A $PM_{1.0/2.5/10}$ Trichotomous Virtual Impactor Based Sampler: Design and Applied to Arid Southwest Aerosols Part I: Design[†]

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Abstract

A $PM_{1.0/2.5/10}$ Trichotomous sampler has been developed to determine if the particles in the saddle point between the coarse and fine particle modes (specifically the $1.0\ \mu\text{m}$ to $2.5\ \mu\text{m}$ size range) are primarily coarse or fine mode particles. The sampler consists of a standard high volume sampler with two high volume virtual impactors (one with a cut size of $2.5\ \mu\text{m}$ and the other with a cut size of $1.0\ \mu\text{m}$) inserted between the PM_{10} inlet and the 8×10 inch (20×25 cm) after filter. By using nine $47\ \text{mm}$ filters, at various locations within the trichotomous sampler, a technique has been developed for subtracting out the effects of particles smaller than the cutsize of a virtual impactor from the minor flow particle collection.

Keywords: atmospheric aerosols, virtual impactors, PM_{10} , $PM_{2.5}$, PM_1

Introduction

Many types of studies require measuring the aerodynamic diameter size distribution of air-borne (aerosol) particles, where the aerodynamic diameter of a particle is the diameter of a unit density sphere that has the same falling speed as the particle in question. One type of inertial classifier is the most common method for aerodynamic particle size classification, that being the air jet impacting on a solid plate inertial impactor (Marple, 1970). Since impactors were first developed in 1860, many single stage and cascade impactors have been designed, built, tested, and sometimes made commercially available (Marple, 2004).

One shortcoming of the inertial impactor is that particles can bounce off of the impaction plate (particle bounce), or can be blown off the plate after collection (particle blow-off). This will result in particles that are intended to be collected on a certain stage

being collected on subsequent stages of the cascade impactor, giving an erroneous size distribution measurement.

A variation of the inertial impactor, which solves the particle bounce problem, is the virtual impactor (**Fig. 1a**), which replaces the impaction plate with an open ended tube, called a collection probe, a diameter of which is about 35% larger than the nozzle diameter (Xu, 1991). The entrance to the collection probe creates a condition that can be thought of as a virtual impaction surface (thus the name) through which particles pass into a void. Large particles penetrate far into the collection probe and are carried out the opposite end with a small percentage of the total flow, known as the minor flow. Smaller particles that do not penetrate as far into the probe, reverse direction and leave at the outer circumference of the probe with the remaining flow, known as the major flow. Performance of the virtual impactor stage is characterized by a collection efficiency curve, as shown in **Fig. 1b**. The size of particles that are collected with 50% efficiency is called the cutsize of the virtual impactor stage. Efficiency, defined as the percentage of particles passing through the virtual impactor nozzle and collected in the minor flow (Marple and Chein,

[†] Accepted: April 15, 2012

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1980), can have collection characteristics that are similar to inertial impactors.

Although the virtual impactor configuration solves the particle bounce problem of the inertial impactor, it does create another problem unique to virtual impactors. The problem is that the minor flow contains particles smaller than the cutsize in a concentration equal to that in the major flow. These small particles in the minor flow will be referred to as “background” particles in this paper and constitute a contamination of the large particle fraction with small background particles, and is the reason that the efficiency curve does not go to zero at small particles sizes in **Fig. 1b**.

A number of researchers have developed designs to eliminate these background particles by providing a clean particle free core of air in the central portion of the flow passing through the nozzle (Masuda et al., 1978; Chen et al.1986). This clean core of air will then be the air that passes through the collection probe, thus eliminating small background particles in the minor flow. This clean core of air does compli-

cate the flow system of an otherwise simple classifier and is nearly impossible to incorporate into virtual impactors that have more than one nozzle/collection probe set in one stage, or in cascade designs.

In this paper we describe another solution to the background particle problem. The solution is to collect particles smaller than the virtual impactor cutsize on a filter that is identical in size, material, and flow rate to the filter collecting the particles larger than the cutsize (minor flow collection). Identical analysis of both filters will allow for the effects of the background particles to be subtracted from the particles larger than the cutsize. This technique is the one chosen in the design of the $PM_{1.0/2.5/10}$ Trichotomous sampler described in Part I of this paper. Part II, to be published in the 2013 issue of KONA, will describe the use of the $PM_{1.0/2.5/10}$ Trichotomous sampler in a study of atmospheric aerosol particles in the southwestern US, specifically in Phoenix, Arizona.

Design Criteria for the $PM_{1.0/2.5/10}$ Trichotomous Sampler

When the fine particle standard was established in the US in1997, there was much discussion among experts as to whether the standard should be set at 1.0 μm or 2.5 μm . The problem arose from the nature of the particle size distributions in atmospheric aerosols. Whitby (1978) discovered that atmospheric particle size distributions were trimodal in nature, with fresh combustion particles in the smallest mode, aged combustion particles in the intermediate mode (fine particle mode) and mechanically generated particles in the largest mode (coarse particle mode). An excellent discussion of this topic is presented by John (2011).

It was generally agreed that the particle size separating the fine and coarse particle modes was in the

Fig. 1 Virtual Impactor Stage and Particle Collection Efficiency curve.

- a) Nozzle/collection probe virtual impactor stage
- b) Particle collection efficiency curve

Fig. 2 Fine and Coarse Particle Modes. From U.S. Environmental Protection Agency (1982).

1 μm to 2.5 μm range. Particles in this size range consist of particles from the lower tail of the coarse particle mode and particles from the upper tail of the fine particle mode (see **Fig. 2**). The discussion centered on the question of whether the particles in the range of 1 μm to 2.5 μm were mostly fine or mostly coarse mode particles.

The $\text{PM}_{1.0/2.5/10}$ Trichotomous sampler was designed to answer this question by using two virtual impactors in series (cascade) with cut sizes of 2.5 μm and 1.0 μm . It was decided to use the standard 40 cfm (1.13 m^3/min) 10 μm classifying inlet of the PM_{10} sampler as the sampler's first stage to avoid the need to develop a new sampling inlet.

$\text{PM}_{1.0/2.5/10}$ Trichotomous Sampler

Major Components

The superstructure of the trichotomous sampler is the standard high volume 40 cfm (1.13 m^3/min) flowrate PM_{10} sampler, which consists of a PM_{10} size selective inlet (McFarland et.al., 1984) and an 8 $\times$ 10 inch (20 $\times$ 25 cm) filter, but the heart of the $\text{PM}_{1.0/2.5/10}$ Trichotomous sampler is two high volume virtual impactors (HVVIs) (Marple and Olson, 1995) with cut sizes of 2.5 μm and 1.0 μm . The HVVIs, being of small size (8.25 in. $\times$ 6.75 in. $\times$ 2.75 in. high) (21cm $\times$ 17cm $\times$ 7cm) and yet having a flow rate of 40 cfm, were designed specifically to further size classify particles in the high volume PM_{10} sampler (Marple et.al., 1990). Two HVVIs are inserted in series between the PM_{10} inlet and the 8 $\times$ 10 filter. The 2.5 μm HVVI is located inside the lower cavity of the PM_{10} size selective inlet, with an additional chamber inserted between the inlet and the 8 $\times$ 10 filter to house the 1 μm HVVI, which is mounted directly above the 8 $\times$ 10 inch filter.

Figs. 3, 4 and 5 show schematics of the sampler and the two HVVIs and **Fig. 6** shows photos of the major components. The colored filter holders in these figures will be explained in the following section.

A schematic of the overall sampler is presented in **Fig. 3**. The flow path through the sampler is through: 1) the 10 μm size selective inlet, 2) the 2.5 μm HVVI, 3) the 1.0 μm HVVI and then 4) the 8 $\times$ 10 inch after filter. Air is pulled through the sampler using two blowers in series rather than just one blower as in the standard high volume sampler. The blower system consists of a standard high volume blower with an auxiliary blower mounted at its exhaust. This

modification to the standard high volume sampler is necessary due to the additional pressure drop of the HVVIs. Flow control is achieved with a mass flow controller supplied with the high volume sampler. This flow controller controls the speed of the second

Fig. 3 Schematic of $\text{PM}_{1.0/2.5/10}$ Trichotomous Sampler.

Fig. 4 Schematic of 2.5 μm HVVI.

Fig. 5 Schematic of 1.0 μm HVVI.

Fig. 6 Photos of PM_{10/2.5/10} Trichotomous Sampler.
a) Assembled sampler; b) 2.5 µm HVVI; c) 1.0 µm HVVI
A-PM10 inlet; B-Intermediate chamber; C-Base; D-2.5 µm HVVI; E-1.0 µm HVVI; F-After filter.

Fig. 7 47 mm filter holder.

blower only, thus, controlling the back pressure of the first blower, which operates at full speed.

Flow paths through the two HVVIs are similar and shown schematically in **Figs. 4** and **5**. Flow enters the HVVIs through nozzles (12 and 80 nozzles for the 2.5µm and 1.0µm HVVIs, respectively) on either side of the HVVI housings. Particles larger than the cutsize are collected with the minor flow in the center chamber, along with 5% of the particles smaller than the cutsize (the minor flow is 5% of the total flow for both HVVIs). Particles smaller than the cut size remain with the major flow and exit through the bottom of the HVVI housings.

Fig. 6 shows photos of major components of the sampler. **Fig. 6a** shows the assembled sampler with the PM10 high volume inlet, the intermediate chamber and the high volume sampler stand. Sets of pres-

sure gages and control valves, located on both sides of the stand, are for controlling the flow through the various filters in the sampler. **Fig. 6b** shows the 2.5 µm HVVI located inside the PM₁₀ inlet and on top of the intermediate chamber. **Fig. 6c** shows the 1.0 µm HVVI inside the intermediate section and on top of the standard 8 × 10 inch high volume filter. Both 2.5 µm and 1.0 µm HVVIs have bases specifically designed for the trichotomous sampler to accommodate the various 47 mm filters.

Filter Sample Locations

Nine 47 mm diameter filters are in various locations in the trichotomous sampler to collect particle samples of PM₁₀, PM_{2.5}, PM₁, PM_{2.5-10} and PM_{1-2.5}. The filters are inserted into filter holders and the holders are clamped into manifolds within the trichotomous sampler. These filter holders are also used to transport the filters to and from the field test site. To ensure that the filter holders are inserted into the correct location in the sampler, filter holders, and manifolds, are color coded. In addition, the filter holders, shown in **Fig. 7**, are of special design so that they can only be inserted into the manifolds in one direction, insuring that the filter holders cannot be inserted backwards and the flow will always be in the correct direction through the filters. At some locations, two filters were used for the purpose of using two different particle analysis techniques.

Placement of the nine 47 mm filters in the trichotomous sampler are shown on the schematics in **Fig. 3**, and in the photos in **Figs. 8** and **9**, where **Figs. 8**

and 9 shows the bases of the 2.5 μm and 1.0 μm HVVIs, respectively. The heads of the HVVIs have been removed in these photos.

Filters shown in Figs. 8 and 9 are as follows:

Fig. 8

1. One 47mm PM_{10} filter (A, the grey holder) located after the PM_{10} inlet and before the 2.5 μm HVVI.
2. One 47mm $\text{PM}_{2.5-10}$ filter (B, the gold holder) samples particles from the minor flow of the 2.5 μm HVVI. Also shown is the 2×7 inch (5×17.5 cm) minor flow filter so that the total minor flow rate can be brought to 2 cfm.

Fig. 9

3. One 47mm $\text{PM}_{2.5}$ filter (D, the blue holder)

Fig. 8 Photo of 2.5 μm base showing 47 mm filter holder placements.

A- PM_{10} filter (grey filter holder); B- $\text{PM}_{2.5-10}$ filter (gold filter holder); C- $\text{PM}_{2.5-10}$ 2×7 inch filter.

Fig. 9 Photo of 1.0 μm base showing 47 mm filter holder placements.

D- $\text{PM}_{2.5}$ filter (blue filter holder); E- $\text{PM}_{1-2.5}$ filter (red filter holders); F- PM_1 filter (green filter holders); G-background control filters (black filter holders); H- $\text{PM}_{<1}$ 8×10 inch filter.

samples the 2.5 μm HVVI major flow aerosol.

4. Two 47mm $\text{PM}_{1-2.5}$ filters (E, the red holders), which sample the 1.0 μm HVVI minor flow aerosol.
5. Two 47mm PM_1 filter (F, the green holders) which samples the 1.0 μm HVVI major flow aerosol.
6. Two 47mm background filters (G, the black holders) located above the 8×10 inch final filter. These filters have zero flow rate (are used as control filters).

The flow rate through each filter is controlled by a flow circuit consisting of an orifice flow meter, connected to a Magnehelic pressure gage, and followed by a manual flow control valve. Flow from each filter is routed back into the primary flow circuit downstream of the 8×10 inch filter, allowing the flow rate to be controlled, and remains constant at 40 cfm. Since a maximum of 2 cfm is passing through any 47 mm filter, normally the flow remains relatively constant over a 24 hour sampling period. Therefore, the control valve for each filter need only be set at the onset of sampling. However, for heavy particle loading conditions, an intermediate adjustment of flow rate can easily be made.

Collection Characterizes

There are three inertial classifiers in the trichotomous sampler: a PM_{10} high volume inlet, and two HVVIs virtual impactors. The PM_{10} inlet uses inertial impactor technology to remove particles larger than 10 μm , and has been the subject of many wind tunnel

Fig. 10 Particle classification curves for 1.0 and 2.5 HVVIs.

evaluation and calibrations.

The 2.5 μm HVVI was designed specifically to further classify particles within the standard high volume PM₁₀ sampler. Initial application was separation of coarse mechanically generated aerosol particles from smoke particles being emitted from wood burning fireplaces (Marple, et.al., 1990). Since these mechanically generated aerosols are solid, the 2.5 μm HVVI was calibrated with solid ammonium fluorescein particles generated using a vibrating orifice monodisperse aerosol generator (VOMAG) (Berglund and Liu, 1973). The collection efficiency curve of the 2.5 μm HVVI is shown in **Fig. 10**.

However, the 1.0 μm HVVI was designed specifically for use in the trichotomous sampler and had to be calibrated for this program. Since particles less than 1 μm in diameter are formed by condensation, liquid particles were used in its calibration. In a method commonly used in our laboratory, a VOMAG was used to generate oleic acid droplets tagged with uranine dye. By washing out various parts of the classifier with known amounts of wash solution and analyzing the wash solution with a fluorometer to determine the dye concentration, the collection efficiency of the HVVI was determined as a function of particle size. The resulting efficiency curve for the 1.0 μm HVVI is also shown in **Fig. 8**. Note in the efficiency curves for both 2.5 μm and 1.0 μm HVVIs that the lower efficiency asymptotically approaches the fraction of the minor flow (5%).

Analysis Techniques

The PM_{1.0/2.5/10} Trichotomous sampler was developed to provide a means for determining if particles in the 1.0 to 2.5 μm size range are mostly coarse or mostly fine mode particles. Since coarse and fine mode particles originate from different sources, more than one analysis method had to be employed; one for coarse particles and one for fine particles. Therefore, two filters were used in some locations within the trichotomous sampler.

Part II of this paper, to be published in the 2013 issue of KONA, describes the use of PM_{1.0/2.5/10} Trichotomous samplers in a study of atmospheric aerosol particles in the southwestern US, specifically in Phoenix, Arizona. Proton-induced X-ray emission (PIXE) and photon-induced x-ray fluorescence (XRF) methods were used to determine the concentration and composition of the coarse particle mode. Both of these methods are commonly used due to their non-destructive multi-element capabilities and relatively

good sensitivities. A different analysis technique was used to analyze the filters for fine particles. The water-soluble portion of suspended particulate matter was quantified using ion chromatography (IC).

Filters in the grey, gold, blue, red and green filter holders were subjected to PIXI analysis and filters in the red and green filter holders were subjected to IC analysis.

Conclusion

An ambient high volume sampler has been specifically developed to answer the question of whether particulate matter in the saddle point between the coarse and fine particle modes (1.0 μm to 2.5 μm range) consist primarily of coarse or fine particles. The sampler consists of the standard 40 cfm high volume ambient air PM₁₀ sampler with two high volume virtual impactors, one with a cut size of 2.5 μm and the other with a cut size of 1.0 μm , inserted between the PM₁₀ inlet and the 8 $\times$ 10 inch after filter. Particles were collected on seven 47 mm filters at various locations within the sampler to enable analyses by different techniques to determine the fraction of the particles in the 1.0 μm to 2.5 μm range that was from the coarse mode aerosol or the fine mode aerosol.

Acknowledgements

Development and calibration of the PM_{1.0/2.5/10} Trichotomous sampler has been supported by the National Mining Association.

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