AN IMPROVED WETTED-WALL BIOAEROSOL SAMPLING CYCLONE

A Thesis

by

MANPREET SINGH PHULL

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

August 2005

Major Subject: Mechanical Engineering

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Approved by:

Co-Chairs of Committee, Andrew R. McFarland
John Haglund
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ABSTRACT

An Improved Wetted-Wall Bioaerosol

Sampling Cyclone. (August 2005)

Manpreet Singh Phull, B.Tech., IIT Madras, India

Chair of Advisory Committee: Dr. Andrew R. McFarland

A modified wetted-wall cyclone using different methods of water injection techniques upstream of the inlet was designed as an improvement to a wetted-wall cyclone developed by White, which uses liquid injection through a port on the wall of the cyclone inlet. The new cyclone has a high aerosol sampling flow rate (1250 L/min) and maintains constant cut-point with the modified White-type cyclone along with greater collection efficiency, lower time response, and reduced pressure drop.

The final air-blast atomizer cyclone (AAC2.1a) design considered has an aerosol-to-hydrosol collection efficiency cut-point of 1.3 µm with collection efficiencies at 1 and 2 µm of 39.9% and 86%, respectively. The efficiency reported for the modified White-type cyclone for particle sizes of 1 and 2 µm was 40.5% and 76.3%, respectively, under no water bypass conditions. The aerosol-to-aerosol transmission efficiency for the AAC2.1a configuration was found to be approximately 53.7% for 1 µm diameter particles as compared with 67.2% for the modified White-type cyclone.

Dry and wet time response tests were performed in which the modified White-type cyclone had an initial response of 2.5 minutes for a wet start and 1 minute for a dry start for a condition where there was no liquid carryover through the cyclone outlet. The rise time for AAC2.1a cyclone under dry and wet start conditions was 0.5 minutes and 1.3 minutes, respectively. The decay response of the modified White-type cyclone was 1.1 minutes for a

wet start and 1.2 minutes for a dry start. The corresponding numbers for AAC2.1a cyclone were 1.4 minutes for a dry start and 1 minute for a wet start condition.

Off design tests were run at approximately ±10% air flow rates to see the effect on cyclone performance. It was seen that at a 10% higher flow rate (1350 L/min) the efficiency was 54.3%. At a 10% lower flow rate (1125 L/min) the efficiency was 33.7% as compared with an efficiency of 39.9% at 1250 L/min for 1.0 μm PSL particles. It was found that at a water input of 0.8 mL/min the efficiency reduced to 79.3% as compared to 86% at an input flow rate of 1.6 mL/min for 2 μm size PSL.

DEDICATION

This work is dedicated to my parents, Bhupendra S. Phull and Amarjeet Kaur, whose love and support are my inspiration for all that I do. To my brother, Harsheet S. Phull, who has encouraged me and helped me during the difficult times of my life.

ACKNOWLEDGEMENTS

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I would like to express my gratitude to my advisor, Dr. Andrew R. McFarland, for his guidance, encouragement, and advice that has inspired me to be a better student as well as a better person.

I would like to thank the members of my committee for their time and guidance, especially Dr. John Haglund for sharing his technical expertise through the course of this study. Finally, I would like to thank the members of the Aerosol Technology Laboratory, especially Youngjin Seo for his support and help.

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NOMENCLATURE

A	coefficient
B	coefficient
C	concentration
$C_{aerosol}$	concentration of aerosol sample
$C_{corrected}$	concentration of sample corrected for normalized volume of water collected
$C_{hydrosol}$	concentration of hydrosol sample
$C_{reference}$	concentration of reference sample
$C_{wallloss}$	concentration of wall loss sample
F	fraction of full-scale response
F_{water}	normalized correction factor for volume of water collected
η_{AA}	aerosol-to-aerosol collection efficiency
η_{AH}	aerosol-to-hydrosol collection efficiency
$\overline{\eta}_{AH}$	average aerosol-to-hydrosol collection efficiency
$m_{initial}$	initial mass of ethyl acetate sample
m_{final}	final mass of ethyl acetate sample
P_{std}	atmospheric pressure
Q	air flowrate
$Q_{standard}$	air flowrate as measured at standard atmospheric conditions
R	fluorometric reading
$\rho_{ethylacetate}$	density of ethyl acetate
t	time
V	volume of ethyl acetate
$V_{initial}$	initial volume of ethyl acetate
V_{water_i}	volume of water collected for individual sample
$\overline{V}_{water}$	average volume of water collected over all samples
WL	wall-loss

INTRODUCTION

The capability for real-time detection of airborne pathogens and toxins is necessary for the protection of military personnel and critical public environments (e.g., subways, sporting events, government buildings). Devices for near real-time detection and identification of airborne pathogens have been developed in which an aerosol sample and collection system is interfaced with a rapid biological particle detector/analyzer. Most detection technologies require that the sample be delivered in the form of a liquid suspension (hydrosol) at relatively low flow rates on the order of a few mL/min. Furthermore, as the detectors typically require many hundreds or thousands of particles in order to make a positive identification, a large volume flow rate of air is required in order to provide timely detection of an aerosolized bioaerosol agent.

One device used for rapid collection of aerosol particles and subsequent delivery of the particles in a concentrated hydrosol state is the wetted-wall sampling cyclone. White et al. (1975) developed such a sampling cyclone for collection of bioaerosols. Further refinements were made by Moncla (2004). The modified White and Moncla cyclones operate at an air-sampling rate of approximately 900 L/min where the particles in the sampled air are transferred into a continuous liquid sample at the rate of 1 mL/min for confirmatory analysis and identification. It is necessary that the cyclone efficiently collect particles in the range of 1 to 10 μm aerodynamic diameter, a range identified by the military as the most likely to encompass threat agents.

Preliminary performance characterizations have been completed on the above two wetted-wall cyclone designs. However, there exists problems like water bypass and

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This thesis follows the style and format of *Aerosol Science and Technology*.

recirculation ring which have negative effects on the cyclone performance. In this study, we present an improved wetted-wall cyclone, which has been modified from the existing designs, both physically and by its means of operation. The present study reports the evaluation of the efficiency and time constant of the modified cyclone for mono-disperse aerosol particles generated using Polystyrene Latex solutions for different particle sizes. The modified cyclone is compared with the modified White-type cyclone for its performance. Furthermore, efficiency tests were run under off design airflow and water inflow conditions to see the effects on the cyclone performance.

DESIGN AND THEORY

Two wetted-wall aerosol collection cyclones have been studied and preliminary performance characterizations have been completed. The first one known as the modified White-type cyclone (Figure 1) uses a water injection port and operates at approximately 900 L/min. This cyclone was part of a stand-alone unit. The second design which is a prototype design of the new wetted-wall cyclone, the AAC cyclone (Figure 2), uses an air-blast atomizer for injection of the water. Preliminary aerosol experiments have shown that AAC has a collection efficiency of around 80% for 2 µm AD PSL particles and a cut-point particle size of 1.5µm AD at a flow rate of 900 L/min.

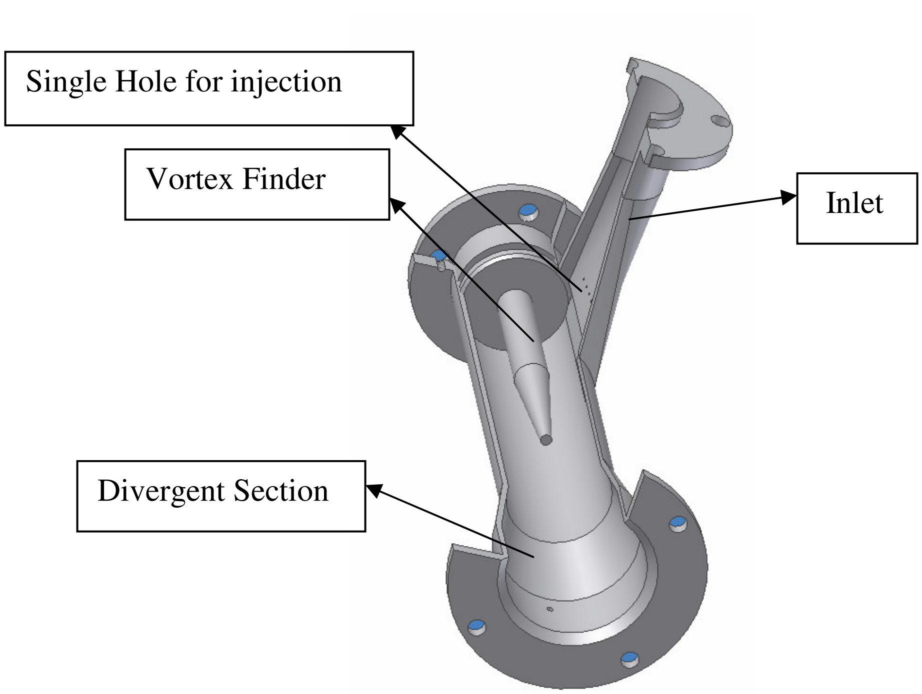

Figure 1. Sectional view of White-type cyclone.

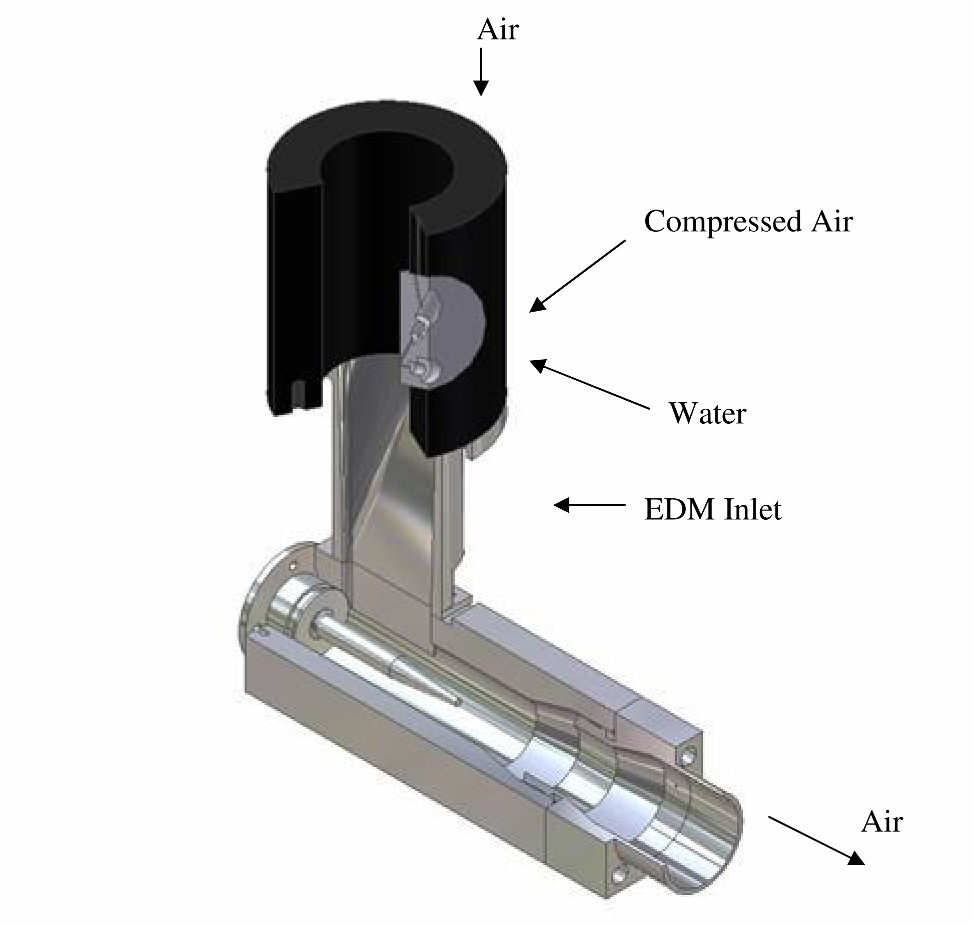

Figure 2. Sectional view of AAC cyclone (Moncla 2004).

Liquid Recirculation Ring and Water Bypass

Two significant liquid sample problems have been observed in each of the cyclone designs described above:

Liquid bypass (Figure 3 and Figure 4) in which the hydrosol sample was carried out of the cyclone in the air exhaust line and

The presence of a liquid recirculation ring at the skimmer location (Figure 5).

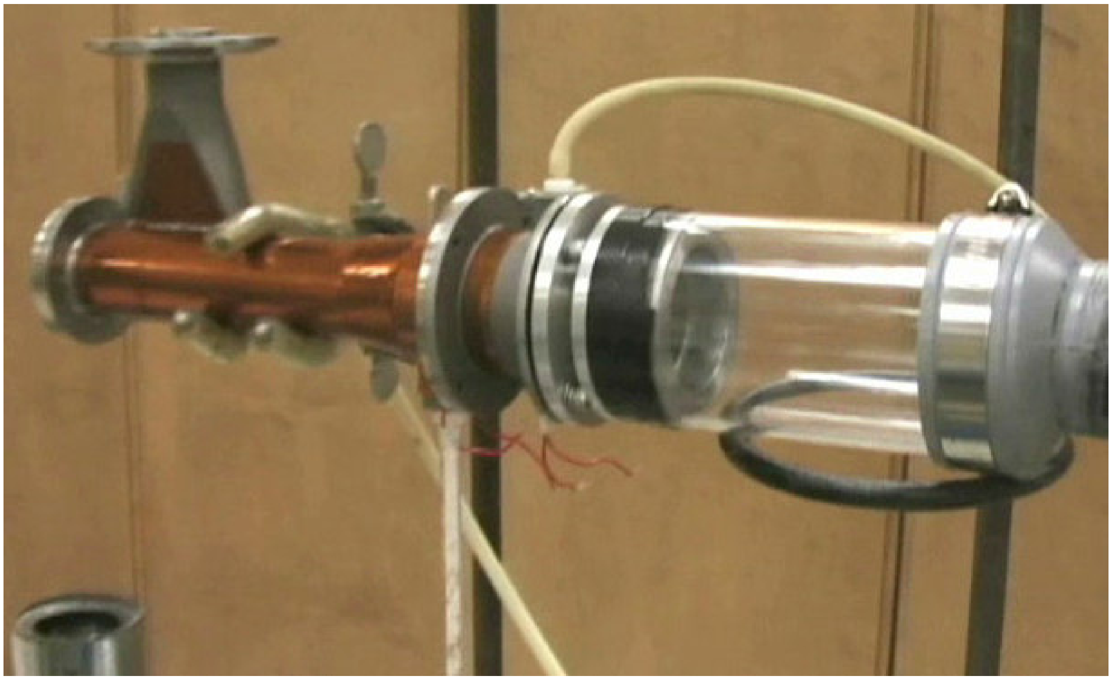

Figure 3. Experimental set-up of White-type cyclone.

Figure 4. Water bypass on the White-type cyclone.

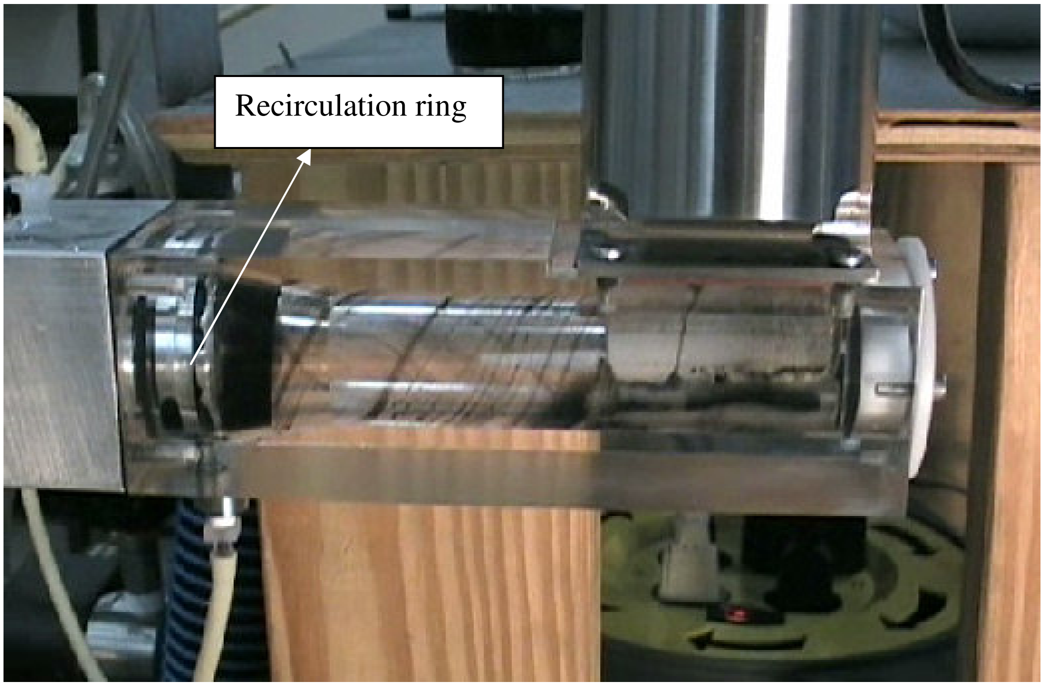

Figure 5. Liquid recirculation ring on the White-type cyclone.

The loss of sample, due to water bypass, reduced the collection efficiency since some of the hydrosol containing particles bypassed the cyclone. The water bypass also caused corrosion of the blower which resulted in reduced blower life and increased chances of accident. The water bypass was evident from the presence of a white powdery substance present on the blower provided by the Army (Figure 6). The second problem of the recirculation ring affected the cyclone time response as well as potentially lowered the collection efficiency.

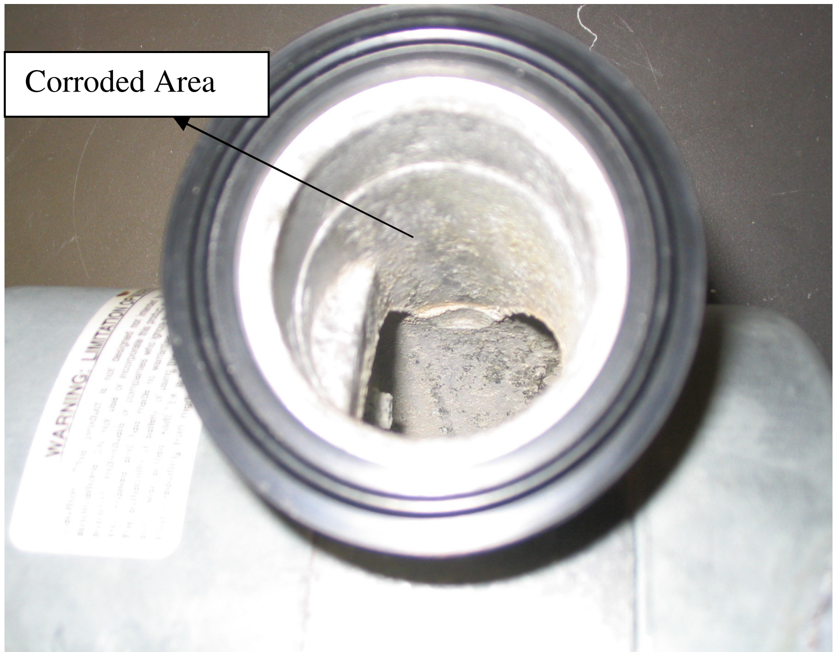

Figure 6. Corroded blower due to water bypass.

Time response was important from the point of view of detecting the presence of any airborne pathogens and toxins present in the environment. A lower time constant allows for early detection of the particles in the atmosphere. The presence of the liquid recirculation ring had a negative effect on the time constant since it prevented the water from being collected on the outlet hydrosol port. Also, visualization studies have shown that the ring was responsible for water bypass as the slightest bump can “short circuit” the water past the outlet skimmer.

All of the previous cyclone body designs had a divergent section just before the skimmer location (Figure 7). The half angle of this divergent section was around 15°. Due to this large angle of divergence flow separation occurred leading to the formation of a high velocity swirling liquid recirculation ring just upstream of the skimmer. The flow separation further prevented the water from going through the gap between the skimmer and the cyclone body and resulted in an increased response time and a high probability of water bypass. This problem was solved by machining a cyclone body with no divergent section. This new cyclone body was a constant diameter cylinder which was 152.4 mm (6.00 inches) long and 38.1 mm (1.5 inches) internal diameter with a 73.5 mm × 6.35 mm (2.5 inches × 0.25 inches) rectangular slot (Figure 8 and Figure 9). The new design prevented the flow separation and formation of the resulting recirculation ring.

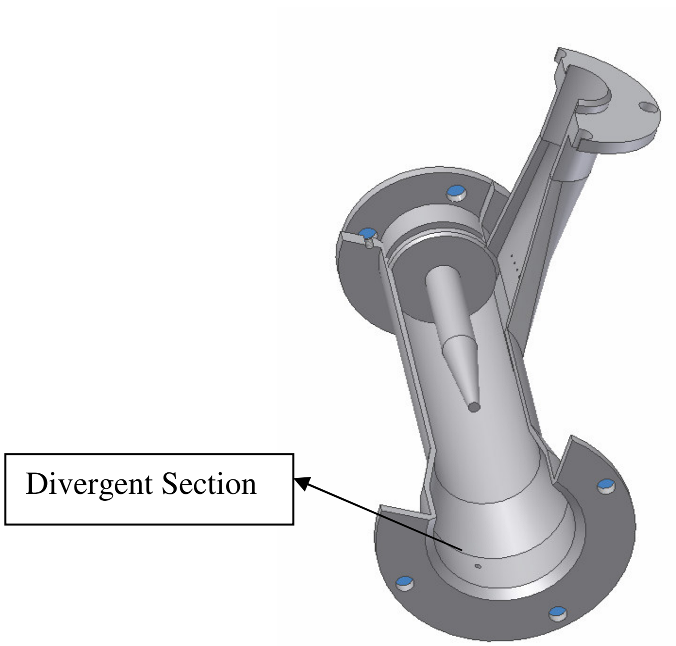

Figure 7. Divergent section on modified White-type cyclone body.

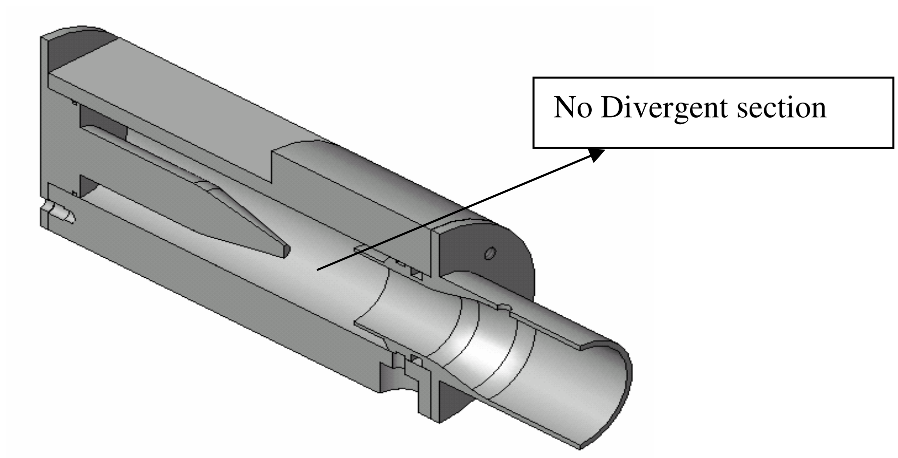

Figure 8. New cyclone body design with no divergent section.

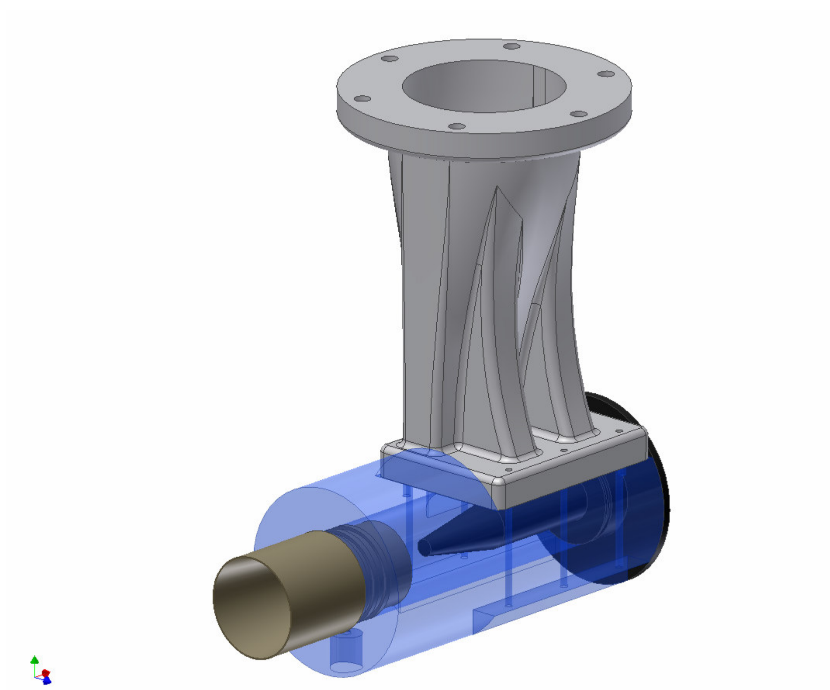

Figure 9. Modified acrylic cyclone assembly with rapid-prototyped inlet.

To eliminate the problem of water bypass, a series of skimmers were machined with varying gaps between the cyclone body and skimmer. It was found that for a gap of two and a half (2.5) thousands of an inch between the cyclone body and the skimmer (a difference of 0.127 mm (0.005 inches) between the diameters) there is negligible bypass. Tests were run using different orientations of the cyclone, different air flow rates, and different water input rates to see the effect on water bypass. The skimmer for the new cyclone had a nose which helped in reducing the water bypass. Also, a divergent section at the rear-end of the skimmer helped in pressure recovery.

Modified Cyclone Body

After solving these two problems the next step of the study was to design a new cyclone which has a high aerosol sample flow rate (1250 L/min) and which maintains constant cut-point with the White-type cyclone. The new cyclone body and the skimmer should prevent water bypass, minimize pressure drop, and should have better collection efficiency than the existing White-type cyclone. To attain a system which has the above properties the inlet of the cyclone body was made longer keeping the width of the slot the same. This inlet was made longer keeping in mind that the average velocity across the inlet has to be the same as the White-type cyclone so that the cut-point remains the same. The average velocity across the White-type cyclone was around 50 m/s for a flow rate of 900 L/min and inlet dimensions of 46.355 mm × 6.35 mm (1.825 inchex × 0.25 inches). Knowing the desired flow rate (1250 L/min), dimensions of the new inlet slot 63.5 mm × 6.35 mm (2.5 inches × 0.25 inches) were calculated.

To reduce the pressure drop across the cyclone, the body diameter was increased from 28.575 mm (1.125 inches) to 38.1 mm (1.5 inches) and necessary changes were made to the vortex finder thickness and length so that the cut-point was not affected. The Stokes number is defined as:

$$S_{tk} = \tau \frac{U_0}{L_C} \qquad [1]$$

where

S_{tk} is the stokes number

τ is the relaxation time

U_0 is the velocity

L_C is the characteristic length (in this case the half-width of inlet slot and distance between the vortex finder and inlet).

According to the above formula, for the same relaxation time and average velocity the half width should be same to have same stokes number. Hence, when designing the new cyclone, inlet slot width and distance between the vortex finder and inlet slot were maintained in the same ratio as the White type cyclone to have the same cut-point.

Water Injection Techniques

Preliminary visualization studies indicate that the single hole used for water injection in the white type cyclone does not allow the injected water to cover the entire inlet area. To overcome this problem, different methods to inject water were employed to have a better and uniform wetting of the entire inlet slot. The different kinds of water injection techniques used are as follows:

AAC 2.0 Cyclone

This design employed an inlet with an integrated air-blast atomizer and was fabricated using a rapid-prototype machine (Figure 10). The inlet consisted of an integrated atomizer with two needles placed at an angle of -15 degrees (liquid needle of gage 30) and -65 degrees (air-blast needle of gage 20) from the horizontal (i.e. downward). Compressed air was supplied through the air needle at a pressure of 34.5 kPa (5psig). A rough estimate based on Ingebo and Foster’s equation for cross current breakup in an air-blast atomizer under the above mentioned conditions results in a 40µm mean drop size (Lefebvre, 1989). It was seen that this rapid prototyped inlet was porous and subjected to air leaks when under vacuum. In addition, it was found out that the air-blast atomizer did not appear to provide optimum wetting at the impaction zone on the cyclone wall. The latest test version of the 1250 L/min cyclone, AAC 2.1a (Figure 11), has the same nominal dimensions as the earlier version, but the inlet was replaced with a new design fabricated with a cast urethane, eliminating the problem of porosity and allowing for different water injection approaches to be compared.

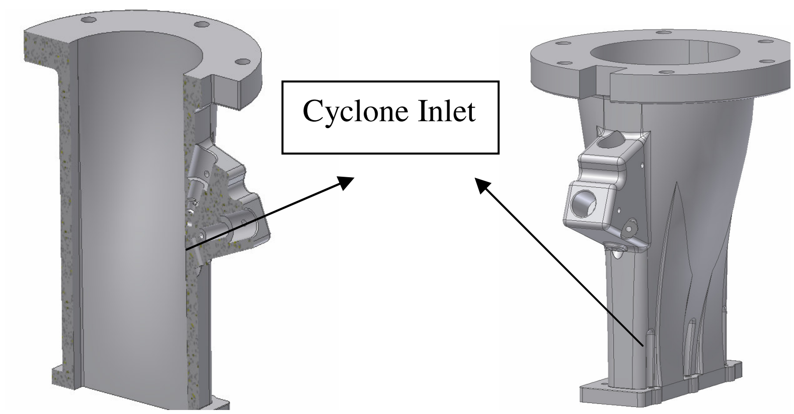

Figure 10. Integrated air-blast atomizer and inlet for AAC2.0 cyclone.

AAC 2.1a Cyclone

The air-blast atomizer for this inlet was of the form of a cylindrical insert housing the liquid (30 gage) and air-blast (20 gage) needles as shown in Figure 11. The needles were held in fixed position relative to one another where the liquid injection needle was maintained at an angle of zero degrees with respect to the horizontal and the air-blast needle was fixed at -45 degrees with respect to the horizontal (i.e. half downward). The air-blast atomizer position was varied over different elevations with respect to the cyclone inlet plane, and from visualization studies, an optimum distance of 3.25” above the cyclone inlet was selected. Compressed air was supplied at a pressure of 82.8 kPa (12psi). It was found out that at this pressure the water spray uniformly covers the inlet slot and hence more effectively washes the particles from the cyclone body as compared to when compressed air was supplied at a pressure of 34.5 kPa (5 psig) for AAC2.0 cyclone.

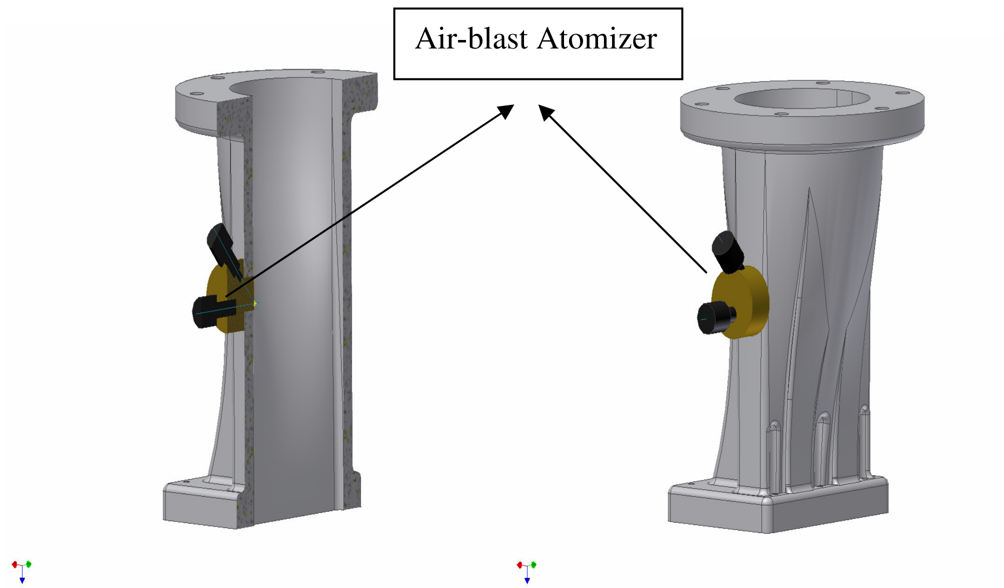

Figure 11. Inlet with homemade air-blast atomizer for AAC2.1a cyclone.

AAC 2.1b Cyclone

A needle spray bar with four holes along the length of the needle was made (Precision MicroFab, Severna Park, MD) and placed transverse to the flow just above of the throat section of the cyclone inlet (Figure 12 and Figure 13) at the centre of inlet slot. The height of the needle from the slot surface was 38.1 mm (1.5 inch). The holes were uniformly spaced and were 0.1016 mm (0.004 inch) in diameter each. The major advantage of using such a needle for injecting water was that it eliminated the need of an extra air supply pump. However, it was seen that the water coming out of the holes was not able to completely cover the impaction region of the inlet. Moreover, there was always a risk of needle holes getting plugged by a small speck of dust because of the small diameter holes. The salt remaining after the TWEEN 20 solution evaporated also caused plugging of the needle spray bar.

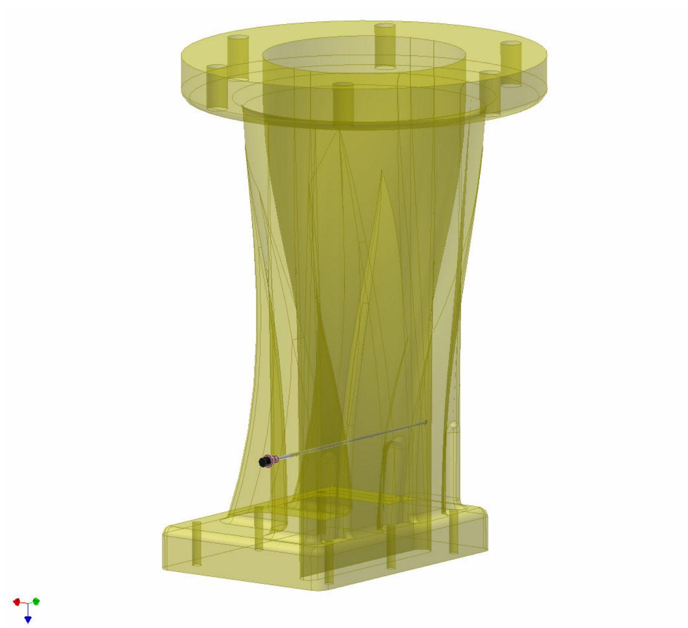

Figure 12. Inlet with needle spray-bar for AAC2.1b cyclone.

Figure 13. Four-hole needle used for AAC2.1b cyclone.

AAC 2.1c Cyclone

A spray bar manifold was made (Small Parts Inc., Miami Lakes, FL) which had the same working principle as the four-hole spray bar except that the water was injected in a direction perpendicular to the air flow (Figure 14 and Figure 15). The manifold had four thick walled capillaries each of diameter 0.127 mm (0.005 inch) and a liquid reservoir at the back of these capillaries (Figure 15). Four equally spaced holes were drilled along the length of the slot on one of the inlets at a height of 6.35 mm (0.25 inch) from the inlet flange. The manifold tubes were made to slide into these holes such that the tubes just protruded out of the inside inlet wall. The manifolds behaved similar to the spray bar needles and the problem of plugging of holes due to dust or evaporation of TWEEN 20 was also observed. Since these can be placed outside the inlet, a heater coil can be placed on its surface and water can be prevented from freezing when operated under cold conditions.

Figure 14. Inlet with spray-bar manifold for AAC2.1c cyclone.

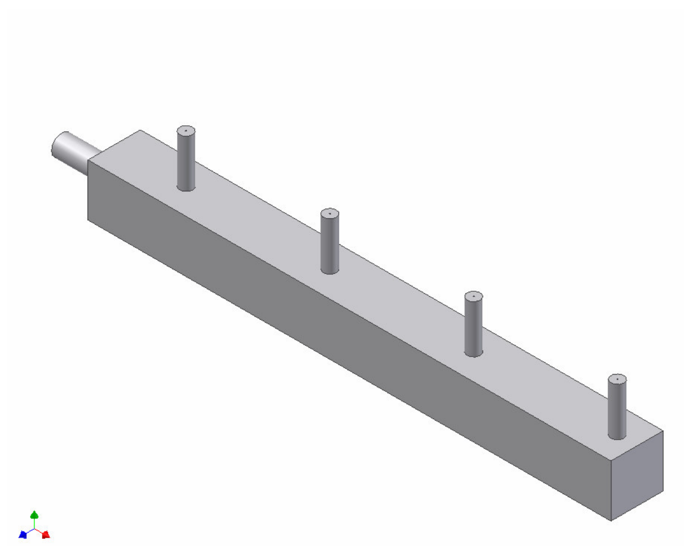

Figure 15. Spray-bar manifold used for AAC2.1c cyclone.

AAC2.1d Cyclone

This method of water injection was same as the method employed by the modified white type cyclone to inject water. A single hole of diameter 1.143 mm (0.045 inch) was drilled on one of the inlets (Fig 16). The location of the port for water injection was approximately 3.175 mm (0.125 mm) above the cyclone entrance and at a longitudinal distance of approximately 13.462 mm (0.53 inch) from the front end of the cyclone inlet slot, corresponding to the same proportional location of the single hole water injection point on the white cyclone. Since the inlet length dimension of the new cyclone is much greater than the white type cyclone, it was seen that single hole injection method for the new design was very ineffective in washing the particles deposited on the cyclone body.

AAC 2.2 Cyclone

The test cyclone AAC 2.1 was intended for use as a rapid-modification and test device, but would not be suitable as a deliverable unit or for heat transfer experiments due to size and materials. Accordingly, a new design of the basic 1250 L/min cyclone was generated. This unit, AAC 2.2, was fabricated of cast aluminum and has a cyclone body and inlet as integrated components. A concern in the use of cast aluminum for the cyclone body was that surface finish and material may reduce the wetting characteristics and thus hydrosol collection efficiency. To prevent wall losses, AAC 2.2 has a stainless steel tube insert glued into the aluminum cyclone body to provide a polished inner surface. The use of stainless tubing for the cyclone internal diameter required a reduction in cyclone body diameter from 38.1 mm (1.5 inch) to 34.798 mm (1.37 inch) to allow common tube sizes to be used. A schematic of AAC 2.2 is seen in figure 17 and Figure 18.

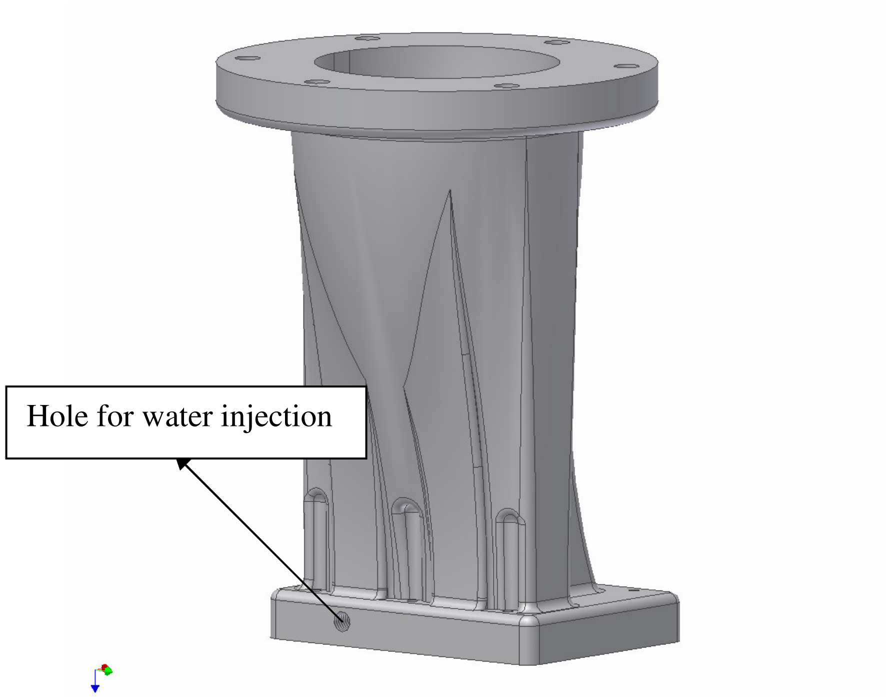

Figure 16. Single hole inlet for AAC2.1d cyclone.

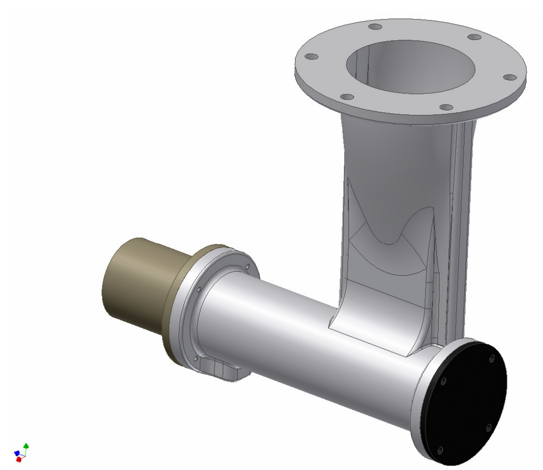

Figure 17. Solid model of AAC2.2 cyclone.

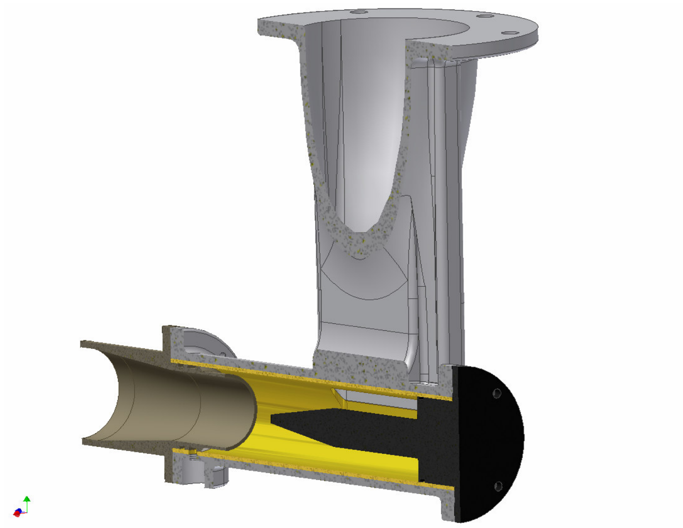

Figure 18. Sectioned view of AAC2.2 cyclone.

EXPERIMENTAL PROCEDURE

Test Apparatus

Particles were introduced into the air stream in the form of an atomized particle/water suspension using a Collision nebulizer (Models CN60 (24 jet), BGI, Inc. Waltham, MA). The liquid atomized in the nebulizer contained a dilute suspension of monodisperse polystyrene latex particles (PSL) which were introduced into the wind tunnel along with HEPA filtered drying air (Figure 19). The test aerosol was then passed through an air blender (Blender Products, Inc. Denver, CO), which uniformly distributes the aerosol over the duct leading to the cyclone inlet. Upon exit from the air blender, the aerosol flow was then passed through a flow-straightener to remove vorticity introduced by the air blender.

The air flow rate was measured with a Laminar Flow Element (CME, Davenport, IA) connected between the blower and cyclone exhaust. Pressure was measured upstream of the LFE (P3), and across the LFE (P4) to obtain the flow rate from a calibration chart provided by the supplier. The upstream pressure(P1) was measured with a Magnehelic pressure gage (Dwyer, Michigan City, IN) whereas the differential pressure across the LFE (P4) was measured with an inclined manometer (Dwyer, Michigan City, IN).Two blowers (Ametek model 116636 and 150092, Paoli, PA) connected in series provided the air flow. The liquid flow into the cyclone was controlled by a peristaltic pump (STEPDOS Model No. 100527, KNF flodos) while the hydrosol sample was recovered from the cyclone by a metered dose diaphragm pump (Model No. 3386, Variable Flow Mini-Pump, Fisher Scientific). Two pressure taps, one upstream of the system (P1) and one downstream of the cyclone (P2) were used to measure the pressure drop across the cyclone. These pressures were measured using Magnehelic pressure gages (Dwyer, Michigan City, IN). The air-blast atomizer was attached to the cyclone inlet and the air needle of the atomizer was operated at 82.8 kPa (12 psig) for the final design. The water needle of the atomizer had a water inflow of 1.6 ml/min for most of the test runs. The water injected into the cyclone was treated with a trace quantity of the surfactant TWEEN 20 (0.6% by volume). Previous studies have shown that the recovery of particles can be significantly improved by use of surfactant (Moncla, 2004; Phan, 2002).

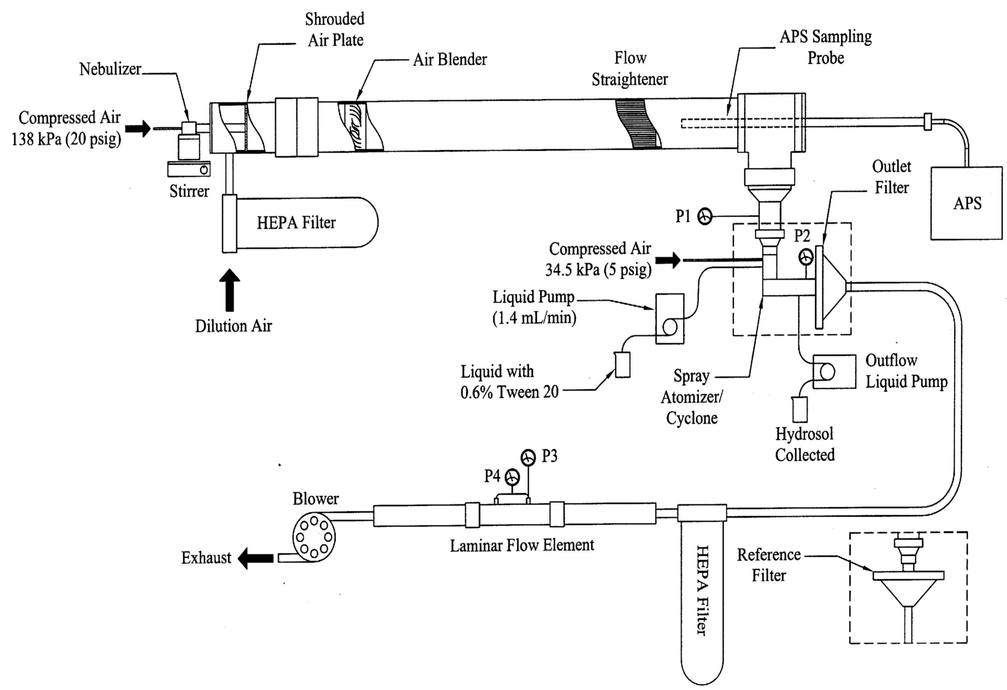

Figure 19. Schematic of test apparatus for aerosol performance evaluation of cyclones (Moncla, 2004).

Aerosol-to-aerosol and aerosol-to-hydrosol efficiencies of the different cyclone configurations were measured for comparison. The White type cyclone was considered as the reference and all the new cyclone designs were compared with the white cyclone. The White type cyclone was operated at a flow rate of approximately 900 L/min whereas all the new cyclone designs were made to operate at 1250 L/min. The input hydrosol flow rate was set to 1.6 mL/min to get a nominal water outflow of 1 mL/min.

A 24-jet Collison nebulizer (Models CN60 (24 jets), BGI, Inc. Waltham, MA) was used to generate monodisperse polystyrene particles (PSL) (Duke Scientific, Palo Alto, CA) of various sizes: 0.4 µm, 1 µm, 2 µm, 3 µm. Particles larger than 3 µm could not be atomized using the Collison nebulizer and hence for larger size particles, namely 5 µm and 10 µm single hole atomization was used to generate particles. The amount of PSL suspended in distilled water is limited by the concentration of PSL doublets in the aerosol, which is caused by two or more PSL occupying the same water droplet. This doublet no longer behaves as a particle of the same size. For the Collison nebulizer used in this study (Model CN60, BGI, INC., Waltham, MA) the limiting concentration is about 10^9particles/mL (May, 1973). The 24-jet Collison nebulizer holds enough PSL suspension to run for 45 minutes without adjusting the height of the jets. For shorter tests, it was desired to mix an individual suspension in the nebulizer jar, and use it for multiple runs and only change the suspension after one total hour of testing. Because there was a change in the concentration of individual suspensions for different hourly runs, a new method was developed in which for every test the nebulizer was rinsed and a fresh suspension was added. To insure that the concentration of each of these suspensions remained constant, a large batch of PSL suspension was made, from which each new test suspension was drawn. The large batch is referred to as the "master solution" (Moncla, 2004). The air pressure to the nebulizer was set at 138 kPa (20 psig). HEPA-filtered drying air was mixed with the spray from the nebulizer.

To measure the aerosol-to-aerosol and aerosol-to-hydrosol efficiencies, tests were conducted with the cyclone being operated three times in the flow and the reference filter used two times. The blower speed was adjusted for every run to ensure that the desired flow rate (900 L/min for white cyclone and 1250 L/min for new cyclone configuration) was obtained. In case of reference filter, sampling of PSL was done for a total of 40 minutes. At the end of 40 minutes, PSL supply was turned off and system was allowed to run for one more minute to ensure that all the particles in experimental setup goes to the reference filter.

For a cyclone run, after the desired flow rate was established, compressed air supply, water inflow pump (1.6 mL/min) and hydrosol recovery pump were turned on and operated till steady-state was reached. The hydrosol recovery pump used was a diaphragm pump operating at 20.8 mL/min of water flow. The PSL was turned on after attaining steady-state and operated for a period of 40 minutes. At the end of 40 minutes, the nebulizer was shut off but the output hydrosol was collected for one more minute to clear the tubing of the PSL particles. A 203 mm × 254 mm (8 inch × 10 inch) glass fiber filter (Type A/E, Pall, East Hills, NY) was placed at the outlet of the cyclone to collect particles that were transmitted through the cyclone. The ratio of the average concentration of particles, collected at this filter, to the average concentration of particles collected on the reference filter gave the aerosol-to-aerosol transmission efficiency.

Test Set-up for Larger Sized Particles (5 µm and 10 µm)

A new setup was built for running larger size particles (5 µm and 10 µm). The 24-jet collision nebulizer was not able to atomize particles larger than 3µm diameter and hence a single-jet atomizer was used to atomize the larger sized particles. The atomizer was placed vertically on one end of the experimental setup. A PSL solution was made (30 drops of PSL in 100 mL of distilled water) and pumped into the atomizer at a flow rate of 2 mL/min using a peristaltic pump (STEPDOS Model No. 100527, KNF flodos). Compressed dry air at 138 kPa (20 psig) was pumped through the air needle of the atomizer which atomized the liquid coming out of the water needle.

The new setup had a tee splitting the main flow into two parts. This kind of setup made it possible to run both the cyclone and reference filter, simultaneously. The air flow was measured by using two different LFE's (CME, Davenport, IA) on either side of the setup. Ametek blowers (Ametek models 116636 and 150092, Paoli, PA) were used to provide the airflow through the cyclone on the right side and the reference on the left side. To check the repeatability of the test setup 3 tests were run with reference filters on the left and right side. It was seen that there was 10-12% difference on the fluorometer readings between the left and right side. For the same side, the difference was less than 5% for the three runs on both sides.

Test duration was 10 minutes and efficiency tests were run for AAC2.1a and the White-type cyclone using 5μm and 10μm particles. The liquid sample was collected in a jar which was evaporated using a heat gun and soaked in ethyl acetate (5mL) for analysis. The reference filters were soaked in 60 mL of ethyl acetate and analyzed for fluorescence.

PSL Analysis Procedure

Preparing the Master Solution

Solid PSL particles were added to distilled water to prepare the master solution which was used to generate the test aerosols. The PSL particle manufacturer (Duke Scientific, Palo Alto, CA) produces particles with an encapsulated fluorescent dye available in three different colors (red, green, and blue). The dye, when released from the PSL sphere by immersion in ethyl acetate was detectable by a fluorometer (Model FM109515, Quantech, Barnstead International, Dubuque, IA). A Collison nebulizer (Models CN60 (24 jet), BGI, Inc. Waltham, MA) was used to generate the particles according to the procedure described above. The concentration of PSL in the master solution was less than 10^9 particles/mL as suggested by May (1973) to ensure that no coagulation of particles occurred in the atomization process.

Aerosol and Hydrosol Filtering

The particles, once generated by the Collison nebulizer, were mixed in the test aerosol delivery duct where they where then introduced to the cyclone inlet or a 203 mm × 254 mm (8 inch × 10 inch) glass-fiber filter. The particles deposited on the cyclone body were recovered in the hydrosol sample, which was in turn filtered using a 25 mm diameter polycarbonate membrane filter (Isopore, Millipore, 0.6μm DTTP) for recovery of the particles.

Fluorescence

Once collected on filters, the PSL particles were dissolved in ethyl acetate to release the fluorescent dye. Results have showed that by dissolving the PSL in ethyl acetate, greater repeatability between like samples can be achieved. To maximize signal intensity, each filter was submerged in 80 ml of ethyl acetate for 203 mm × 254 mm (8 inch × 10 inch) glass-fiber filter and 20 ml ethyl acetate for 25 mm diameter polycarbonate membrane filter to soak the entire filter. Glass jars with lids were used to soak the 25 mm filter whereas the 8 inch × 10 inch filters were cut into 6 parts and then soaked in a plastic container with a threaded lid to prevent any evaporation of ethyl acetate. The filter and ethyl acetate solution was then left for 4-5 hours to ensure proper mixing. Following each of the cyclone tests, the inside of the cyclone was thoroughly cleaned. Cotton-tipped applicators (Puritan Medical Products, Guilford, ME) soaked in ethyl acetate were used to collect PSL deposited on the interior surface. The fluorescent sample was then removed from the container and the dye concentration measured with the fluorometer.

Fluorometric analysis was done using a fluorometer (Model FM109535, Quantech, Barnstead International Fluorometer (Dubuque, IA). The concentration of each of the samples was found by using

$$C = \frac{RV}{Qt} \qquad [2]$$

Where

C is the concentration,

R is the average fluorometer reading adjusted for the background fluorescence,

V is the volume of ethyl acetate,

Q is the air flow rate, and

t is the length of time during which the sample was collected.

Liquid Particle/Oleic Acid Analysis Procedure

Liquid particles were generated using oleic acid containing fluorescein. The particles were generated using a Vibrating Orifice Aerosol Generator (Model 345001, TSI, Inc., MN). The VOAG was generally useful for generating larger sized monodisperse liquid particles in the range from 5 μm to 20 μm. The analysis process for oleic acid particles was similar to the PSL analysis, except that the filters containing the collected particles were dissolved in a 50:50 mixture of isopropyl alcohol and distilled water to release the fluorescent tracer. Filters containing oleic acid particles were allowed to soak for a minimum of four hours in a sealed container prior to analysis. Alcohol and water were used for analysis of oleic acid particles because oleic acid is soluble in isopropyl alcohol.

It is known that fluorescein analysis is sensitive to pH levels (Kesavan et al. 2001) and in the present study a trace quantity (2 drops) of sodium hydroxide was added to each sample to ensure that the pH was greater than 9. The fluorescein concentration was given by:

$$C = \frac{RV}{Qt} \qquad [3]$$

where

C is the concentration,

R is the average fluorometer reading adjusted for the background fluorescence,

V is the volume of ethyl acetate,

Q is the air flow rate, and

t is the length of time during which the sample was collected.

The concentration of each of the 203 mm × 254 mm glass fiber reference filters is averaged together to give $C_{reference}$. The concentration of the hydrosol filters, $C_{hydrosol}$, the outlet filters, $C_{aerosol}$, and the recovery swab tips, $C_{wallloss}$, are then compared with the reference concentration to give the aerosol-to-hydrosol collection efficiency (η_{AH}), aerosol-to-aerosol collection efficiency (η_{AA}), and percent wall loss (WL), respectively.

$$\eta_{AH} = \frac{C_{hydrosol}}{C_{reference}} \quad [4]$$

$$\eta_{AA} = 1 - \frac{C_{aerosol}}{C_{reference}} \quad [5]$$

$$WL = \frac{C_{wallloss}}{C_{reference}} \quad [6]$$

Plots were made for the aerosol-to-hydrosol and aerosol-to-aerosol collection efficiencies as a function of the particle size.

Time Response of the Cyclone

"Dry start time response" and "wet start time response" tests were run with the White-type cyclone and the AAC 2.1a cyclone to know how long it takes for the cyclone to collect and aspirate the hydrosol. It was called "dry start" because everything in the system was switched on at the same time before even steady-state condition was reached. This is the way the White-type cyclone was operated by the Army; hence this method was adopted for the tests performed for this study. For the "wet start" the whole system was brought into steady-state before the hydrosol sample was collected. The same test apparatus used for the aerosol-to-hydrosol transfer tests, described previously, was used for this experiment. The outlet filter was removed for these experiments. The testing procedures follow (Moncla 2004):

The air flow rate and liquid flow rate were set to their respective values of 900 L/min and 1.6 mL/min for the White-type cyclone and 1250 L/min and 1.6 mL/min for the new cyclone (AAC2.1a). Polystyrene latex spheres (PSL) (Duke Scientific, Palo Alto, CA) of 2µm size were used in this evaluation. After the whole system was turned on, ten one-minute samples were collected in sealable, glass sample jars followed by five 2-minute samples, four 3-minute samples, and two 4-minute samples. The nebulizer was then turned off and three 1-minute samples were collected. Each of the sample jars were weighed before and after collecting the hydrosol sample to measure the amount of water collected over each time interval.

In case of a wet test, five one-minute samples were collected in sealable glass sample jars. (Clean empty sample jars were weighed prior to testing.) The nebulizer was then turned on. Ten 1-minute samples were collected followed by five 2-minute samples, four 3-minute samples, and two 4-minute samples. The nebulizer was then turned off and five 1-minute samples were collected. Each of the sample jars were then weighed to measure the amount of water collected over each time interval.

The hydrosol in the samples was allowed to evaporate using a heat gun so that only the PSL remained. Once evaporated, 4 mL of ethyl acetate was added to each jar. The jars were sealed and allowed to soak overnight so that the PSL dissolved in the ethyl acetate. Reference 203 mm × 254 mm glass fiber filters (Type A/E, Pall, East Hills, NY) were taken between each of the cyclone tests. They were run for 40 minutes with aerosolized PSL, and another three minutes with the nebulizer turned off. The reference filters were placed in 80 mL of ethyl acetate, sealed in containers with a lid to prevent evaporation and soaked overnight.

The concentration of the samples was corrected to reflect the amount of water that was collected each minute, as this value was not steady. The amount of water was found from weighing the jars as the samples were collected. These values were then normalized with the average liquid flow rate.

$$F_{water} = \frac{V_{water_i}}{\overline{V}_{water}} \qquad [7]$$

F_{water} is the normalized volume of water collected for each sample, V_{water} is the volume of water collected for each sample period, and $\overline{V}_{water}$ is the average volume of water collected per minute.

The corrected concentration ($C_{corrected}$) for each sample was then the result of dividing by the normalized water correction factor.

$$C_{corrected} = \frac{C}{F_{water}} \qquad [8]$$

Once the concentration of each of the samples and reference filters was determined, the samples were compared individually to the average value of the concentration of the reference filters to find the aerosol-to-hydrosol collection efficiency of the cyclone at each time, η_{AH}.

$$\eta_{AH} = \frac{C_{corrected}}{C_{reference}} \qquad [9]$$

A plot of the aerosol-to-hydrosol collection efficiency as a function of time was then constructed in order to determine the time constant of the initial response and final decay of the cyclones.

For the initial response of the system, the fraction of the full-scale (*F*) for each sample was first found according to:

$$F = \frac{\eta_{AH}}{\overline{\eta}_{AH}} \quad [10]$$

where $\overline{\eta}_{AH}$ is the average aerosol-to-hydrosol collection efficiency over all of the samples near the full-scale collection capability of the cyclone.

For each test of a cyclone, the first five samples following the start of the PSL flow were used to evaluate the initial response. These values were then averaged together and a curve was fit using Microsoft Excel. The equation for this curve is:

$$F = 1 - \frac{1}{1 + At^{B}} \quad [11]$$

where the constants *A* and *B* are found by optimizing the curve fit. The time at which 63% of the full-scale collection efficiency is realized (*t*) can then be calculated using Equation [10] and the values of *A* and *B*. The time response of each of the cyclones was corrected for the range of collection efficiency by multiplying by the instantaneous aerosol-to-hydrosol collection efficiency at each time interval.

The time constant for the decay of the cyclone once the aerosol challenge was removed was found using:

$$F = \frac{1}{1 + At^{B}} \qquad [12]$$

and the same techniques for the initial response were followed.

RESULTS AND DISCUSSION

Aerosol-to-Hydrosol and Aerosol-to-Aerosol Performance

The steady-state aerosol-to-hydrosol collection efficiencies for various cyclone designs were determined for PSL particles from 0.4 µm to 10 µm. The steady-state efficiency was determined by first bringing the cyclone air and liquid flow rates to constant value (1250 L/min and 1.6 mL/min for the new cyclone design and 900 L/min and 1.6 mL/min for the White cyclone, respectively) prior to introduction of the test aerosol. The air and liquid flow rates were then maintained at the operational values throughout the duration of the test. The aerosol-to-hydrosol efficiency was defined as the fraction of particles of a given size introduced at the cyclone inlet that were recovered in the collected hydrosol sample. Additionally, the 'aerosol-to-aerosol' efficiency was determined from the fraction of total particles recovered from a filter placed at the cyclone exhaust. Different methods of water injection into the new cyclone body were tested to compare the performance of the various designs and to come up with the best suitable design which had no recirculation ring, negligible bypass, lower pressure drop and relatively higher aerosol-to-hydrosol and aerosol-to-aerosol collection efficiencies. The results obtained using the above cyclone designs are shown below.

Modified White-Type Cyclone

The steady-state efficiency of the modified White cyclone at an air flow rate of 900 L/min and a liquid flow rate of 1.6 mL/min was determined according to the procedure described above for testing of various AAC cyclones. Water bypass at the skimmer was observed in most of the runs (on an average of four out of every five runs). The steady-state efficiency was determined from only those tests in which bypass did not occur or very little bypass occurred, and thus represented the maximum possible efficiency of the

White cyclone for the given operational conditions. The results are seen in Figure 20 and Figure 21.

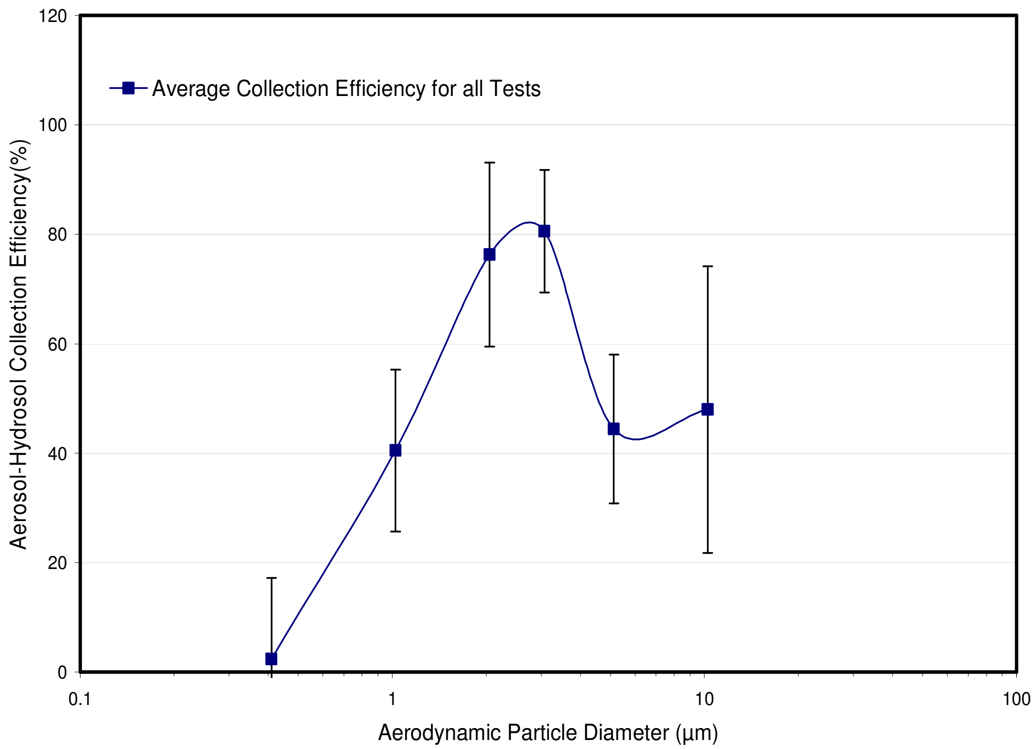

Figure 20. Steady-state aerosol-hydrosol efficiency for modified White cyclone at an air flow rate of 900 L/min and a liquid input rate of 1.6 mL/min.

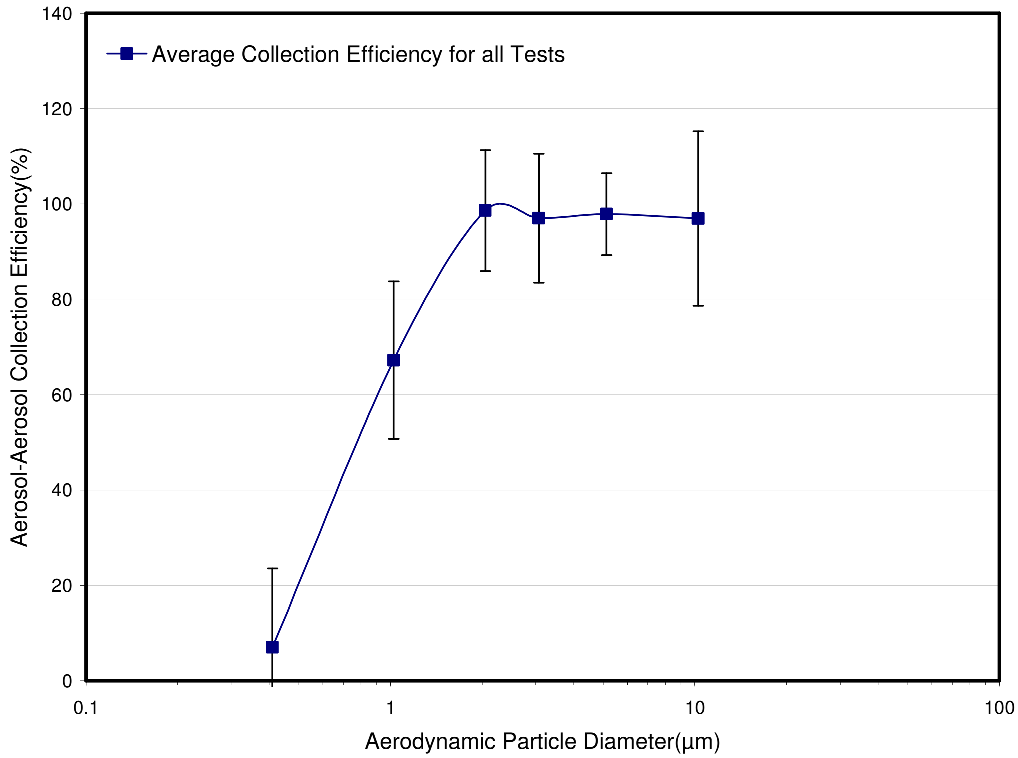

Figure 21. Steady-state aerosol-aerosol efficiency for JBPDS cyclone at an air flow rate of 900 L/min and a liquid input rate of 1.6 mL/min.

AAC 2.1b and AAC2.1c Cyclone

Figures 22 through 25 show the aerosol-to-hydrosol and aerosol-to aerosol collection efficiencies of the two configurations. Both configurations have the same working principle. The only difference being the direction in which the water spray from the spray bar comes out. The efficiencies of the spray bars (78% and 78.5% aerosol-hydrosol efficiency for 2 µm PSL) were comparable to the air-blast atomizer cyclone. However, the problem of holes becoming plugged on the needle and manifold, due to the salt remaining after evaporation of the TWEEN 20 solution, makes it difficult to use.

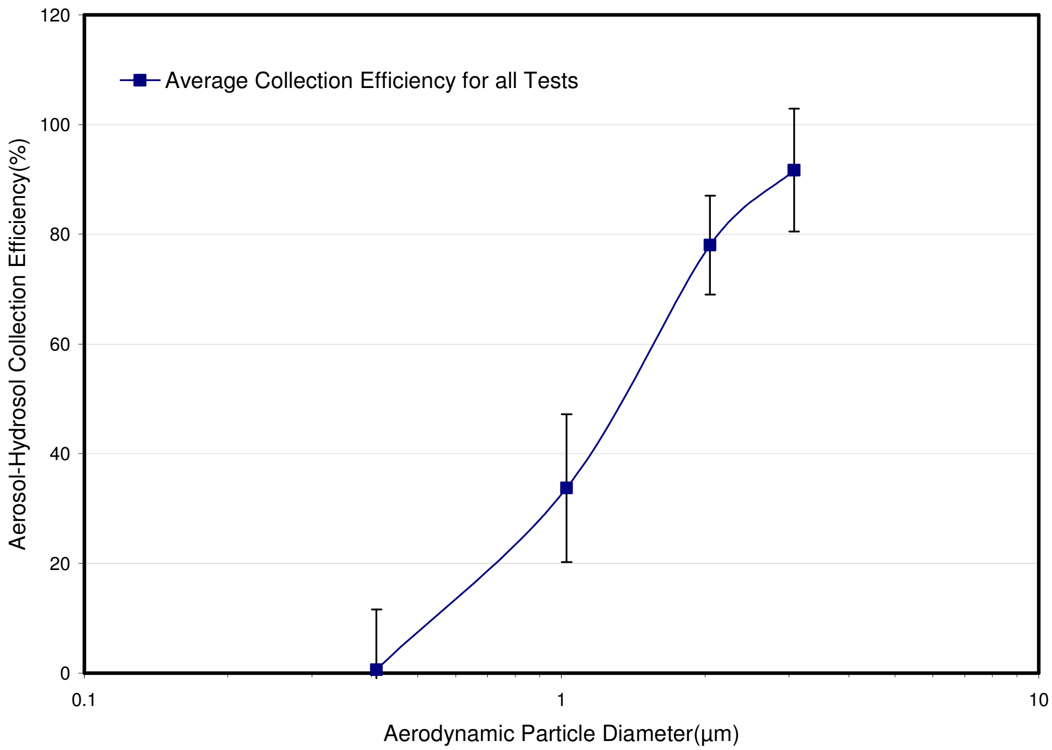

Figure 22. Steady-state aerosol-hydrosol efficiency for AAC2.1b cyclone at an air flow rate of 1250 L/min and a liquid input rate of 1.6 mL/min.

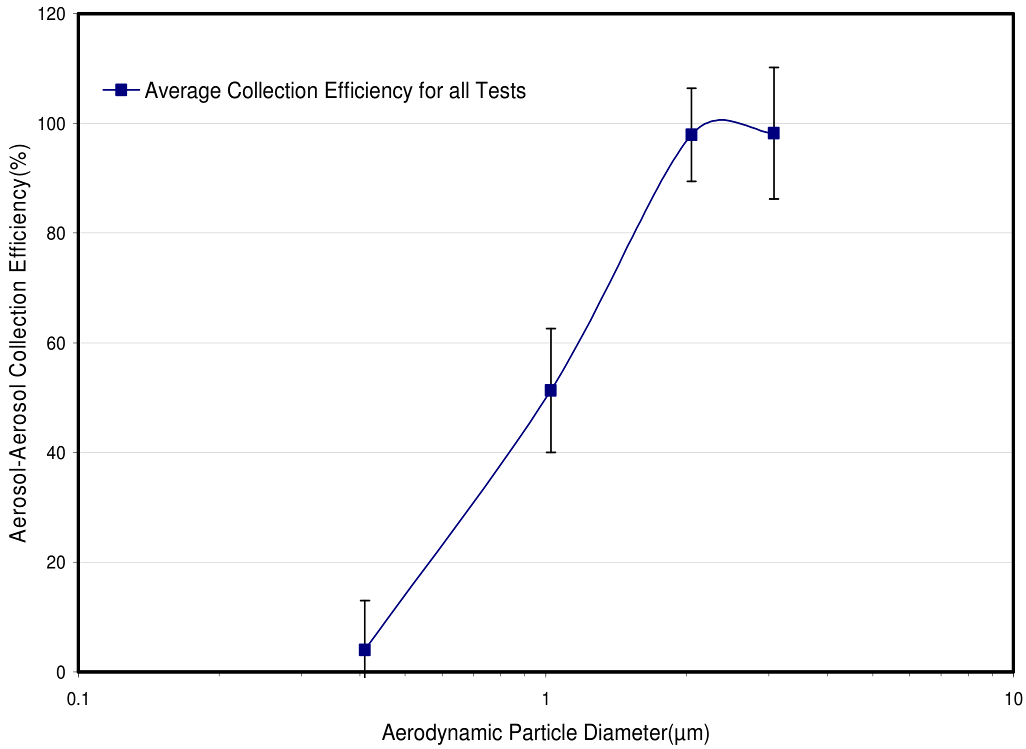

Figure 23. Steady-state aerosol-aerosol efficiency for AAC2.1b cyclone at an air flow rate of 1250 L/min and a liquid input rate of 1.6 mL/min.

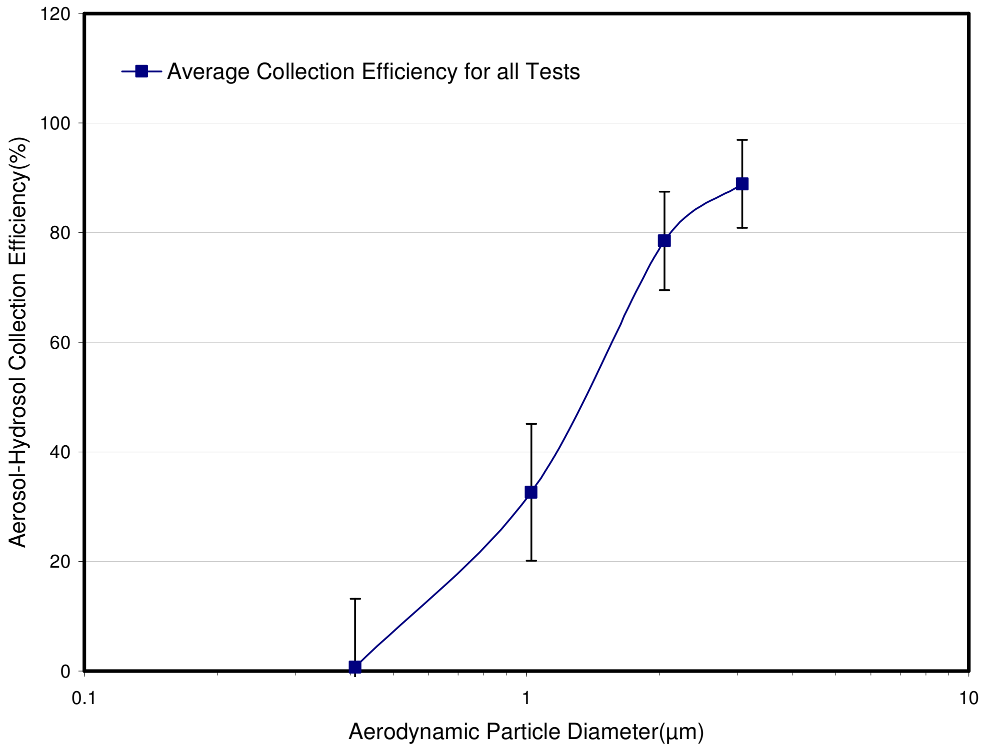

Figure 24. Steady-state aerosol-hydrosol efficiency for AAC2.1c cyclone at an air flow rate of 1250 L/min and a liquid input rate of 1.6 mL/min.

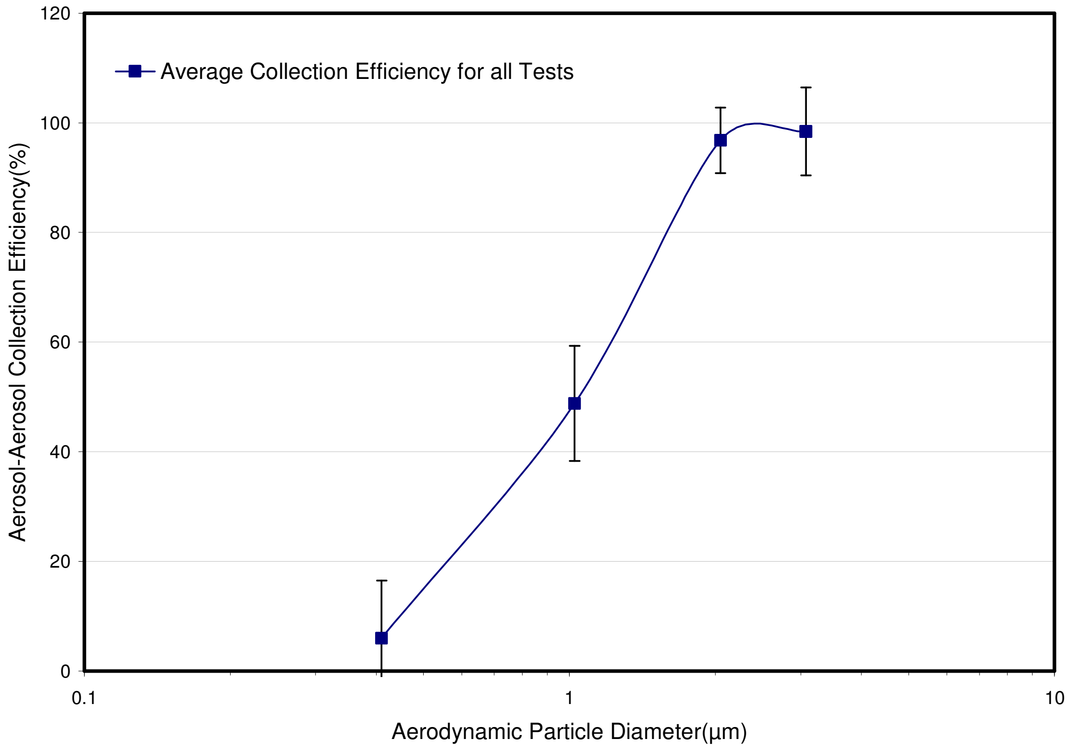

Figure 25. Steady-state aerosol-aerosol efficiency for AAC2.1c cyclone at an air flow rate of 1250 L/min and a liquid input rate of 1.6 mL/min.

AAC 2.1d Cyclone

Figures 26 and 27 show the results obtained using single-hole injection method which was similar to the method used by the modified White-type cyclone for water injection. It was seen that the efficiency numbers were less compared to other techniques used for injecting water. Visualization studies show that a single rivulet of water can be seen swirling around the body which was ineffective in washing the entire impaction zone. Also, it was observed that the position of this rivulet was not constant which was responsible for a large range of error bars. This was evident from the cyclone body losses recovered at the conclusion of each test for single injection which indicated that approximately an additional 12% of the particles are recovered from the cyclone body when using single-hole water injection as compared to less than 2% when spray atomization was used to inject the water.

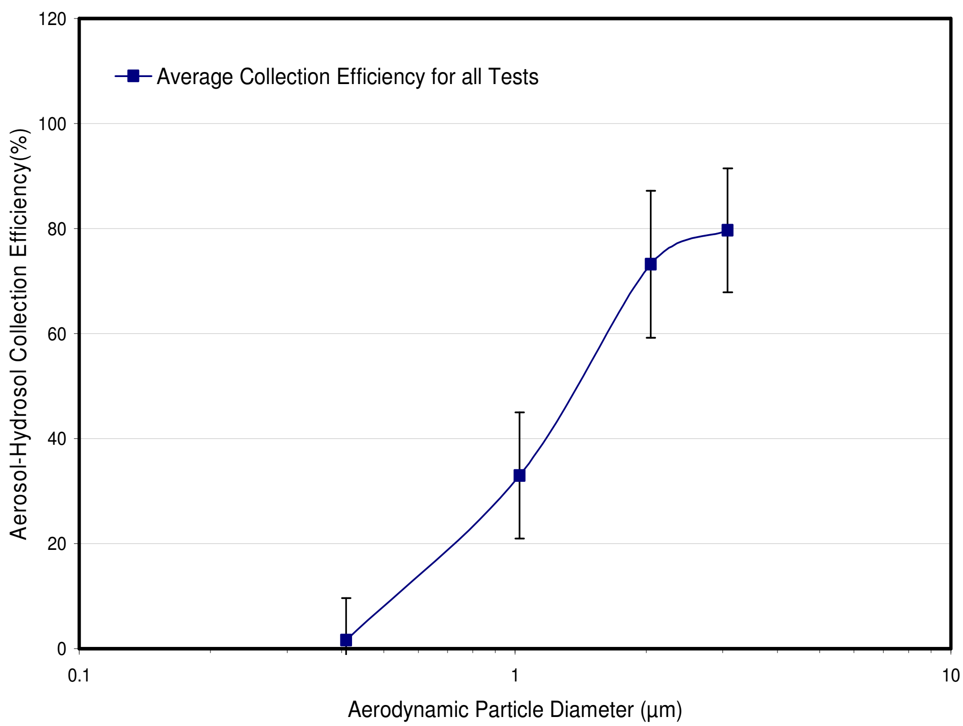

Figure 26. Steady-state aerosol-hydrosol efficiency for AAC2.1d cyclone at an air flow rate of 1250 L/min and a liquid input rate of 1.6 mL/min.

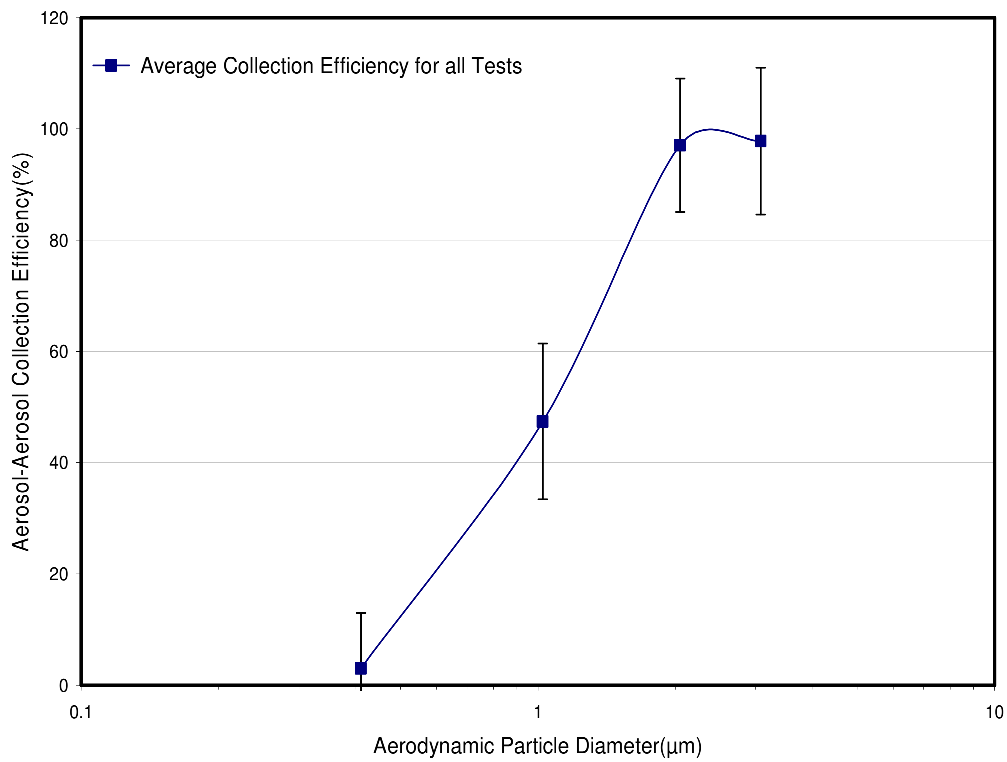

Figure 27. Steady-state aerosol-aerosol efficiency for AAC2.1d cyclone at an air flow rate of 1250 L/min and a liquid input rate of 1.6 mL/min.

AAC 2.0 Cyclone

This is the new cyclone and inlet with an integrated air-blast atomizer and fabricated using a rapid-prototype machine. Figures 28 and 29 show the efficiency results obtained. Visualization studies show that the fixed angle of air-blast atomizer did not appear to provide optimum wetting at the impaction zone on the cyclone wall. This is evident by the lower efficiency data obtained (76% aerosol-hydrosol efficiency for 2 µm PSL) compared to the efficiency obtained for the latest design, AAC2.1a (87% aerosol-hydrosol efficiency for 2 µm PSL). The aerosol-to-hydrosol efficiency curve shows that the cut-point is around 1.4 µm whereas the aerosol-aerosol curve shows that the cut-point is approximately 1 µm.

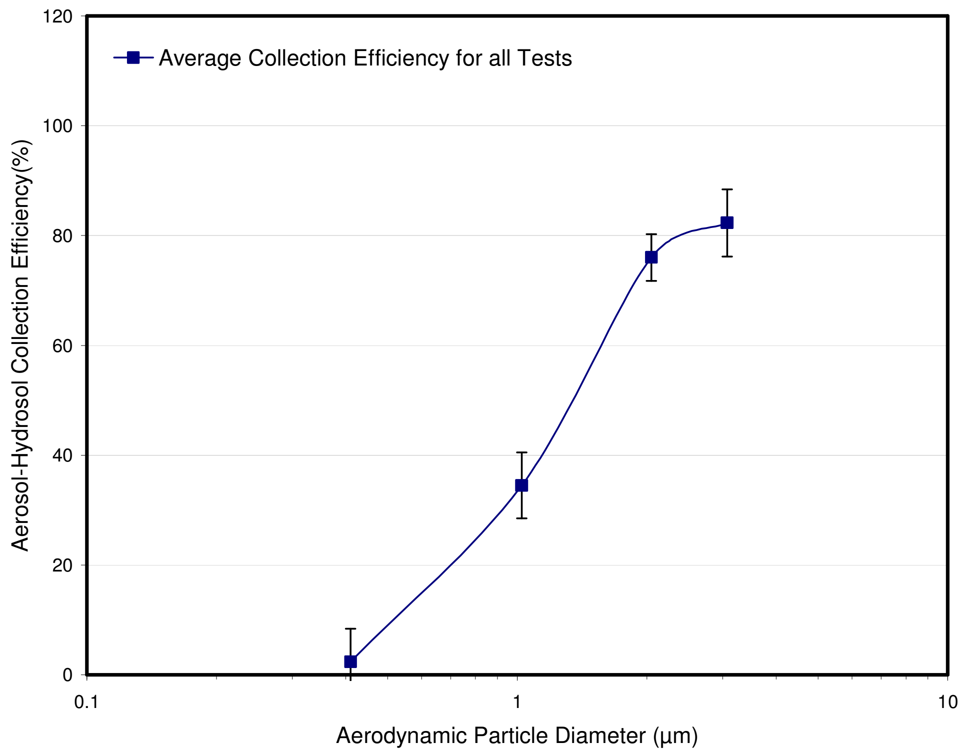

Figure 28. Steady-state aerosol-hydrosol efficiency for AAC2.0 cyclone at an air flow rate of 1250 L/min and a liquid input rate of 1.6 mL/min.

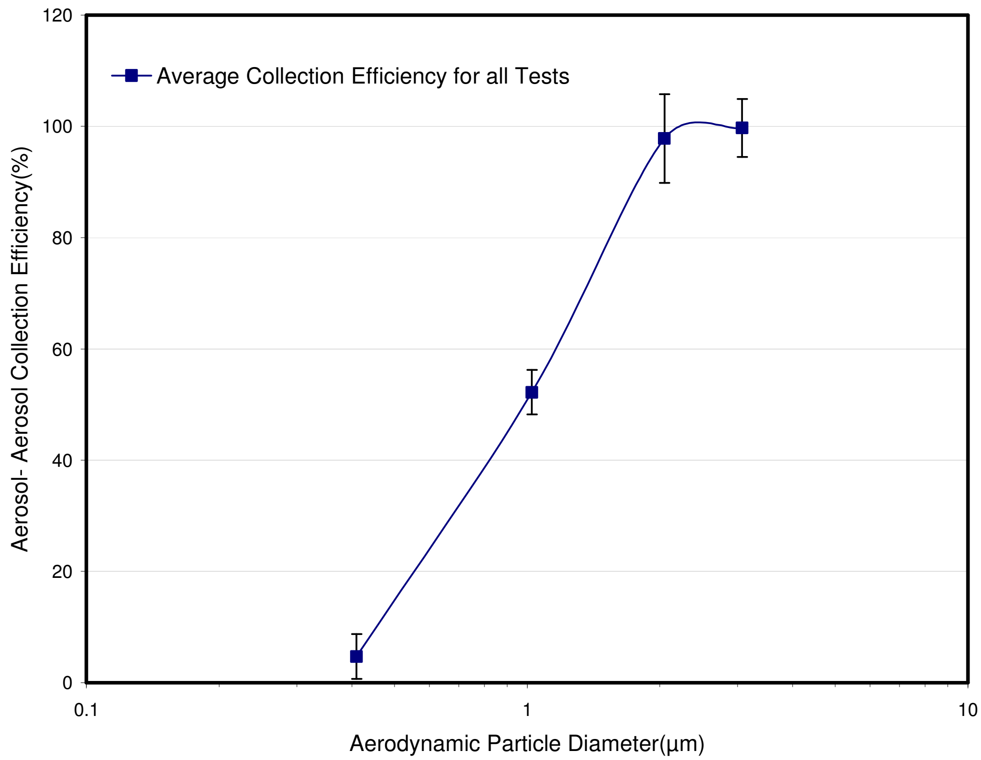

Figure 29. Steady-state aerosol-aerosol efficiency for AAC2.0 cyclone at an air flow rate of 1250 L/min and a liquid input rate of 1.6 mL/min.

AAC 2.1a Cyclone

Efficiency tests were run using PSL particles to see the effect of the location of the air-blast atomizer on the efficiency (Figure 30 and Figure 31). The particle sizes used were 0.4 µm, 1 µm, 2 µm, 3 µm, 5.0 µm, and 10.0 µm. It was seen that when the air-blast atomizer was closer to the inlet, the efficiency was less compared to when it was at a certain height. This was clear from the visualization studies which show that when placed closer to the inlet the water spray was not able to cover the entire impaction zone; hence its capability to wash away the particles was reduced. When a 2um PSL was run with the air-blast atomizer at 3.5 inches high, the A-H efficiency was 86% whereas when the atomizer was kept at 1.25 inches high the efficiency was 68%. The same PSL solution was used for these tests.

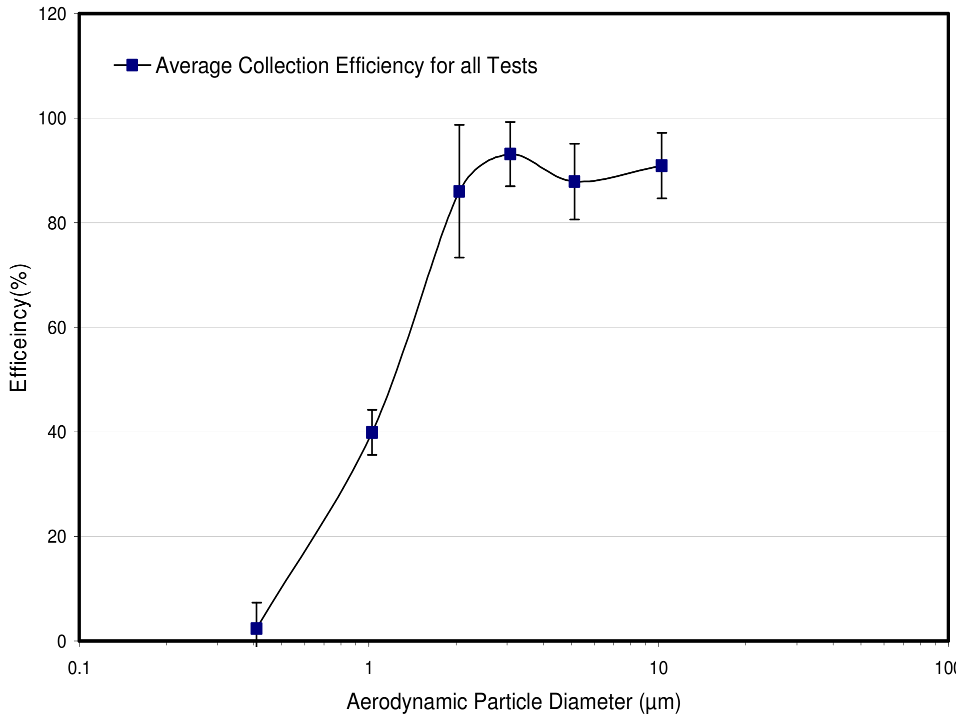

Figure 30. Steady-state aerosol-hydrosol efficiency for AAC2.1a cyclone at an air flow rate of 1250 L/min and a liquid input rate of 1.6 mL/min.

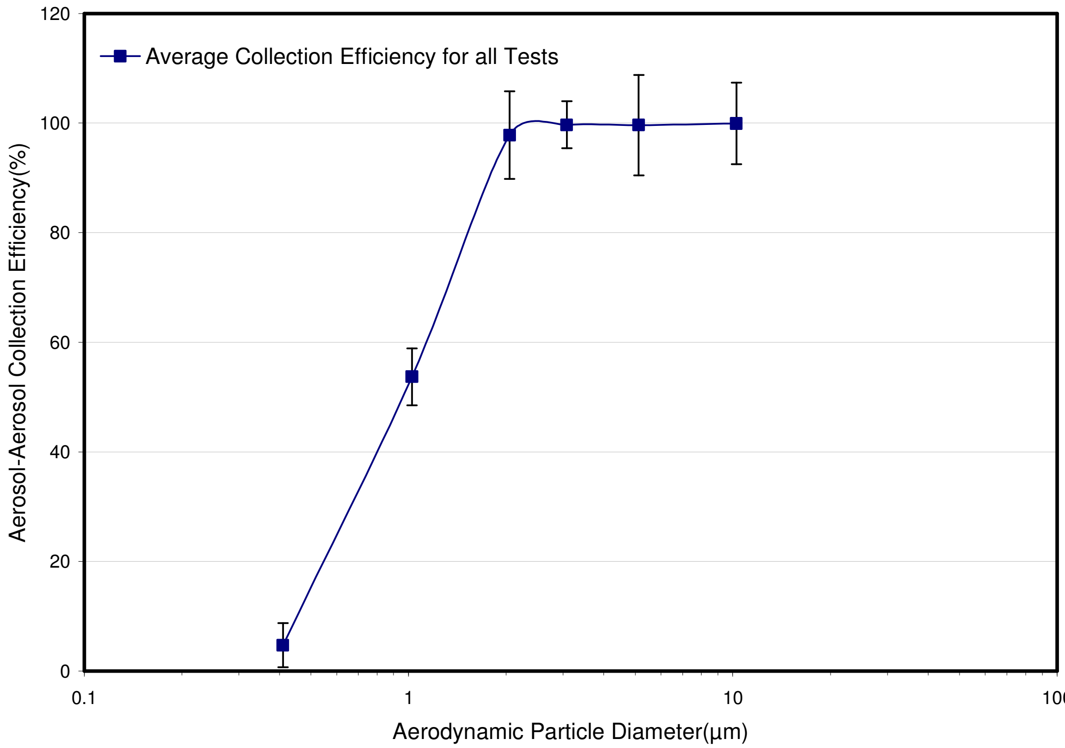

Figure 31. Steady-state aerosol-aerosol efficiency for AAC2.1a cyclone at an air flow rate of 1250 L/min and a liquid input rate of 1.6 mL/min.

Qualitatively and quantitatively, the air-blast atomization technique appeared to produce the most uniform coverage of water film at the impaction zone of the cyclone as compared to all other designs. It was also evident from the good efficiency data and lower range of error bars. Tests using larger size PSL particles (5.0 µm and 10.0 µm) were further conducted on the AAC2.1a and modified White-type cyclone to compare the performance of the two designs. While an efficiency of around 87% was obtained for the AAC2.1A cyclone for 2 µm PSL, it was seen that for single-hole injection the efficiency numbers were low.

Time Response of the Cyclone

Time response tests were run for the modified White-type cyclone and the AAC 2.1a cyclone. Two types of time constant tests were run: “dry time constant test” and “wet time constant test”. In a dry start the cyclone and the test aerosol were started simultaneously with no pre-wetting of the cyclone interior surface. This is the way the White-type cyclone is operated by the Army; hence this method of operation was studied. Figures 32 and 33 show the results obtained for both cyclones. The time constant to recognize a signal was found to be 1 minute and 0.5 minutes for White cyclone and AAC2.1a, respectively, and the time constant for the cyclone to clear itself, once a challenge is no longer present, is 1.4 minutes for the White cyclone and 1.5 minutes for the AAC2.1a cyclone.

In a wet start the cyclone was brought to steady-state condition for the air and liquid flow followed by the sudden introduction of the test aerosol at the cyclone inlet. Figures 34 and 35 show the results obtained for the wet time constant tests. The time response to recognize the presence of a challenge is 2.5 minutes for the White cyclone and 1.3 minutes for the AAC2.1a cyclone. The response time for the decay of the signal is 1.1 minutes and 1 minute for the White cyclone and AAC2.1a cyclone, respectively.

For the modified White cyclone, liquid carryover was observed in most of the runs. The curves below have at least two runs where there was negligible bypass. This was done to determine the time constant when the cyclone operates at its maximum possible efficiency.

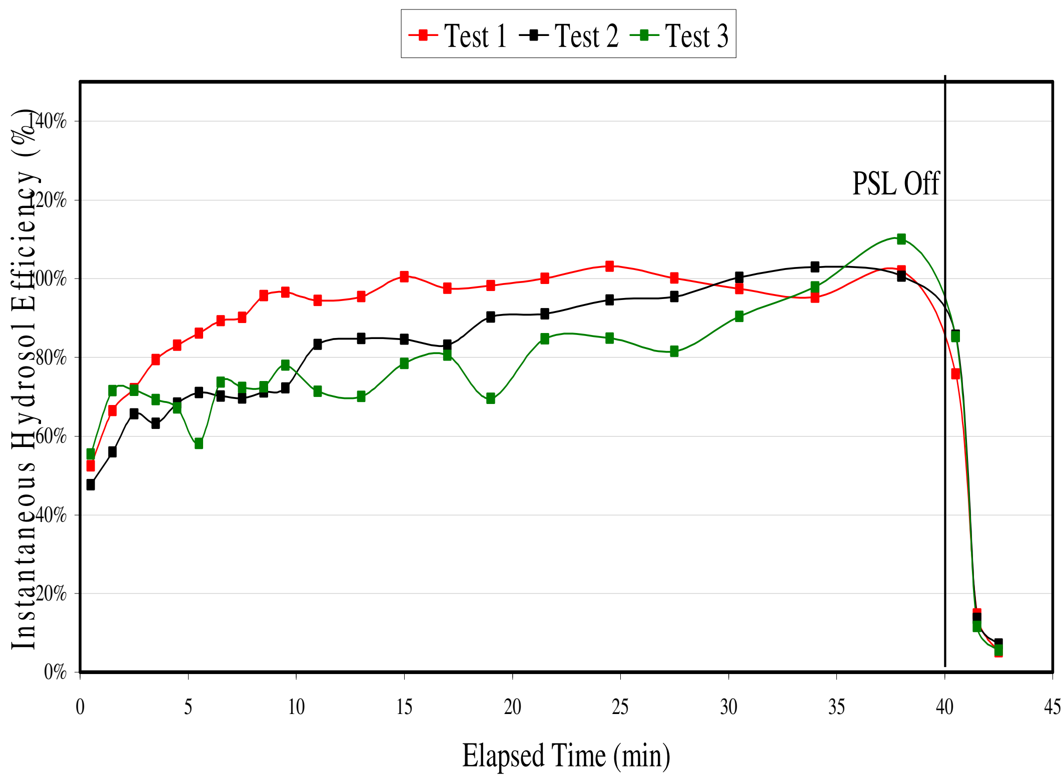

Figure 32. Dry time response of the AAC2.1a cyclone.

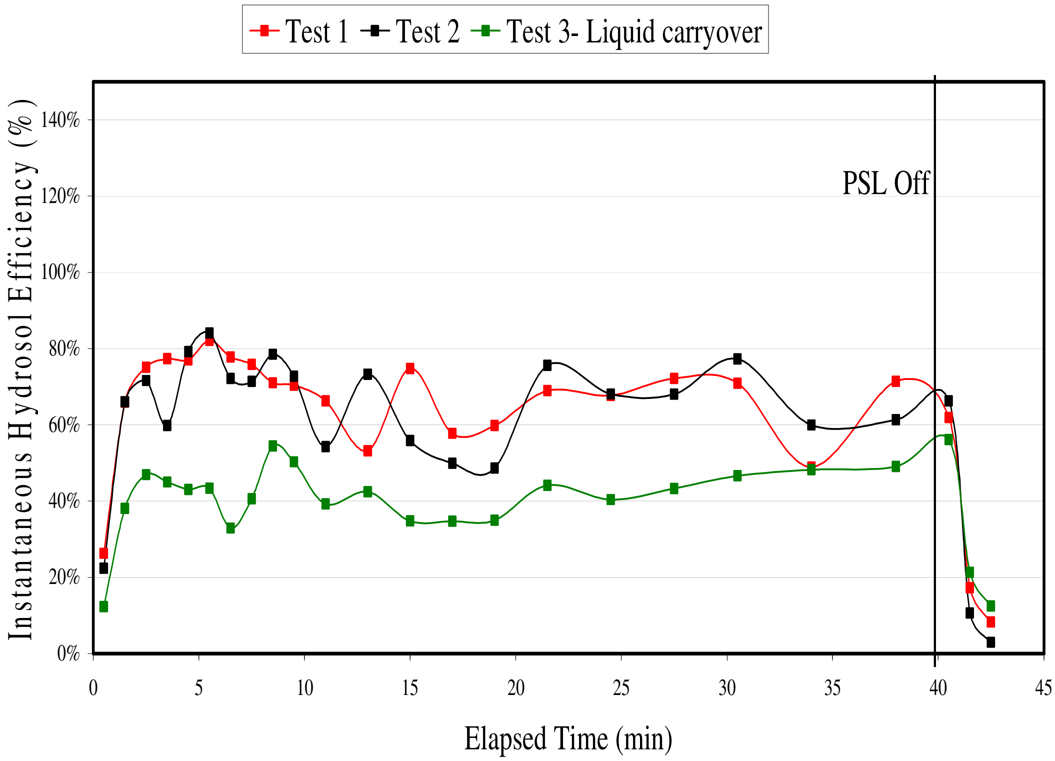

Figure 33. Dry time response of the modified White-type cyclone.

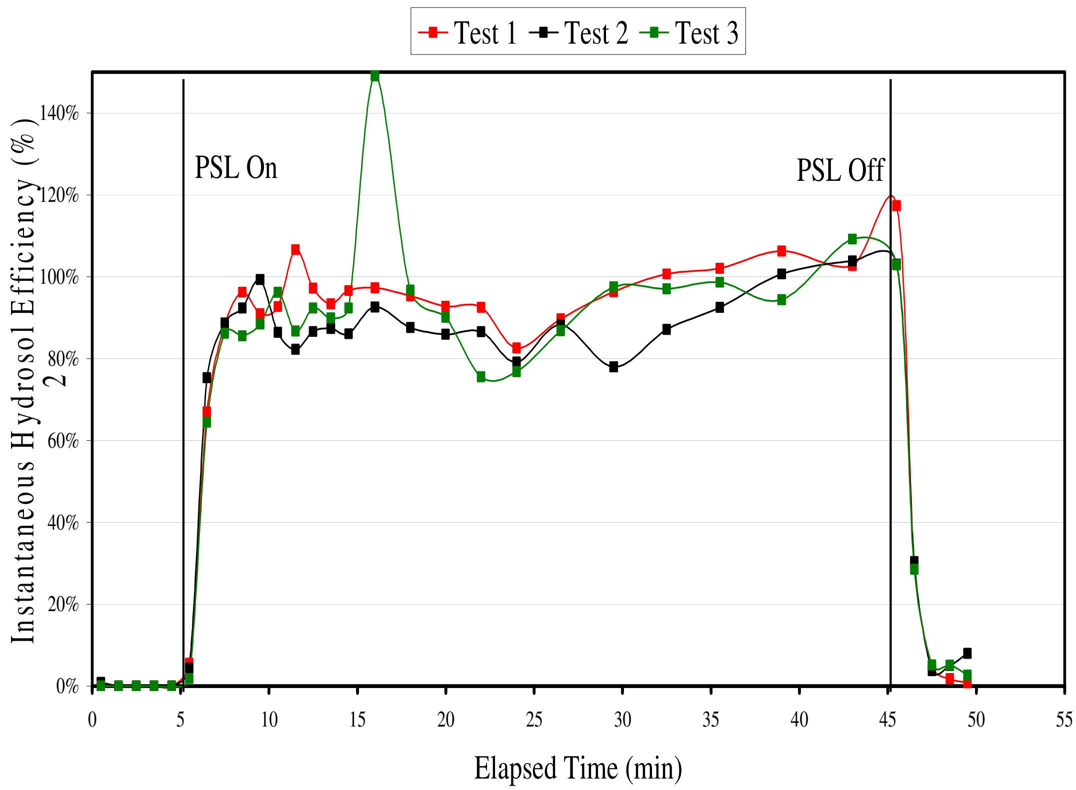

Figure 34**.** Wet time response of the AAC2.1a cyclone.

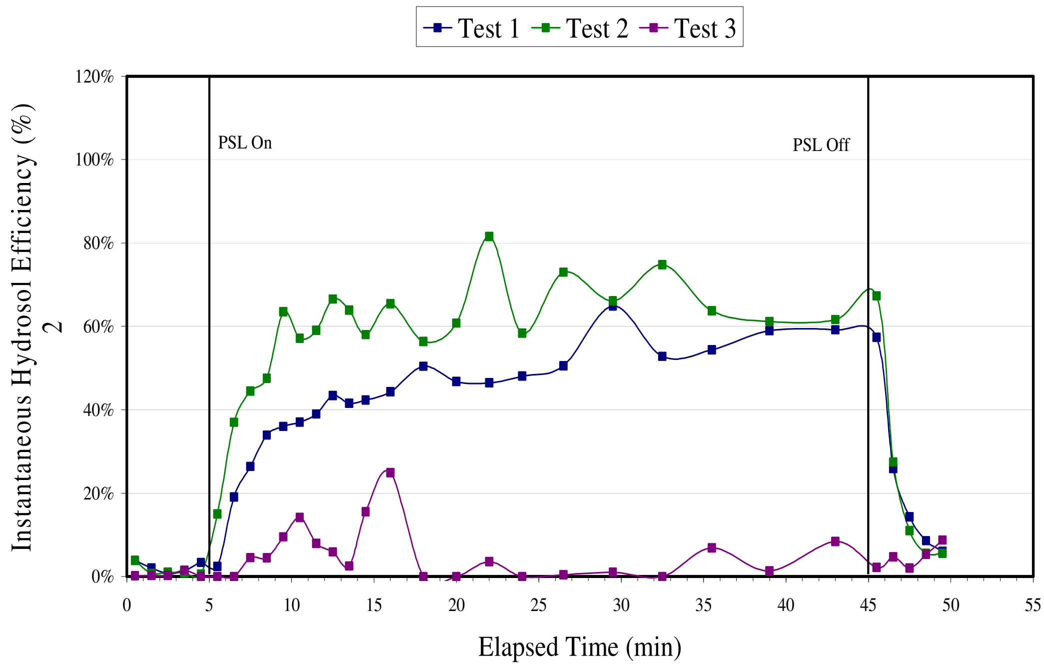

Figure 35. Wet time response of the modified White cyclone.

ERROR ANALYSIS

The errors associated with the above results can be classified mainly into two types: systematic errors and precision errors. The systematic errors refer to the uncertainties associated with the way the experiment was conducted or from the experimental set up. All reasonable steps were taken to minimize systematic errors. The second major type of error can be quantified as a precision error. These errors are the result of the resolution to measure certain parameters that are important in determination of the experimental results.

Systematic Errors

One potential systematic error is the filtering of hydrosol sample. The hydrosol samples were filtered using a vacuum pump and a 25 mm diameter polycarbonate membrane filter (Isopore, Millipore, 0.6 μm DTTP) for recovery of the particles. Ideally, the hydrosol should be evaporated to prevent any loss of particles but due to the large volume of each sample it was practically difficult to evaporate the samples using a heat gun. To minimize the possibility of this potential error, the glass holder and the funnel into which the sample was drained down were rinsed with distilled water and the particles deposited on the edge of the filter holder were swiped away with cotton swabs soaked in ethyl acetate.

Another type of systematic error would occur if the dishes used to soak the glass fiber filters in a solvent were not sufficiently clean. The presence of residual fluorescence from previous tests could also have detrimental effects on the experimental results. As a result, a dish cleansing procedure was established for the PSL particles used.

In the case of solid PSL spheres, the solvent used to dissolve the spheres was ethyl acetate. In order to ensure that the containers are clean following the experiments, the container was rinsed twice with ethyl acetate followed by two rinses with isopropyl alcohol and then twice with distilled water to make sure that all the residual particles are washed away. The container was then allowed to air dry.

To make sure that the experiments are not influenced by preexisting fluorescence in containers, a few trial containers that had been cleaned using the procedure described above were filled with a sample solution and its fluorescence was measured. It was seen that the background from preexisting fluorescence was not any higher than the background of distilled water or ethyl acetate and hence this method of cleaning the containers was considered in all the experiments.

The same experimental set up and procedure was used for both the cyclones and the reference samples taken. Hence, it can be assumed that any other errors present in both the reference and cyclone cancel out and minimize their significance.

Precision Error

The precision errors result due to uncertainty associated with the resolution to measure certain parameters that are important in the determination of experimental results. Common examples being our ability to measure the volumetric flow rate, the volume of solvent the glass fiber filters are soaked in, and the precision of the fluorometer. These errors will propagate and cause an overall level of uncertainty for specific data points. The uncertainty will be evaluated based on the Kline & McClintock method.

The Kline McClintock uncertainty analysis method is defined as:

$$\delta R = \left[\sum_{i=1}^{M} \left(\frac{\partial R}{\partial X_i} \delta X_i \right)^2 \right]^{\frac{1}{2}} \qquad [13]$$

where

δR = Uncertainty associated with the calculation R.

X_i = Variable

δX_i = Uncertainty associated with the variable X_i

The most important error is the uncertainty associated with the efficiency calculation. The uncertainty of the collection efficiency is determined below:

$$\eta_{collection} = \frac{Q_{\exp}.V_{\exp}.T_{\exp}.F_{\exp}}{Q_{ref}.V_{ref}.T_{ref}.F_{ref}} \qquad [14]$$

where

Q_{exp} and Q_{ref} are uncertainties associated with flow rate (5%)

V_{exp} and V_{ref} are uncertainties in the Repipet Dispenser, Barnstead (0/1%)

Q_{exp} and Q_{ref} are uncertainties associated with the stop watch (0.1%)

Q_{exp} and Q_{ref} are uncertainties associated with the fluorometer value (5% to 12%)

Using the Kline McClintock uncertainty analysis method, we get:

$$\frac{\delta \eta_{collection}}{\eta_{collection}} = \left[\begin{array}{l} \left(\frac{\delta Q_{\exp}}{Q_{\exp}} \right)^2 + \left(-\frac{\delta Q_{ref}}{Q_{ref}} \right)^2 + \left(\frac{\delta V_{\exp}}{V_{\exp}} \right)^2 + \left(-\frac{\delta V_{ref}}{V_{ref}} \right)^2 + \\ \left(\frac{\delta T_{\exp}}{T_{\exp}} \right)^2 + \left(-\frac{\delta T_{ref}}{T_{ref}} \right)^2 + \left(\frac{\delta F_{\exp}}{F_{\exp}} \right)^2 + \left(\frac{\delta F_{\exp}}{F_{\exp}} \right)^2 \end{array} \right] \qquad [15]$$

$$\frac{\delta\eta_{collection}}{\eta_{collection}}=\left[\begin{array}{l}(0.05)^2+(-0.05)^2+(0.001)^2+(-0.001)^2+(0.001)^2+\\(-0.001)^2+\left(\frac{\delta F_{\exp}}{F_{\exp}}\right)^2+\left(-\frac{\delta F_{ref}}{F_{ref}}\right)^2\end{array}\right] \qquad [16]$$

The uncertainty of the fluorescence value varies with each experimental data point. The fluorescence value obtained from the Turner Quantech Digital filter fluorometer (Model FM109515, Quantech, Barnstead International, Dubuque, IA) was found to vary between 5% to 12%. The predicted uncertainty based on the Kline-McClintock analysis based on the range of fluorometer uncertainties shows the uncertainty for the efficiency calculation to lie between 10% and 18.38%.

SUMMARY AND CONCLUSIONS

Aerosol-to-Hydrosol and Aerosol-to-Aerosol Performance

A new cyclone design was considered which was better than the modified White-type cyclone which had problems like liquid carryover and water recirculation ring that inhibit its ability to consistently deliver liquid samples and increased the time response of the cyclone. For the White cyclone, the aerosol-aerosol transmission cut-point was found to be 0.8 µm and the aerosol-hydrosol collection efficiency cut-point was 1.3 µm without the effects of liquid carryover considered. However, carryover was seen in most of the runs.

The new design had no liquid carryover and recirculation ring problems and the AAC2.1d, which used the same method of water injection as the modified White-type cyclone, had an aerosol-aerosol transmission efficiency cut-point of 1.1 µm and an aerosol-hydrosol collection efficiency cut-point of 1.5 µm.

Different methods of liquid injection were studied and it was found that the air-blast atomizer technique worked the best with an aerosol-hydrosol efficiency of 86% and an aerosol-aerosol efficiency of 97.8% for 2µm PSL particles. Other water injection techniques like needle spray bar and manifold efficiency gave aerosol-hydrosol efficiencies of 78% and 78.5% and aerosol-aerosol transmission efficiencies of 97.9% and 96.8%, respectively. However, the high probability of the holes becoming plugged, due to a small speck of dust or evaporation of the TWEEN 20 solution, restricts their usage. Furthermore, visualization studies showed that the air-blast technique was able to completely cover the impaction zone whereas the spray-bar and single-hole methods of water injection did not cover the entire zone. This was evident from the high percentage of wall losses observed (12%) in the case of the spray-bar technique as compared to the air-blast method where the wall losses were around 2%.

Time Response of the Cyclone

The time response of the White-type cyclone was shown to be 2.5 minutes for the wet start and 1 minute for the dry start. These values correspond to no liquid carryover conditions. The decay response for no liquid carryover is 1.1 minutes for wet start and 1.2 minutes for dry start. The elimination of the water recirculation ring and water bypass resulted in a reduced value of time response for the new design (AAC2.1a) leading to early detection of aerosols. The AAC2.1a has an initial response of 0.5 minutes for dry start and 1.28 minutes for wet start and a decay response of 1.4 minutes for dry start and 1minute for wet start. There was no liquid carryover seen for any of the runs for AAC2.1a cyclone.

Final Remarks

In conclusion, a modification was presented of the current White-type cyclone design which has a higher sampling rate and maintains the same cut-point as the White cyclone. Different water injection techniques were studied and the one which uses an air-blast (AAC2.1a) to inject water was shown to be the most efficient in its working. Two major problems of water bypass and recirculation ring were eliminated which resulted in both a better aerosol-to-hydrosol collection efficiency across a range of particle sizes as well as reduced value of time response which makes early detection of airborne pathogens possible. Furthermore, the new design reduces the pressure drop across the cyclone thereby reducing the power requirements of the system.

RECOMMENDATIONS FOR FUTURE WORK

An alternative method for recovering particles in the form of a hydrosol was presented. Although the new design has no problem of water bypass it is still unclear as to what exactly causes the water bypass in the modified White-type cyclone. It was seen that the presence of fibers or debris tends to increase the occurrence of bypass. Also, the water build-up due to the recirculation ring increases the occurrence of water bypass by acting as a bridge between the cyclone body and the skimmer; hence a small disturbance can "short circuit" the water past the skimmer. There is also a need to study the behavior of a cyclone with changing temperatures, rough motions, and inclinations, which are the actual conditions at which the cyclone operates.

The water injection techniques used have the possibility of water droplets freezing under cold conditions. Since the water is injected in the form of a fine spray for the AAC2.1a cyclone, the probability of freezing is even higher. Hence, there is a need to do some heat transfer studies on the modified cyclone which could help prevent water from freezing under these conditions. A new blower should be selected or designed to reduce the power consumption of the system.

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APPENDIX

Table 1. Aerosol-to-hydrosol collection and aerosol-aerosol transmission efficiencies of White-type cyclone.

Particle Size(μm)	AD(μm)	A-H Efficiency(%)	A-A Penetration(%)	A-A Efficiency(%)
0.4	0.409878031	2.4	93	7
1	1.024695077	40.5	32.8	67.2
2	2.049390153	76.3	1.4	98.6
3	3.07408523	80.6	3	97
5	5.123475383	44.43	2.15	97.85
10	10.24695077	48	3.05	96.95

Table 2. Aerosol-to-hydrosol collection and aerosol-aerosol transmission efficiencies of AAC2.1a cyclone.

Particle Size(μm)	AD(μm)	A-H Efficiency(%)	A-A Penetration(%)	A-A Efficiency(%)
0.4	0.409878031	2.4	95.3	4.7
1	1.024695077	39.9	46.3	53.7
2	2.049390153	86	2.2	97.8
3	3.07408523	93.1	0.3	99.7
5	5.123475383	87.86	0.38	99.62
10	10.24695077	90.9	0.06	99.94

Table 3. Aerosol-to-hydrosol collection and aerosol-aerosol transmission efficiencies of AAC2.1b cyclone.

Particle Size(µm)	AD(µm)	A-H Efficiency(%)	A-A Penetration(%)	A-A Efficiency(%)
0.4	0.409878031	0.6	96	4
1	1.024695077	33.7	48.7	51.3
2	2.049390153	78	2.1	97.9
3	3.07408523	91.7	1.8	98.2

Table 4. Aerosol-to-hydrosol collection and aerosol-aerosol transmission efficiencies of AAC2.1c cyclone.

Particle Size(µm)	AD(µm)	A-H Efficiency(%)	A-A Penetration(%)	A-A Efficiency(%)
0.4	0.409878031	0.7	94	6
1	1.024695077	32.6	51.2	48.8
2	2.049390153	78.5	3.2	96.8
3	3.07408523	88.9	1.6	98.4

Table 5. Aerosol-to-hydrosol collection and aerosol-aerosol transmission efficiencies of AAC2.1d cyclone.

Particle Size(µm)	AD(µm)	A-H Efficiency(%)	A-A Penetration(%)	A-A Efficiency(%)
0.4	0.409878031	1.6	97	3
1	1.024695077	33	52.6	47.4
2	2.049390153	73.2	2.9	97.1
3	3.07408523	79.7	2.2	97.8

Table 6. Aerosol-to-hydrosol collection and aerosol-aerosol transmission efficiencies of AAC2.0 cyclone.

Particle Size(μm)	AD(μm)	A-H Efficiency(%)	A-A Penetration(%)	A-A Efficiency(%)
0.4	0.409878031	2.4	95.3	4.7
1	1.024695077	34.5	47.8	52.2
2	2.049390153	76	2.2	97.8
3	3.07408523	82.3	0.3	99.7

Table 7. Time response of cyclones.

	Time Response (sec)	Decay Response (sec)
White-type (ca.2003)-Dry Start	59	72
White-type (ca.2003)-Wet Start	149	66
AAC2.1a -Dry start	28	84
AAC2.1a - Wet start	76.8	61

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