Development of Low Volume Substrate Based Particulate Matter Sampler

by

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A thesis submitted in partial fulfillment of the requirements for the degree of Masters of Science in Civil Engineering

Khulna University of Engineering & Technology

Khulna 9203, Bangladesh

January 2019

Declaration

This is to certify that the M.Sc. thesis work entitled "Development of Low Volume Substrate Based Particulate Matter Sampler" has been carried out by Md. Shah Alam in the Department of Civil Engineering, Khulna University of Engineering & Technology, Khulna, Bangladesh. The above thesis work or any part of this work has not been submitted anywhere for the award of any degree or diploma.

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Acknowledgement

At the very beginning I would like to express all of my admiration and devotion to the Almighty Allah (SWT), the most beneficent who has enabled me to perform this research work and to submit this thesis.

A dissertation can't be completed without the help of many peoples, to contribute directly or indirectly through their constructive criticism in the evaluation and preparation of research work. During the thesis conducting period, I have received cordial help from many quarters, which I like to put on record here with deep gratitude and great pleasure.

First and foremost, I would like to express my deep sense of gratitude and high gratefulness with due respect to Professor Dr. Kazi ABM Mohiuddin, my thesis supervisor for his guidance, understanding, patience, and most importantly his friendship during my post-graduate thesis in KUET. I am greatly indebted to his supervisor for generous help and unfailing enthusiasm in the completion of this study. Without his valuable direction and cordial assistance it would have been impossible to carry out this study under a number of constraints.

I want to give my warm and deep gratitude to Professor Dr. Quazi Hamidul Bari, Director, Institute of Disaster Management, KUET for his support by providing the kind opportunity to use the instrument for experimental work. I also am grateful to Professor Dr. Mizanur Rahman Badal, Department of chemistry (KUET) for providing the laboratory facilities for gravimetric analysis

I acknowledge the assistance of the staffs of Environmental Engineering Laboratory of the Department of Civil Engineering (KUET) Bangladesh. I am also acknowledges the help of Mr. Masud Kaiser Mitul, operator of Fab-Lab, KUET.

If anyone gets any advantage or help from this paper, I think my perseverance will be succeeded.

January, 2019 Md. Shah Alam

Abstract

Air pollution has arisen as a major concern in the present era due to its adverse impact on human health and surrounding environment. Among the six criteria pollutants, the atmospheric particulate matters have been considered as a challenge to ensure air quality in Bangladesh because the Air Quality Index (AQI) value for particulate matter (PM) is mostly ranges from caution to extremely unhealthy. However, air quality sampling and monitoring program in Bangladesh is very insignificant due to expensive PM sampler dealing with nano to micro scale parameters. This study focuses on the development of a low cost PM sampler which is low volume, multi-nozzle and substrate based. The design parameters such as nozzle number, nozzle diameter and nozzle to plate distance were determined from the dimensionless factor named stokes number (Stk) introducing the Reynolds number (Re). The optimal nozzle configuration array was selected to avoid the effect of cross flow parameter upon the collection characteristics.

The PM sampler operates at a flow rate of 5 L/min and consists of two different sets of circular nozzles designed for cut-off PM_{10} (Diameter of particle less than 10μm) and $PM_{2.5}$ (Diameter of particle less than 2.5μm). The designed PM sampler was fabricated from the Fab-Lab of Khulna University of Engineering and Technology (KUET) using the silver metallic PLA filament which is light weight and corrosion resistant. Microscopic analysis of the substrate was performed to investigate cut-off performance. Gravimetric analysis was conducted to evaluate the field performance of the developed PM with a sensor based (light-scattering) reference sampler within the KUET campus. The loss of particle on this study was determined by counting the particle inside the sampler's wall as well as the stagnant corner point of the inside of the PM sampler.

A stage wise sharp cut-off was found for PM_{10} and $PM_{2.5}$ of developed PM sampler. The average mass concentration of PM_{10} and $PM_{2.5}$ was found as 108μg/m^3 and 49μg/m^3, respectively. The average mass concentration of PM_{10} and $PM_{2.5}$ was found very close to the reference sampler. The average particle loss for the impactor nozzle and sampler body was found 12.0% which shows good agreement with previous studies. The obtained cross-flow parameter for the stage PM_{10} (0.20) and $PM_{2.5}$ (0.29) were also satisfying the critical value ($<$ 1.2). Overall, the PM sampler was developed as light-weight, easy to use, portable, low maintenance required, and low cost which can be implemented for PM monitoring in Bangladesh.

Table of Content

List of Table

List of Figure

Chapter 1

Introduction

1.1 Problem statement

The surrounding atmosphere of Bangladesh is rapidly polluting day by day due to the various man made and industrial activities which is strongly related to air pollution. In the recent years, air pollution has arisen as a major concern especially attributed to continuous emission of particulate matter (PM), and many other harmful gaseous emissions to the ambient atmosphere. The atmospheric particulate matter (PM) especially the fine particle like PM_{10} (Dia. of particle less than 10μm) and $PM_{2.5}$ (Dia. of particle less than 2.5μm) is creating a significant adverse effect on both human health and surrounding environment than the coarse particle. The mass concentration of fine particulate matter to ambient environment is a major reason for premature deaths (Massey *et. al.*, 2012), functional change in human cardiovascular and respiratory system (Gupta *et. al.*, 2011) especially for sensitive personnel (elderly and diseased). The particulate matter can penetrate into the lung tissues and finally enter into the blood stream and can change the blood chemistry (Harrison and Yin, 2000). The particulate matter comes to ambient atmosphere mainly from biomass burning, industrial process, power plant and diesel powered vehicles. In the developing country, people have limited availability to reduce the sources of pollution due to the shortage of adequate resources and technologies. Therefore, the measurement and regular monitoring of particulate matter is needed. As a result, the PM sampler is universally used to monitor air quality.

Generally, a large variety of particulate matter sampling instrument are existed. They are used for different purpose and they have different technique to measure the size distribution and concentration ($\mu g/m^3$) of airborne particulate matter from the source and ambient atmosphere. In which some depends on the principles of electrical and thermal precipitation of dust, while others operated by dust settlement, by filtration of dust, by impaction of dust laden air stream onto the collection or impaction surface (K. R. May, 1945). At present the impaction based cascade impactor is widely used for sampling and separation of airborne particulate matter due to its simple design and operation, sharp separation of particles and relatively high collection efficiency (Kumar & Gupta, 2015; Moore *et. al.*, 2014; Novosselov *et. al.*, 2014; Gupta *et. al.*, 2011; Furuuchi *et. al.*, 2010; Singh *et. al.*, 2003; Kwon *et. al.*, 2003; Peters *et. al.*, 2001). Typically, a cascade impactor is a combination of a number of identical stages having nozzle and impaction plate. However, it can be single or multiple stages owing single or multiple nozzles as per requirement. Development of six-stage and single-nozzle cascade impactor was reported by Mitchell and Pilcher (1957). Anderson (1958) evaluated six-stages and multi-nozzle cascade impactor. Brink (1958, 1963) used a five-stage and single-nozzle cascade impactor to size the particles at 0.3μm to 3.0μm range. Cohen and Montan (1967) reported an eight stages and multi-nozzle cascade impactor. Newton *et. al.* (1977) and Marple *et. al.* (1987) designed and calibrated the cascade impactor for the particle size 1.0μm to 10.0μm. Marple *et. al.* (1991) evaluated a ten-stage Microorifice Uniform Deposit Impactor (MOUDI) to size the particle at 0.056μm to 10μm. A numerous study has conducted to design, calibrate and evaluate the field performance of cascade sampler i.e. Peters *et. al.*, 2001; Demokritou *et. al.*, 2001; Kwon *et. al.*, 2002 & 2003; Misra *et. al.*, 2002; Singh *et. al.*, 2003; Kim *et. al.*, 2006; Furuuchi *et. al.*, 2010; Singh *et. al.*, 2010; Gupta *et. al.*, 2011; Giorio *et. al.*, 2013; Novosselov *et. al.*, 2014; Moore *et. al.*, 2014; Kumar and Gupta, 2015.

In Bangladesh due to the change of ambient conditions and different anthropogenic activities, air pollution is a major problem here. So there is a constant need to develop an airborne particulate matter sampler to cope up the upcoming challenges. This research presents the design, fabrication and field performance evaluation of a two stage (PM_{10} and $PM_{2.5}$), low-vol substrate based, multiple nozzle inertia cascade impactor. There are some practices in our country to monitor the particulate matter by importing single stage substrate based cascade sampler and some sensor based sampler. In this study, low-vol substrate based inertial cascade impactor being a two stage multi-nozzle which will give PM_{10} and $PM_{2.5}$ for a single operation. This is the most important advantage upon the present practice. The developed sampler can be used to collect filter samples over a long time sampling period which can be analyzed later to assess various chemical components. This would provide the scope to study the temporal variation of PM composition. Being a low-vol sampler, it will be light weight, handy, portable and comparatively low cost. The obtained concentration of particulate matter by the developed sampler will be lower than the sensory method due to losses of particles for inlet losses, interstage losses, particle re-entrainment (bounce-off and blow-off) (Marple *et al.*, 1976). However, the sensor based (light-scattering) sampler overestimate the PM mass concentration 1.5 times than the gravimetric sampling (Shi *et. al.*, 2017). In the respect of the rate of particulate pollution, there are significant deficiencies of monitoring facility in our country due to the high cost of sampler. On the other hand, there is absence of our own developed sampler. This study will give the first attempt to fabricate the PM sampler for performing gradual increase of the monitoring facility.

1.2 Objectives

Particulate matter (PM) has a great epidemic effect on environment as well as human health. In the developing country, people have limited availability to reduce the sources of pollution due to the shortage of adequate resources and technologies. Therefore, the measurement and regular monitoring of particulate matter is needed. As a result, the PM sampler is universally used to monitor air quality. The overall objective of this research is to develop a substrate based particulate matter (PM) sampler as summarized below:

- To design a two stage PM sampler with multiple nozzles
- To fabricate the PN sampler according to design
- Performance evaluation and validation of the PM sampler

This study provides the scope for determining the concentration of atmospheric particles (PM, µg/m^3) in air and also provides the scope for determining the chemical composition of particulate matter and health risk assessment.

1.3 Organization of the thesis

This study consists of five chapters which are described as below:

Chapter 01: Chapter one contains the Introduction of this study where general background; objectives and scope; and structure of the thesis were discussed.

Chapter 02: Chapter two contains the Literature Review of this study where source of air pollution which covers natural source of air pollution and anthropogenic source of air pollution; particulate matter (PM) in air; size of particulate matter; composition of particulate matter; effect of particulate matter which covers human health effect, wildlife effect and environmental effect; AQI system in Bangladesh; air sampling instruments and methods which covers midget impinger, particle trap impactor, virtual impactor and cascade impactor; working principle of cascade impactor; advantage of cascade impactor; feature of cascade impactor which covers high volume sampler, medium volume sampler, low volume sampler, single nozzle and multi-nozzle sampler; design of cascade sampler and description of various cascade sampler were discussed.

Chapter 03: Chapter three contains Materials and Methods where design of sampler; fabrication of sampler; sampling site and field evaluation; measurement of PM such as mass concentration, cut-off performance and particle loss were discussed.

Chapter 04: Chapter four contains the Result and Discussion where sampler description; field performance evaluation of sampler; mass concentration of PM; cut-off performance of the impactor; loss of particle and cost analysis were discussed.

Chapter 05: Chapter five contains conclusions and recommendations of this study.

Chapter 2

Literature Review

2.1 General

The good air is a mixture of different gaseous component of nitrogen (78%), oxygen (21%), carbon-dioxide (0.03%), argon, and others. The quality of good air can be deteriorated by the entry of several kinds of harmful gases and particle fragment which is marked as criteria pollutants. There are six criteria pollutants such as ozone (O_3), carbon-monoxide (CO), nitrogen-dioxide (NO_2), sulfur-dioxide (SO_2), lead (Pb), and particulate matter (PM).

2.2 Source of air pollution

The surrounding earth atmosphere is polluting bit by bit from the very beginning of mankind. There are many cause and many sources which are responsible for the present increasing rate of air pollution. Pollutant can enter into the atmosphere directly due to the natural and anthropogenic sources and indirectly by forming in the atmosphere through the interaction of primary pollutants (gas-to-particle conversion processes). All of those sources can be sharply classified into two sections. One is natural causes and other is anthropogenic causes.

2.2.1 Natural source of air pollution

The event of air pollution from a source which is occurred automatically in nature is called the natural source of air pollution. Volcanic eruption is one of them, for which a large amount of ash and smoke spread into the ambient air. It creates the high rate of particulate matter (PM) mass concentration in the surrounding air and sustain for a certain period.

Figure 2-1 Source of natural pollution

Dust storm is also a natural event of air pollution. It occurs for a certain region and suddenly spoiled the air quality mainly by increasing the dust particle into the air. The wildfire/bushfire, sea spray are also natural sources of air pollution.

2.2.2 Anthropogenic source of air pollution

The event of air pollution from a source which is occurred due to the human's activity is called the anthropogenic causes of air pollution. It is assumed that man has started to pollute the air by discovering the use of fire. An anthropogenic activity mainly includes the man's technological achievement which is strongly related to particulate matter (PM) pollution such as power plants, industrial facilities, trucks and automobiles, construction activities, straw burning, biomass burning etc. Some religious, occasional and recreational activities are also responsible for air pollution.

Figure 2-2 Anthropogenic source of air pollution

2.3 Particulate matter (PM) in air

The airborne particulate matter (tiny fragment of liquid or solid particles suspended in the atmosphere) may be primarily emitted into the atmosphere directly from natural or anthropogenic sources as discussed in previous section. Also indirectly by forming in the atmosphere through the interaction of primary pollutants (gas-to-particle conversion processes). Among the six criteria pollutant (Ozone, particulate matter, Carbon monoxide, Nitrogen dioxide, Sulfur dioxide, lead) the particulate matter (PM) pollutant is the major concern of the developing country. Exposure to ambient particulate matter (PM) has recently received considerable attention as the result of epidemiological findings, which showed associations between ambient particulate concentrations and mortality.

2.4 Size of particulate matter

The average human eye cannot see particles smaller than 40µm. It is particles larger than 100µm and smaller than 0.01µm that are of little interest to most modern manufacturing processes because particles larger than 100µm are easily filtered and particles smaller than 0.01µm are too small to cause damage. In addition, the International Organization for Standardization (ISO) does not provide classifications for particles smaller than 0.1µm (called ultrafine particles) nor particles larger than 5.0µm (called macro particles) (Li *et al.*, 2009) Table: 2.1 lists some common particles and their relative sizes.

Table 2-1 List of common particles and their relative sizes (Li *et. al.*, 2009)

Particle	Content Particle Size (μm)
Hair	50 – 150
Visible	50
Flu virus	0.07
Pollen	7 – 100
Sneeze particles	10 – 300
Dust	0.1 – 100
Bacteria	1.0 – 10

There are several different ways to measure a particle size in terms of aerodynamic diameter. Figure 2.2 shows the standard methods used to measure the aerodynamic diameter of an irregular shaped particle. A sphere, modeled in Figure 2.1 as dashed lines, represents the equivalent polystyrene latex sphere (PSL) particle. PSLs are synthetic particles used to calibrate particle counters and test filters. (Li *et. al.*, 2009).

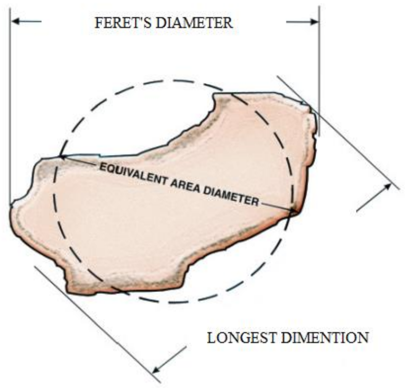


Figure 2-3 Particle dimensions measurement

The airborne particulate matter is not well round spherical shape. For the simplicity of their size distribution study, an aerodynamic diameter is used to classify the air dust particle. The particle whose aerodynamic diameter is less than 10µm (d< 10µm) is called PM_{10}. Similarly, $PM_{2.5}$ is particle of aerodynamic diameter less than 2.5µm (d< 2.5µm), $PM_{1.0}$ is d< 1.0µm, $PM_{0.1}$ is d < 0.1µm and so on. For the better understanding, a diagram is given below:

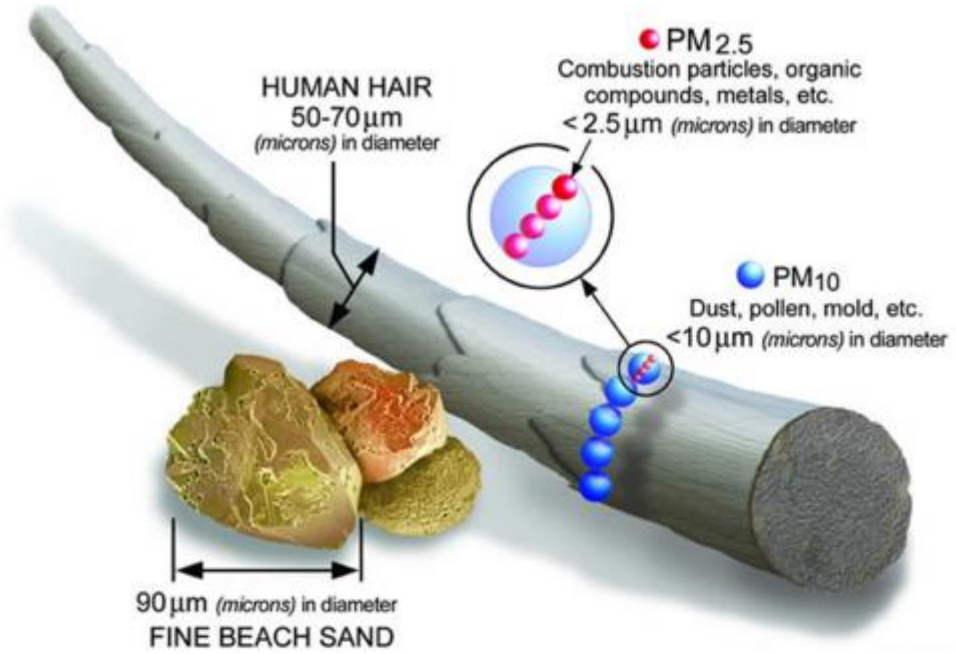


Figure 2-4 Aerosol size distributions

2.5 Composition of particulate matter

Fine particles have a diameter smaller than about 2.5μm, and are produced by the condensation of vapors, accumulation, and coagulation. They have a chemical composition that reflects the condensable trace gases in the atmosphere: SO_2, NH_3, HNO_3, VOC's, and H_2O. The chemical composition is water with SO_2^{4-}, NO^{3-}, NH $^{4+}$, Pb, Cl^-, Br^-, C(soot), and organic matter; where biomass burning is prevalent, K+. Coarse Particles have a diameter greater than about 2.5μm, are produced by mechanical weathering of surface materials. Their lifetimes, controlled by fallout and washout, are generally short. The composition of particles in this size range reflects that of the earth's surface−silicate (SiO_2), iron and aluminum oxides, $CaCO_3$and $MgCO_3$; over the oceans, NaCl.

2.6 Effect of particulate matter (PM)

In recent year, the airborne particulate matter pollution has become a common problem mainly attributed to continuous emission of particulate matter, and many harmful gasses into the ambient atmosphere. The pollutant enters into the air atmosphere due to natural and anthropogenic causes. Particulate matter originates from different kinds of sources, including diesel trucks, power plants, industrial processes, biomass burning, dust storm etc. The ambient particulate matter (PM) being an air pollutant has become the major concern over the surrounding environment because of its adverse impact over the human health, animal and wildlife, environmental and global climate change. The effect of aerosol particle also can be described as local impact (effect on human health and visibility reduction etc.), regional impact (effect on forests, animal, lakes, ozone production etc.) and global impact (effect on climate change).

2.6.1 Human health effect

The particulate matter (PM) especially the coarse particle like PM_{10} (Dia. of particle less than 10µm) and the fine particle like $PM_{2.5}$ (Dia. of particle less than 2.5µm) is creating a significant adverse effect on both human health and atmospheric environment. The impact of fine particle is posing a more significant concern than the coarse particle. The same amount of PM mass deposited in the lung, toxicity tends to increase as particle size decreases because it provides increased surface area per unit mass. Several studies in the past have linked respirable particulate matter (PM) to the deteriorating lung and heart functioning and even reduced life expectancy (Koenig *et. al.*, 2005). A wide number of epidemiological studies have conducted to find out the cause and effect relations between respiratory effects and exposures to ambient PM. The overall health impact for PM mass concentration is summarized as below:

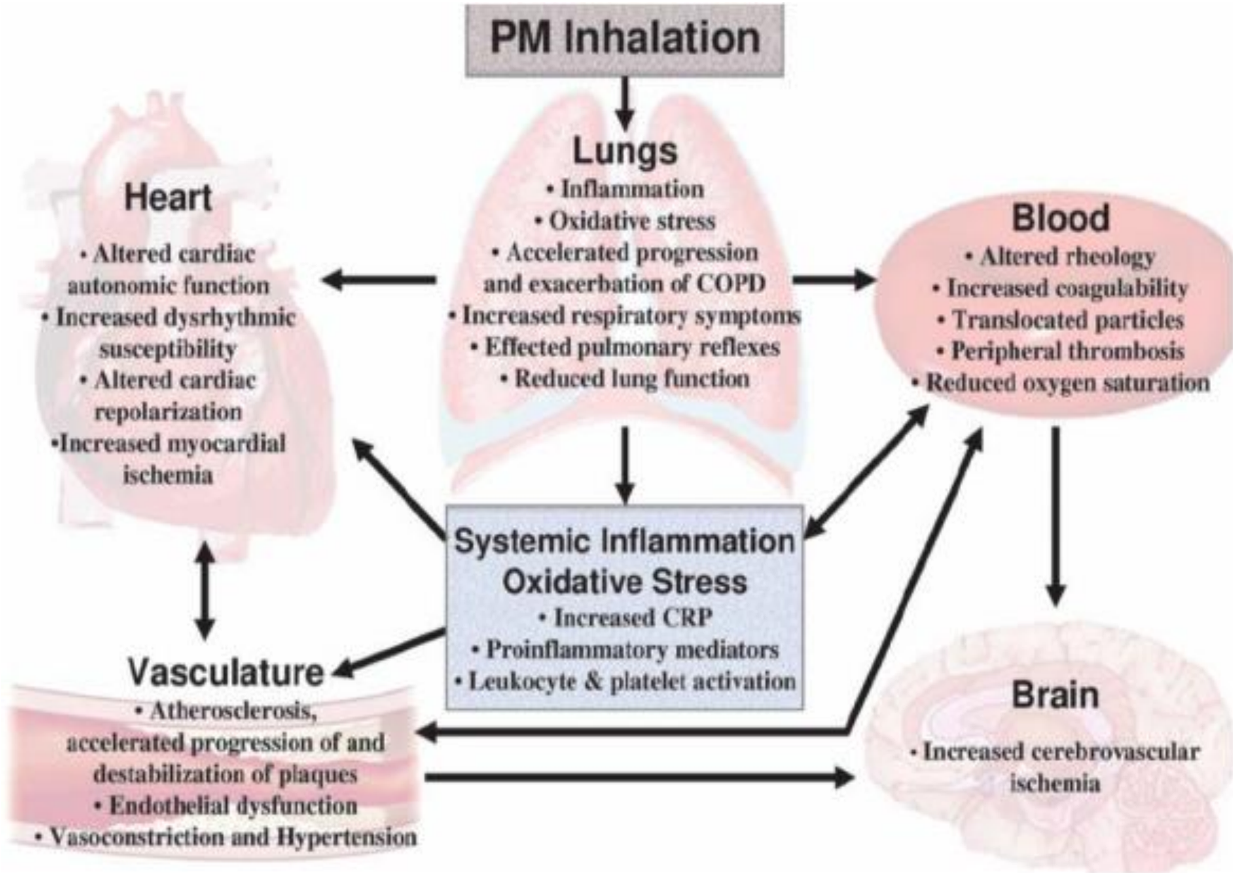


Figure 2-5 The overall health impact for PM mass concentration

<u>Effect of PM_{10}:</u>

- Long-term exposure of PM_{10} for years or decades is responsible for cardiovascular and infant mortality, morbidity, lung growth and respiratory system will be affected.
- Short-term exposure of PM_{10} for a subsequence day, the patients with asthma, pneumonia, and other respiratory diseases as well as patients with cardio-vascular diseases and diabetes are especially affected.
- The smaller the particles, the deeper they can penetrate into the respiratory system and the more hazardous they are to breathe.
- PM_{10} causes changes in blood chemistry that can result in clots that may lead to heart attacks.
- PM_{10} pollution can cause lung irritation, which leads to increased permeability in lung tissue.
- PM_{10} aggravates the severity of chronic lung diseases, causing rapid loss of airway function.

- PM_{10} causes inflammation of lung tissue, resulting in the release of chemicals that can impact heart function.
- PM_{10} can increase susceptibility to viral and bacterial pathogens leading to pneumonia in vulnerable persons who are unable to clear these infections.

Source: A. D. Kappos *et. al.*, 2004; S. Bakand *et. al.*, 2012; R. Zimmermann, (2011); A. Preutthipan *et. al.*, 2004; A. Seaton *et. al.*, 1995.

Effect of $PM_{2.5}$:

The mass concentration of fine particulate matter to ambient environment is a major reason for premature deaths (Massey *et. al.*, 2012), functional change in human cardiovascular and respiratory system (Gupta *et. al.*, 2011) especially for sensitive personnel (elderly and diseased). Fine particles are of greater concern because they can penetrate into lung tissues and ultimately enter into the blood stream which can change the blood chemistry (Harrison and Yin, 2000; Cohen *et. al.*, 2005; Kunzli and Tager, 2005; Sharma and Agrawal, 2005; Huang and Ghio, 2006). It also causes wheezing, coughing, chest tightness, breathing difficulties, worsening of existing lung problem, risk of heart attack. In addition of long-term exposure of PM pollution can cause cancer and damage to the immune, neurological, reproductive, and respiratory systems. In extreme cases, it can even cause death.

2.6.2 Wildlife effect

Like humans, animals can experience health problems if they are exposed to sufficient concentrations of air toxics over time. Studies show that air toxics are contributing to birth defects, reproductive failure, and disease in animals. Persistent toxic air pollutants (those that break down slowly in the environment) are of particular concern in aquatic ecosystems. These pollutants accumulate in sediments and may bio-magnify in tissues of animals at the top of the food chain to concentrations many times higher than in the water or air.

2.6.3 Environmental effect

Particulate matter can cause serious problems in the environment. Some of the problems are the change in the radiation balance of the earth directly by absorbing and scattering incoming sunlight and indirectly by acting as cloud condensation nuclei (CCN) to form clouds, change in cloud formation, contribution to global warming, and reduced visibility (Tiwari *et. al.*, 2015).

Haze effect:

Haze is caused when sunlight encounters tiny pollution particles in the air. Haze obscures the clarity, color, texture, and form of what we see. Some haze-causing pollutants (mostly fine particles) are directly emitted to the atmosphere by sources such as power plants, industrial facilities, trucks and automobiles, and construction activities. Others are formed when gases emitted to the air (such as sulfur dioxide and nitrogen oxides) form particles as they are carried downwind.

Crop and forest damage:

Ground-level secondary aerosol particles can lead to reductions in agricultural crop and commercial forest yields, reduced growth and survivability of tree seedlings, and increased plant susceptibility to disease, pests and other environmental stresses (such as harsh weather). As described above, crop and forest damage can also result from acid rain and from increased UV radiation caused by ozone depletion.

Global climate change:

The Earth's atmosphere contains a delicate balance of naturally occurring gases that trap some of the sun's heat near the Earth's surface. This “greenhouse effect” keeps the Earth’s temperature stable. Unfortunately, evidence is mounting that humans have disturbed this natural balance by producing large amounts of some of these greenhouse gases, including carbon dioxide and methane. As a result, the Earth's atmosphere appears to be trapping more of the sun's heat, causing the Earth’s average temperature to raise - a phenomenon known as global warming. Many scientists believe that global warming could have significant impacts on human health, agriculture, water resources, forests, wildlife, and coastal areas.

2.7 Air quality standard

The term air quality index (AQI) is used to determine the existing condition of air quality of that place. An Air Quality Index (AQI) is a communication vehicle to quickly and effectively describe ambient air quality relative to the relevant national air quality standards. The AQI is an index for reporting daily air quality. It tells us how clean or polluted your air is, and what associated health effects might be a concern. The AQI focuses on health effects that you may experience within a few hours or days after breathing polluted air. It is based on the exposure to all of the criteria pollutants (PM, CO, O_3, SO_2, and NO_2) with the AQI based on the worst exposure concentration for any of these pollutants. It helps to warn sensitive populations that they should take appropriate measures to reduce their exposure to the ambient air and to inform the general public that there are serious problems with air quality that need to be addressed as a societal responsibility to the whole population. Different countries affix different colors and assign different values to the same descriptor of potential risk.

2.7.1 AQI standard for Bangladesh

The first step is to review the Ambient Air Quality Standards. These are presented in Table 2-8. Given the continuing observation of occasional high lead concentrations, it may be reasonable to include lead in the AQI system. These values are not very different from the NAAQS values for the United States. Thus, the relationships between the observed concentrations and the associated AQI values should be similar to those presented in Table 2-2.

Table 2-2 Bangladesh National Ambient Air Quality Standards

Pollutant	Objective	Averaging time
Carbon Monoxide (CO)	10 mg/m^3 (9 ppm)	8-hour
	40 mg/m^3 (35 ppm)	1-hour
Nitrogen Dioxide (NO_2)	100 µg/m^3 (0.053 ppm)	Annual
	157 µg/m^3 (0.08 ppm)	8-hour
Ozone (O_3)	157 µg/m^3 (0.08 ppm)	8-hour
	235 µg/m^3 (0.12 ppm)	1-hour
Sulfur Dioxide (SO_2)	365 µg/m^3 (0.14 ppm)	24-hour
	80 µg/m^3 (0.03 ppm)	Annual
PM_{10}	150 µg/m^3	24-hour
	50 µg/m^3	Annual
$PM_{2.5}$	65 µg/m^3	24-hour
	15 µg/m^3	Annual
Lead (Pb	0.5 µg/m^3	Annual

2.8 Air sampling instruments and methods

There are several instruments and methods available to measure the different characteristics of particulate matter (PM). The most important characteristics involving the measurements of particulate matter are PM mass concentration ($\mu g/m^3$) and particle size distribution. Particulate mass concentration measurements are important to find out the standard limit of emission which provides the standards of air quality. Particle size distribution can determine the behavior of the particle in ambient atmosphere such as the finer particles can remain in the atmosphere for a longer period of time than that of larger sizes. The instruments which measure particle size distribution use the behavior of particles diffusion, aerodynamics, and optical and electrical mobility (Kulkarni *et. al.*, 2011). Generally, a large variety of particulate matter sampling instrument are existed. They are used for different purpose and they have different technique to measure the size distribution and concentration ($\mu g/m^3$) of airborne particulate matter from the source and ambient atmosphere. In which some depends on the principles of electrical and thermal precipitation of dust, while others operated by dust settlement, by filtration of dust, by impaction of dust laden air stream onto the collection or impaction surface. Impactors are instruments for measuring size distribution in PM mass, which working principle is gravimetry, with single or multiple impact stages and in some equipment with single or multiple nozzle are found.

2.8.1 Impactor

The impactors are widely used for the size distribution analysis of atmospheric aerosol especially particulate matter (PM). Impactor also used frequently for sampling and separating airborne particles because they are simple in construction and have high separation and collection capabilities. There are common varieties of impactor used for aerosol study as listed below (Kim *et. al.*, 2006):

- Midget impinger
- Particle trap impactor (Cup impactor)
- Virtual impactor
- Inertial cascade impactor

2.8.1.1 Midget impinger

The particulate matter (PM) sampler is universally used to monitor air quality. Historically, a wide variety of dust sampling instruments have existed, and they used several techniques to measure dust or particulate matter in air (ILO, 1965). For years in the U.S., the most common PM sampler device was the midget impinger, developed in 1937 by the U.S., Bureau of Mines.

2.8.1.2 Particles Trap Impactor (Cup Impactor):

The concept of particle trap impactor or cup impactor was first introduced by Biswash and Flagan (1988), which is intended to collect particles in the trap rather than to sample aerosol particles. It was investigated that the effect of solid particle loading on the collection efficiency of an impactor with different impaction surface designs. The particle trap impactor was applied to a sampling inlet with a cutoff diameter of 10μm or 2.5μm. Major advantages of the particle trap impactors are their freedom from particle bounce-off and the problem of overload. The designs of particle trap impactors are based on those of inertial impactors and virtual impactors. The particle trap impactors are similar to inertial impactors in that they use inertial force and do not have a minor flow rate. Also, the particle trap impactors are somewhat similar to virtual impactors in that they have virtual space to collect the particles (Kim *et. al.*, 2006).

2.8.1.3 Virtual Impactor:

Virtual impactors have been designed to eliminate problems of bounce and re-entrainment and to allow the collection of larger particles (Chen *et. al.*, 1986; Marple & Chein, 1980). In a virtual impactor, the intake air is typically divided into two air streams: the major and the minor flow. The major flow carries most of the fine particles smaller than the cutoff diameter and the minor flow carries all the coarse particles above the cutoff diameter with a small fraction of the fine particles. Various studies on virtual impactors have been carried out for particle collection and mass concentration. The virtual impactor was designed and tested with multi-nozzle virtual impactors for high-volume particle collection. Virtual impactors, however, have an inherent problem that a small fraction of the fine particles are collected with large particles.

2.8.1.4 Cascade Impactor:

Inertial impactors have been used extensively to measure aerosol size distribution and to collect samples for further chemical analysis. It consists of an acceleration nozzle and a flat plate. In inertial impactors, particles larger than the cutoff diameter of the impactor will impact on the collection plate while particles smaller than the cutoff diameter will follow the streamlines and not be collected on the plate. Many researchers have investigated inertial impactors to collect and separate aerosol particles and found inherent problems which were particle bounce and re-entrainment.

2.9 Working principle of cascade impactor:

The cascade impactor is a type of inertial aerosol sampler invented by May (1945) for aerodynamic size distribution measurements of aerosols. In a cascade impactor, an aerosol sample is drawn through a series of successively smaller orifices consisting of round holes or rectangular slits with a collection surface placed perpendicular to the direction of flow and very close to the exit of each orifice. At each stage the aerosol is accelerated in passage through the stage orifice or orifices and the particles must make a right angle change of direction to follow the air streamline; larger particles are unable to negotiate the right-angle turn and impact upon the collector. The impactor stages are designed to provide progressively higher jet speeds so that the average size of particles collected at each stage is successively smaller. An efficient filter usually follows the final stage to collect all the smaller particles which successfully pass through the impactor.

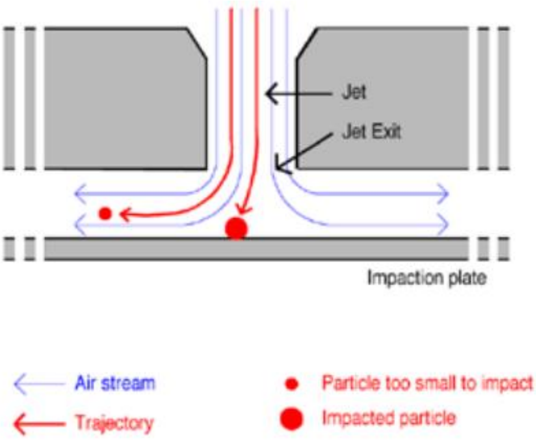


Figure 2-6 Principle of impactor

2.10 Advantage of cascade impactor:

However, in the present time inertial impactor are widely used for the size-selective collection of aerosol particles. One reason for their wide usage is that the principle of operation is simple: a jet of particle-laden air is directed at a flat impaction plate. Large particles are collected on the plate while smaller particles follow the airflow out of the impaction region and are not collected. Secondly the particles in an impactor are classified by their aerodynamic diameter (an important size parameter in many fields of study, including those related to respirable particle health effects). Thirdly, it is easy to collect particles in discrete size ranges by passing the aerosol through a number of stages (one stage consisting of a nozzle and impaction plate) series, with each subsequent stage collecting particles smaller than the one before it. The most important feature of the inertial cascade impactor is the collection efficiency curve which represents the percentage accumulation of particles of any size accumulated on the impaction plate as a function of the particle diameter (Marple *et. al.*, 1976; Marple *et. al.*, 1987; Marple *et. al.*, 1991).

2.11 Feature of cascade sampler

Typically, a cascade impactor is a combination of a number of identical stages having nozzle and impaction plate. However, it can be single or multiple stages owing single or multiple nozzles as per requirement. The cascade sampler is classified according to the flow rate and nozzle number. Based on the flow rate, the sampler can be separated as high volume sampler (HVS), medium volume sampler (MVS) and low volume sampler (LVS). Based on nozzle number, the sampler can be separated as single nozzle sampler and multi-nozzle sampler.

2.11.1 High volume sampler (HVS)

The sampler owing the flow rate of 150 L/min to more can be defined as high volume sampler (HVS). The main advantage of HVS is that it can reduce the sampling duration as per need basis. This type of sampler is heavy in weight, high power consuming, high maintenance required and highly expensive in nature. Moreover, the HVS while sampling makes a higher pressure drop. As a result, the impaction surface velocity will increase upon the impaction regions which create the change of losing the semi-volatile fraction during sampling.

2.11.2 Medium volume sampler (MVS)

The sampler with the designed flow rate at the range of 25 L/min to 150 L/min is called medium volume sampler (MVS). This type of sampler needs moderate time during sampling to obtain any acceptable value of PM mass concentration as compared to HVS. But it also needs high power consumption for operation, heavy weight in nature, high maintenance required and high cost. The MVS create high pressure drop during sampling which will increase the impaction surface velocity. As a result, there is a change of losing the semi-volatile fraction from ambient particulate mass (PM).

2.11.3 Low volume sampler (LVS)

The sampler of flow rate between the range of 01 (LPM) to 25 LPM is called low volume sampler (LVS) or low-vol sampler. The main drawback of the LVS is that it needs a more sampling duration to obtain the acceptable value of mass concentration of PM as compared to the HVS and MVS. Moreover, the LVS sampler is light-weight, easy to use, portable, low maintenance, and low cost. Owing a low flow rate, it will reduce the pressure significantly. As a result, the loss of semi-volatile fraction will reduce.

2.11.4 Single nozzle sampler

The openings through which an air laden particle stream passes from one stage to another successive stage of a sampler is called nozzle. In this type of sampler each stage contains a single nozzle. Mainly in high volume sampler (HVS), single nozzle system is used. Development of six-stage and single-nozzle cascade impactor was reported by Mitchell and Pilcher (1957). Brink (1958, 1963) used a five-stage and single-nozzle cascade impactor to size the particles at 0.3μm to 3.0μm range.

2.11.5 Multi-nozzle sampler

Multi-nozzle impactors are widely used for sampling aerosol particles under low Reynolds number conditions without large pressure drop, as compared to single-nozzle impactors at the same flow rate. It was shown that the impactors with sharp collection efficiency curves can be obtained if the velocity profiles at the nozzle exit are uniform across the nozzle, in the case of the single-nozzle impactor (Marple & Liu, 1974). Cohen and Montan (1967) reported an eight stages and multi-nozzle cascade impactor. Newton *et. al.* (1977) and Marple *et. al.* (1987) designed and calibrated the cascade impactor for the particle size 1.0μm to 10.0μm.

Marple *et. al.* (1991) evaluated a ten-stage Microorifice Uniform Deposit Impactor (MOUDI) to size the particle at 0.056μm to 10μm.

In the case of multi-nozzle impactors, it is very difficult to perform the quantitative analysis due to the complexity of the flow fields. As a result, all the theoretical work, and many of the experimental work, has been performed for the single-nozzle impactors. The results of single-nozzle impactor analysis have often been applied to multi-nozzle impactors, which are assumed to act as a group of individual nozzles. However, an important fact is ignored when considering this approach, i.e., the interaction between the 6ows from neighboring nozzles can change not only the 6uid mechanics in the impaction region, but also the location of the jet stagnation points, and the impaction characteristics of each nozzle. The cross-6ow in separation region can significantly deflect the air jets of the outer nozzles, and hence affect the characteristics of impaction. Thus, the cross-flow influences the particle collection efficiency (Kwon *et. al.*, 2002).

2.12 Design of cascade sampler

2.12.1 General consideration

In an impactor, whether a particle impacts depends on the drag force on the particle, particle momentum and effective transit time across the substrate plate. Impactor theory combines these factors into a dimensionless parameter called Stokes number (Stk). The cut point of the impaction stage with multiple accelerating nozzles can be calculated by using the Stokes equation, as follows (Baron and Willeke, 2001):

$$Stk = \frac{\rho_p D_p^2 U C_c}{9\mu W}$$

Where, ρ_p is the particle density, μ is the dynamic viscosity of air, D_p is particle diameter (μm), U jet velocity through the each single impactor nozzle, W is nozzle diameter (mm), and C_c Cunningham slip correction factor which is given by the following equation:

$$C = 1 + \frac{0.163}{D_p P_2} + \frac{0.0549}{D_p P_2} e^{-6.66 D_p P_2}$$

The pressure in the impactor region is P_2. By assuming the pressure drop in the stage is equal to the dynamic pressure of the flowing air stream

$$P_2 = P_1 - \frac{1}{2}\rho U^2$$

Where,

P_1= Static pressure at impactor stage inlet

P_2= Static pressure at impaction plate

U = Average velocity in the flowing air stream

2.12.2 Influence of Reynolds number

The theoretical influence of the Reynolds number on the efficiency curve is shown in figure 2:4 for the both round and rectangular nozzle impactor. The Reynolds number is based on the hydraulic diameter of the nozzle throat. The particle size is a dimension less particle diameter expressed in units of the square - root of the Stokes number ($\sqrt{Stk}$). The Stokes number is defined as the ratio of the particle stopping distance of the half width or the radius of the impactor throat.

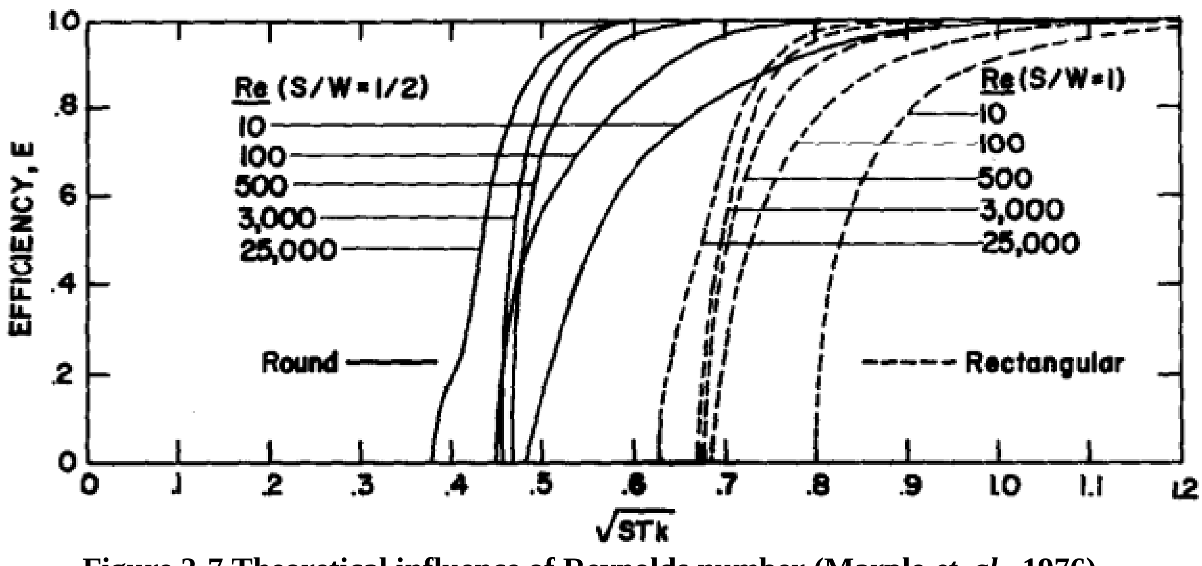


Figure 2-7 Theoretical influence of Reynolds number (Marple *et. al.,* 1976)

In above the curves of figure 2:4, it can be said that the sharpness of cut is best for Re = 500 and 3000. The poorer cutoff characteristic at lower Reynolds numbers is caused by a thick viscous boundary layer in the jet of the impactor. For the high Reynolds number case (Re = 25000) the knee in the efficiency curve at the low values of efficiency appears to be caused by a very thin boundary layer over portions of the impaction plate adjacent to the stagnation point. For round impactors the Reynolds number through the nozzle can be controlled by using more than one identical nozzle per stage. The relationship between the number of round jets, n, and the Reynolds number is found by expressing the average velocity within the round jets, U, as below:

$$U = \frac{4Q}{\pi n W^2}$$

Where, Q is the total volumetric flow rate through the stage. This velocity can be substituted into the expression for Reynolds number and Stokes number at 50% collection probability (Stk_{50}):

$$Re = \frac{\rho U W}{\mu} = \frac{4\rho Q}{\pi n \mu W}$$

$$Stk_{50} = \frac{4\rho_p Q C D_{50}^2}{9\pi n \mu W^3}$$

2.12.3 Cross-flow parameter

There are many designs of inertial impactors which are used for sampling atmospheric aerosol particles. Impactors can be single stage, consisting of a nozzle and an impaction plate, or a cascade impactor with several stages in series. The simplest design for a stage is a single nozzle with a flat impaction plate. However, many designs use stages with multiple nozzles of identical sine, which allows for compact impactors to be designed at rather considerable flow rates and moderate pressure drops. The results of single-nozzle impactor analysis are often applied to multiple-nozzle impactors. Here it is assumed to be a group of individual nozzles, each operating as though they are single nozzles. However, an important fact is, often ignored that the interaction of flow from adjacent nozzles can change not only the fluid mechanics in the impaction region, but also the locations of the jet stagnation points, and the impaction characteristics of each nozzle. The effect of cross-flow can be eliminated by increasing the nozzle-to-plate distance and improving the configuration of nozzle array to allow the air flow to escape the periphery more easily (Fang *et. al.*, 1991).

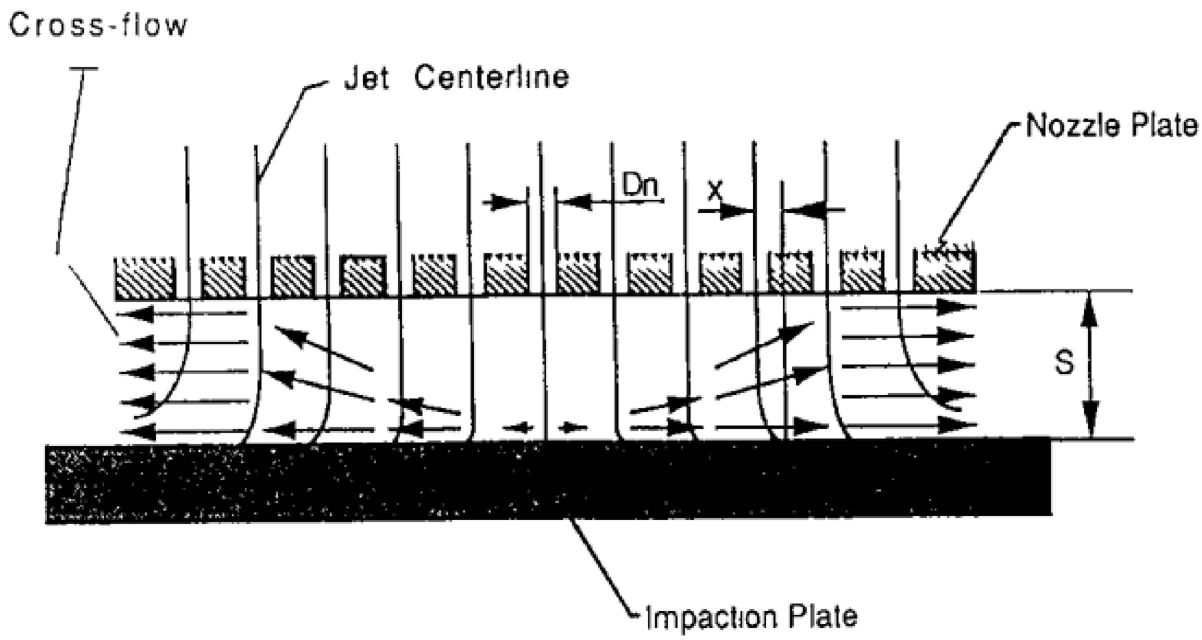


Figure 2-8 Cross-flow view of multi-nozzle impactor (Fang *et. al.*, 1991)

The study of the flow fields and particle impaction characteristics are more complicated in multi-nozzle impactors than that of in single-nozzle impactors for a specified volumetric flow rate, since the jets of air must penetrate cross- flowing air to impinge on the impaction plate. From the above figure 2-5 it is clear that the cross-flow in a multiple nozzle impactor is no uniform. Therefore some assumptions about the case illustrated in figure 2-5 have to be made to use the analogy between the flow conditions in the multi-nozzle impactor. The assumption is described as below:

- First, the nozzles of the multi-nozzle impactor are assumed to be of the same size and to be distributed uniformly on the nozzle plate, i.e. the density of nozzles (number of nozzles per unit area) is constant over the nozzle cluster area.
- Second, all nozzles are assumed to experience equal upstream and downstream pressures, since cross-flow between the nozzle plate and the impaction plate does not cause a significant decrease in the downstream pressure of the outer nozzles compared to the pressure drop across the nozzles.

A cross-flow parameter has been derived to predict the deflection of the air jet by the cross-flow. This parameter is expressed as a function of the geometric parameters for the multi-nozzle impactor, i.e. as $\frac{WN}{4D_c}$ where W is the nozzle diameter, N is the number of nozzles and Dc is the nozzle cluster diameter. Previous studies showed that the critical value of the cross flow parameter for a multi-nozzle impactor is 1.2. Impactors operating with a cross-flow parameter larger than this critical value are shown to possess poor particle collection characteristics.

2.12.4 Configuration of nozzle array

After considering the cross-flow parameter, the configuration of nozzle array is another important parameter for the design consideration to obtain a better collection efficiency of a multi-nozzle cascade impactor. In the case of multi-nozzle impactors, however, quantitative analysis has not been performed due to the complexity of the flow fields. Nearly all the theoretical work, and much of the experimental work, has been performed on single-nozzle impactors. The results of single-nozzle impactor analysis have often been applied to multi-nozzle impactors, which are assumed to act as a group of individual nozzles. Kwon *et. al.*, (2002) reported a study to determine the optimum nozzle arrangement for the better size distribution collection efficiency. On that study, five types of nozzle plates were designed and fabricated to determine the effects of nozzle array on the collection efficiency as shown in figure below:

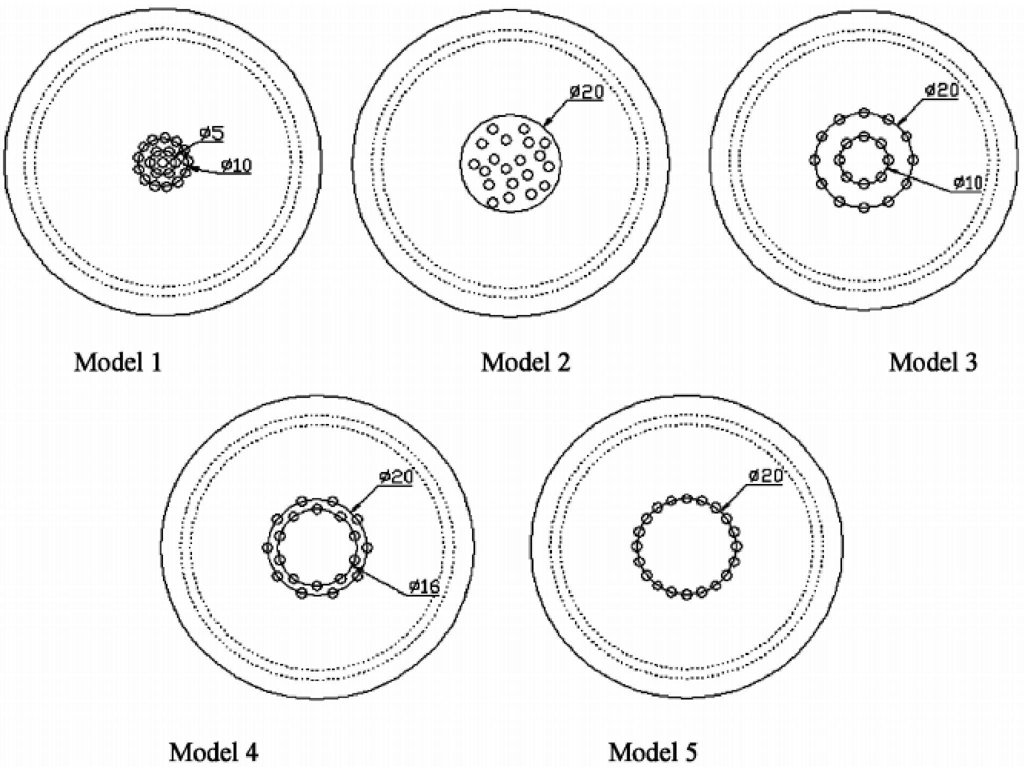


Figure 2-9 Configuration of nozzle array (Kwon *et. al.*, 2002)

Model 1-3 were designed to satisfy the cross-flow parameter. However it was not done for 4-5, because the density of the nozzle (number of nozzle per unit area) is not constant. Each plate contains 20 no of nozzle with the same diameter of 2mm. in model 1-3 all the nozzle was drilled within the nozzle cluster diameter less than 22mm, which satisfies the criteria of cross-flow parameter. Model 4 was designed to have ten nozzles on the periphery of a 16 mm circle, and the other ten nozzles on a 20 mm circle, and Model 5 was designed to have all the twenty nozzles on the periphery of a 20 mm circle. The layout of Model 3 was of the type generally used in the commercial MOUDI and Andersen impactor (Andersen Instruments Inc., Atlanta, GA), while Model 5 represents the Berner-type impactor in which the nozzles are located symmetrically on the periphery of a circle. Table 2 shows the details of the nozzle plates. It was found that the collection efficiencies and cut-off diameters of models 2 (random nozzle array) and model 5 (one circle nozzle array) satisfied the design criteria in terms of both the experimental and visual evaluations.

2.13 Description of various cascade sampler

Historically, a wide variety of dust sampling instruments have existed, and they used several techniques to measure dust or particulate matter (PM) in air.

Development of six-stage and single-nozzle cascade impactor was reported by Mitchell and Pilcher (1957). Brink (1958, 1963) used a five-stage and single-nozzle cascade impactor to size the particles at 0.3μm to 3.0μm range. Cohen and Montan (1967) reported an eight stages and multi-nozzle cascade impactor. Newton *et. al.* (1977) and Marple *et. al.* (1987) designed and calibrated the cascade impactor for the particle size 1.0μm to 10.0μm. Marple *et. al.* (1991) evaluated a ten-stage Microorifice Uniform Deposit Impactor (MOUDI) to size the particle at 0.056μm to 10μm.

2.13.1 Description of MOUDI **sampler**

Marple *et al.*, (1991) described the general purpose of cascade impactor that had been developed in the laboratory and used in a variety of studies including visibility studies, underground mine studies, and general atmospheric pollution studies. The impactor, called a microorifice uniform deposit impactor (MOUDI model 100, MSP Corp., Minneapolis, Minn.), is the integration of two earlier impactor developments: the microorifice impactor (MOI) and the uniform deposit impactor (UDI).The MOUDI had several features normally not found in other cascade impactors. The MOUDI is eight-stage cascade impactor with cut-off distribution size ranges from 0.056μm to 18μm at a flow rate of 30 L/min.

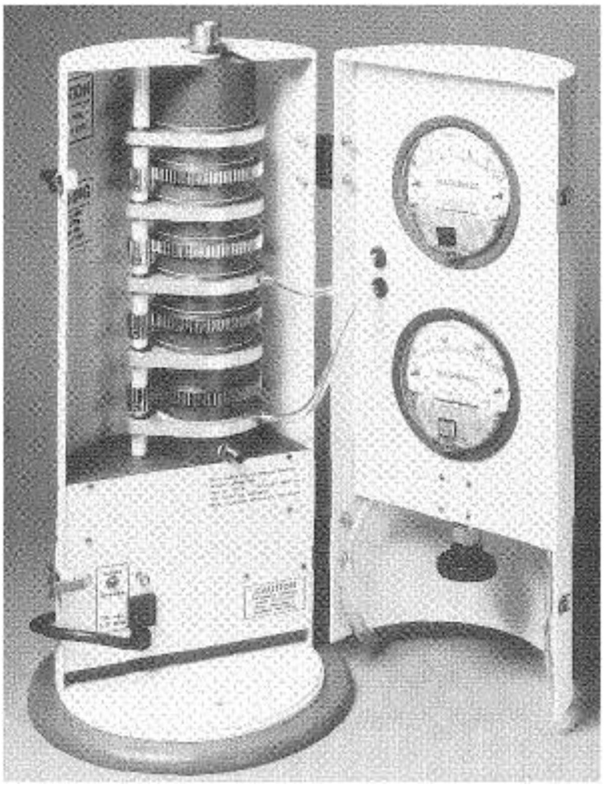


Figure 2-10 Microorifice Uniform Deposit Impactor (MOUDI)

These include collection of particles as small as 0.056µm in aerodynamic diameter with a moderate pressure drop, uniform particle collection on the impaction plates, interchangeable impaction plates to allow for the plates to be easily and quickly changed in the field, and covers for these substrates to provide a means for safe storage and/or transport of the collected particles to the laboratory for analysis.

The uniform deposit was achieved by using multiple nozzles at each stage and rotating the impaction plate beneath the nozzles. By placing the nozzles at specific distances from the center of rotation, a uniform deposit was obtained upon the rotating impaction plate. Each stage contains the impaction plate for the nozzles above and the nozzles for the impaction plate below. By rotating this stage relative to the stage above and the stage below, the impaction plate was rotated relative to the upper nozzle plate and the nozzle plate was rotated relative to the lower impaction plate. Rotation of alternate stages of the impactor, while the other stages are held stationary, results in every nozzle plate having rotation relative to its corresponding impaction plate. The usage of the word "stage" here was somewhat different than in the general description of the cascade impactor, where stage referred to a nozzle and its respective impaction plate (Marple et al., 1991).

2.13.2 Furuuchi sampler

A four-stage inertial cascade impactor for sampling of PM_{10}, $PM_{2.5}$, $PM_{1.0}$ and $PM_{0.5}$ was designed and evaluated its performance by Furuuchi *et. al.*, 2010. The sampler was designed to operate at a flow rate of 40 L/min, which allows the sufficiently fast sampling of PM.

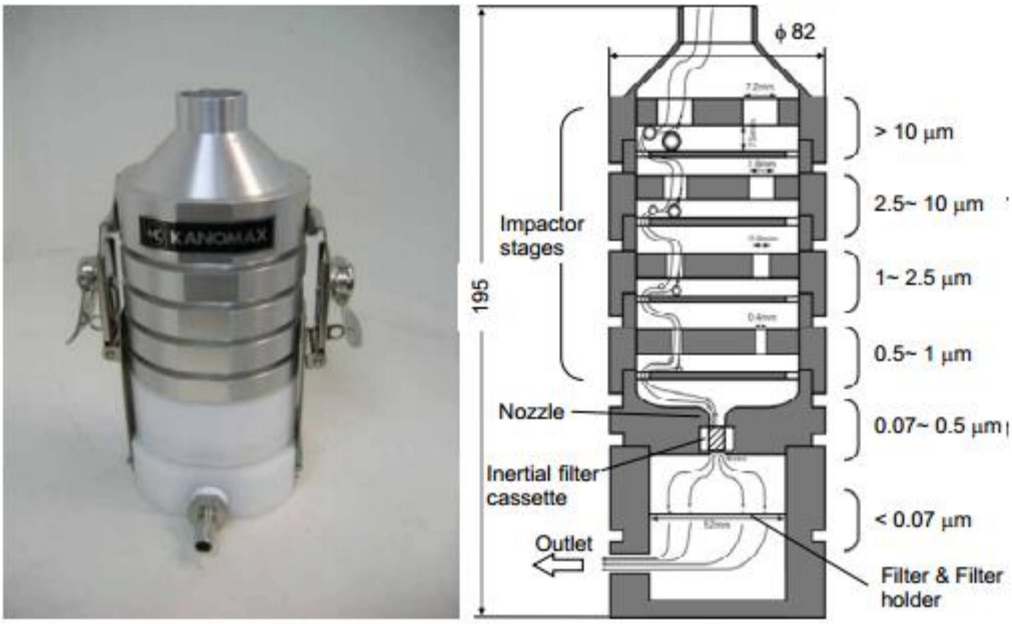


Figure 2-11 A PM sampler reported by Furuuchi *et. al.*, 2010

The designed sampling flow rate is more than twice that of commercial low-volume samplers (16.7 L/min) but less than that of high volume air samplers (500–1000 L/min). The advantage of the sampler is that the sampling flow rate can be readily changed, depending on the needs in the field. The inertial filter is designed so that the webbed stainless steel fibers (Nippon Seisen Co. Ltd., felt type, SUS-304) are packed on a support of crossed 200μm stainless steel wires in a plastic holder (polyoxymethylene, POM), and the holder is placed in the throat of nozzle. The specifications of each impactor stage are shown in Table 2-3.

Table 2-3 Specifications of impactor stages

Stage	PM_{10}	$PM_{2.5}$	$PM_{1.0}$	$PM_{0.5}$
Nozzle diameter (mm)	7.2	1.8	0.8	0.4
Nozzle length (mm)	7.5	3	2	2
Nozzle-plate separation (mm)	7.5	4.5	2	2
Number of nozzles at each stage (-)	6	25	50	100
Diameter of impaction plate (mm)	60	60	60	60
Air velocity through nozzle (m/s)	2.73	10.8	26.5	53.1

2.13.3 PCIS sampler

A four-stage personal cascade impactor sampler (PCIS) for size separation of the following aerodynamic particle diameter ranges: < 0.25, 0.25–0.5, 0.5–1.0, 1.0–2.5 and 2.5–10μm was developed by Misra *et. al.*, 2002. The PCIS operates at a flow rate of 9 L/min using a very high efficiency, battery-operated light pump at a negligible pressure drop.

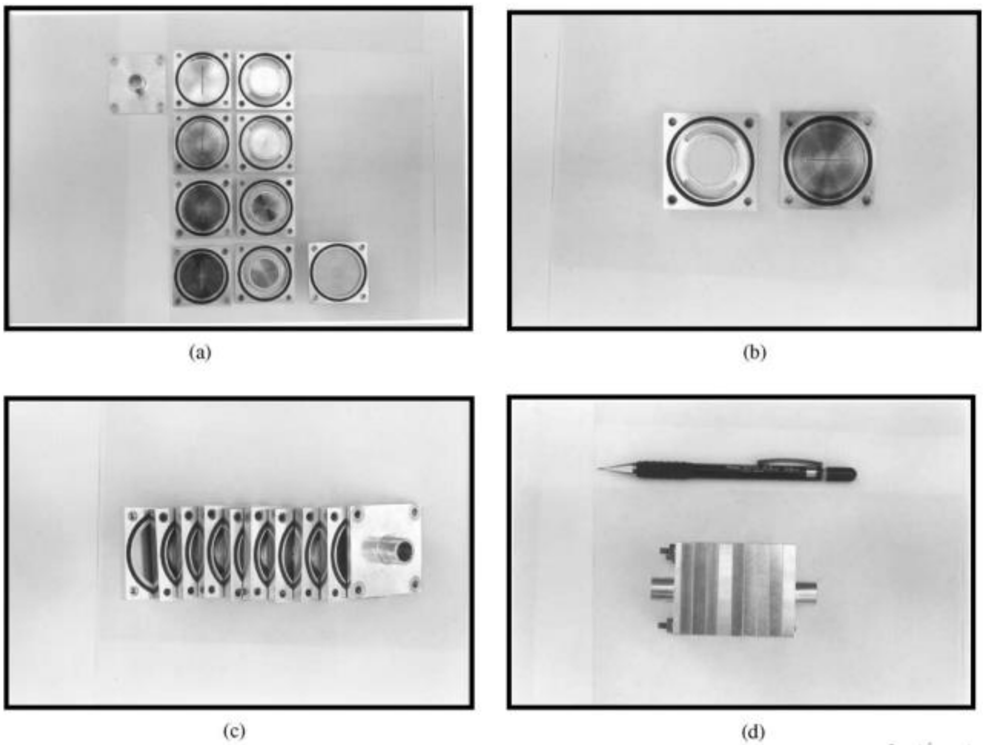


Figure 2-12 A PCIS developed by Misra *et. al.*, 2002

It operates in conjunction with a small, battery-operated personal pump, developed by SKC Inc. (Eighty Four, PA). The low-pressure drop makes it possible to operate the sampler with a very low noise level, which is a very desirable feature in personal monitoring. The entire sampler is enclosed in a cassette holder, 4 cm in diameter and 6 cm high, made of soft aluminum in order to avoid particle losses due to electrostatic deposition. The total weight of the sampler is approximately 150 g, thus easy to be used by subjects such as children or elderly. The pump weighs about 450 g (including the battery) and is placed inside a small pouch with snap latch and foam inserts to protect the pump during transport. The technical design and operation parameters of the personal cascade impactor sampler are given in Table 2:10.

Table 2-4 Design and operating parameters of the Personal Cascade Impactor Sampler (PCIS)

Design impaction cutpoint (µm)	Experimentally determined cutpoint (µm)[e]	D^a (cm)	U^b (cm/s)	ΔP^c (in of H_2O)	L^d (cm)
2.5	2.60	0.09	645.5	0.3	1.9
1	0.95	0.05	2041.2	0.6	2.1
0.5	0.52	0.036	2110.0	1.5	1.9
0.25	0.23	0.014	4568.8	3.9	2.5
Teflon filter	—	3.7	10.3	4.7	—

2.13.4 K-JIST sampler

A five-stage inertial cascade impactor (K-JIST cascade impactor) was designed and tested by Kwon *et. al.*, 2003. Each stage of the impactor was calibrated using a gravimetric or counting method and the fully assembled impactor was evaluated by using a fluorometric method. The cut-point diameters of stages 1–5 were chosen to be 10µm, 5µm, 2.5µm, 1.0µm and 0.7µm, respectively, with the nominal flow rate of 30 L/min. The design and operation parameters of the K-JIST cascade impactor is summarized as below:

Table 2-5 Design and operation parameters of the K-JIST cascade impactor

Stage no.	Number of nozzles	W(mm)	V (m/s)	Re	S/W	T/W	Cut-point diameter (μm)
1	3	9.04	2.60	1563	0.5	0.4	10
2	12	3.24	5.06	1091	1.0	1.5	5.0
3	12	2.04	12.76	1732	2.1	2.9	2.5
4	20	0.93	36.52	2270	5.4	5.5	1.0
5	40	0.58	46.63	1814	8.2	8.8	0.7

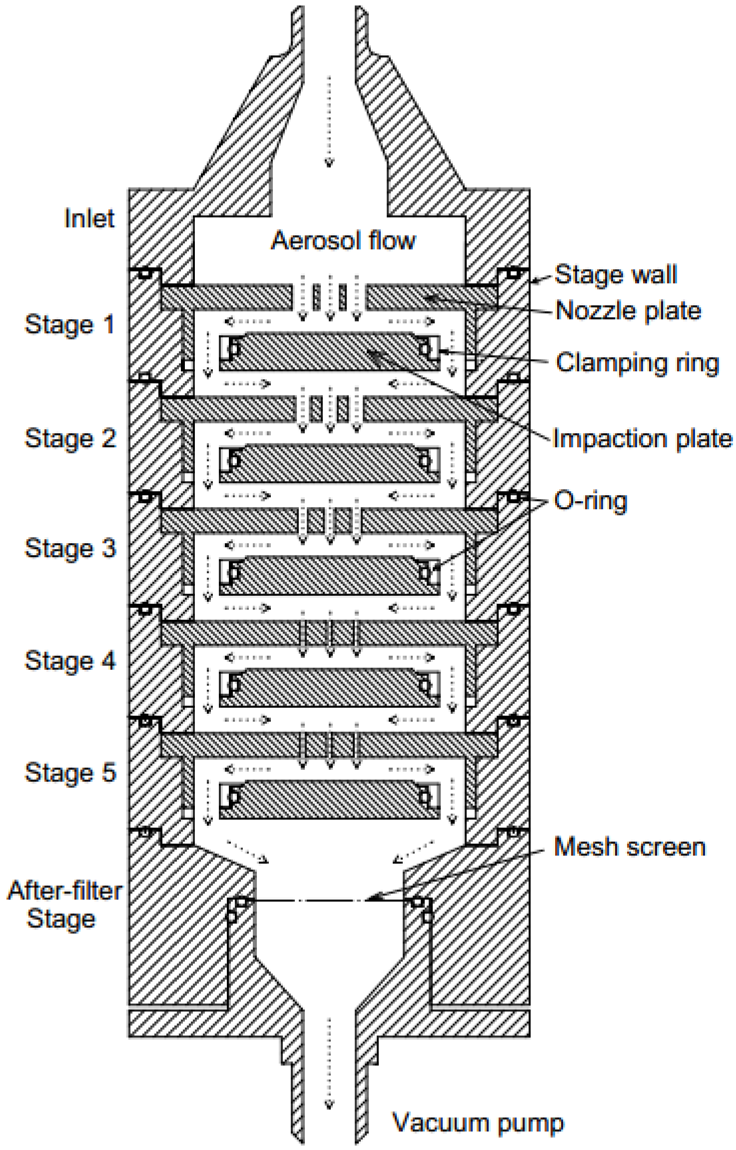


Figure 2-13 A five-stage K-JIST sampler was developed by Kwon *et. al.*, 2003

2.13.5 VCCI sampler

A variable configuration cascade impactor (VCCI) including of 7 normal pressure and 4 low-pressure stages has been designed and developed by Singh *et. al.*, 2010. In configuration-1, it operates as a low-pressure impactor, with a sampling flow rate of 10 L/min and classifies the particles from 0.1µm to 21µm in eleven size classes. In configuration-2, it operates as a normal pressure impactor, with a sampling flow rate of 45 L/min, and classifies the particles from 0.53µm to 10µm in seven size classes.

Figure 2-14 A variable configuration cascade impactor (VCCI) developed by Singh *et. al.*, 2010

A new design concept that makes the impactor amenable to operation in various configurations is the stage-loading arrangement. The stages are arranged one over the other and tightened through a set of three wing-nut rod assemblies, instead of the spring loaded arrangement commonly employed in other commercial impactors. Neoprene gaskets have been used between the stages to ensure leak tightness of the system. The threaded wing-nut rods make it possible to load less than the total number of stages without altering the performance of the impactor. With this design, it is possible to assemble and operate a single unit in the following three configurations:

- When all the eleven stages are present along with the critical orifice, the unit becomes the low-pressure impactor, operational at a sampling low rate of 10 L min^{-1}. In this configuration, it classifies the particles from 0.1µm to 21.3µm. This is referred to as configuration, VCCI-(1)

- When only the top 7 atmospheric pressure stages are present with the back-up stage, the unit becomes the conventional impactor operational at 45 L min^{-1}.In this configuration, it classifies the particles from 0.53µm to 10µm. This is referred to as configuration, VCCI-(2)
- In PMx configuration, the unit can be operated with reduced number of stages so as to collect particles only below a required aerodynamic diameter. This is referred to as configuration, VCCI-(3).

2.13.6 IITK sampler

A single stage inertial cascade impactor with multiple nozzles for sampling of 2.5µm dia. particle was designed, developed and evaluated the field performance by Gupta *et. al.*, 2011. The operation flow rate was 15 L/min.

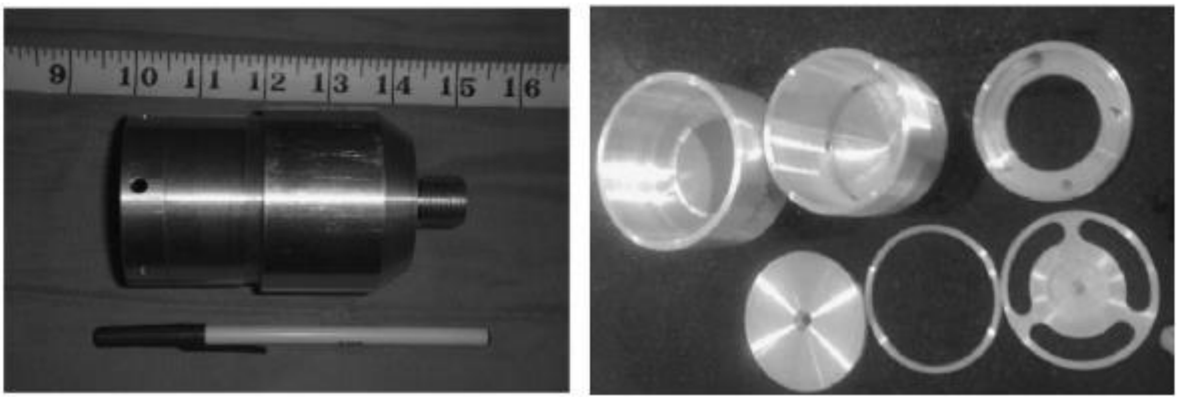


Figure 2-15 A multi-nozzle $PM_{2.5}$ sampler developed by Gupta *et. at.*, 2011

The sampler was fabricated from the metal aluminum as this metal is corrosion resistant, lightweight; there is no problem of static charge and easy to machine as per design specifications. Also, it can be artificially or naturally (via atmospheric oxidation) anodized to prevent corrosion and minimize mechanical wearing of sampler parts and cut down the overall sampling losses. The main impactor consisted of one round impactor nozzle, which was actually conical in shape, one spacer and impaction substrate plate. The sampler also had a rain cover at the inlet figure 2:15 shows the developed air sampler as well as its internal components in the sequence in which they are arranged inside it including a 47 mm filter holder inside it.

2.13.7 Variable configuration sampler

A variable configuration sampler for sampling of $PM_{1.0}/PM_{2.5}$ was developed by A. Kumar and T. Gupta in 2015. The impactor operates at a flow rate of 175 L/min and consists of two different sets of circular acceleration nozzles designed for $PM_{2.5}$ (particle aerodynamic diameter < 2.5 µm) and $PM_{1.0}$ (particle aerodynamic diameter < 1 µm), either of them could be used at a time as per the objective of sampling. This sampler can be used to collect filter samples over shorter time intervals (owing to its higher operating flow rate of 175 L/min) which can be analyzed later on to assess various chemical parameters. This would provide a very finely time-resolved temporal variation of PM composition which can eventually be used (in combination with meteorological data) to clearly understand the role of various physico-chemical processes active in different seasons.

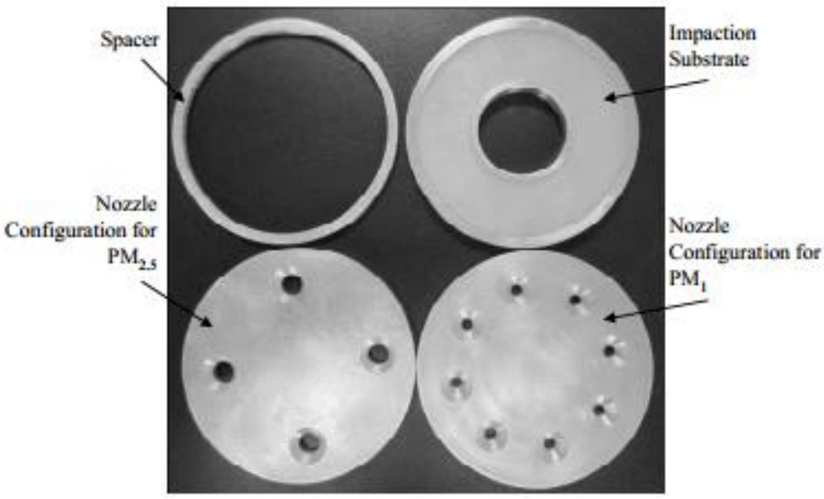


Figure 2-16 A variable configuration sampler for sampling of $PM_{1.0}/PM_{2.5}$ developed by A. Kumar and T. Gupta, 2015

Chapter 3

Materials and Methods

3.1 Design of sampler

A substrate based inertial cascade impactor has selected to design in this research for size-selective study of air particulates matter which aerodynamic diameter is less than 10μm. The inertial cascade impactor is commonly used due to its simple operation principle. In this impactor, the particle impaction depends on the resulting drag force upon the particle, particle mass and effective traveling time across the substrate plate (A. Kumar and P. Gupta, 2015). The designed impactor will have multiple nozzle and different nozzle number (n) and nozzle diameter (W) at each stage. The nozzle number (n), nozzle diameter (W) and nozzle-to-plate distance (S) are the major design parameter. Impactor theory describe these parameter by using a dimensionless factor called stokes number (Stk). In 1976 Marple and Willeke developed a design aided chart for round nozzle slit of desired cut-off particle diameter controlling the total number & size of nozzle, nozzle-to-plate distance and total volumetric flow rate through the stage. However, the chart was used as a guideline to design the impactor with Reynolds number (Re) of 500 using the square root of Stokes number at 50% collection efficiency ($\sqrt{Stk_{50}}$) for a constant flow rate 05 liter per minute (LPM). The typical design procedure is given below:

- At first the desired cut-off particle diameter (D_p) has chosen. If the density of particle (ρ_p) is different from unity, then need to calculate $\sqrt{C}\, D_{50}$ (where D_{50} is the equivalent aerodynamic diameter of a unit density sphere) from:

$$\sqrt{C}\, D_{50} = \sqrt{\rho_p}\sqrt{C}\, D_p$$

Here, C is the Cunningham slip correction. The variation of Cunningham slip correction is normally negligible for small diameter difference.

- The number and size of round nozzle for operating Reynolds number (Re), flow rate and aerodynamic cut-off size ($\sqrt{C}$ D_{50}) has determined using design guideline provided by Marple and Willeke.

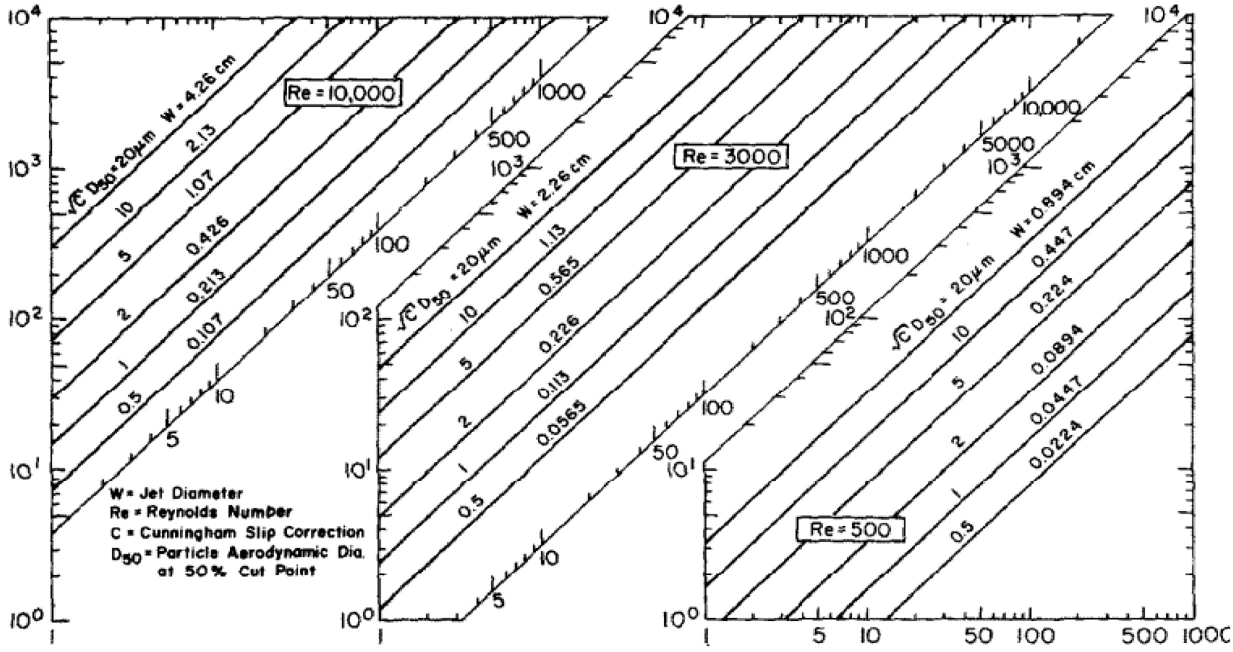


Figure 3-1 Design aided chart by Marple and Willeke, 1976

- A convenient nozzle diameter has selected from the found value.
- The Reynolds number (Re) was checked for the obtained convenient nozzle diameter by using equation:

$$Re = \frac{\rho V_o W}{\mu} = \frac{4\rho Q}{\pi n \mu W}$$

Where,

ρ = Fluid density (1.205×10^{-3}g cm^{-3} for unit density particles and air flow at normal temperature and pressure)

V_o= Average velocity within the nozzle

W= Diameter of the nozzle

μ= 1.81×10^{-4} P

Q= Flow rate

n= Number of nozzle

- The value of $\sqrt{Stk_{50}}$ has determined from the design guideline chart and calculated the cut-off size, $\sqrt{C}$ D_p by using equation:

$$Stk_{50} = \frac{4\rho_p QCD_{50}^2}{9\pi n\mu W^3}$$

Where, Stk_{50} is Stokes number and D_{50} is particle diameter at 50% collection efficiency respectively. C is Cunningham slip correction.

$$C = 1 + \frac{0.163}{D_p P_2} + \frac{0.0549}{D_p P_2} e^{-6.66 D_p P_2}$$

- The pressure in the impactor region isP_2. By assuming the pressure drop in the stage is equal to the dynamic pressure of the flowing air stream

$$P_2 = P_1 - \frac{1}{2}\rho V_0^2$$

Where,

P_1= Static pressure at impactor stage inlet

P_2= Static pressure at impaction plate

V_0= Average velocity in the flowing air stream

- After determining the impactor nozzle number and size diameter at each stage, it is also important to design the impactor jet-to-plate distance criteria. In this study the jet-to-plate distance has determined by using the following relationship:

$$\frac{S}{W} = 1.0$$

The total design parameters are summarized below:

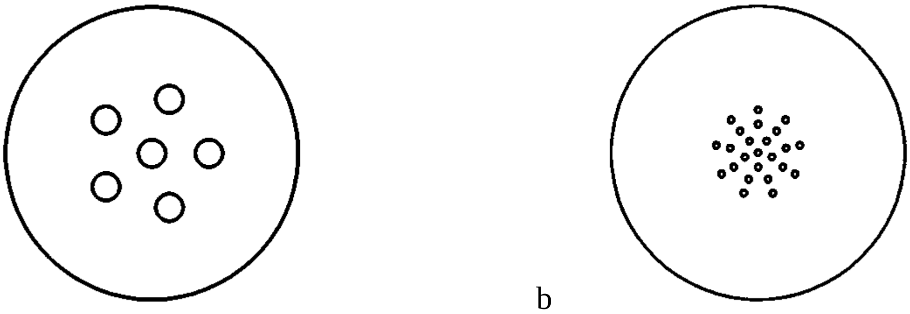
Table 3-1 Design parameters of developed PM sampler

Stage no.	Nominal cut-off dia. (μm)	$\frac{S}{W}$	Reynolds number	Velocity (m/sec)
01	10	1.0	500	1.33
02	2.5	1.0	500	5.29

All the design and operation parameters are based on 05 L/min flow rate at standard atmospheric temperature and pressure.

3.2 Fabrication of sampler

A typical schematic diagram of designed sampler is shown in figure 3:2. The sampler consist of indistinguishable stage wall and impaction plate but different from the jet-to-plate distance, nozzle numbers (n) and nozzle diameter (W). Each stage contains the nozzle plate to maintain the air flow for the impaction plate below and the impaction plate for the nozzle plate is above. Both the nozzle plate and impaction plate with clamping ring are moveable of this sampler. The impaction plate and the nozzle plate both are considered as 47mm diameter. By using removable clamping ring in impaction plate, variety of substrate like foil and filters can be used as per requirements. The nozzle plate is made of 4mm acrylic board and the optimal nozzle array was selected (Kwon *et. al.*, 2002) as shown in figure 3:1.



a b

Figure 3-2 A typical configuration of nozzle array for (a) PM_{10} and (b) $PM_{2.5}$

Sampler inlet parts, stage wall to support the nozzle plate (it was designed by maintaining the nozzle jet-to-impaction distance for each stage), impaction stage with clamping ring are made of Silver Metallic PLA filament. 3D printer (Ultimaker-2 Cura extended) was used to fabricate the sampler's body shown in figure 3.3.

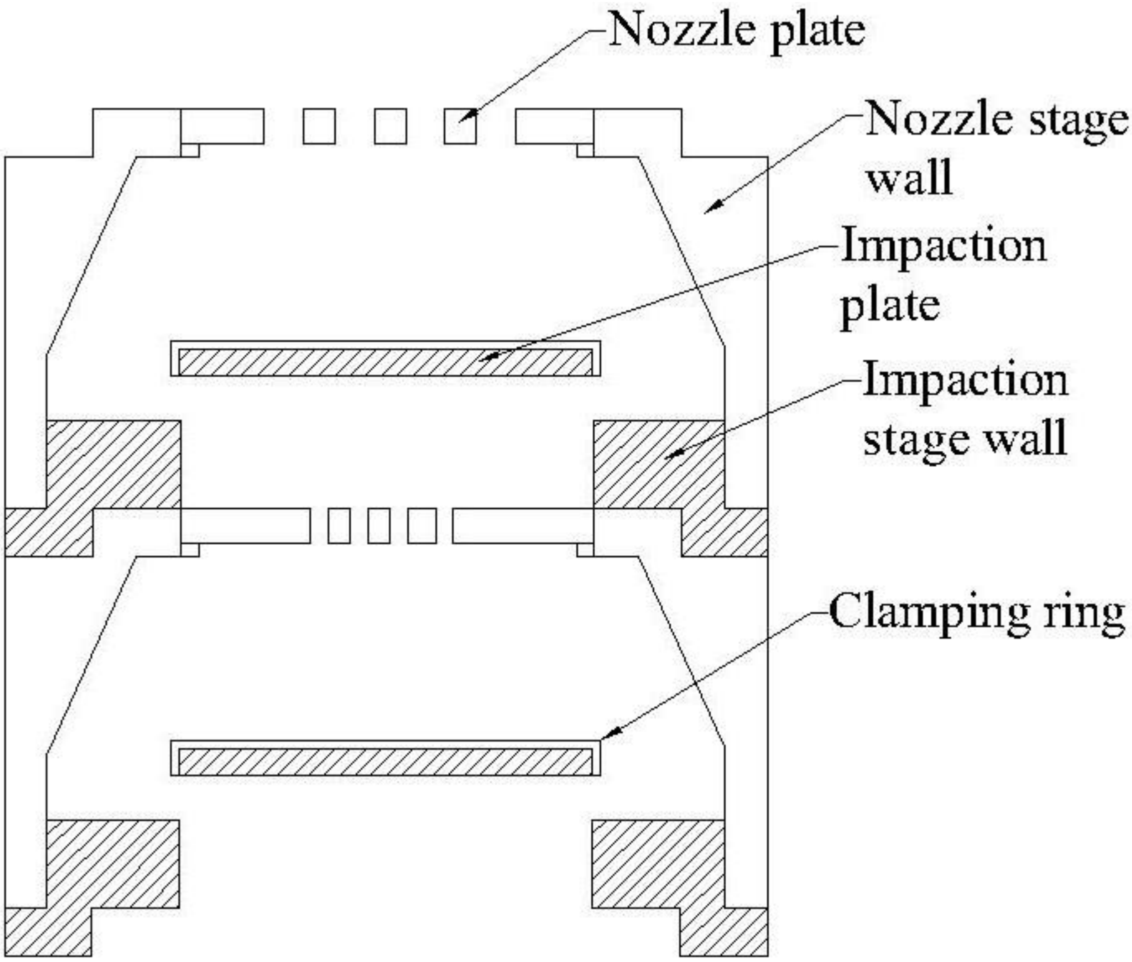
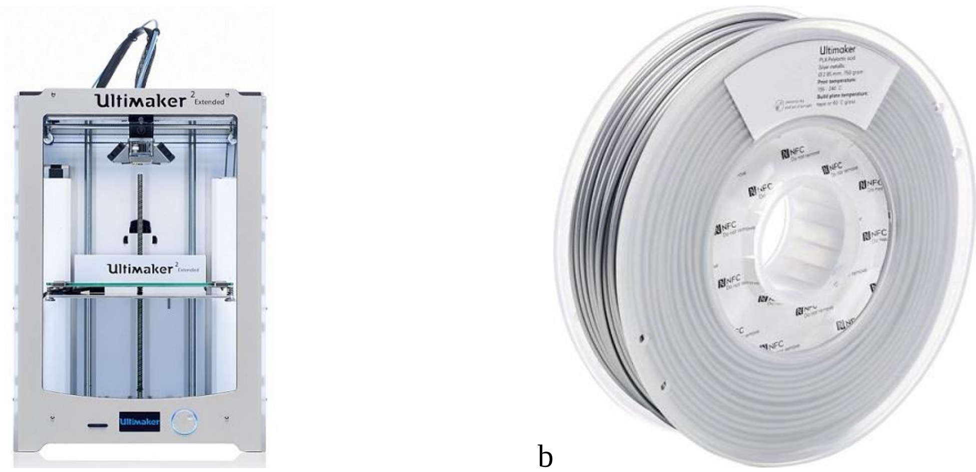


Figure 3-3 A schematic diagram of developed PM sampler

The different stages of the sampler are not monolithic. They are separable and airtight while assembling for operation.



a b

Figure 3-4 (a) 3D printer and (b) Silver Metallic PLA

In this sampler, the air will flow through the nozzle of decreasing diameter and increasing nozzle number for impaction over the selected substrate at impaction stage from the inlet stage to the final nozzle stage. After passing through the final nozzle stage, the air stream will be drawn through the filter. A meshed stainless steel screen is placed on the outlet to support the filter paper. Inlet, each impactor stage and final filter stage are tightened to prevent air leakage from the impactor during operation.

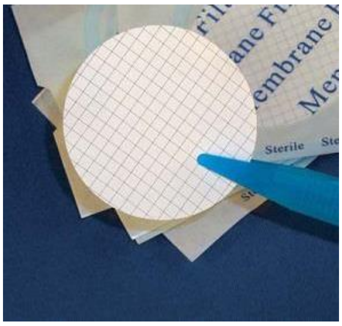
3.3 Sampling site and field evaluation

Sampling was carried out using the designed sampler and a standard sampler simultaneously inside the Nirala-Sabujbag residential area and Khulna University of Engineering and Technology (KUET) during the month of November 2018 and December 2018 respectively. The two samplers (designed and reference) were placed at a distance of 4m apart from each other. A day time sampling was performed at the height of 1.0m. The sampling duration was 08 hours averaging time (09:00AM to 05:00PM) long for each sampling of three different days. The flow was maintaining 05 liters per minute (LPM) as constant throughout the sampling period. A mini vacuum pump (MIS-00111, China) was used as the source of suction of 05 liters per minute (LPM). The flow was continuously checked by using a tube type acrylic flow meter (CNBTR LZQ-3) during the sampling period shown in figure 3:4 below:

a b

Figure 3-5 (a) Mini vacuum pump (b) Acrylic flow meter

A Cellulose nitrate filter paper of 47mm diameter and 0.45μm pore was used as substrate in this study. It was also used for the final filtration of air at last stage. The pre-mass and the post-mass of filter paper were taken using a micro balance (AUW-220D, Uni Bloc.) as for the gravimetric analysis shown in figure 3:5.



a

b

Figure 3-6 (a) A cellulose nitrate filter paper and (b) Micro balance

Before taking the pre-mass or before sampling, the filter paper was pre-conditioned for 24 hours within a closed room of 25ºC temperature (T) and 50% relative humidity (RH). During the sampling days the outdoor maximum temperature was 35ºC and minimum temperature was 21ºC and the maximum and minimum outdoor relative humidity was 91% and 57% respectively. After sampling the filter paper was post-conditioned as same temperature (25ºC) and relative humidity (50%) as like as pre-conditioned.

A handheld portable light scattering particulate matter sampling instrument (3016-IAQ) was used as the reference sampler. It consists of a PM sensor, a microprocessor, a real-time clock, a data logger, a temperature and relative humidity sensor, a network module, and a small light emitting diode (LED) display screen. It has a PM sensor which can detect the particle from both the source of pollution and ambient atmosphere up to the range of 0.3μm to 10μm.

Figure 3-7 A PM sensor instrument

The total experimental setup for the field sampling is shown in figure below:

Figure 3-8 The field experimental setup of (a) designed sampler (b) standard reference sampler

3.4 Measurement of PM

3.4.1 Mass concentration

Determination of mass concentration of particulate matter is one of the major parts in this study. Concentration of particulate matter can be determined in terms of particulate mass (m), number (N) and surface area (S) (Simone *et. al.*, 2015). These different parameters (m, N and S) can be obtained by using several principals like gravimetric, optical, microbalance etc.

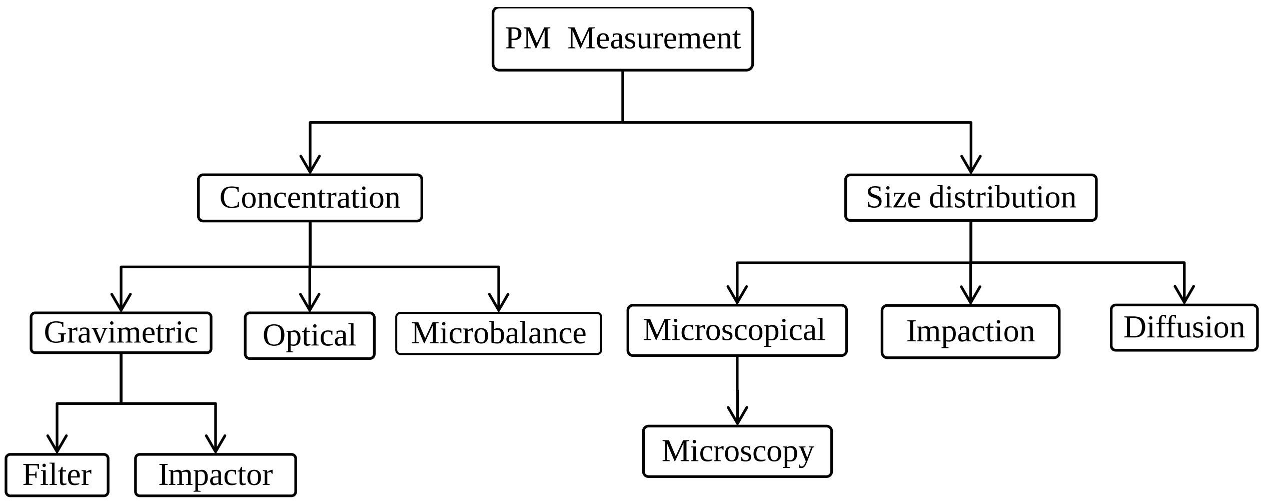


Figure 3-9 Methods for PM measurement

Gravimetric analysis will be conducted to measure the mass concentration of particulate matters (PM) in this study. In the gravimetric method, the PM mass concentration is measured by determining the pre-mass (before sampling) and post-mass (after sampling) of the filter papers. The mass concentration of each individual sampling can be determined by using the following relationship:

$$PM = \frac{M_{post} - M_{pre}}{Q \times T}$$

Where,

PM= Mass concentration of desired particulate matters (PM), $\mu g/m^3$

M_{pre}= Weight of filter paper before sampling, μg

M_{post}= Weight of filter paper after sampling, μg

Q= Constant air suction rate, m^3/min

T= Duration of sampling, min

All the pre-mass and post-mass of the filter paper must be taken under keeping constant temperature (25ºC) and relative humidity (55%) for 24 hrs.

3.4.2 Cut-off size distribution

Determination of size distribution of particles upon the impaction plate's substrate at different stage according to the designed cut-off diameter (D_p) is a significant part of this study. To determine the size in terms of aerodynamic diameter, microscopical method of analysis is conducted. This method is based on improving the visibility.

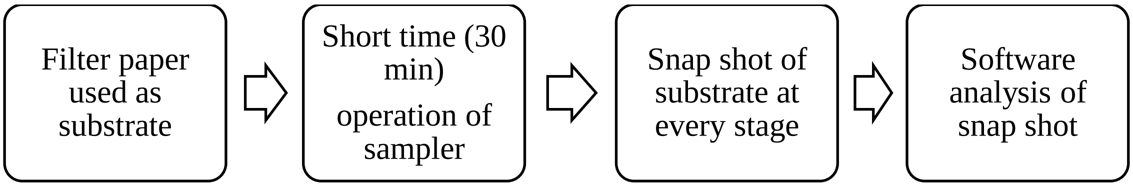


Figure 3-10 Flow chart for cut-off performance

An optical portable microscope is used to take the snap shot or picture at different location of filter paper used as substrate as well as final filtration at last stage. The obtained pictures are analyzed with default software for this optical microscope named "Portable Capture". This Software can detect and calculate the size of the particles up to 1μm from the snap shot.

Figure 3-11 An optical portable microscope

A short time (30 min) sampling is conducted using 47mm diameter cellulose nitrate filter paper at every stage. Short time sampling is preferred to avoid the successive deposition of particle layer. Successive deposition will increase the possibility of error during the measurement of diameter of a single particle by forming a large secondary particle.

3.4.3 Particle Loss

It is very important to determine the interstage loss of particle for a newly developed sampler. Because the collection efficiency curve of a sampler at different stage for different desired cut-off is depends on the nature of the loss of particles on both the impaction substrate and impactor walls & acceleration nozzle. The principal of the inertia cascade impactor and sampler's assembly is also responsible for particle loss. Particles losses within the sampler's assembly, when the particle stream (air stream) make turbulence flow while changing the stage in the acceleration nozzle region. Particle losses are measured by taking the snap shot at different stage of sampler after sampling. Whole the sampler's parts are washed by ethanol to avoid the overestimation of particle for an identical sampling. An optical portable microscope is used to take snap shot and the snap shot is analyzed using "Portable Capture" to determine the diameter of the lost particles. The average volume of the particle is calculated from the diameter, and the average mass is calculated from the average volume. The obtained mass of lost particle is occupied by the area of snap shot. Total mass of lost particle is quantified to multiply the average mass from snap shot with the total exposed area.

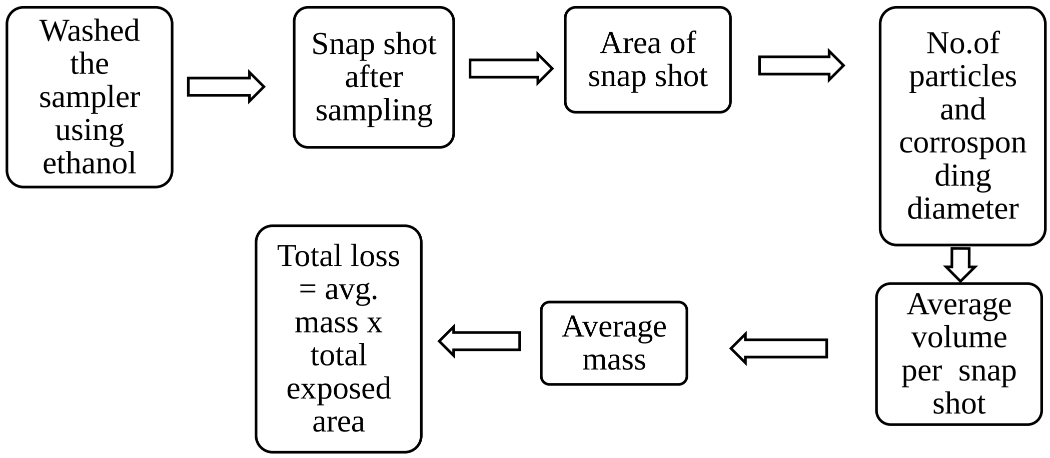


Figure 3-12 Flow chart to calculate the loss

Chapter 4

Results and Discussion

4.1 Physical Overview of developed PM sampler

A substrate based inertial cascade impactor type sampler has designed in this study. The sampler consists of two stages for cut-off different particle sizes (the target cut-off sizes are 2.5μm and 10μm). Each stage of an impactor is composed of a nozzle plate, an impaction plate, and a stage wall. The nozzle plate consists of multiple-nozzle system with optimum nozzle array's configuration. The multiple-nozzle has more advantage as compared to single-nozzle system for a same flow rate in the case of airborne particle sampling under low Reynolds number without large pressure drop (Kwon *et. al.*, 2002). The impaction plate has a removable circular ring to clamp the substrate (foil or filter paper) onto the impaction plate. There is a protection shed upon the inlet section to avoid the entry of rain and fliers into the sampler during sampling. After impacting the last stage the air stream will exit the sampler drawn through the filter paper. As it is last stage, the air stream will pass through the filter paper to trap the rest of the part of the particles after being desired cut-off. The mesh screen is installed at outlet stage to support the filter paper.

Figure 4-1 Partial disassemble of developed PM sampler

Table 4-1 Design and operation parameters of developed PM sampler

Stage no.	Nominal cut-off dia. (μm)	Nozzle numbers	Nozzle dia.(mm)	Velocity (m/sec)	$\frac{S}{W}$	Reynolds number
01	10	04	4.47	1.33	1.0	500
02	2.5	16	1.12	5.29	1.0	500

4.2 Technical feature of developed sampler

A two stage cascade impactor for the size separation of the following aerodynamic particle diameter 10μm and 2.5μm. The sampler was fabricated from the silver metallic PLA filament as this is corrosion resistant, lightweight; there is no problem of static charge and easy to machine as per design specifications. The sampler operates at a flow rate of 05 L/min using a very high efficiency, both battery-operated light pump and AC source of 50 Hz using adapter of 12V DC, 2A at a negligible pressure drop. The low-pressure drop makes it possible to operate the sampler with a very low noise level. The total weight of the sampler is approximately 288 g and the pump weight is 450 g. Twenty-four hours sampling can be performed by using this sampler without any interruption. The sampler will operate from the standard power source (220 VAC, 50 Hz, 2A). If the standard power source fails there is a backup optional power source (12 VDC, 2A). The summary of the technical feature is given below:

Table 4-2 Technical feature of developed sampler

	Developed sampler
Impactor stage	Two (02)
Flow rate (L/min)	Five (05)
Cut-off diameter (μm)	10 and 2.5
Dimension (D x H)	87mm x 113mm
Total weight (gm.)	633
Impactor weight (gm.)	288
Pump weight (gm.)	450
Power (standard)	220 VAC, 50 Hz, 2A
Power (optional)	12 VDC, 2A
Adapter (optional)	12 VDC, 2A
Pump power	Model- JH12-65, DC 12V
Sampling type	Single

4.3 Performance evaluation

4.3.1 Physical Performance and Maintenance of PM Sampler

The sampler worked particularly well without any disturbance throughout the whole sampling hours (24 hrs, 08 hrs and 04 hrs long sampling duration). There was not found any visible sign of deposition of particle inside the sampler's body, throat section of sampler's inlet and outlet. Also there was no sign of overloading and deformation of substrate at impaction plate and final direct suction stage.

Owing a low-vol, light weight and negligible pressure drop, it requires low maintenance. Before and after sampling, the inner parts of the dissembled sampler need to clean by using weak ethanol solution. After twenty-four (24) hours sampling, the heat produced by the pump of the sampler is not significant. As a result a minimum settling period is required between various successive sampling. So the time which is required to change the substrate for two successive sampling is enough for the settling period of the sampler's pump.

4.3.2 Variety of substrate

A widespread range of substrate can be used with the developed sampler since the impaction plates are removable and the substrates clamp onto the plates with clamp rings. The restrictions are to manage the actual jet-to-plate distance and the selected impaction surface has to be large enough to accumulate the whole deposit, which requires 47mm diameter surface. Usually the nature of substrate essential for the sampler is selected by the nature of aerosol to be collected and the nature of post-analysis. The sampler is used to collect liquid or sticky aerosol then the particle bounce will not be a problem. Then any kind of substrate can be used. The analysis technique which will deploy to analyze after sampling is also a part of concern for the selection of substrate. A chemically clean, low atomic weight material such as Teflon (Teflon filters, Gelman Science Inc., Ann Arbor, Mich.) can be used for X-ray fluorescence (XRF) analysis. The collected samples are to be used to analyze the mass distribution, then any kind of substrate with a stable tare weight and low mass can be used. However, materials such as aluminum foil and plastic film also good for mass distribution analysis. Some materials can pick up moisture; thus, the tare weight will be a function of the humidity to which the substrates have been exposed and this material would not be suitable for a mass distribution measurement. There are two types of filter paper for collecting particulate matter, namely fabric and porous membrane filters both of 47mm diameter filter paper can be used as substrate in the developed sampler as listed below:

Table 4-3 Classification and characteristics of substrate

Classification	Types
Fibrous Filters	Cellulose fiber Glass fiber Quartz fiber
Porous Membrane Filters	Cellulose ester membrane Fluoro pore membrane Nuclear pore membrane Silver membrane

4.3.3 Evaluation of PM mass Concentration

The mass concentration of particulate matter (PM) was determined by using Gravimetric analysis. It is a quantitative method which is based upon the determination of mass. In this study only the mass concentration of PM_{10} and $PM_{2.5}$ was measured using two samplers (one is the developed sampler of this study and another is light-scattering sensor based sampler which is act as a reference sampler) for ten different days shown in figure 3:7. The mass concentrations of particulate matter both PM_{10} and $PM_{2.5}$ are quite different for the two samplers as given below:

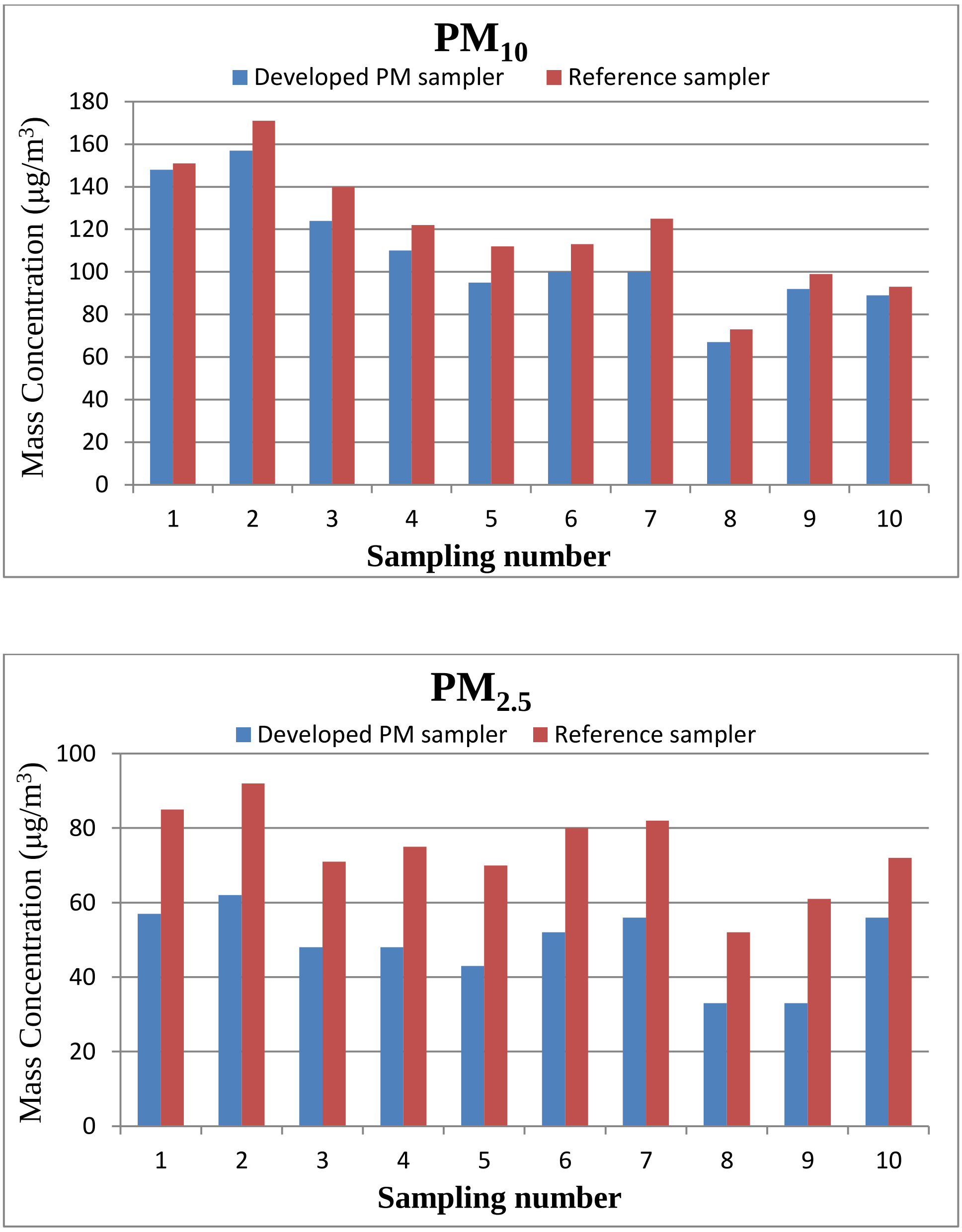


Figure 4-2 Comparison of PM mass concentration with Reference and Design sampler

From the above result it is seen that the mass concentration of PM_{10} ($\mu g/m^3$) for both developed PM sampler and reference PM sampler is relatively high for first two sampling. This might be caused due to the construction activity near the sampling site during the sampling period. Both the reference and developed sampler is showing the high value of PM mass concentration of PM_{10} for the first two sampling. Ten sampling data represent that the obtained PM mass concentration (PM_{10} & $PM_{2.5}$, $\mu g/m^3$) from developed PM sampler is not same to the reference PM sampler. This variation might be due to the different nature of the sampler. The reference sampler is sensor based but the designed one is substrate based impaction type sampler. What is the correlation among the obtained variation, how they vary, to understand this study was performed as below:

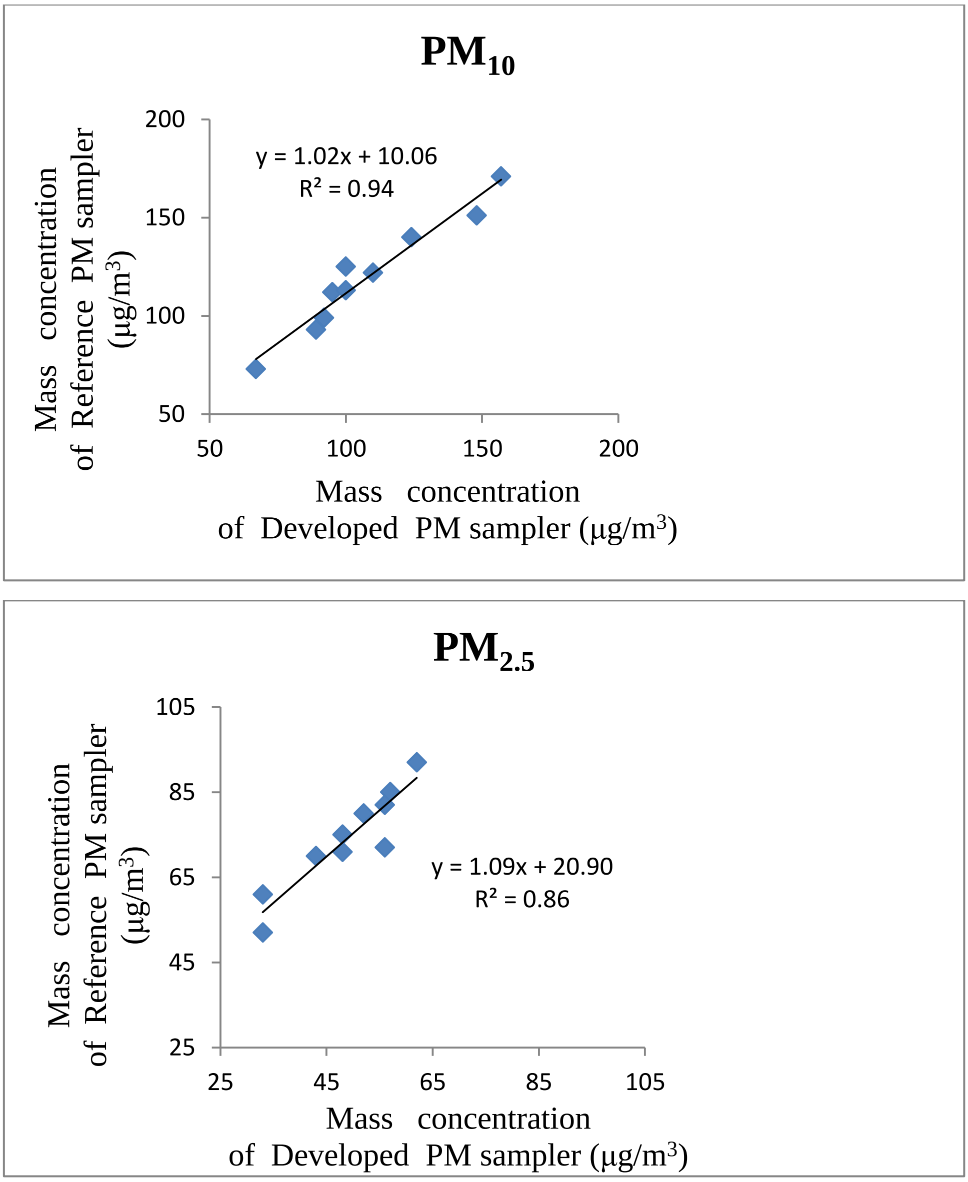


Figure 4-3 Comparison of PM mass concentration

The PM mass concentration obtained with the developed PM sampler and reference PM sampler are shown in above figure 4-3, along with a linear regression line and correlation coefficient. The result of ten sets of developed sampler obtained with reference sampler indicates a strong correlation between the two samplers both for mass concentration for PM_{10} and $PM_{2.5}$. The mass concentration of PM_{10} and $PM_{2.5}$ are correlated with R^2 value 0.94 and 0.86 respectively.

4.3.4 Cut-off Performance of the Impactor

To investigate the cut-off performance of the designed sampler, it was used for three short time (30 min.) sampling at three different days. For a specific cut-off stage, the particle of larger size will be deposited on that stage and the lower will move to next stage for next cut-off. The obtained snap shots of filter paper after sampling for the first stage are given below:

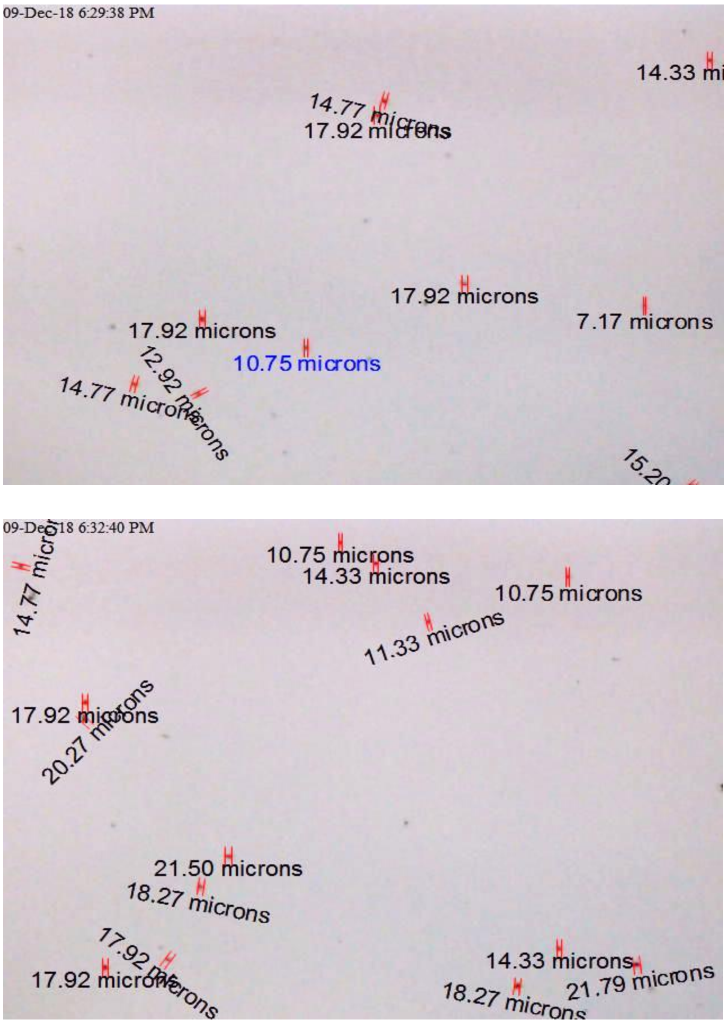
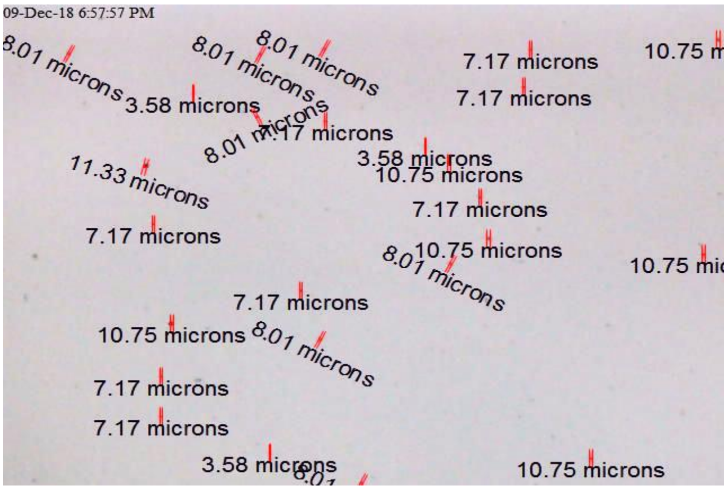


Figure 4-4 10µm Cut-off performance of developed sampler

From the above pictures, it is clear that particle size larger than 10µm dia. has settled on the substrate and lower sizes go to the next stage for further cut-off. So the cut-off performance of first stage for the particle size 10µm (particle size larger than 10µm will settle on the substrate and the smaller will go to next stage) of developed sampler is satisfactory. The snap shot of the next cut-off in second stage for the particle size 2.5µm is given below:



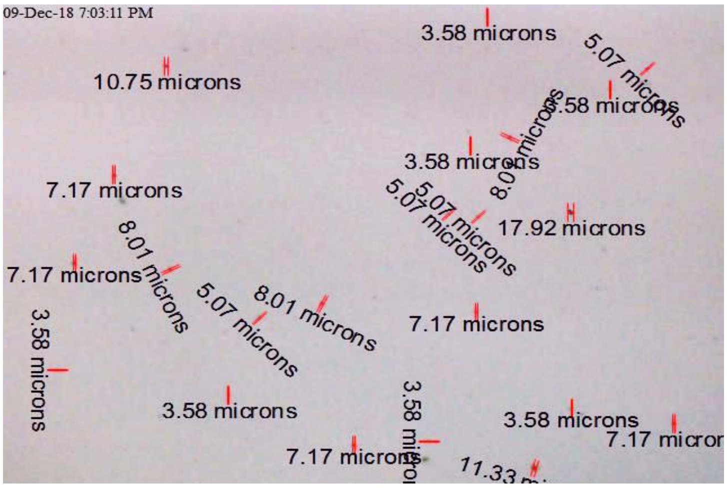


Figure 4-5 2.5µm Cut-off performance of developed sampler

The second stage of the sampler has designed for 2.5µm cut-off. So the particle larger than 2.5µm and smaller than 10µm will be deposited on the substrate surface. From the above pictures, it is found that a minor amount of larger sized particles (greater than 10µm) deposited in the first two sampling. But it is found a sharp cut-off for 2.5µm in the 3rd sampling. So the overall cut-off performance (10µm and 2.5µm) of the developed sampler is satisfactory.

4.4 Evaluation of particle loss

Three individual outdoor sampling was carried out for 08 hours duration to investigate the particle losses due to the impactor nozzle and stage wall. The loss of particle on this study was determined by counting the particle inside the sampler's wall as well as the stagnant corner point of the inside of the sampler. In the inertia cascade impactor and sampler's assembly is also responsible for particle loss. The number of particle was counted from the microscopic snap shot which is based on increase the visibility. In a gravimetric analysis, conditioning of filter paper before and after sampling is the mandatory part for the determination of PM mass concentration ($\mu g/m^3$). The conditioning is responsible for particle loss. Twenty-four (24) conditioning produce the 4% loss. Also some water bound semi-volatile particle will be lost during conditioning (Liu *et. al.*, 2014). The obtained value was 13%, 12% and 11% respectively for overall loss (combination of PM_{10} and $PM_{2.5}$). The average value is 11.93% which has a good agreement with the previous study without Michael *et. al.*, 1970 and G.J. Newton *et. al.*, 1977 as shown in table below:

Table 4-4 Comparison of overall loss of particles

	Total loss of particle (%)
Developed sampler of this study	12.00
Marple *et. al.*, 1991	11.00
Gupta et. al., 2011	10.00
M. Singh *et. al.*, 2003	9.23
Kumar and Gupta, 2015	10.00
Michael *et. al.*, 1970	17.00
Kwon *et. al.*, 2003	11.70
G.J. Newton *et. al.*,1977	3.00
Furuuchi *et. al.*, 2010	11.00
C. Misra *et. al.*, 2002	10.00

4.5 Cross-flow analysis

The cross-flow parameter was evaluated for the both stage PM_{10} and $PM_{2.5}$. For a multiple nozzle sampler, it is the theoretical geometric parameter of the nozzle which is depends on the nozzle diameter (W) and nozzle cluster diameter (Dc). The critical value for the better collection characteristic must be less than 1.2.

Table 4-5 Cross-flow parameters for developed PM sampler

Stage	Nozzle diameter (W)	No. of nozzle (n)	Nozzle cluster diameter (Dc)	Cross-flow parameter ($\frac{WN}{4D_c}$)
PM_{10}	4.47 mm	04	22.50 mm	0.20
$PM_{2.5}$	1.12 mm	15	14.56 mm	0.29

The obtained cross-flow parameter for the stage PM_{10} and $PM_{2.5}$ were 0.20 and 0.29 respectively. Both of the value is less than the critical value (1.2). So the developed PM sampler having the effect of cross-flow will provide the good collection efficiency.

4.6 AQI value

Air quality Indexing was performed by busing the obtained data from the ten sampling days. It was performed separately for both PM_{10} and $PM_{2.5}$. AQI value for PM_{10} is moderate for all sampling days which are shown in table 4-6.

Table 4-6 AQI value for PM_{10}

Sampling no.	AQI value	Range	Category
01	88	51-100	Moderate
02	95	51-100	Moderate
03	74	51-100	Moderate
04	74	51-100	Moderate
05	66	51-100	Moderate
06	80	51-100	Moderate
07	86	51-100	Moderate
08	51	51-100	Moderate
09	51	51-100	Moderate
10	86	51-100	Moderate

Table 4-7 AQI value for $PM_{2.5}$

Sampling day	AQI value	Range	Category
01	99	51-100	Moderate
02	105	101-150	Caution
03	83	51-100	Moderate
04	73	51-100	Moderate
05	63	51-100	Moderate
06	67	51-100	Moderate
07	67	51-100	Moderate
08	45	0-50	Good
09	61	51-100	Moderate
10	59	51-100	Moderate

The AQI value for $PM_{2.5}$ was found as caution to good during the ten sampling days. The second sampling was found as caution and eight sampling is found as good, rest of the sampling was as moderate which is shown in table 4-6.

4.7 Cost analysis

Among the air quality monitoring instrument, the PM size distribution sampler is most costly instrument. The high cost of the dust sampler is the main reason for the lack of monitoring facility of airborne particulate matter in ambient atmosphere. It is also the governing factor for the deficiency of monitoring in the developing country like Bangladesh. The main purpose of this study is to develop a low cost sampler as compared to the market available dust sampler at present. In the present time the European and Indian manufacture are ruling the market of dust sampler. The present market prize of low-vol two stages (PM_{10} and $PM_{2.5}$) sampler of both European and Indian region are listed below:

Table 4-8 Prize of low-vol two stages (PM_{10} and $PM_{2.5}$) sampler

Type of sampler	Price (tk.)
Low-vol sampler (PM_{10} and $PM_{2.5}$) (origin of Europe)	1056000
Low-vol sampler (PM_{10} and $PM_{2.5}$) (origin of India)	450000
Developed PM sampler (PM_{10} and $PM_{2.5}$)	50000

The overall total cost of the developed sampler in this study is 50000 taka which is 21 times lower than the European market and 9 times lower than the Indian market.

Chapter 5

Conclusions and Further studies

5.1 Conclusions:

The substrate based inertial cascade impactors are widely used for airborne particulate matter (PM) sampling due to their wide range of effectively size segregation of particle according to their aerodynamic diameter. This research involved the design, fabrication and performance evaluation of a two stage PM sampler at an opening flow rate is 5 L/min, which is capable of separating the particles from the air stream greater than 10μm and 2.5μm at the first stage and second stage respectively on the non-greased impaction substrate. The finer particles are collected onto the 47mm diameter backup filter paper. A short time sampling of 30 minutes was conducted in KUET campus. It was also evaluated under field condition to collect the ambient particulate matter for 04 hours, 08 hours and 24 hours long duration with a co-located sensor based (light-scattering) reference sampler. The major findings of this study are listed below:

- A two stage PM sampler of size 87mm x 113mm (D x H) was constructed by using silver metallic PLA filament which will make the sampler light weight and corrosion resistance.
- The laboratory analysis of filter paper which is used as substrate was performed using microscope for cut-off performance, and it was found a good agreement as like as design.
- The measurement of PM mass concentration with a co-located sampler was very close and the mass concentration of PM_{10} and $PM_{2.5}$ are correlated with R^2 value 0.94 and 0.86 respectively.
- The average particle loss for the impactor nozzle and sampler body was 12.0% and flow variation was negligible.
- The obtained cross-flow parameter for the stage PM_{10} and $PM_{2.5}$ were 0.20 and 0.29 respectively. Both of the value is less than the critical value (1.2).
- The developed sampler is low-vol, multi-nozzle and operates with low Reynolds (Re) number which reduces the loss of semi-volatile fraction and flow turbulence.

5.2 Further studies:

The developed PM sampler can be upgraded in terms of quality and efficiency considering the following issues:

- Using vibrating orifice monodisperse aerosol generator (VOMAG) for particle characterization study.
- Stage cut-off $PM_{1.0}$ and $PM_{0.1}$ can be introduced for measuring ultrafine and nano particles.

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