 210# Cap	4	No
Split Lock Washer 3/8 in Screw Size, 0.68 in OD, 0.09 in min Thick	100	No
Steel Step Stand with Handrail 20-1/4 inTop Step Height, 2 Step, 225 lb Capacity	1	No
Plastic Storage Box with Tote Tray 16-1/8 in Width X 6-5/8 in Depth X 7 in Height	1	No
Flow Conditioner, as described in Section 3.1.3	1	Yes

(b) Recommended components.

Table 4.2: Total Cost of Materials.

Material Category	Total Price
Pipes, tubes, and flange	$1,734.55
Structural support	$565.14
Filter	$1,905.40
Unions	$525.80
Miscellaneous	$753.12
Total	$5,484.01

4.2 Cost of Materials

Table 4.2 includes the total cost of materials for this project. No costs for services performed, such as welding and machined parts, are provided. For a complete break down of all material costs, please see Section A.4.

4.3 Assembly Instructions

Using Chapter 2 as a guideline and the components listed in Table 4.1, the system can be constructed. The outline of the system can be seen in Figure 2.1 and a completed system can be seen in Figure 2.16. Prior to assembly some portions of the plenum need to be machined or welded together. A list of these services include: welding flanges onto pipe sections, machining nozzles for specific flow rates, and other various machined parts. These parts are marked in Table 4.1 under Services.

Beginning with the structural support, see Section 2.5, the strut channels are connected together into an 8 ft by 2 ft by 2.3 ft structure using the nuts, bolts, and brackets. Metal sheets provide extra bracing to aid in structural support. An image of the free standing structure, with very few components added, can be seen in Figure 2.15. Once the support structure is built, it should be placed in the location of choice and secured either via wall brackets or through weight on the bottom. One strut channel should be located in the middle of the back portion of the structural support for attaching the plenum. This channel is what the parallel strut-mount clamps use to hold the plenum in place.

To connect the plenum sections, start at the bottom. Measure the height of the bottom filter and allow an additional inch of space. This distance was 20 inches for the prototype.

This is where the bottom of section 3 will start on the center strut channel of the structure. Using the parallel strut-mount clamps, hang section 3 in place. Place the flow straightener at the bottom of section 3. The exhaust filter with an ISO K flange centering ring then connects to the bottom of section 3 using flange clamps. Next, add an ISO K flange centering ring between section 3 and section 2 via the flange clamps. Parallel strut-mount section 2 to the center strut channel. Insert the ISO K flange centering ring between section 2 and section 1 then clamp together, ensuring that the injection port on section 1 is accessible for connection to an aerosol generator. Strut-mount section 1 to the center strut channel. Add the centering ring and the flow throttle plate to top of section 1 and clamp the inlet filter to the system. Finally, attach the vacuum to the bottom filter. The vacuum system should have the components to achieve the correct flow rate installed as necessary.

When installing or changing isokinetic nozzles, section 3 and the exhaust filter must be removed from the structure. Nozzle installation can be done prior to initial assembly, if desired. Identify the nozzles required for each instrument to be tested. It is recommended that a rotational orientation protocol for section 3 of the system be established and followed carefully to prevent confusion and instrument/nozzle mismatches. For instance, labeling on the external surface is highly recommended. Noting the port placement of each nozzle, the nozzles can then be installed in section 3. The nozzles in this prototype are designed to have a tight fit around the inside ports of section 3 and may require some force when installing. However, due to the nozzles being made out of aluminum, they can be easily damaged and care should be taken during their installation. Section 3 and the exhaust filter can then be reassembled to the system and are ready for testing.

4.4 Recommended Improvements

While the system is in working condition, improvements to the design would be beneficial. A more consistent aerosol generator that could provide stable concentrations of particulate would help in any calibration or correlation methods.

A vacuum system with more stable flow that meets the required flow rate may alleviate some of the flow issues described in Section 3.1. For instance, a battery operated hand-held

vacuum on DC power could be investigated. Another improvement would be to connect the vacuum to the plenum system with a designed flange that connected directly to the bottom filter. If using the same pipes as the prototype, the design for this connection could be similar to Figure 2.6 but with the appropriate sized opening. One such design can be seen in Appendix A.1 Figure A.8. A hose restrictor located in the vacuum system, see Figure 2.14, could be replaced with a more precise, metal version.

Finally, a more sturdy flow conditioner could be made from a 3D printer by designing a flow conditioner in a honeycomb style for the 5 inch design that was found to be most effective. Honeycomb style flow conditioners are also readily available for purchase and could be used. The flow conditioner should be made out of a material that could be easily cleaned, as necessary, and would not be damaged by aerosol. Along with the flow conditioner, the flow restrictor plate located at the top of section 1 could be replaced with a component made of out metal.

Chapter 5

User's Manual

5.1 Introduction

The plenum is a vertical sampling chamber into which a homogenized set of particles may be dispersed and then sampled by multiple instruments downstream in the chamber. For a simple drawing of the plenum, see Figure 5.1. It is made from stainless steel tubing with an inlet filtered to control external particles from entering the system with a High-Efficiency Particulate Air (HEPA) filter. Particles are introduced into the system near the top, dispersing horizontally, and pulled downward by a vacuum pump in a plug flow fashion.

At the sampling site, the instruments sample at their required flow rates through isokinetic nozzles. These nozzles are designed to maintain inlet velocities at the bulk velocity in the plenum system and are designed for the specific instruments based on their flow rate requirements. The nozzles have a smooth internal transition from the nozzle to the sampling tubing.

The end of the calibration system consists of another HEPA filter to eliminate particles from entering the vacuum system and the exhausted air. After the bottom filter there is the vacuum, which controls the overall flow rate of the system.

This specific model has a two part flow conditioner installed. The flow restrictor or throttle plate should be installed on the top of the plenum, after the inlet filter. The flow straightener should be installed at the bottom of the plenum above the exhaust filter.

The vacuum pump system has some flow adjustments. These adjustments include a flow restrictor with a centered, 0.25 in diameter hole to cover the vacuum's hose inlet, acting as a throttle, and a variable transformer to allow the user to adjust the voltage going to the system.

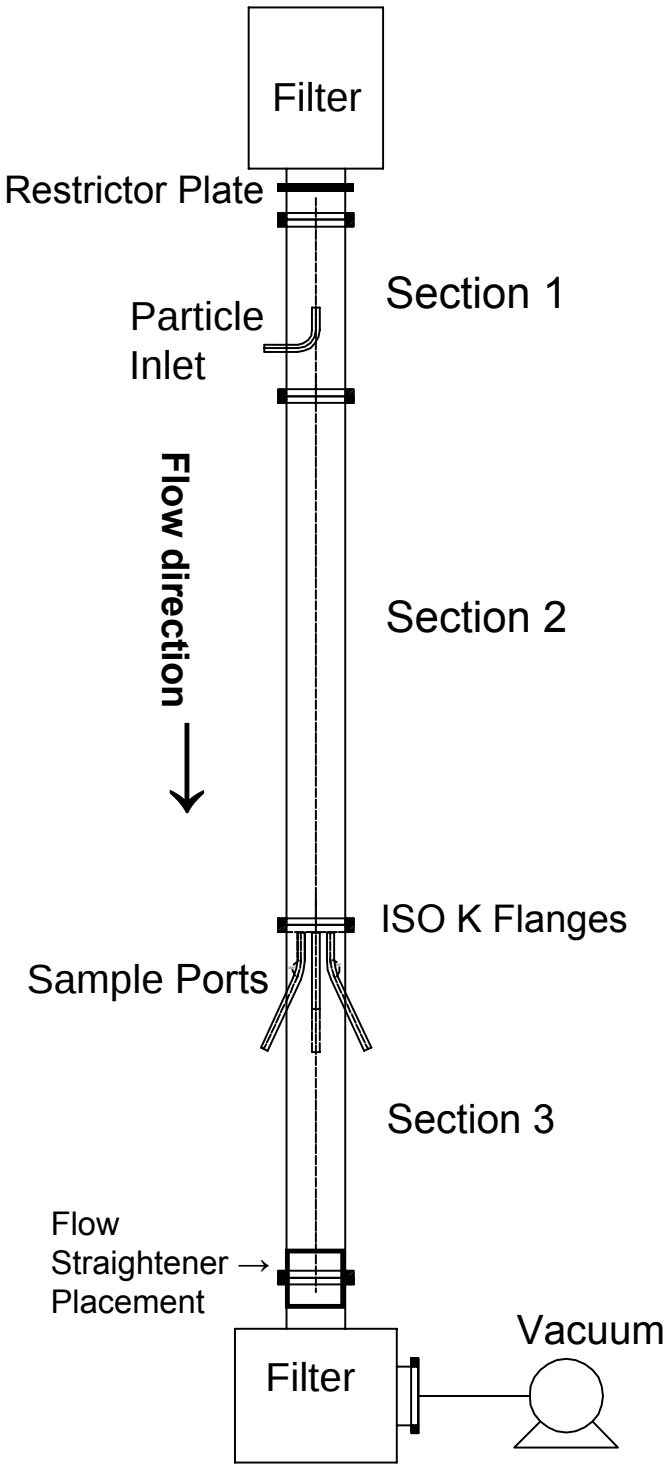


Fig. 5.1: Drawing of the plenum system.

5.2 Specifications

System Specifications

System Flow Rate:	100 L/min (velocity = 0.22 m/s)
Number of Sample Ports:	4
Structure:	Length: 8.33 ft
	Width: 2 ft
	Depth: 2.3 ft

Plenum Specifications

Diameter:	4 in OD (3.83 in ID)
Injection Port Diameter:	0.5 in
Sampling Port Diameter:	0.5 in
Total Length:	9 ft
Length of Plenum:	6 ft
Section 1 Length:	1 ft
Section 2 Length:	3 ft
Section 3 Length:	2 ft
Uninterrupted Flow from Sample Plane:	Upstream: $\geq$32 in
	Downstream: $\geq$15 in

Nozzle Specifications

Blank Nozzle:	Flow rate range: 0 L/min
	Inlet Diameter: 0 in
0.9 L/min Nozzle:	Flow rate range: 0.9 L/min ±10%
	Inlet Diameter: 0.363 in
1.0 L/min Nozzle:	Flow rate range: 1.0 L/min ±10%
	Inlet Diameter: 0.383 in
1.2 L/min Nozzle:	Flow rate range: 1.2 L/min ±10%
	Inlet Diameter: 0.420 in
5.0 L/min Nozzle:	Flow rate range: 5 L/min ±10%
	Inlet Diameter: 0.857 in

5.3 Installation

Once all the components of the system have been gathered, one must assemble the structural support system and plenum. The system components are listed in Table 5.1. Some portions of the plenum need to be machined or welded together. These services need to be finished before the system can be operational. A list of these services include: welding flanges onto pipe sections, machining nozzles for specific flow rates, and other machined components.

Beginning with the structural support, the strut channels are connected together into an 8 ft by 2 ft by 2.3 ft structure using the nuts, bolts, and brackets. To aid in the structural support, use metal sheets to provide extra bracing can be used. Once the support structure is built, it should be placed in the location of choice and supported either via a wall bracket or through weight on the bottom. One strut channel should be located in the middle of the back portion of the structural support for attaching the plenum. This channel is what the parallel strut-mount clamps use to hold the plenum in place. The structural support with sections 1 and 2 connected can be seen in Figure 5.2.

To connect the plenum sections, start at the bottom. Measure the height of the bottom filter and allow an additional inch of space. This distance is 20 inches for the prototype. This

Table 5.1: List of components needed or recommended for a flow-through sampling chamber.

Components	Quantity
Stainless Steel Tubing (304L), 3 lengths, 1 ft, 2 ft, 3 ft	1
ISO-K Weld Flanges (304L SS)	8
Double Clamps for "K" Flanges	25
Centering Ring for "K" Flanges	4
Type 316 SS Smooth-Bore Seamless Tubing, 1/2 in, length 3 ft	1
Conductive Silicon Tubing, 1/2 in FTG, length 25 ft	1
Steel Strut Channel Slotted, 1-5/8 in X 1-5/8 in, Zinc-Plated, 2 ft Length	12
Steel Strut Channel Slotted, 1-5/8 in X 1-5/8 in, Zinc-Plated, 8 ft Length	7
Parallel Strut-Mount Clamp for 4 in OD, 3-1/2 in Pipe/Rigid Conduit, Zinc Pltd STL	3
Strut Channel Accessory 90 Degree Angle Bracket, 2-hole, Zinc-Plated Steel	30
Cover for 1-5/8 in Single Strut, Green Plastic	10
Caster for Strut Channel W/Side Wheel Brake, Swivel, 3 in X 1-1/4 in, 210# Cap	4
Grade 8 Alloy Steel Head Cap Screw, 3/8 in - 16 Thrd, 1 in L, Fully Thrd	50
Grade 8 Alloy Steel Head Cap Screw, 3/8 in - 16 Thrd, 1-1/2 in L, Fully Thrd	50
Steel Flat Washer SAE, 3/8 in Screw Size, 13/16 in OD, 0.05 in - 0.08 in Thick	50
Split Lock Washer 3/8 in Screw Size, 0.68 in OD, 0.09 in min Thick	100
Nut for Strut Channel Zinc-Plated STL, for 1-5/8 in Wide Strut, 3/8 in - 16 Thrd	75
Outlet Vacuum Filter with HEPA Filter	1
Air Intake Filter with HEPA Filter	1
Ultra Torr Reducing Union 1 in X 3/4 in Ultra Torr	2
Ultra Torr Reducing Union 1/2 in X 1/4 in Ultra Torr	2
Ultra Torr Reducing Union 1/2 in X 1/8 in Ultra Torr	2
Hose connecting barb for 1/2 in	2
Steel Step Stand with Handrail 20-1/4 inTop Step Height, 2 Step, 225 lb Capacity	1
Plastic Storage Box with Tote Tray 16-1/8 in Width X 6-5/8 in Depth X 7 in Height Overall, Gray	1
Variable Transformer	1
Hot-wire Anemometer	1
Vacuum	1
Aerosol Generator	1
Nozzles for specific flow rates	4+
Blank nozzles	4
Flow conditioner	1

Fig. 5.2: Structural support and sections 1 and 2 connected to system.

is where the bottom of section 3 will start on the center strut channel of the structure. Using the parallel strut-mount clamps, hang section 3 in place. Place the flow straightener at the bottom of section 3. The exhaust filter, with an ISO K flange centering ring, then connects to the bottom of section 3 using flange clamps. Next, add the ISO K flange centering ring between section 3 and section 2 and clamp together via the flange clamps. Parallel strut-mount section 2 to the center strut channel. Insert another ISO K flange centering ring between section 2 and section 1 then clamp together, ensuring that the injection port on section 1 is accessible for connection to an aerosol generator. Strut-mount section 1 to the center strut channel. Add an ISO K flange centering ring and the flow throttle plate to top of section 1 and clamp the inlet filter to the system. Finally, attach the vacuum to the bottom filter. The vacuum system should have the components to achieve the correct flow rate installed as necessary.

When installing or changing isokinetic nozzles, section 3 and the exhaust filter must be removed from the structure. Nozzle installation can be done prior to initial assembly, if desired. Identify the nozzles required for each instrument to be tested. It is recommended that a rotational orientation protocol for section 3 of the system be established and followed carefully to prevent confusion and instrument/nozzle mismatches. For instance, labeling on the external surface is highly recommended. Noting the port placement of each nozzle, the nozzles can then be installed in section 3. The nozzles in this prototype are designed to have a tight fit around the inside ports of section 3 and may require some force when installing. However, due to the nozzles being made out of aluminum, they can be easily damaged and care should be taken during their installation. Section 3 and the exhaust filter can then be reassembled to the system and are ready for testing.

Two views of the assembled plenum can be seen in Figures 5.3 and 5.4. Figure 5.4 also shows particle samplers attached to the plenum.

Fig. 5.3: Complete assembled calibration system.

Fig. 5.4: Completed system with aerosol generators and instruments added.

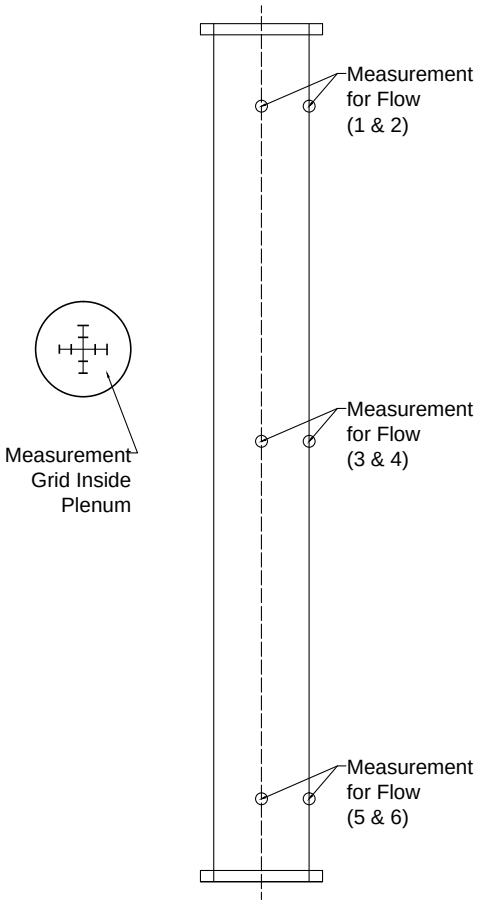


Fig. 5.5: Measurement locations and measurement grid on section 2 of the plenum.

5.4 Flow Measurements

The rate and horizontal uniformity of plenum flow should be checked before the start of every run. To do this, insert the hot-wire anemometer into the flow measurement holes 5 and 6, located directly above the sampling ports. Figure 5.5 shows the measurement grid for the flow measurements. Record 5 points of velocity across the plane in both directions, as designated in the sampling grid. Make adjustments to the flow as needed to meet the desired velocity. Once the structure is completely built and the system has been tested for flow, it is ready to be used.

5.5 Uniform Particle Dispersion Verification

The particle uniformity should be checked prior to using the system. Four identical instruments should be connected to the system with the same length of tubing and placed in such a way as no section of tubing is bent beyond an angle of thirty degrees.

Label each sample port and determine an initial rotation orientation. An example is shown in Figure 5.6. Determine instrument placement around the plenum. For the ease of naming convention throughout the data, each instrument can be named with their respective number (1-4), what port it was connected to, and at what degree the port was located (e.g., with the wall being zero degrees and increasing clockwise). An example is Instrument 1(D,45). Now place the isokinetic sampling nozzle best corresponding to the instrument flow rate on the appropriate sample port.

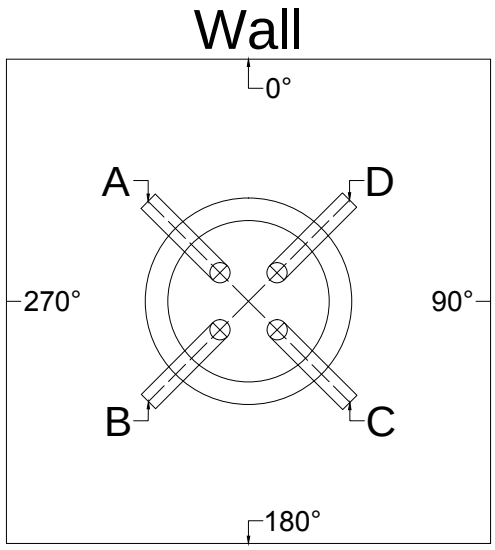


Fig. 5.6: Drawing of the sample ports, as labeled, in their initial locations.

Using a permutational (rotational) procedure, the aerosol distribution can be evaluated. An example of a simple test procedure showing the location of Port A for all sampling locations can be seen in Table 5.2. The resulting data can then be evaluated to check for uniformity.

Table 5.2: Measurement schedule for determining aerosol distribution across system.

	Port	Location	Flow Rate
Initial	A	315	1
90 deg turn	A	225	1
180 deg turn	A	135	1
210 deg turn	A	105	1
240 deg turn	A	75	1
270 deg turn	A	45	1

Table 5.3: Example of instrument flow rates

Instrument	Nozzle	Port
OPC 4	1.0 L/min	A
APS	1.0 L/min	B
Grimm	1.2 L/min	C
OPC 1	1.2 L/min	D

5.6 Example Setup for Data Collection

1. Determine flow rates of aerosol instruments and select the appropriate nozzles. Refer to instrument manuals or measurements.

2. Assign instrument location by port (see Table 5.3).

3. Place the appropriate nozzles onto the ports on section 3, noting each location (see Figure 5.7).

4. Connect section 3 to the rest of the system and clamp in place, being careful not to bump the nozzles against section 2. Check that clamps are tight at all locations.

5. Connect all instruments to the ports via the appropriate connections

6. Connect the aerosol generator.

7. Turn on the vacuum system.

8. Check and record the flow rate via the hot-wire anemometer across the plane.

   (a) Adjust the flow rate via the variable transformer until it is approximately the correct flow rate of 0.22 m/s across the plane.

Fig. 5.7: Nozzles on section 2 of the plenum.

(b) Check the flow rate with the hot-wire anemometer at flow measurement hole 5 or 6 and adjust variable transformer until it reaches the desired rate.

(c) Record flow rate measurements across the plane for both flow measurement holes 5 and 6 in 1 inch increments.

9. Turn on all instruments and start recording data.

10. Turn on aerosol generator but do not add particles into the system.

11. Re-check the flow rate via the hot-wire anemometer and make adjustments as needed.

12. Run "clean" sample through system for 10 minutes.

(a) Clean sample means running the aerosol generator with no particle addition. This is done to have a zero reading before the actual particle sample and to allow any instruments warmup time as needed.

13. Begin sending particles through the aerosol generator and record time.

14. Sample for desired period of time.

(a) For the SSPD, this is approximately 20 minutes.

15. Once finished running particles, run another "clean" sample for at least 10 minutes.

(a) This clean cycle is to help clean out any residual particles that may be in the system.

16. Collect recorded data as required from respective instruments.

17. Turn off instruments, vacuum system, and aerosol generator.

18. Disconnect instruments as desired.

5.7 Plenum Cleaning and Maintenance

Maintenance of the system should be performed annually or as needed. To clean the plenum system, the components must first be separated from the structural support. The stainless steel components can be washed with soap and water, followed by an isopropyl alcohol or hexane rinse and air dried. The nozzles can be cleaned with the same procedure, taking care to not damage the nozzles.

The HEPA filters should be cleaned periodically to prevent clogging. Since the size of these filters allow for extended time in the system, there may not be clogging issues. To clean the filters, vacuum excess dust and particles off of the filter then wash with water and allow to try. Replace filters as needed based on holes in filter, inability to clean filter, or extensive use.

The flow conditioner located at the bottom of section 3 should be checked for buildup prior to installation, as well as after extensive testing periods. If buildup has occurred, use a compressed air duster to remove any particles. The air throttle located at the top of section 1 can be simply wiped clean with a damp cloth and allowed to dry.

5.8 Troubleshooting Guide

5.8.1 Failed Clean Air Check

1. Check that there are no particles being added into the system via the aerosol generator. If the aerosol generator is running, disconnect it from system and plug the particle inlet with rubber or cork stopper.

2. Check all known potential exposure locations, e.g. flow measurement check ports, for leaks. If one of these potential locations are not plugged, plug with rubber or cork stopper.

3. Check system for any other potential leaks by removing the top filter and blocking the air inlet, while the vacuum is running. These leaks could occur at the section joints and clamps may need to be tightened.

4. Check air filters for damage and particle buildup. Clean filters as needed.

5.8.2 Flow Rate at Wrong Velocity

1. Verify that the flow controls on the vacuum are properly installed.

2. Adjust the variable transformer to a rate close to desired flow rate (0.22 m/s) and follow steps for adjusting flow rate described in Section 5.6.

5.9 Safety

This section gives instructions to promote safe and proper operation of the calibration system.

The calibration system has a structural support design that requires anchoring to either the floor or wall because of a high center of gravity. Without this anchoring there is a tipping hazard.

When installing components to the system, some parts may require two people. These parts include, but are not limited to: aerosol generator installation, inlet filter installation, and moving the structure.

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Appendix

A.1 Plenum Drawings and Documentation

The following images are drawings and documentation for the plenum components, including: flange design, inlet and sampling ports, and nozzles.

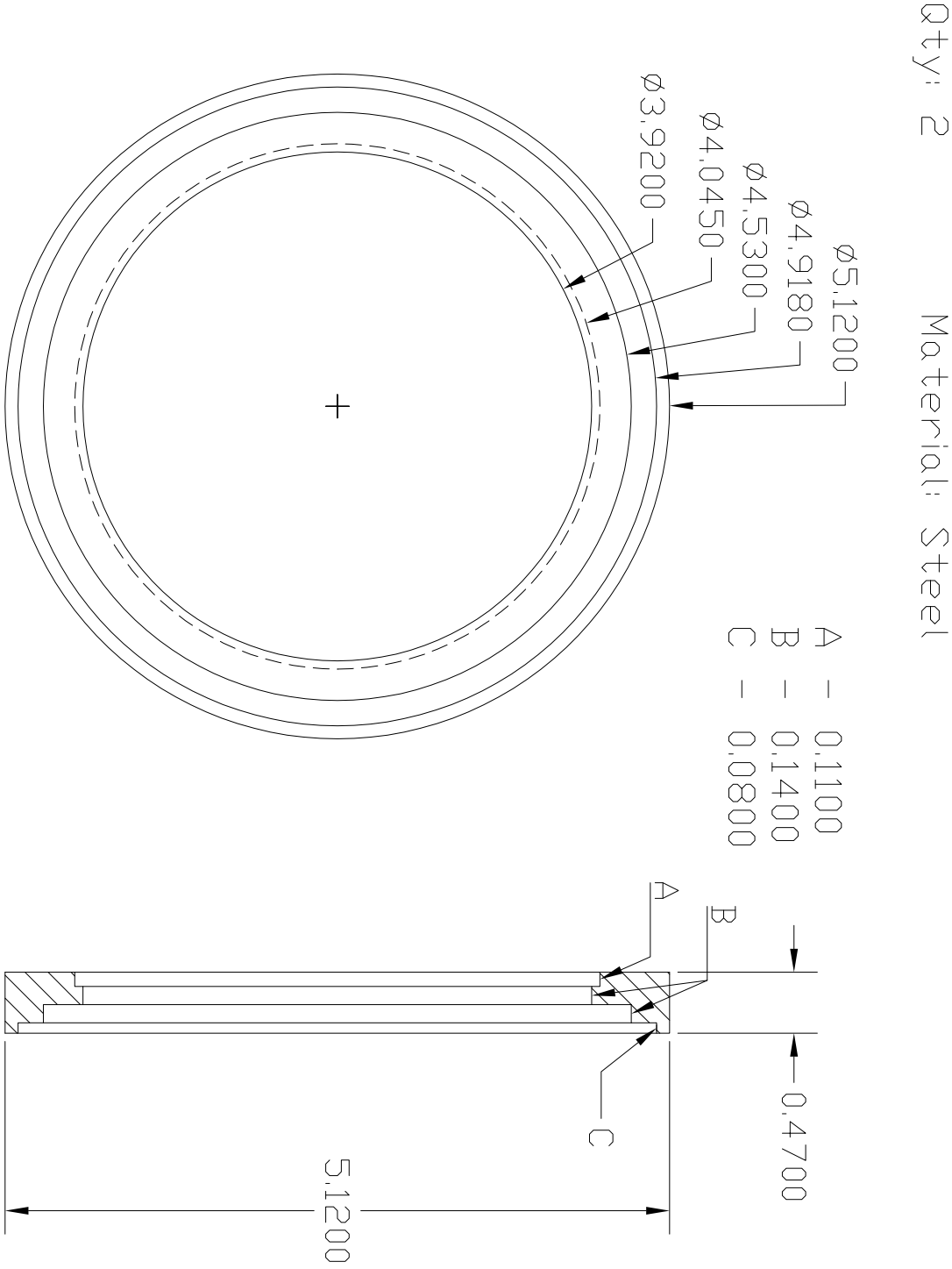

Fig. A.1: Flange machined to convert inlet HEPA filter flange to fit pipe

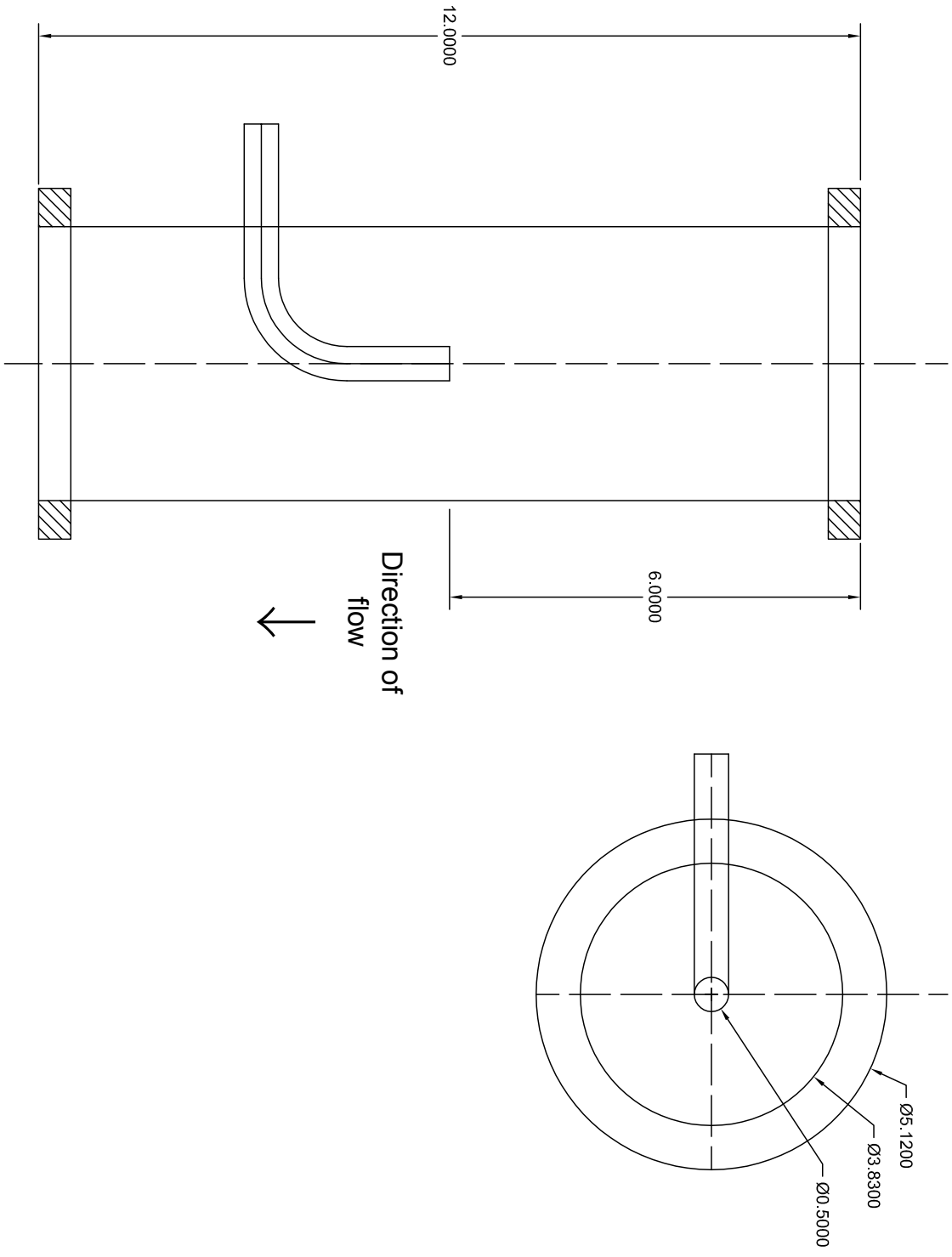

Fig. A.2: Drawing of the injection site

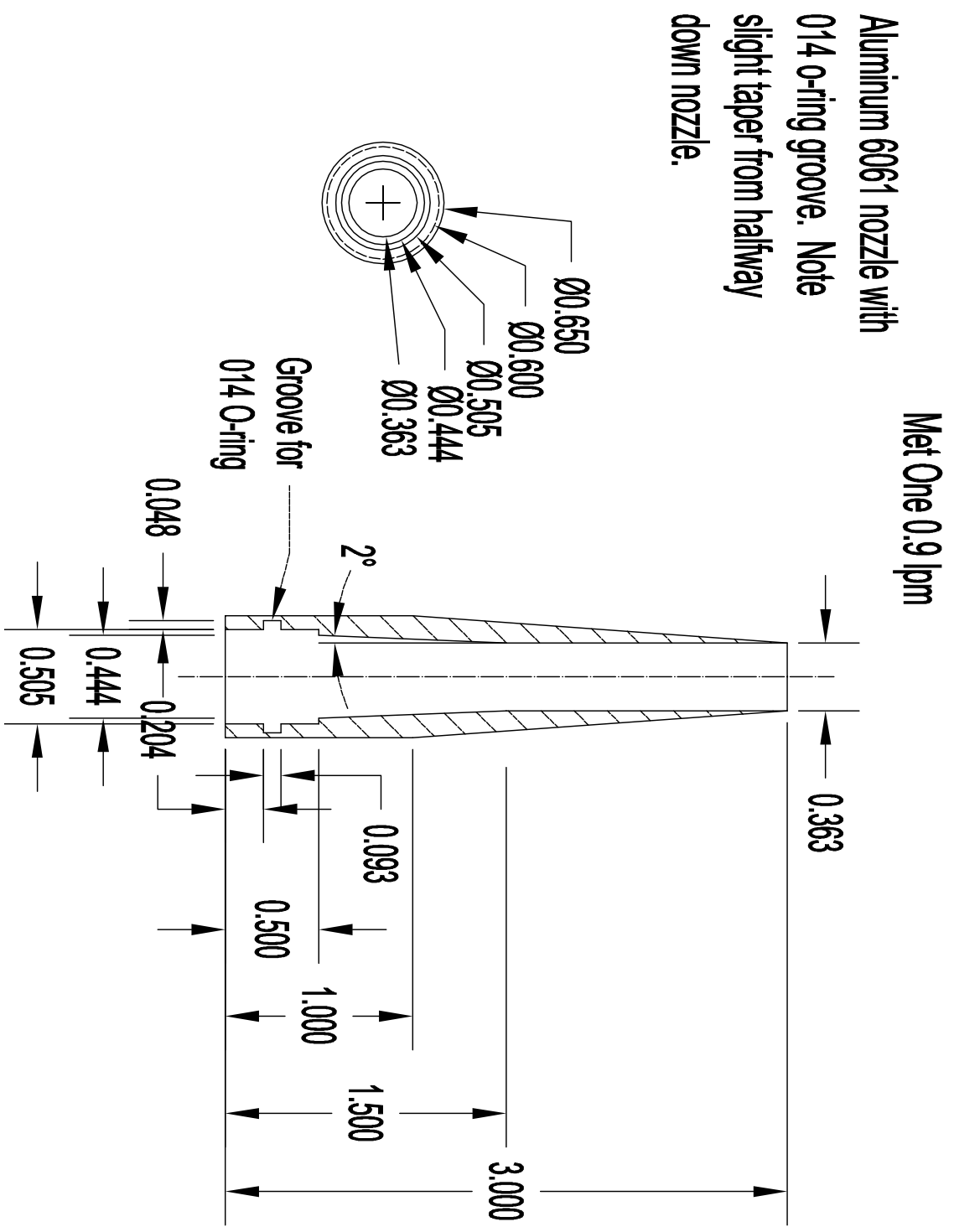

Fig. A.3: Plenum nozzle for 0.9 L/min flow rate

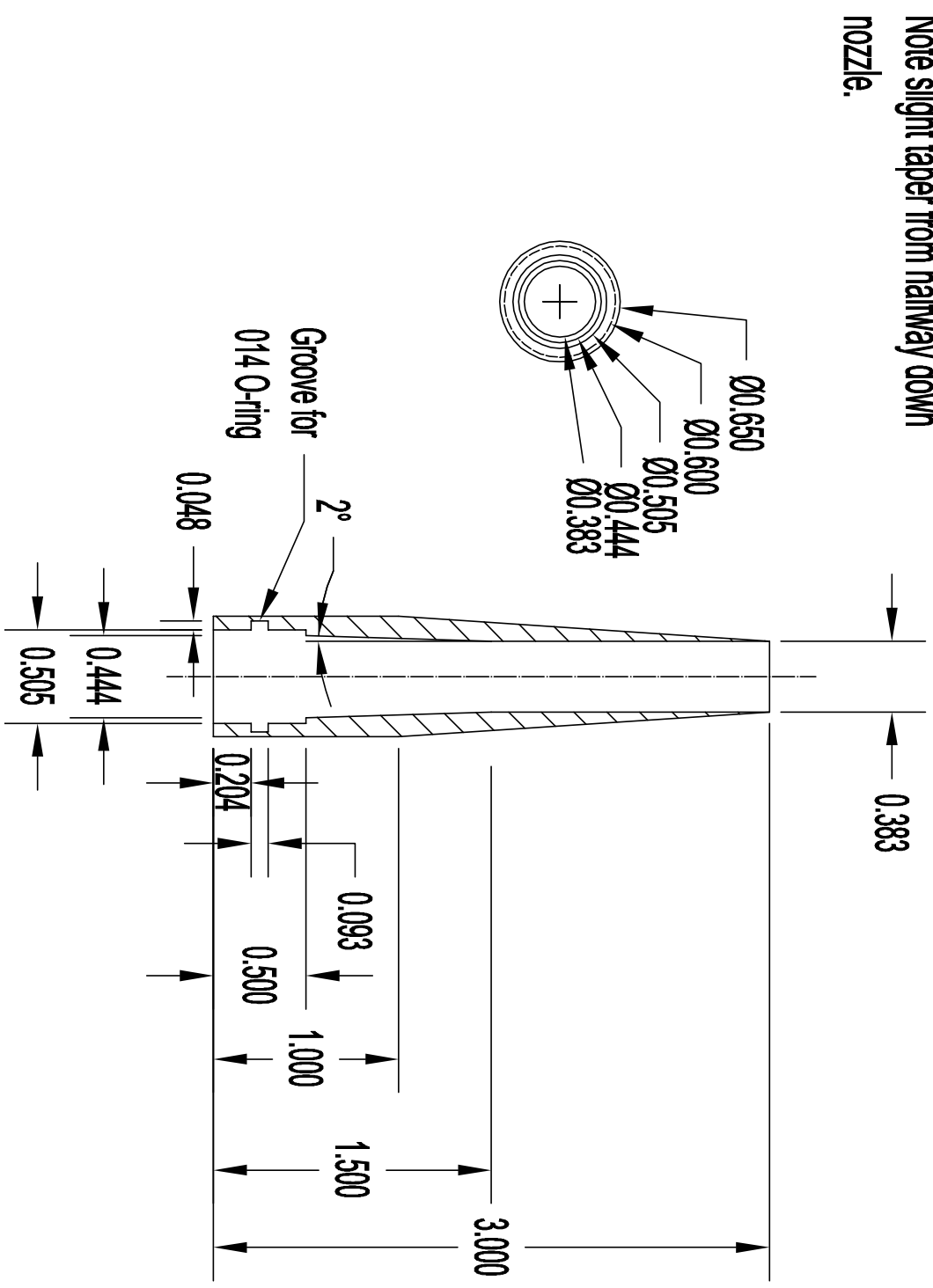

Fig. A.4: Plenum nozzle for 1.0 L/min flow rate

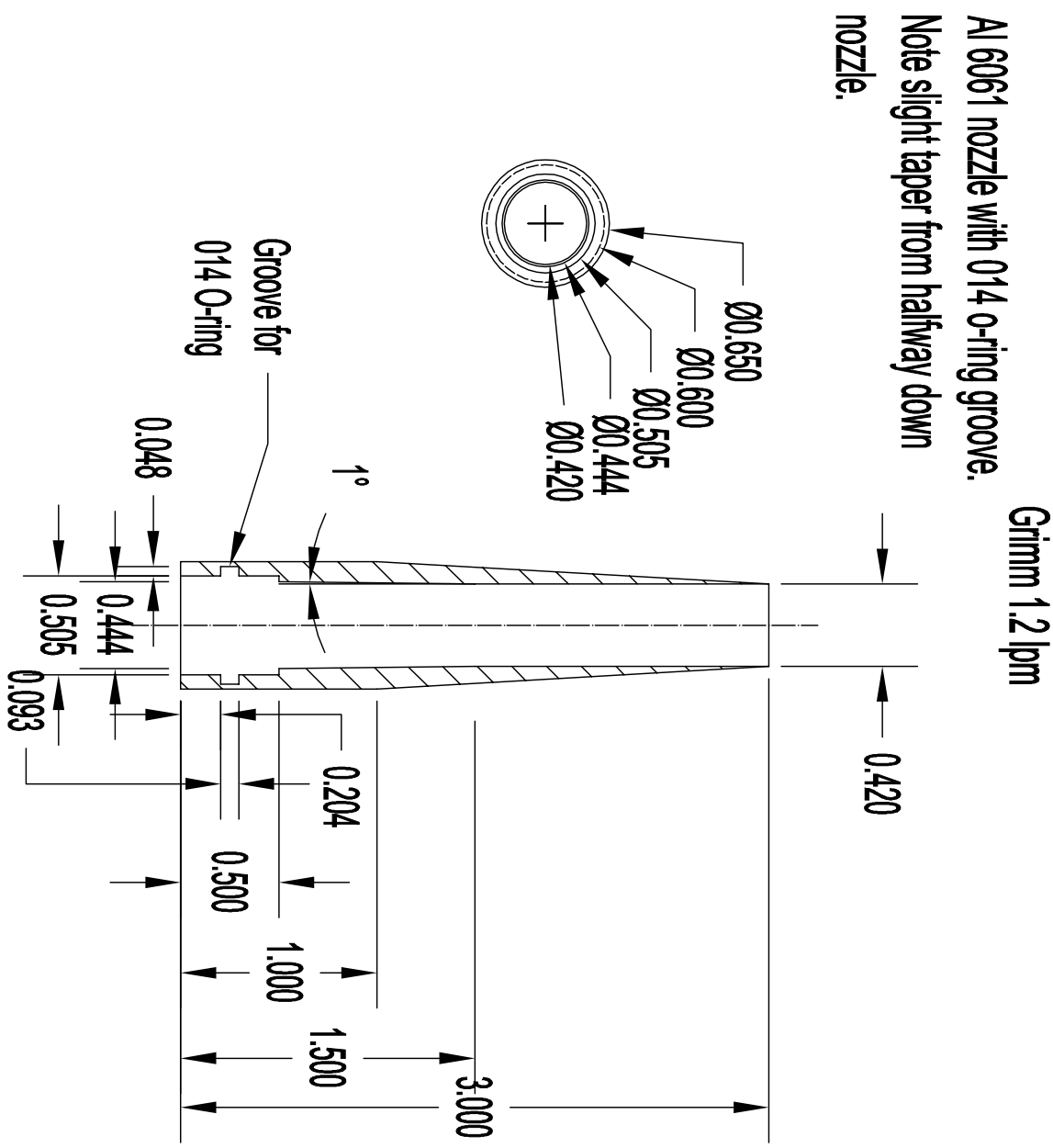

Fig. A.5: Plenum nozzle for 1.2 L/min flow rate

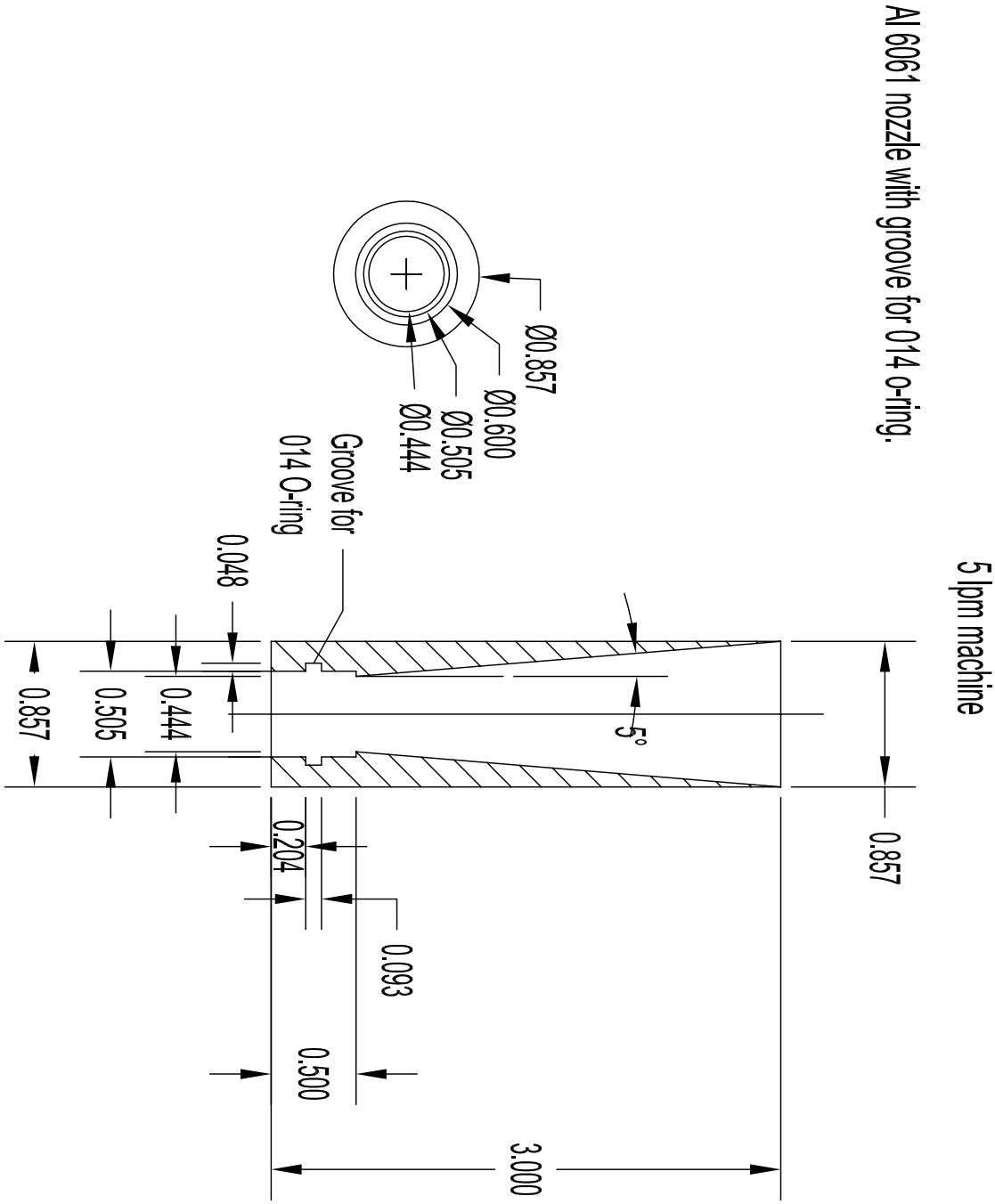

Fig. A.6: Plenum nozzle for 5 L/min flow rate

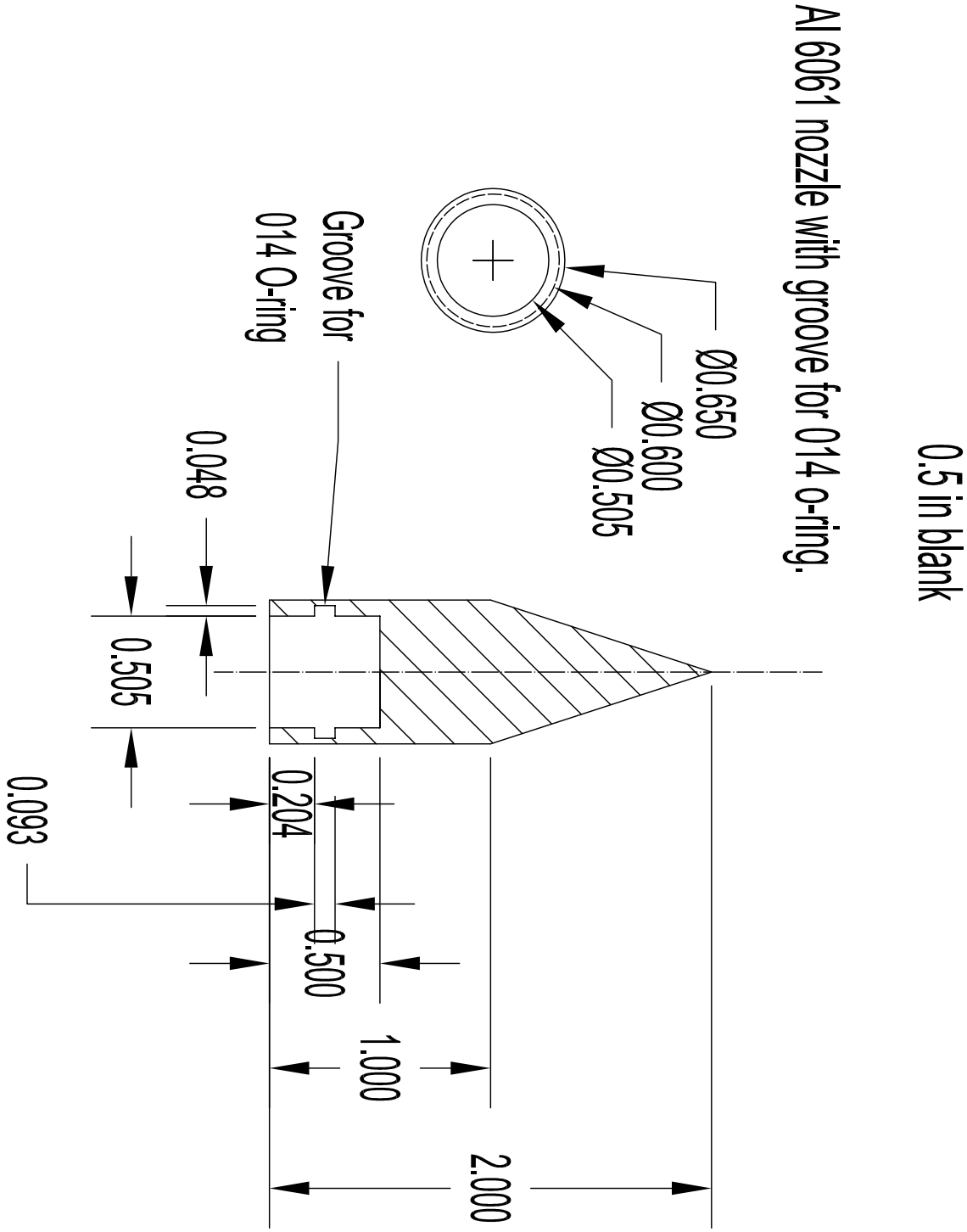

Fig. A.7: Plenum nozzle for 0 L/min flow rate (blank)

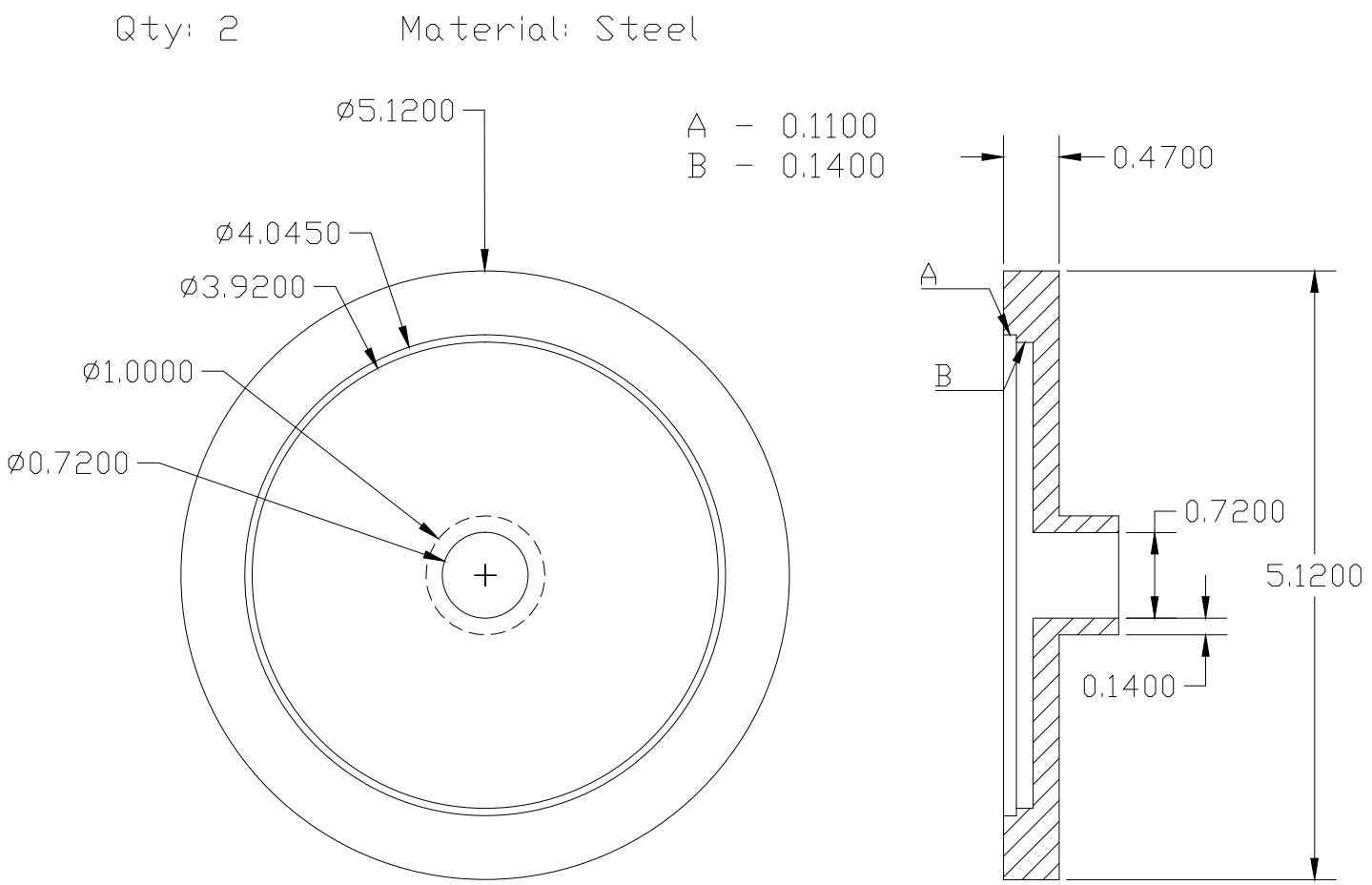

Fig. A.8: Flange to convert outlet HEPA filter flange to vacuum

A.2 Additional Flow Evaluation Data

The following tables are the full flow evaluation data for each of the flow conditioning options. For more information on this section, see Section 3.1.

Table A.1: Three inch straws at top with two inch choke

Locations	1”	1.5”	2”	2.5”	3”
5	0.16	0.22	0.25	0.24	0.22
6	0.16	0.21	0.22	0.24	0.22
5	0.16	0.21	0.23	0.23	0.21
6	0.16	0.21	0.23	0.24	0.21
5	0.16	0.22	0.24	0.25	0.22
6	0.16	0.21	0.24	0.24	0.21
Average	0.16	0.213	0.235	0.24	0.215
Std. Dev.	0	0.005	0.010	0.006	0.005

(a) Measurements from the flow conditioner.

	Avg (site 5)	Std. Dev (site 5)	Avg (site 6)	Std. Dev (site 6)
1	0.16	0	0.16	0
1.5	0.22	0.006	0.21	0
2	0.24	0.01	0.23	0.01
2.5	0.24	0.01	0.24	0
3	0.22	0.006	0.21	0.006

(b) Statistical averages and standard deviations for each location.

Table A.2: Three inch straws at bottom with two inch choke

Locations	1”	1.5”	2”	2.5”	3”
5	0.20	0.20	0.21	0.22	0.23
6	0.20	0.21	0.22	0.22	0.23
5	0.21	0.23	0.24	0.26	0.25
6	0.22	0.24	0.25	0.25	0.25
5	0.23	0.25	0.26	0.26	0.26
6	0.22	0.25	0.26	0.27	0.26
Average	0.21	0.23	0.24	0.25	0.25
Std. Dev.	0.012	0.021	0.021	0.022	0.014

(a) Measurements from the flow conditioner.

	Avg (site 5)	Std. Dev (site 5)	Avg (site 6)	Std. Dev (site 6)
1	0.21	0.015	0.21	0.012
1.5	0.23	0.025	0.23	0.021
2	0.24	0.025	0.24	0.021
2.5	0.25	0.023	0.25	0.025
3	0.25	0.015	0.25	0.015

(b) Statistical averages and standard deviations for each location.

Table A.3: Five inch straws at bottom with two inch choke

Locations	1”	1.5”	2”	2.5”	3”
5	0.20	0.22	0.22	0.22	0.22
6	0.19	0.20	0.22	0.22	0.22
5	0.20	0.21	0.21	0.21	0.21
6	0.19	0.21	0.21	0.22	0.21
5	0.21	0.22	0.24	0.24	0.24
6	0.22	0.23	0.24	0.25	0.24
Average	0.20	0.22	0.22	0.23	0.22
Std. Dev.	0.012	0.01	0.014	0.015	0.014

(a) Measurements from the flow conditioner.

	Avg (site 5)	Std. Dev (site 5)	Avg (site 6)	Std. Dev (site 6)
1	0.20	0.006	0.20	0.017
1.5	0.22	0.006	0.21	0.015
2	0.22	0.015	0.22	0.015
2.5	0.22	0.015	0.23	0.017
3	0.22	0.015	0.22	0.015

(b) Statistical averages and standard deviations for each location.

Table A.4: Five inch straws at top with no choke

Locations	1”	1.5”	2”	2.5”	3”
5	0.16	0.23	0.24	0.25	0.25
6	0.25	0.26	0.25	0.25	0.22
5	0.17	0.22	0.24	0.26	0.26
6	0.24	0.25	0.25	0.24	0.22
5	0.17	0.22	0.23	0.25	0.24
6	0.23	0.25	0.24	0.24	0.22
Average	0.20	0.24	0.24	0.25	0.24
Std. Dev.	0.041	0.017	0.008	0.008	0.018

(a) Measurements from the flow conditioner.

	Avg (site 5)	Std. Dev (site 5)	Avg (site 6)	Std. Dev (site 6)
1	0.17	0.006	0.24	0.010
1.5	0.22	0.006	0.25	0.006
2	0.24	0.006	0.25	0.006
2.5	0.25	0.006	0.24	0.006
3	0.25	0.010	0.22	0

(b) Statistical averages and standard deviations for each location.

Table A.5: Six inch straws at bottom with two inch choke

Locations	1”	1.5”	2”	2.5”	3”
5	0.16	0.20	0.22	0.22	0.20
6	0.17	0.20	0.20	0.20	0.19
5	0.17	0.20	0.21	0.21	0.20
6	0.18	0.22	0.22	0.22	0.20
5	0.17	0.22	0.22	0.23	0.21
6	0.18	0.23	0.23	0.23	0.21
Average	0.17	0.21	0.22	0.22	0.20
Std. Dev.	0.008	0.013	0.010	0.0012	0.008

(a) Measurements from the flow conditioner.

	Avg (site 5)	Std. Dev (site 5)	Avg (site 6)	Std. Dev (site 6)
1	0.17	0.006	0.18	0.006
1.5	0.21	0.012	0.22	0.015
2	0.22	0.006	0.22	0.015
2.5	0.22	0.010	0.22	0.015
3	0.20	0.006	0.20	0.010

(b) Statistical averages and standard deviations for each location.

A.3 Additional Aerosol Evaluation Data

The following table is the complete measurement schedule for determining the aerosol distribution across the system plane. For more information on this table, see Section 3.2.

Table A.6: Measurement schedule for determining aerosol distribution across system sampling plane.

	Site	Port	Location	Flow Rate
Initial	3	A	315	1
Initial	4	B	225	1
Initial	2	C	135	1.2
Initial	1	D	45	1.2
90 deg turn	1	D	315	1.2
90 deg turn	3	A	225	1
90 deg turn	4	B	135	1
90 deg turn	2	C	45	1.2
180 deg turn	1	C	315	1.2
180 deg turn	2	D	225	1.2
180 deg turn	4	A	135	1
180 deg turn	3	B	45	1
210 deg turn	1	C	285	1.2
210 deg turn	2	D	195	1.2
210 deg turn	4	A	102	1
210 deg turn	3	B	15	1
240 deg turn	4	B	345	1
240 deg turn	2	C	255	1.2
240 deg turn	1	D	165	1.2
240 deg turn	3	A	75	1
270 deg turn	4	B	315	1
270 deg turn	2	C	225	1.2
270 deg turn	1	D	135	1.2
270 deg turn	3	A	45	1

A.4 Cost Of Materials

The following tables are the complete breakdown of cost. For more information, see Section 4.2.

Table A.7: Pipes, tubes, and flange cost of materials.

Part Name	Vendor	Part #	Qty	Unit Price	Total Price
Stainless Steel Tubing (304L)	Lesker	SST-0400I	72	$3.65	$262.80
ISO-K Weld Flanges (304L SS) - Flange Size ISO100	Lesker	QF100-SWK	8	$75.00	$600.00
Double Clamps ISO63-ISO250 "K" Flanges	Lesker	QF-SDC-AL1	25	$6.20	$155.00
Centering Ring (SS with Fluorocarbon O-Ring) ISO100 "K" Flanges	Lesker	QF100-SAVR	4	$66.00	$264.00
Type 316 SS Smooth-Bore Seamless Tubing 1/2 in OD, 0.444 in, 0.028 in wall, 3 ft length	McMaster-Carr	89785K843	1	$27.75	$27.75
Conductive Silicon Tubing, 25 ft, 0.44 in ID x 0.75 in OD, 1/2 in FTG	TSI, Inc.	3001835	1	$425.00	$425.00
Subtotal					$1,734.55

Table A.8: Structural support cost of materials.

Part Name	Vendor	Part #	Qty	Unit Price	Total Price
Steel Strut Channel Slotted, 1-5/8 in X 1-5/8 in, Zinc-Plated, 2 ft Length	McMaster-Carr	3310T53	12	$7.48	$89.76
Steel Strut Channel Slotted, 1-5/8 in X 1-5/8 in, Zinc-Plated, 8 ft Length	McMaster-Carr	3310T214	7	$26.93	$188.51
Parallel Strut-Mount Clamp for 4 in OD, 3-1/2 in Pipe/Rigid Conduit, Zinc Pltd STL	McMaster-Carr	3193T21	3	$4.95	$14.85
Strut Channel Accessory 90 Degree Angle Bracket, 2-hole, Zinc-Plated Steel	McMaster-Carr	33125T32	30	$1.24	$37.20
Cover for 1-5/8 in Single Strut, Green Plastic	McMaster-Carr	3312T63	20	$1.87	$37.40
Caster for Strut Channel W/Side Wheel Brake, Swivel, 3 in X 1-1/4 in, 210# Cap	McMaster-Carr	2356T14	4	$20.38	$81.52
Grade 8 Alloy Steel Head Cap Screw Zinc Yellow Pltd, 3/8 in - 16 Thrd, 1 in L, Fully Thrd, packs of 50	McMaster-Carr	92620A624	1	$10.82	$10.82
Grade 8 Alloy Steel Head Cap Screw Zinc Yellow Pltd, 3/8 in - 16 Thrd, 1-1/2 in L, Fully Thrd, packs of 50	McMaster-Carr	91257A628	1	$9.62	$9.62
Zinc & Yellow Grade 8 Steel Flat Washer SAE, 3/8 in Screw Size, 13/16 in OD, 0.05 in - 0.08 in Thick, packs of 50	McMaster-Carr	98023A031	1	$5.14	$5.14
Zinc-Plated Steel Split Lock Washer 3/8 inScrew Size, 0.68 in OD, 0.09 in min Thick, packs of 100	McMaster-Carr	91102A760	1	$3.92	$3.92
Nut for Strut Channel Zinc-Plated STL, for 1-5/8 in Wide Strut, 3/8 in - 16 Thrd, Packs of 5	McMaster-Carr	3259T32	15	$5.76	$86.40
Subtotal					$565.14

Table A.9: Filter cost of materials.

Part Name	Vendor	Part #	Qty	Unit Price	Total Price
Inlet Vacuum Filter Carbon Steel with Zinc Clear Plated Finish ISO K100 Inlet/Outlet, Polyester Element	Lesker	PFI239 K100	1	$1,050.00	$1,050.00
ISO K100 Inlet/Outlet 520 Activated Carbon Impregnated Polyester Media (99+% Efficient at 5 microns)	Lesker	PFIHE238	1	$405.00	$405.00
Air Intake Filter 4 in Flange Connection, 520 Max SCFM, 14 in H, 10 in Dia	McMaster-Carr	4399K84	1	$246.48	$248.48
Replacement HEPA Filter Element 0.3 Micron, 200 SCFM, 7-7/8 in Outside Diameter	McMaster-Carr	9179K22	1	$201.92	$201.92
Subtotal					$1,905.40

Table A.10: Unions cost of materials.

Part Name	Vendor	Part #	Qty	Unit Price	Total Price
Ultra Torr Reducing Union 1 in X 3/4 in Ultra Torr	Swagelok	SS-16-UT-6-12	2	$137.30	$274.60
Ultra Torr Reducing Union 1/2 in X 1/4 in Ultra Torr	Swagelok	SS-8-UT-6-4	2	$45.10	$90.20
Ultra Torr Reducing Union 1/2 in X 1/8 in Ultra Torr	Swagelok	SS-8-UT-6-2	2	$54.00	$108.00
Hose connecting barb for 1/2 in	Swagelok	SS-8-HC-7-8	2	$26.50	$53.00
Subtotal					$525.80

Table A.11: Miscellaneous cost of materials.

Part Name	Vendor	Part #	Qty	Unit Price	Total Price
Steel Step Stand with Handrail 20-1/4 inTop Step Height, 2 Step, 225 lb Capacity	McMaster-Carr	8254T41	1	$40.57	$40.57
Plastic Storage Box with Tote Tray 16-1/8 in Width X 6-5/8 in Depth X 7 in Height Overall, Gray	McMaster-Carr	6576A11	1	$18.12	$18.12
Variac Variable Transformer	ISE, Inc.	3PN1210B	1	$406.00	$406.00
Kanomax A004, Anemomaster Model 1	MegaDepot	KAN-183-01	1	$276.10	$288.43
Subtotal					$753.12