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A DEVICE TO VALIDATE CONCENTRATION MEASURED BY DIRECT READING INSTRUMENTS FOR AEROSOLS

by

Sabah Khalid Saleh

A thesis submitted in partial fulfillment
of the requirements for the Master of
Science degree in Occupational and Environmental Health (Industrial Hygiene)
in the Graduate College of
The University of Iowa

December 2011

Thesis Supervisor: Associate Professor Thomas Peters

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CERTIFICATE OF APPROVAL

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MASTER'S THESIS

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This is to certify that the Master's thesis of

Sabah Khalid Saleh

has been approved by the Examining Committee for the thesis requirement for the Master of Science degree in Occupational and Environmental Health (Industrial Hygiene) at the December 2011 graduation.

Thesis Committee: _____
Thomas Peters, Thesis Supervisor

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To: My parents Khalid and Sarah for their never ending support. My wife Alaa for her encouragement, patience, and believe in me. My children Khaled, Ahmad, and Sarah for bringing joy to my life.

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ABSTRACT

Direct reading instruments (DRIs) are popular devices for measuring aerosols because they provide rapid on-site measurement of particle size and/or concentration. However, the output of DRIs may drift over time requiring frequent manufacturer calibration. Given the possibility of drift, the output of DRIs should ideally be verified to ensure proper response before and after field use. Methods for verifying the output of DRIs particle size reading are available for use in laboratory and field. However, methods for verifying the DRIs concentration reading are complex and often use of stationary installations that are not suited for field work. The objective of this study was to develop a verification device that can be used in the field to verify the output of DRIs for measuring aerosol concentration.

The new device uses a nebulizer that produces aerosols through vibrating mesh technology. This vibrating mesh nebulizer (VMN) uses only electrical input to generate aerosols and does not require compressed air.

The verification device was able to produce stable output of aerosols at low concentrations (0.2 mg/m^3 to 1.2 mg/m^3). It was also possible to produce different concentration levels of aerosol by changing the electrical current to the VMN. The verification device was used to monitor and validate the output of a condensation particle counter and a photometer. Results showed that both instruments having valid output and did not require manufacture calibration.

The verification device made it possible to monitor and verify the output of two DRIs. This was achieved by generating reproducible aerosol output with specific composition. This verification device presents a practical method to verify the concentration output of DRIs for measuring aerosols.

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CHAPTER I

INTRODUCTION AND LITERATURE REVIEW

An average of 400,000 workers suffer from work related illnesses every year, and an average 140 workers die from work related diseases every day (Levy et al., 2006). Many of these diseases result from exposure to harmful substances in the workplace. Inhalation is a major route of exposure to these substances. To prevent illness from inhalation, the Occupational Safety and Health Administration (OSHA) mandates airborne concentrations be maintained below published permissible exposure limits (OSHA, 2006).

Airborne concentrations of harmful substances can be measured using different techniques and equipment. Direct reading instruments (DRIs) are a popular way to quickly and simply measure airborne concentrations. They provide instantaneous readings of concentration in air, monitor them over time, and provide measurements in electronic format (Coffey & Pearce, 2010). In the industrial hygiene field, DRIs are available for gases, vapors, and aerosols.

DRIs require frequent calibration to ensure accuracy of measurements. The calibration process varies from instrument to instrument. For gases and vapors, calibration and verification methods are available. These methods generally use known concentration of gas to verify DRI response. On the other hand, the devices for calibrating and/or verifying output of aerosol concentrations have complex set up and use stationary installations. For that reason, there is a need for newer devices that simplify the process of calibrating and/or verifying output of aerosol DRIs.

This chapter begins with a description of adverse health effects associated with exposure to aerosols and the methods used to assess exposures. Then it describes the advantages and limitations of using DRIs for measuring aerosols. After that, a review of some of the calibration methods used for DRIs is provided. In the last section of the

chapter, the new technology of Vibrating Mesh Nebulizers (VMNs) and how they may be used to generate aerosol is presented. The objective of this study is provided at the end of this chapter.

Aerosols and Their Health Impact

Aerosols are defined as a suspension of solid or liquid particles in a gas. They can occur in the forms of dust, fume, smoke, mist, fog, haze, clouds, or smog (Hinds, 1999). Aerosols are often categorized by their particle diameter. EPA classifies particles larger than 10 μm as supercoarse, from 10 to 2.5 μm as coarse, smaller than 1 μm as fine, and smaller than 0.1 μm as ultrafine (EPA, 2010). The American Conference of Governmental Industrial Hygienists (ACGIH) classifies occupational size fractions as inhalable, thoracic, and respirable (ACGIH, 2009). Aerosols can occur naturally in the environment or be human made (Johnson & Vincent, 2003). The most abundant naturally occurring aerosols are sea salt and mineral dust (Zender, 2007).

In the workplace, most aerosols are man-made. Often concentrations of man-made aerosols are considerably higher than the naturally occurring ones in the ambient environment (Kim et al., 2004). Occupational aerosols are generated from various equipment, processes, and activities. For example, mechanical handling activities, such as mining, produce relatively large coarse particles, whereas hot processes, such as welding, produce relatively small fine and ultrafine particles (Vincent & Clement, 2011). Man-made aerosols can be end products like nanotubes and quantum dots, or they can be unwanted by-products like coal dust and metal fumes.

The behavior of inhaled particles in the human body depends strongly on their size, shape, density, and chemical composition. The size of a particle is a main factor of determining where in the respiratory tract a particle will deposit (Wallace et al., 2006). Inhaled particles larger than 5 μm will mostly deposit in the nasopharyngeal region. Those between 5 μm and 1 μm will mostly deposit in the tracheobronchial region

(Witschi & Last, 2003). Particles with size of 0.5 μm or smaller will mostly deposit in the alveolar region (Hinds, 1999).

Exposure to aerosols with different chemical composition may cause various toxicological effects on human health. For example, exposure to asbestos dust can cause asbestosis, exposure to coal dust can cause black lung disease, and exposure to welding fumes can cause metal fume fever (Ahsan et al., 2009).

Regulations and Conventional Exposure Assessment

Regulations and standards are set by multiple bodies to protect workers from inhaling aerosols at harmful levels. EPA regulates environmental exposure by setting standards such as PM-10 and PM2.5 (EPA, 2010). OSHA regulates occupational exposure to harmful substances by establishing and enforcing its Permissible Exposure Limits (PELs) (OSHA, 2006). The National Institute for Occupational Safety and Health (NIOSH) has developed Recommended Exposure Limits (RELs). These RELs are based on a time-weighted average (TWA) exposure of ten-hour workday and forty-hour workweek. The ACGIH has developed Threshold Limit Values (TLVs) that are based on TWA exposure of eight-hour workday and forty-hour workweek. Both of the RELs and TLVs are recommended limits based on scientific research. These limits provide comprehensive and updated information regarding exposure to harmful substance.

Industrial hygienists conduct air sampling to collect information about the air contaminants such as composition, particle size, length of exposure, and concentration levels. This information can help determine if contaminant exposure exceed regulatory limits (Smith & Schneider, 2006). Air sampling of gases and vapors mostly focus on collecting information about the contaminant concentration and type (Breysse & Lees, 2003). Air sampling of aerosols focuses on collecting information such as aerosol morphology, concentration, and particle size (Johnson & Vincent, 2003). Many of the air sampling conventional methods involve collecting samples that are analyzed in

laboratory. For example, cyclones and impactors separate large particles before collecting airborne contaminant on a filter that is analyzed in laboratory to measure particles concentration in air (Abdel-salam, 2006). The results/concentrations from samples collected by these conventional methods are not available for days/weeks. The length of time associated with conventional methods is problematic when fast sample analysis is required (seconds to minutes).

Direct Reading Instruments for Gases, Vapors, and Aerosols

DRIs have been developed and improved over the years to overcome the limitations of conventional air sampling methods. DRIs are designed to sample and analyze air contaminants within the instrument in a relatively short time (Baron, 1994). Industrial hygienists use DRI for applications like background sampling, walk-through surveys, particle measurements, assessment of indoor air quality, and evaluation of contaminant removal systems (Thorpe & Walsh, 2007). These measurements show the change in contaminant behavior over time and allow for more detailed analysis.

DRIs for aerosols use optical, electrical, resonance oscillation, or beta absorption techniques to provide information on particles size, size distribution, mass concentration, number concentration, or surface area concentration. These DRIs are available in many sizes, which influence where they will be used. Some DRI are designed to be used in laboratories for research, and they usually consist of complex stationary installations. The scanning mobility particle sizer (SMPS) is an example of a DRI that is used in research laboratories. Field DRIs are smaller, portable, lightweight, and simple to use making them amenable for use in the field. Many of these instruments have battery charging capabilities and do not require the use of electrical current line while operating. Light-scattering photometers are an example of a field DRI. Photometers relate the amount of light scattered by an aerosol to mass concentration (Baron, 1994). Condensation particle

counters (CPCs) are another example of field DRIs. The CPC measures number concentration of fine and ultrafine particles by enlarging their particles size then uses photometer for detection (Sem, 2002). The CPC draws the air containing the aerosol through a heated saturator chamber. In the chamber, alcohol vapor is diffused with the airstream. Then, the airflow containing the aerosol and alcohol vapor is passed through a cooled condenser. The cooling effect causes the alcohol vapor to condensate on the particle in the sampled air. This process enlarges the particles to a size detectable by the optical detector inside the CPC.

Methods to Calibrate and Validate DRI Output

The DRI output may drift reducing its accuracy, and it is important to correct for that drift by calibrating the instrument. DRIs are usually calibrated both in the field and in the manufacturer factory. Factory calibration is performed by the DRI manufacturer to ensure that the instrument has proper response when compared with similar instruments. Field calibration can be performed to adjust for instrument drift and improve the accuracy level (Todd, 2003).

The calibration process differs by instrument type. Most DRIs for gases and vapors have similar general calibration process. These DRIs are designed to detect certain gases such as ammonia or hydrogen sulfide. The general calibration procedure involves the use of span gas cylinders that contain known concentration of the gas detectable by the DRI. These span gas cylinders are commercially available for wide range of DRIs. The use of span gas provides a convenient way to field-verify gas and vapor DRIs. In contrast, aerosols DRIs have the same calibration necessity as the gas DRIs. However, it is more difficult to verify the output from aerosol instruments. For example, DRI that measure particle size or size distribution, are calibrated by using known sizes of nebulized monodisperse polystyrene latex (PSL) spheres (Berglund & Liu, 1973). These PSL spheres are commercially available for wide range of particle size. On the other

hand, the methods for verifying the concentration are complex and often involve the use of stationary installations.

The general process of calibrating DRIs that output number concentration is performed by measuring the instrument response to known particle number concentration (Ojanpera et al., 2010). For example, the process for calibrating condensation particle counters involves the use of differential mobility analyzer, combined with a calibrated aerosol electrometer, as a number calibration standard (Liu et al., 1975). This method has also been used to calibrate instruments that measure particle size distribution (Mulholland et al., 2006).

DRIs that measure number concentration of large particles (coarse) can be calibrated against reference measurement of mass concentration (Ojanpera et al., 2010). For example an aerodynamic particle sizer was calibrated against gravimetric mass concentration measured by a cascade impactor (Armendariz & Leith, 2002). However, this method is not practical for small particles (fine and ultra-fine) because of the prolonged measurement times of air contaminants (Ojanpera et al., 2010). Also there are commercial instruments, like TSI Vibrating Orifice Aerosol Generator (VOAG), that can generate uniformed particles that can be used to calibrate instruments that measure particle size or number concentration (Lee et al., 2010). The VOAG has a stationary design that is suitable for laboratory settings but not for field applications. There is shortage in the literature for devices that are designed to be used in the field to verify DRIs concentration output. Nebulizers are designed to generate aerosols and could be used as the base for making devices from verifying DRIs output in the field.

Aerosol Generation Using Nebulizer

Nebulizers are popular medical devices used to deliver medication to the deep part of the respiratory tract. Nebulizers can change liquids into inhalable aerosols and are used in aerosol drug therapy by delivering drugs directly in the airways of patients with

severe airflow obstruction (Marino, 2006). Nebulizers are used in the therapy of diseases like chronic obstructive pulmonary disease (COPD), asthma, and cystic fibrosis (Newman & Turner, 2005).

Nebulizers have been used for a long time in the medical field. One of the early known electrical nebulizers was invited by Weil in Frankfurt in1930s and it was named the "Pneumostat". This device was used to make aerosols from medical liquids using power from an electrical compressor (Henning, 2008). Nebulizer technology has improved over the years and different types of nebulizers are commercially available for the public. Most conventional nebulizers use compressed air or oxygen under high velocity to aerosolize liquid medicine (Finlay, 2011).

In the field of industrial hygiene, nebulizers have been used to generate monodisperse aerosols that are used in applications like filter testing and instrument calibration (Lind, Danner, & Guentay, 2010). The jet and ultrasonic nebulizers are popular nebulizers used to generate aerosols. However, jet and ultrasonic nebulizers have their limitations as aerosol generators. The jet nebulizer requires the use of compressed air, and the ultrasonic nebulizer increases the temperature of the nebulizer solution (Steckel & Eskandar, 2003). The use of compressed air is a big drawback and limits the use of conventional nebulizer as aerosol generators outside of the laboratory.

A new generation of nebulizers, known as vibrating mesh nebulizers (VMN), has been recently developed. The VMN forces liquid through a vibrating mesh of micron sized holes turning it into aerosols (Newman & Turner, 2005). VMNs do not use compressed air nor generate heat when operating, which overcome the limitations of both jet and ultrasonic nebulizers (Ghazanfari et al., 2007). VMN have the advantage of being portable, small, and battery-operated (Newman & Turner, 2005).

Study Objective

DRIs for counting aerosols are regularly used in research laboratory and field sampling. The methods for validating the DRIs reading of particle size distribution are available for use in laboratory and field settings. However, the methods for validating DRIs concentration reading have complex set up and use stationary equipment that are not suited for field application. DRIs for measuring aerosol concentration in the field are most affected by the lack of these validating means. There is a need for more methods and instruments that can be used in the field to check and validate output of aerosols DRIs measuring number and mass concentrations.

Thus, the objective of this study was to develop a reliable, robust, and in-field device to generate reproducible aerosol concentrations of specific composition to verify DRI output. In this study, a verification device was developed using a VMN to generate aerosols. The output from this device can be used to verify the output of in-field DRI for measuring aerosols concentration.

CHAPTER II

EXPERIMENTAL STUDY

Introduction

Direct reading instruments (DRIs) are common equipment used for measuring airborne contaminants. DRIs are designed to sample and analyze air contaminants within the instrument in a relatively short time (Baron, 1994). DRIs for measuring aerosols are available in two types. The first type is the sizer and it measures the particle size and concentration. These sizers are relatively expensive, bulky, and not practical for industrial hygienists use in filed. The other type of aerosol DRIs is designed to measure particle mass and number concentrations (Abdel-salam, 2006). These DRIs are cost effective, portable, lightweight, and simple to use making them suitable for industrial hygienists use in filed. Light-scattering photometers and condensation particle counters (CPCs) are two examples of DRIs commonly used by industrial hygienists (Sem, 2002).

The output of a DRI can drift. Thus, it is important to correct for that drift by calibrating the instrument (Todd, 2003) and verify the accuracy of readings prior to use. Methods are available to validate sizing accuracy of DRIs. For example, known size of monodisperse polystyrene latex (PSL) spheres are commonly used to validate particle sizing DRIs (Berglund & Liu, 1973). In contrast, methods to verify concentration are not common. These methods often use complex set up and stationary equipment not suited for field application. For example, a differential mobility analyzer combined with a calibrated aerosol electrometer was used as a number calibration standard (Liu et al., 1975). This method uses compressed air to generate aerosols. Another example was calibrating an aerodynamic particle sizer against a gravimetric mass concentration measured by a cascade impactor (Armendariz & Leith, 2002). This method is not practical for small particles (fine and ultra-fine) because of the prolonged measurement times of air contaminants (Ojanpera et al., 2010). The vibrating orifice aerosol generator

(VOAG), by TSI, is an example of a device that can generate uniform particles that can be used to validate DRIs particle size or number concentration (Lee et al., 2010). The VOAG is bulky and difficult to operate making it suitable for laboratory use but not for field applications.

There is a need for methods for validating DRIs concentration reading in field. Developing such method would require the use of an aerosol generating device. Medical nebulizers are designed to change liquids into inhalable aerosols and can be used to generate aerosol. The traditional pneumatic and jet nebulizers have been used to generate aerosols (Steckel & Eskandar, 2003). However, these nebulizers require compressed air to function (Clay et al., 1983), and that complicates their field use.

Technological advances led to the creation of a new type of vibrating mesh nebulizers (VMN) for aerosols drug therapy (Newman & Turner, 2005). The VMNs use a vibrating plate with precision holes to aerosolize liquid. These nebulizers have the advantages of electrically generating low-velocity aerosol without using compressed air (Ghazanfari et al., 2007).

The objective of this study was to develop a reliable, robust, and portable verification device that can be used to validate the concentration output of DRIs for aerosols. This device uses a VMN to generate aerosols at different concentrations and stable rate. The VMN generates aerosols at high rate that surpassed the concentration limit of detection of most DRIs. This high generation rate was overcome by modifying the VMN controller to produce adjustable concentrations of aerosols.

Methods

Evaluation of a Vibrating Mesh Nebulizer

We evaluated the output of a VMN (Model Aeroneb Solo System, Aerogen, Galway, Ireland). The VMN forces liquid through a vibrating mesh of micron-sized holes turning it into aerosols. VMNs do not use compressed air nor generate heat when

operating, which overcome the limitations of both jet and ultrasonic nebulizers. VMN have the advantage of being portable and small.

The evaluation was conducted by testing three VMN units of the same model to assess the differences in their output and their ability to produce repeatable output over time. The experimental set up used for testing the VMN units is shown in Figure 1. Each VMN unit was used to generate aerosols that were injected into the mixing chamber. The volume of the mixing chamber was 450 L, and the air flow rate delivered to it was 1290 L/min. A CPC (Model 3007, TSI Inc., Shoreview, MN) was used to measure the number concentration in the sampling chamber. A saline solution of 0.9% sodium chloride (Baxter, Deerfield, IL) was used for all tests described in this work.

The concentration output of each unit was measured in three tests repeated over three days. Each test consisted of three minute measurements with six second logging interval for a total of thirty samples. An illustration of the test measurements is provided in Appendix A. A two-way analysis of variance (ANOVA) statistical test was used to evaluate the differences in output between the three VMN units and evaluate the differences in output over time.

Evaluation of the Verification Device Performance

The VMN came with a battery-operated controller that provided power to the VMN. The controller provided a constant current to the VMN and was controlled by a single power button. Turning the controller on caused the VMN to produce full output, and turning the controller off caused the VMN to stop. The controller, provided by factory, was designed to either turn on or off the VMN producing one level of concentration. For that reason, the VMN controller was modified to produce adjustable concentration levels of aerosols. The modified controller consists of three parts: a pulse width modulation (PWM) program, a data acquisition board, and an optical relay as shown in Figure 2. The PWM computer program (LabVIEW, Version 9.0, National

Instruments, Austin, TX) commands the data acquisition board to send a 5-volt signal at defined intervals to the optical relay. The optical relay powers on the nebulizer when it receives a 5-volt signal and off when no signal is received.

The PWM program allowed us to control the fraction of time that the VMN is on with frequency and duty cycle. The relationship between VMN time on, duty cycle, and frequency is based on the following equation:

$$\text{VMN time on} = \frac{\text{Duty cycle}}{100\%} \times \frac{1}{\text{Frequency}}$$

where duty cycle is the percent of time cycle that the power is on and 1/frequency is the time of one cycle. For example, a frequency 1 Hz and duty cycle of 50% will result in VMN on time of 0.5 seconds.

The verification device that incorporates a VMN is shown in Figure 3. The verification device has two air pumps to provide a constant airflow and transport the generated aerosol through the device. The pump at the start of the experimental set up supplies air to the device, and the second pump at the end of the system pulls air. The airflow entering the verification device is filtered by a high efficiency particulate air (HEPA) filter (Model Pall HEPA Capsule, Pall Life Sciences, Ann Arbor, MI).

The filtered air moves through the VMN, where the aerosols are generated. The modified controller is used to adjust the particle generation rate of the VMN. After the nebulizer, the air containing the aerosol enters a mixing chamber. Then the airflow passes through a Diffusion Dryer (Diffusion Dryer, Model 3062, TSI Inc., Shoreview, MN) to remove water vapor from the generated aerosols. The dry aerosol is passed through a modified HEPA filter (Model HEPA-CAP 36, Whatman Ltd, Piscataway, NJ) to reduce the concentration from the nebulizer. It was modified by piercing a hole of diameter 1 mm, to allow a small percentage of the particles to pass through. Evaluation of the modified HEPA filter reduction factor is provided in Appendix B.

The airflow is then passed through an eight-way manifold to distribute the aerosol. Up to six DRIs can be simultaneously connected to the manifold for validation measurements. The manifold connecting ports are kept closed when not in use. The other end of the manifold is connected to an aerosol photometer (MicroDust pro, Model 176000A, Casella USA, Amherst, NH) to measure particulate mass concentration in the range of 0.001 to 2500 mg/m^3. The photometer was made a permanent part of the verification device to account for variability in VMN output between days. This photometer is supplied with its own optical calibration element that can be used to restore the instrument to factory calibration settings. This calibration element can generate a fixed optical scattering effect that can be used for span calibration. This method of confirming the factory calibration enables the photometer to be used as a reference instrument to evaluate other DRIs performance.

Then lastly, the airflow is exhausted by the air pump located after the photometer. That pump is equipped with its own HEPA filter to clean the exhaust air. The DRIs connected to manifold have air pumps that add additional flow suction to the verification device. This additional flow suction is corrected by lowering the flow from the exiting air pump. For all tests, the flow rate in the system was maintained at 30 L/min, with the static pressure being slightly positive at 0.5 inches of water. The positive pressure helps to keep the nebulizer running at lower generating rates.

The verification device is operated firstly by adding the saline solution to the nebulizer. Then secondly, the DRIs are connected to the flow manifold. Then, both pumps are used to balance the flow and maintain it at 30 L/min.

The nebulizer generation rate was measured as a function of duty cycle and frequency. The following equations were used to calculate the nebulizer emissions rate:

$$\dot{E}m = Cm\ (mg/\ m^3) \times Q\ (L/min) \times (1\ m^3/1000\ L)$$

$$\dot{E}n = Cn\ (particles\ /\ cm^3) \times Q\ (L/min) \times (1000\ cm^3/1\ m^3)$$

where Ėm is the mass emissions rate, Cm is the mass concentration, Q is the flow, Ėn is the number emissions rate, and the Cn is the number concentration. Measurements were taken at frequencies of 1, 10, and 100 Hz and at duty cycle of 5, 10, and 20%. Each of the nine test conditions was repeated three times to assess the variability in measurements.

The particle size distribution of the generated aerosol was measured with a scanning mobility particle sizer (SMPS, Model 5.402, GRIMM Technologies, Inc. Douglasville, GA) at different PWM program settings (duty cycles and frequencies). For a frequency of 1 Hz, the size distribution was measured for duty cycles of 5, 10, and 20%. For a duty cycle of 20%, the size distribution was measured for frequencies of 1, 10, and 100 Hz. Each test condition was repeated three times to assess the variability between repeatable measurements.

Quality Control Charts and Validating DRIs Readout

Quality control charts have been used as the primary method to monitor and validate the concentration reading of aerosol DRIs. The quality control charts were made using the verification device, the reference photometer, and the test DRI. The first step in developing quality control charts was to use the verification device to generate specific concentration of aerosols. Then, concentration measurements were taken using the reference photometer and the DRI being tested. For each test, a concentration ratio was computed using the test DRI measurements as numerator and the reference photometer measurements as denominator in accordance to the following equation:

Concentration Ratio = DRI measurement / Reference photometer measurement these measurements were repeated three times to obtain three separate concentration ratios. The mean of these concentration ratios was used to develop the central line in the quality control chart. Then an upper and lower limit lines were developed as three standard deviations from the central line.

Three quality control charts were made for each test DRI at low, medium, and high concentration levels. The PWM setting was 5% duty cycle for low, 10% duty cycle for medium, and 20% duty cycle for high concentrations. And the PWM frequency was set to 1 Hz for all settings. The verification device was used to create quality control charts for two aerosol measuring DRIs. The first was a CPC (Model 3007, TSI Inc., Shoreview, MN) and the second was a pDR-1200 (personalDataram, Thermo Fisher Scientific Inc, Waltham, MA).

Then, repeated tests were performed on six days to monitor and validate the concentration output of both DRIs. These measurements were made at low, medium, and high concentration levels using the verification device. The new measurements were used to calculate and plot new ratio values on the quality control chart previously made for the DRI. The DRI was considered to have valid readings if the concentration ratio value within the upper and lower limits of the quality control chart.

Results and Discussion

Evaluation of the Vibrating Mesh Nebulizer

Table 1 shows the two-way ANOVA results of testing the differences of output between three VMN units and the differences of output between days. Table 2 shows a summary of the number concentration mean measurements from testing three VMN units at three days. The overall means of the number concentrations produced by three VMN units were not statistically different ($p = 0.148$). This result suggests that different VMN nebulizers produce similar aerosols concentration. Thus, different VMN units can be interchanged. Interchanging units may be important if they become clogged or otherwise break.

The two-way ANOVA also showed that there was a slight but significant difference in VMN output between days ($p = 0.037$). This result shows that the output of the VMN could change when used at different days. To account for this change, a

photometer was used as reference instrument in the developed verification device. The functionality of both the verification device and reference photometer were discussed in methods section.

Evaluation of the Verification Device Output

The nebulizer mass emission rate is shown in Figure 4. Changing the PWM duty cycle and frequency changed the nebulizer mass emission rate. Higher duty cycles increased the nebulizer output and higher frequencies reduced it. The highest mass emission rate was produced at higher duty cycle and lower frequency PWM setting. These results were expected because the nebulizer was designed to run longer at larger duty cycle and smaller frequency PWM settings. These results show that the verification device concentration output can controlling by changing the PWM frequency or duty cycle settings.

Changing the PWM frequency to adjust aerosol concentrations had variable results. As shown in Figure 4, the nebulizer emission rate at 10 Hz frequency had similar values to those at 1 Hz frequency. The nebulizer mass emission rate at 100 Hz frequency was very small when compared to the other frequencies.

Adjusting the duty cycle resulted in a noticeable change in the verification device mass output. The mass output at 1 Hz frequency was 0.33 mg/min, 0.64 mg/min, and 1.3 mg/min for duty cycles 5%, 10%, and 20% respectively. These results demonstrate that the mass output of the device was more sensitive to changes in duty cycle than it was to changes in frequency.

The nebulizer number emission rate is shown in Figure 5, and it behaved similarly to the mass emission rate. Controlling the verification device output was best achieved at PWM setting of 1 Hz frequency and multiple duty cycles. Maintaining the frequency at 1 Hz and modifying the duty cycle setting was shown to be the most stable method to adjust nebulizer output.

The particle size distribution at different PWM settings is shown in Figure 6 and Figure 7. The particle size distribution was observed to generally be lognormally distributed. The particle geometric mean diameter at different PWM settings had a range between 59 nm to 73 nm (Table 3 and Table 4). Also, the geometric standard deviation ranged from 2.4 to 2.6. The changes in PWM setting did not have a major impact on the particle size distribution. Measurements taken by the SMPS showed that the particle size distribution was not affected by changing the PWM settings.

Quality Control Charts and Validating DRIs Readout

Figure 8 shows the CPC quality control charts developed at low, medium, and high concentration settings. The central line, which was obtained from the ratio between the CPC and photometer, had concentration ratios of 10300 for low concentration chart, 10100 for medium concentration chart, and 10300 for high concentration chart. The six test measurements that were taken to validate CPC reading fell within three standard deviations for all three charts. This shows that there was no noticeable drift in the CPC readings.

The pDR quality control charts are shown in Figure 9. The central line had concentration ratio values of 0.42 for low concentration chart, 0.43 for medium concentration chart, and 0.44 for high concentration chart. The six test measurements fell within the upper and lower control limits for all three charts.

The process of using quality control charts to validate the CPC and pDR measurements showed that there were no drifts in their output. The test measurement ratio values fell within the upper and lower control limits indicating constant DRIs response over different times. This procedure provides a reliable method of monitoring the response of the DRIs over time. Any drifts in the DRI output are expected to be observed as excursions in the quality control chart for that instrument.

Conclusion

The verification device used a VMN to generate aerosols at multiple concentration levels. The VMN output changed between days and a reference photometer was used to correct for this change. This reference photometer could be restored to factory calibration settings by using an optical calibration element. The verification device made it possible to verify the output of other aerosol DRIs like the CPC and pDR. The components of the verification device were fairly small and portable. This configuration, allowed the verification device to be used both in laboratory and field without restrictions.

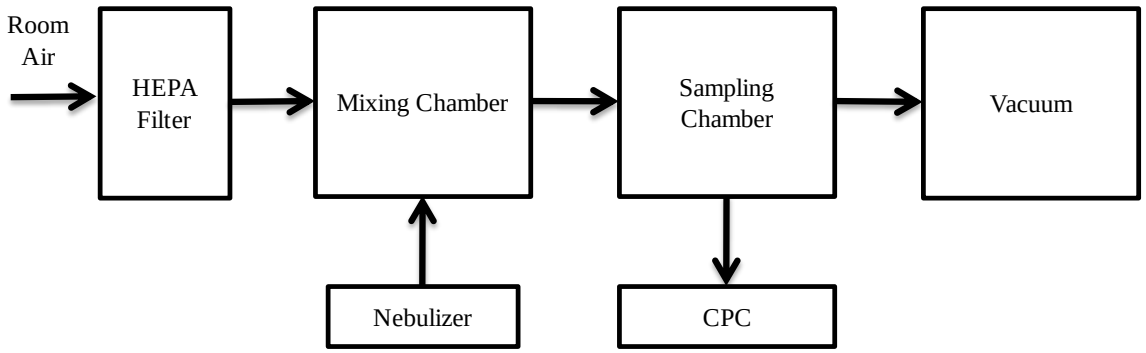

Figure 1: Experimental Setup for Evaluating the VMN.

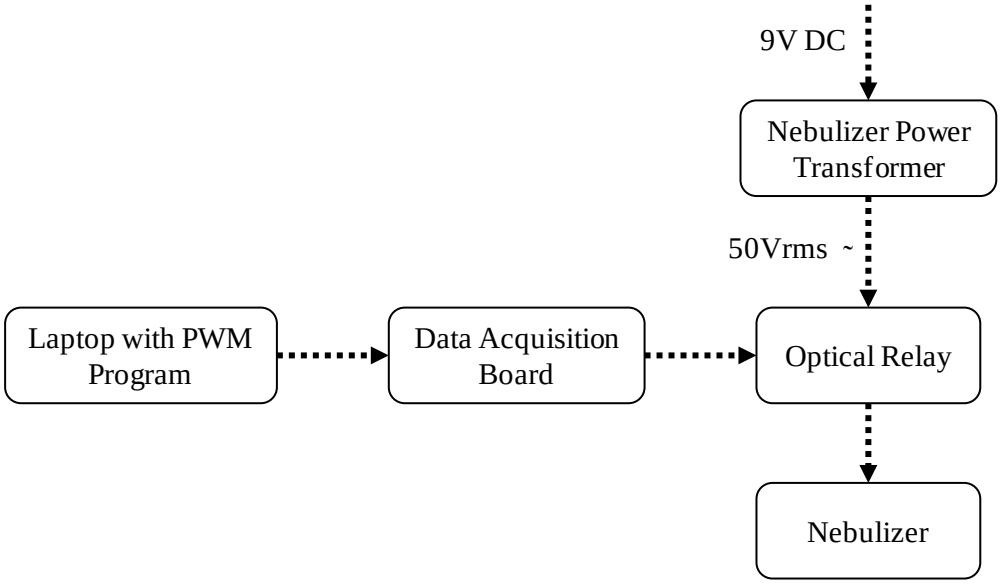

Figure 2: Schematic Diagram of the Controller for the VMN.

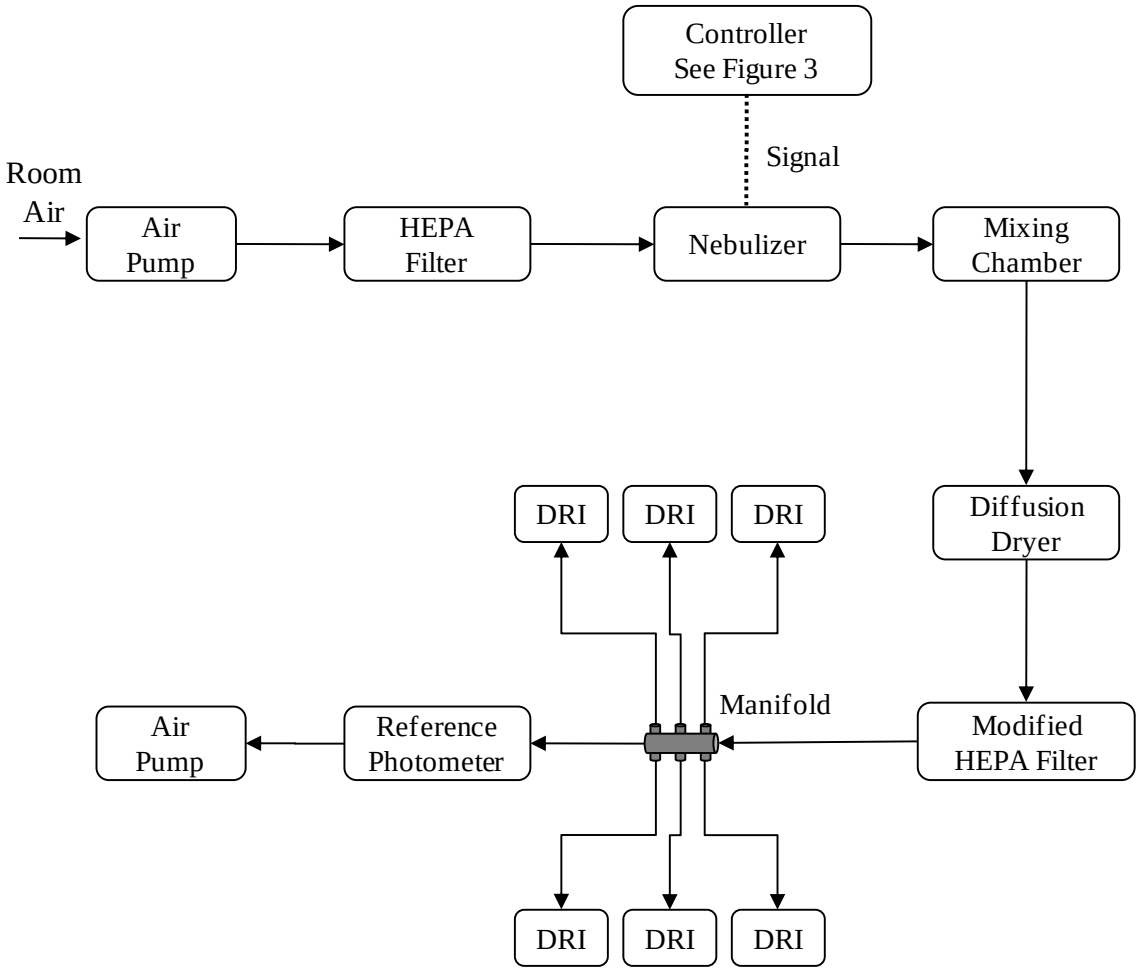

Figure 3: Verification Device Experimental Set Up.

Table 1: Summary of two-way ANOVA statistical test evaluating the number concentration measurements of three VMN units at three days.

Source	DF	SS	MS	F	P
Nebulizer	2	25577637	12788818	2.13	0.148
Days	2	47717383	23858691	3.97	0.037
Interaction	4	6316661	1579165	0.26	0.898
Error	18	108088669	6004926		
Total	26	187700350			

Table 2: Summary of number concentration mean measurements of testing three VMN units at three days.

VMN Unit	Day 1	Day 2	Day 3	Overall Mean
A	68,023 (1,789)	64,651 (1,593)	66,490 (2,180)	66,389 (1,854)
B	67,734 (1,130)	63,730 (1,655)	64,067 (1,621)	65,177 (1,468)
C	65,154 (1,530)	62,955 (1,075)	63,908 (1,870)	64,005 (1,492)
Overall Mean	66,972 (1,483)	63,778 (1,441)	64,822 (1,891)	

Note: The measurements were taken using a CPC and the units are in particles/cm^3 with the standard deviation shown in parentheses.

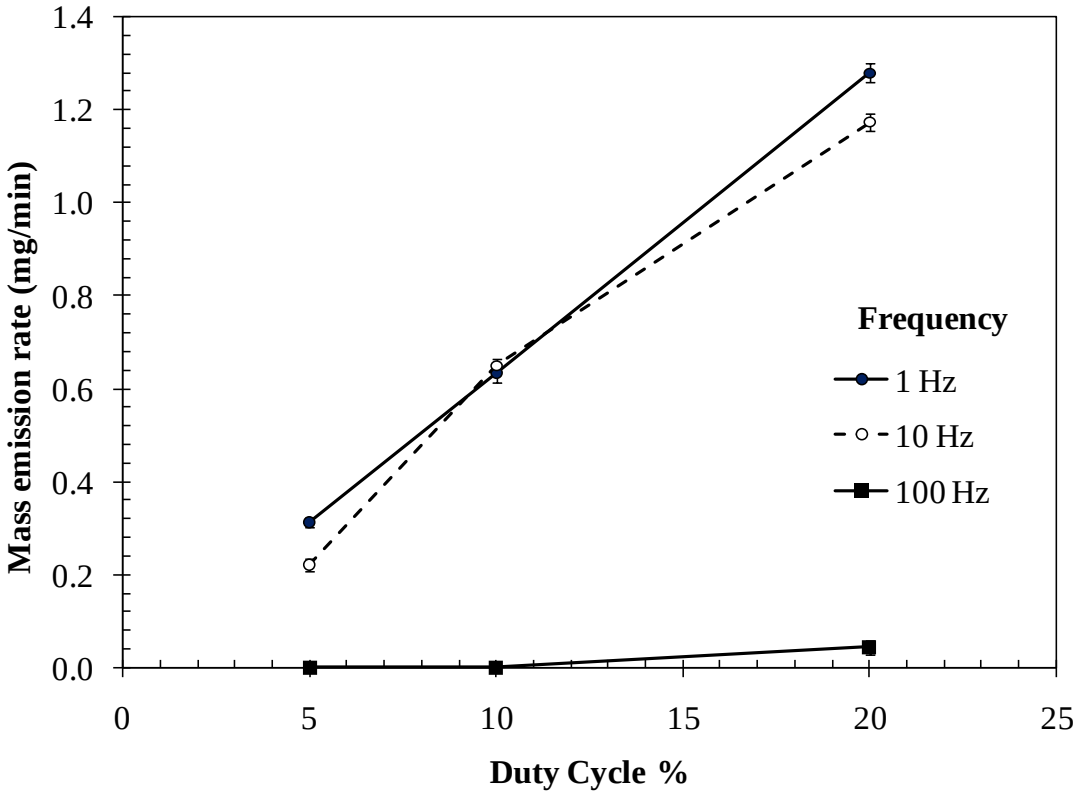

Figure 4: Nebulizer Mass Emission Rate as a Function of VMN Duty Cycle and Frequency. The mass output was adjusted to account for the dilution of modified HEPA filter. The error bars represents one standard deviation.

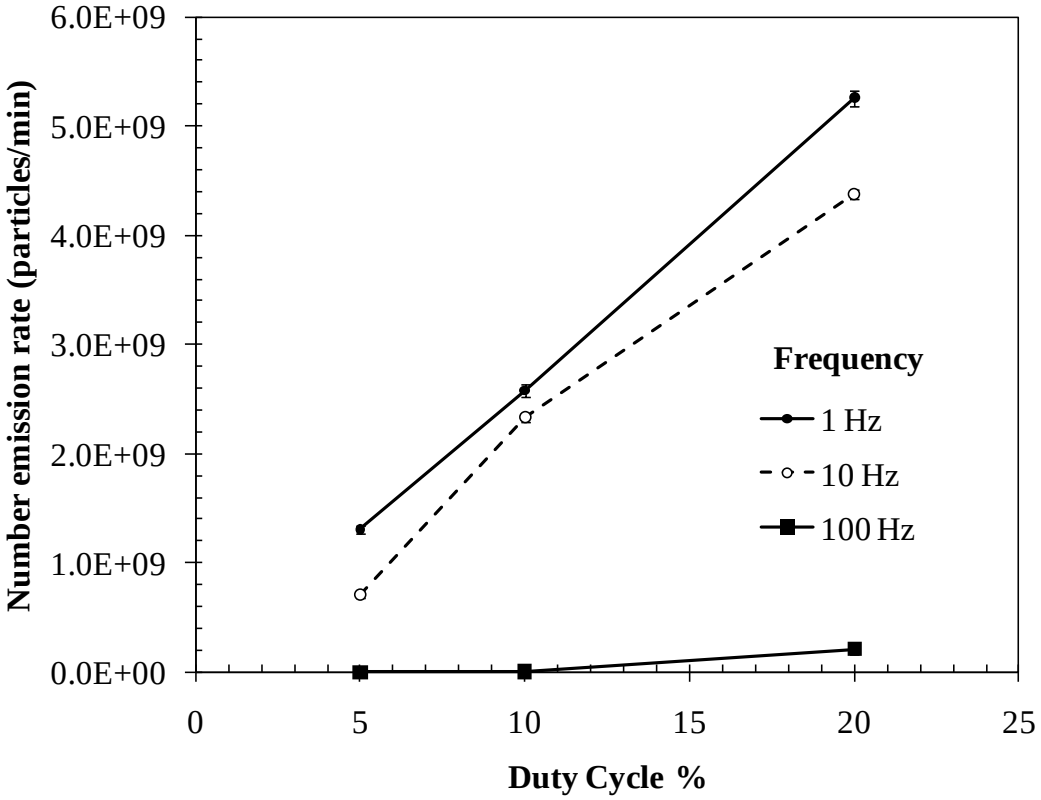

Figure 5: Nebulizer Number Emission Rate as a Function of VMN Duty Cycle and Frequency. The number output has been adjusted to account for the dilution of modified HEPA filter. The error bars represents one standard deviation.

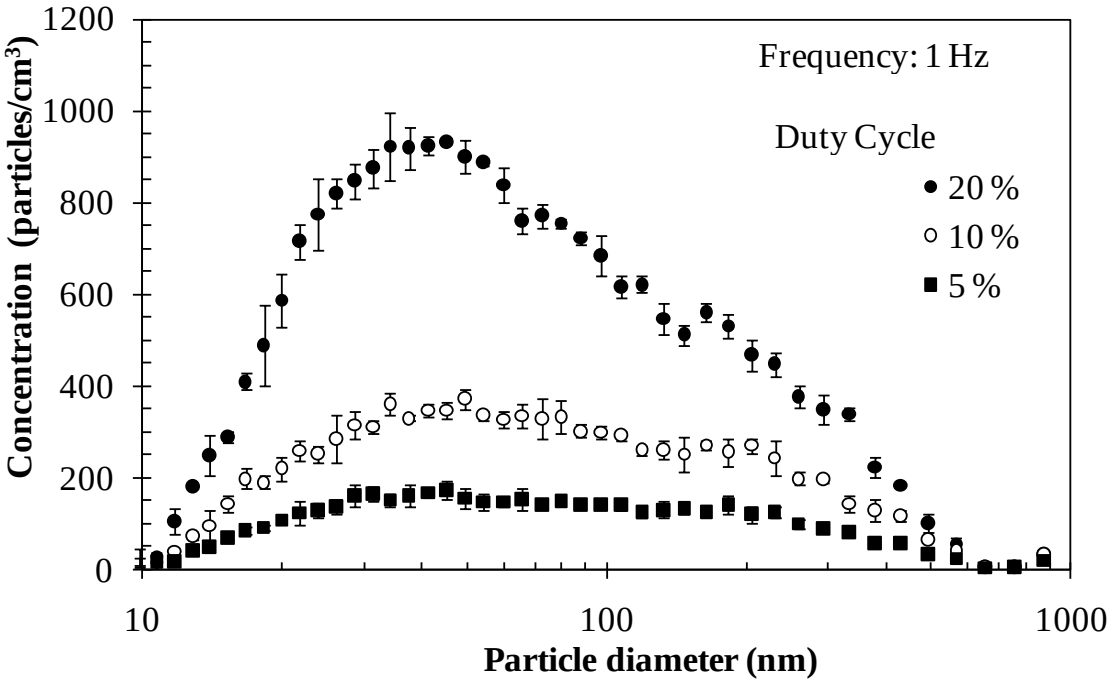

Figure 6: Particle Size Distribution at 1 Hz Frequency and Multiple Duty Cycles. The error bars represents one standard deviation.

Table 3: Particle Size Distribution at 1 Hz Frequency and Multiple Duty Cycles.

	Duty Cycle (%)	Total Count (particles/cm^3)	Geometric Mean Diameter (nm)	GSD
Frequency (1 Hz)	5	4,600	65.8	2.6
	10	9,500	65.7	2.5
	20	22,400	59.0	2.4

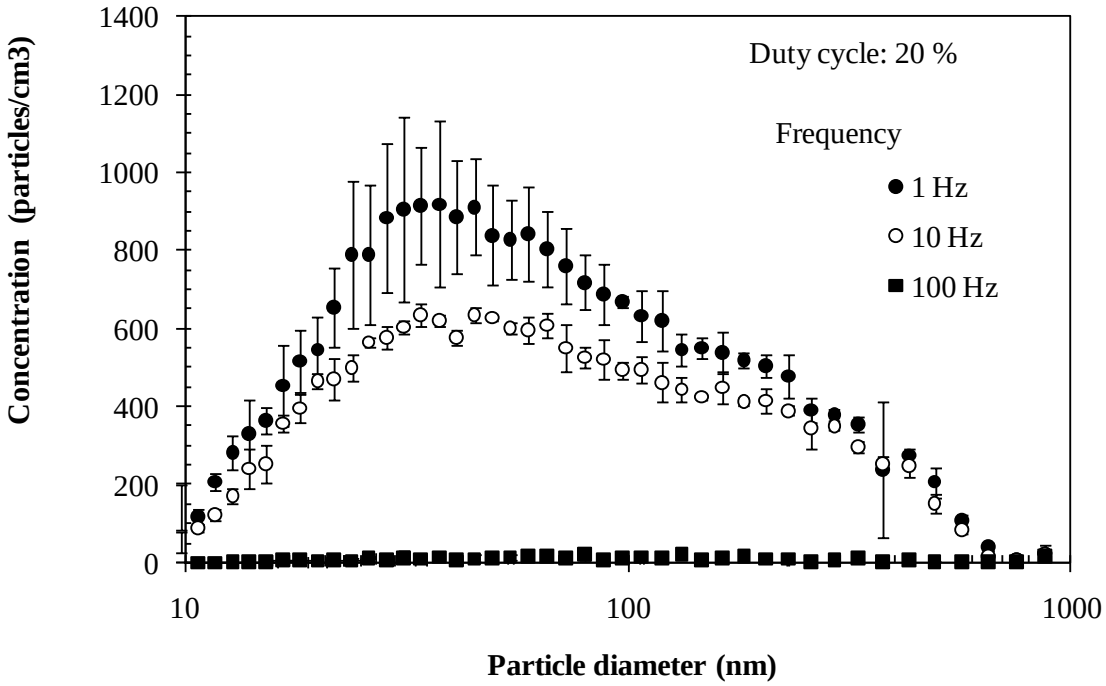

Figure 7: Particle Size Distribution at 20% Duty Cycle and Multiple Frequencies. The error bars represents one standard deviation.

Table 4: Particle Size Distribution at 20% Duty Cycle and Multiple Frequencies.

	Frequency Hz	Total Count (particles/cm^3)	Geometric Mean Diameter (nm)	GSD
Duty Cycle 20%	1	23,000	59.2	2.5
	10	17,000	62.8	2.6
	100	350	73.3	2.4

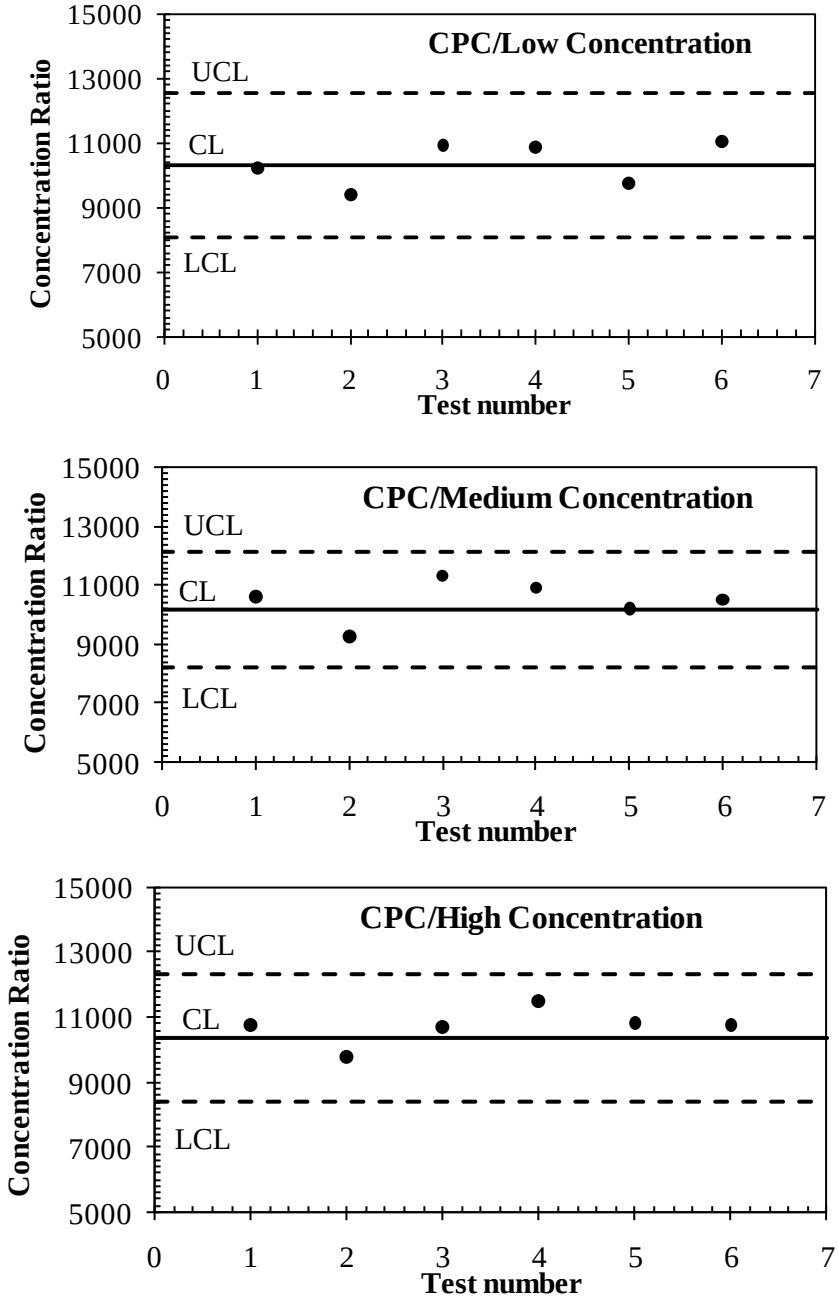

Figure 8: CPC Quality Control Charts at Low, Medium, and High Concentrations. Concentration Ratio = CPC number concentration divided by photometer mass concentration.

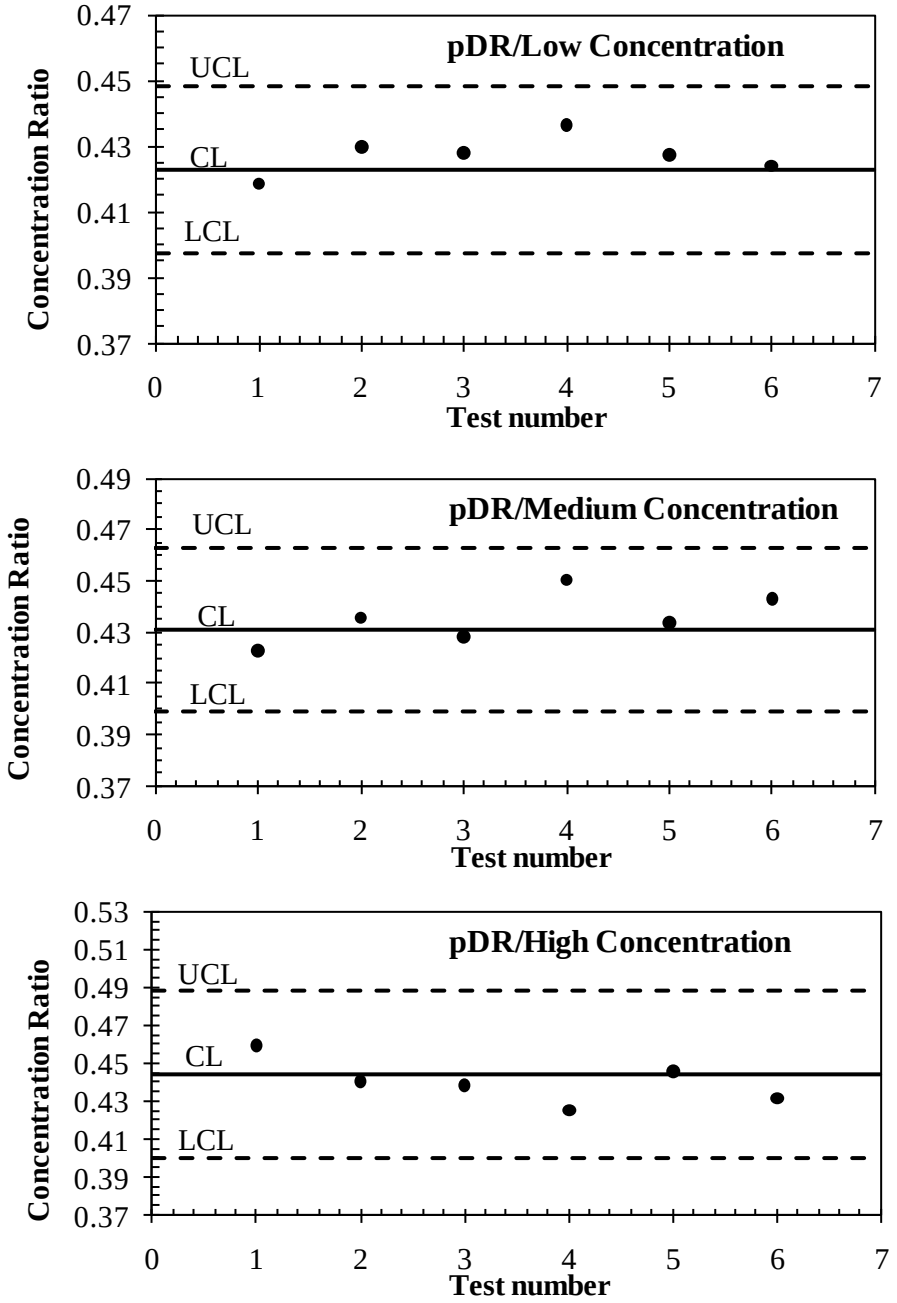

Figure 9: pDR Quality Control Charts at Low, Medium, and High Concentrations. Concentration Ratio = pDR mass concentration divided by photometer mass concentration.

CHAPTER III

CONCLUSION

The existing methods for verifying output of DRIs measuring aerosol concentration use complex set up and stationary equipment. These methods are not practical for implementation in the field. The study aimed to develop a device that can be used to verify the concentration output of aerosol DRIs used in field. This device would be beneficial for field work that involves the use of DRIs for measuring aerosol concentrations.

The verification device developed in this study had simple design that used relatively small components for easy of transport. The study results showed that the verification device was able to produce multiple concentration levels of aerosols in repeatable manner. The results also showed that the verification device can be used to identify drifts in DRI measurement.

The idea of developing the verification device came from the larger need for newer devices that simplify the process of verifying output of aerosol DRIs. Professionals using DRIs for measuring aerosol concentrations can benefit from the verification device. This device presents a practical method to verify the concentration output of aerosol field DRIs.

Future Research

More research should be conducted to improve the design of the verification device. The verification device is intended to be used in the field, and a more compact design would be better suited for the task. Also, the verification device can be used to conduct more testing in field. This will provide additional assessment of the verification device and lead to further improvements.

Further research should also be done using different solution to generate aerosols. A solution containing monodisperse PSL could be used to verify both particle size and concentration.

APPENDIX A: VIBRATING MESH NEBULIZER TEST MEASUREMENTS

Table A1: Test measurements of three VMN units at three days.

VMN Unit	Day 1	Day 2	Day 3
A	67,438 (3,360)	62,229 (3,302)	64,110 (2,650)
	66,683 (1526)	65,751 (600)	66,931 (2,372)
	69,959 (491)	65,974 (876)	68,429 (1,521)
B	64,358 (1,307)	63,296 (2,184)	61,174 (2,232)
	68,884 (1,237)	63,683 (1,575)	62,599 (1,534)
	69,961 (844)	64,211 (1,206)	68,428 (1.096)
C	60,684 (1,490)	62,599 (1,569)	64,228 (1,887)
	65,822 (1,589)	63,360 (926)	63,114 (1,936)
	68,954 (1,508)	62,903 (729)	64,383 (1,789)

Note: Each test consisted of three minute measurements with six second logging interval for a total of thirty samples. Each test shown in the table represents the mean of the thirty samples. Three replicate tests of each VMN unit were conducted over three days. The measurements were taken using a CPC and the units are in particles/cm^3 with the standard deviation shown in parentheses.

APPENDIX B: MODIFIED HEPA FILTER

The verification device experimental design used a HEPA filter (Model HEPA-CAP 36, Whatman Ltd, Piscataway, NJ) that was modified to reduce the high concentration output from the nebulizer. The concentration levels, produced by the nebulizer, were extremely high and not practical for developing a verification device. These concentrations were as high as 89 mg/m^3 and 238,000 $particles/cm^3$. For that reason, a modified HEPA filter was used to reduce the concentration levels produced by the nebulizer. The HEPA filter was modified by piercing a hole of diameter 1 mm, to allow small percentage of the particles to pass through.

The Modified HEPA filter concentration reduction ratio was measured using an aerosol photometer for mass concentration, and a Condensation Particle Counter for number concentration. The measurements were taken with and without the presence of the modified HEPA filter. These measurements were repeated six times using identical PWM and flow settings.

Tables A1 and A2, showed the results of evaluating the modified HEPA concentration reduction factor. The modified HEPA filter reduced the mass concentration by 98%, and reduced the number concentration by 93%

Table B1: Modified HEPA Mass Concentration Reduction Factor.

Run	CASELLA mg/m^3		Reduction Factor
	Without HEPA	With HEPA	
1	81.60	1.52	0.981
2	83.36	1.78	0.979
3	89.28	1.77	0.980
4	86.40	1.77	0.979
5	88.08	1.77	0.980
6	86.48	1.74	0.980
Mean	85.87	1.73	0.980
		Reduction Factor =	98.00%

Table B2: Modified HEPA Number Concentration Reduction Factor.

Run	CPC Particles/cm^3		Reduction Factor
	Without HEPA	With HEPA	
1	238,801	15,125	0.937
2	236,947	15,511	0.935
3	236,749	16,247	0.931
4	238,129	16,280	0.932
5	237,052	16,037	0.932
6	234,771	16,068	0.932
Mean	237,075	15,878	0.933
		Reduction Factor =	93.30%

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