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Design and Theoretical Investigation of a PM2.5 Impactor for Airborne Particulate Matter Sampling

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Abstract

PM2.5, called a particles less than 2.5 μm in diameter, suspended in the air have adverse effects on human health, air quality and visibility, as well as processes in various industries. Its level of mass concentration is an important parameter in evaluating the degree of hazard it poses to the atmosphere. In this study, a PM2.5 impactor for airborne particulate matter sampling was designed and theoretical investigated. The PM2.5 impactor design can be described as an assembly of an acceleration nozzle and a flat plate, called an impaction plate. In PM2.5 impactor, particles with sufficient inertia are unable to follow the streamlines and will impact on the impaction plate. Smaller particles will follow the streamlines and not be collected on the impaction plate. Analytical and numerical model were developed to prediction of collection efficiency, fluid flow field and vector, and particle trajectory in the PM2.5 impactor under various design parameters. The modeling results suggest that an optimal operational domain exists for the PM2.5 impactor. Finally, a prototype of the PM2.5 impactor is planned to be constructed and tested, based on the results of this model.

1. Introduction

A recent particulate air pollution episode has affected Chiang Mai adversely. Aerosol is one of the most important environmental topics and particulate air pollution has become a major national concern. Emissions to air arise from human activities and natural processes. Anthropogenic emissions occur during extraction, distribution and combustion of fossil fuels from various industrial processes, from waste treatment and disposal, from agriculture, and from a range of consumer products. Any solid or liquid material suspended in air with diameter in the range of 1 nm to 100 μm can be considered as particulate matter (PM) [1]. For particulate matter with size smaller than 2.5 μm (PM2.5), they can penetrate the alveoli and bypass the upper respiratory tract. PM2.5 is small enough to allow deposition at places where they can do the most damage.

Sampling and measurement of PM2.5 is needed in order to better understand and control them. A PM2.5 instrument is one of the valuable tools for these applications. Impactors have been widely used for many years for sampling and separating airborne aerosol particles of aerodynamic size for further chemical analysis because they are simple in construction with high separation and collection capabilities [2]. It consists of an acceleration nozzle and a flat plate, called an impaction plate. In inertial impactor, particles with sufficient inertia are unable to follow the streamlines and will impact on the impaction plate. Smaller particles will follow the streamlines and not be collected on the impaction plate. The aerodynamic particle size at which the particles are separated is called the cut-point diameter. Numerous studies had been carried out in the past [3 – 4].

In this paper, a simple and low cost of PM2.5 impactor for airborne particulate matter sampling was designed and theoretical investigated. Analytical and numerical models were developed to investigate collection efficiency, fluid flow field and vector, and particle trajectory in the impactor to give a better understanding on the operating of the impactor.

2. Design of the PM2.5 Impactor

The PM2.5 impactor was used to sampling airborne particulate matter with size smaller than 2.5 µm based on their aerodynamic diameter. The primary performance requirements of the PM2.5 impactor are dictated by collection

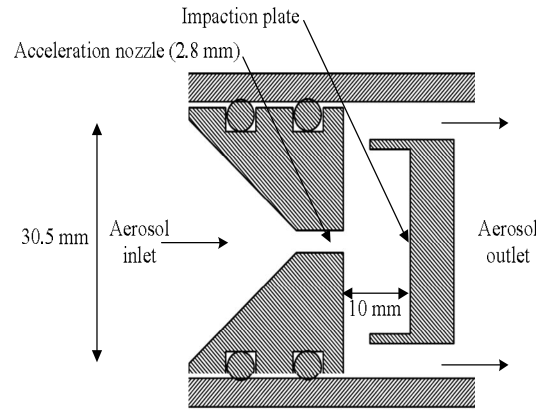


Fig.1 Schematic diagram of the PM2.5 Impactor

efficiency as particle size smaller than 2.5 µm. A schematic diagram of the inertial impactor used in this study is shown in Fig. 1. The design of the impactor is based on the inertial impactor configuration of Marple and Willeke [5]. It consists of an acceleration nozzle and an impaction plate. The acceleration nozzle and the impaction plate are made of a PTFE. In the inertial impactor, the particulate flow of 5 – 15 l/min is accelerated through an acceleration nozzle 2.8 mm in diameter directed at an impaction plate. The distance from the acceleration nozzle to the impaction plate is a 10 to 15 mm. The impaction plate deflects the flow streamlines to a 90^{o} bend. The particles larger than the cut-off diameter of the impactor impact on the impaction plate while the smaller particles follow the streamlines and avoid contact to the impaction plate and exit the impactor.

3. Mathematical Models

3.1 Analytical Model

The most important characteristic of an inertial impactor is the collection efficiency curve which indicates the percent of particles of any size which is collected on the impaction plate as a function of the particle size. According to Marple and Willeke [5], for conventional inertial impactor, the aerosol flow rate, the acceleration nozzle-to-impaction plate distance and the acceleration nozzle diameter are the important parameters governing the performance of the inertial impactor. The acceleration nozzle diameter can be calculated from the Stokes number (Stk). The Stokes number is a dimensionless parameter that characterizes impaction, defined as the ratio of the particle stopping distance to the halfwidth or the radius of the impactor throat. The Stokes number equation for a round jet impactor is defined as [4]:

$$\mathrm{Stk}=\frac{\rho_p C_c d_p^2 U}{9\eta D}, \tag{1}$$

where ρ_p is the particle density, C_c is the Cunningham slip correction factor, d_p is the particle cut-off diameter, U is the mean velocity at the throat, η is the gas viscosity, and D is the acceleration nozzle diameter. Air density and viscosity are 1.225 kg/m^3 and 1.7894 × 10^{-5} kg/m/s, respectively. Temperature of 294^{o}K is used. For the round jet impactor, the expression of the average velocity within the round jets is $U=4Q/\pi D^2$. Substituting the velocity into Equation 1 gives

$$\mathrm{Stk}=\frac{4\rho_p C_c d_p^2 Q}{9\pi\eta D^3}. \tag{2}$$

Solving the above equation for the particle cut-off diameter at 50% collection efficiency, d_{50}, can be calculated by [4]

$$d_{50}\sqrt{C_c}=\sqrt{\frac{9\pi\eta D^3\mathrm{Stk}_{50}}{4\rho_p Q}}. \tag{3}$$

Because C_c is a function of d_{50}, Equation 3 cannot be conveniently solved for particle diameter. For conventional impactor, d_{50} can be estimated from $d_{50}\sqrt{C_c}$ using the following empirical equations: $d_{50}=d_{50}\sqrt{C_c}-0.078\times10^{-8}$ where d_{50} is in m. This equation is accurate within 2% for d_{50} > 0.2 µm and pressure from 0.9 – 1 atm [4]. Thus, the acceleration nozzle diameter is given by

$$D=\sqrt[3]{\frac{4\rho_p\left(d_{50}\sqrt{C_c}\right)^2 Q}{9\pi\eta\mathrm{Stk}_{50}}} \tag{4}$$

where Stk_{50} is the Stokes number of a particle having 50% collection efficiency. For the round jet impactor, Stk_{50} is 0.24, and the ratio of the acceleration nozzle diameter to the nozzle-to-plate distance is 1.0 [4]. In this study, the 50% cut-off diameter >= 1 µm for the size selective inlet of the electrical mobility particle sizing instruments. The fractional particle penetration efficiency (P) of the impactor was determined as follows:

$$P=(1-E)\times100 \tag{5}$$

where E is the particle collection efficiency of the impactor, and it is determined from [6]

$$E = \left[1 + \left(\frac{d_{50}}{d_p}\right)^{2s}\right]^{-1} \tag{6}$$

where *s* is the parameter affecting the steepness of the collection efficiency curve. In the present study, *s* = 1 is arbitrarily assumed for the steepness of the collection efficiency curve. The particle collection efficiency of the impactor was calculated with Microsoft Visual Basic.

3.2. Numerical Model

A numerical model was developed to investigate collection efficiency, fluid flow field and vector, and particle trajectory in the impactor to give a better understanding on the operating of the impactor. Based on the principle of momentum conservation, the continuity and the incompressible Navier-Stokes equations (N-S equation) in the 2-D cylindrical coordinates can be used in this model. In these axisymmetric geometries, the continuity and N-S equations used in this model can be written in the 2-D cylindrical coordinates is given as follows:

Continuity equation:

$$\frac{1}{r}\frac{\partial}{\partial r}(ru_r) + \frac{\partial}{\partial_z}(u_z) = 0 \tag{7}$$

N-S equation:

For the radial component (in *r*-direction),

$$\begin{aligned} &u_r\frac{\partial u_r}{\partial r} + u_z\frac{\partial u_r}{\partial z} - \frac{u_\theta^2}{r} = -\frac{1}{\rho}\frac{\partial p}{\partial r} \\ &+\mu\left(\frac{\partial}{\partial r}\left(\frac{1}{r}\frac{\partial}{\partial r}(ru_r)\right) + \frac{\partial^2 u_r}{\partial z^2}\right) - \mu\frac{1}{r^2}u_r \end{aligned} \tag{8}$$

For the axial component (in *z*-direction),

$$\begin{aligned} &u_r\frac{\partial u_r}{\partial r} + u_z\frac{\partial u_z}{\partial z} = \\ &-\frac{1}{\rho}\frac{\partial p}{\partial z} + \mu\left(\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial u_z}{\partial r}\right) + \frac{\partial^2 u_z}{\partial z^2}\right) \end{aligned} \tag{9}$$

For the circumferential component (in θ -direction)

$$\begin{aligned} &u_r\frac{\partial u_\theta}{\partial r} + u_z\frac{\partial u_\theta}{\partial z} = \\ &\mu\left(\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial u_\theta}{\partial r}\right) + \frac{\partial^2 u_\theta}{\partial z^2}\right) - \frac{2\mu}{r}\left(\frac{\partial u_\theta}{\partial r}\right) \end{aligned} \tag{10}$$

where u_r is the velocity component in the *r*-direction, u_z is the velocity component in the *z*-direction, u_θ is the velocity component in the θ-direction, *p* is the pressure and μ is the kinematic viscosity of air.

For the boundary conditions used, no slip boundary is applied to all the solid walls included in the computation domain, and fixed velocity boundary condition was applied to the inlet. The velocity at inlet was calculated from the flow rate through the impactor. Uniform velocity profile is assumed at the inlet across the cross section of the inlet tubes. The continuity and the N-S equation were numerically solved using a commercial computational fluid dynamic software package, CFDRC™. The CFDRC™ package adopts finite-volume method [7]. Fig. 2 and 3 show computational domain and mesh used for the flow field simulations. An unstructured grid is used. A total of about 5,282 meshes are distributed in computational domain of the impactor.

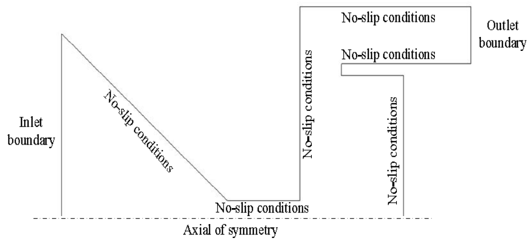


Fig. 2 Computational domain of the impactor.

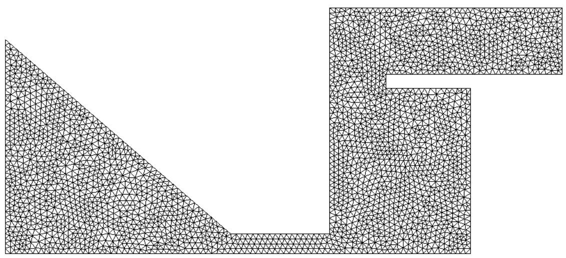


Fig. 3 Computational mesh of the impactor.

4. Results and Discussion

In this study, the calculations were carried out at varying particulate flow rates between 5 to 15 l/min to investigate collection efficiency, flow field and particle trajectory. Fig. 4 shows variation of theoretical collection efficiency curves as a function of particle size at aerosol flow rates of 5, 10 and 15 l/min with the acceleration nozzle diameter of 2.8 mm. Calculations have been performed for particle size range from 10 nm to 100 µm. It was shown that the cut-off diameter decreased as the flow rate increased. With respect to the influence of the particulate flow rate on the performance of the impactor, the cut-off diameter corresponding to 5 and 15 l/min were 2.5 and 1 µm, respectively. It is natural that both throat velocities and collection efficiencies increase as particulate flow rates increase due to increased inertia. Therefore, particles with sufficient inertia are unable to follow

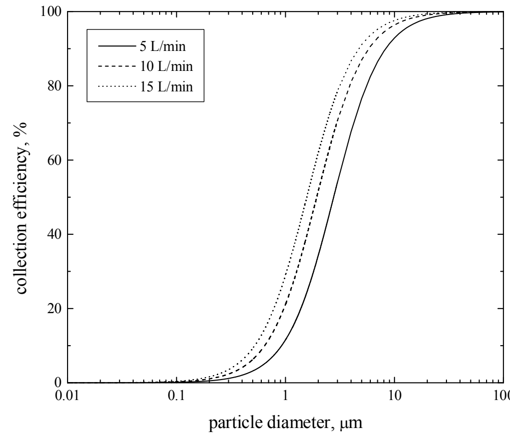
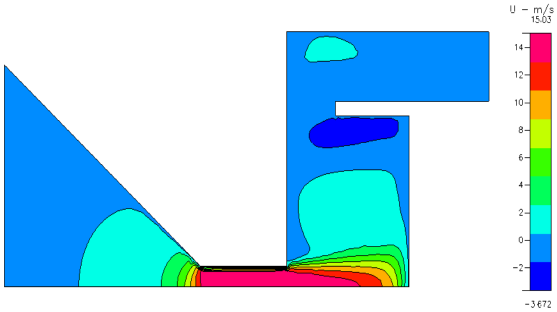


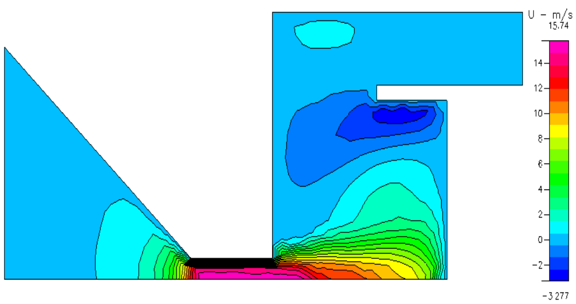
Fig. 4 Variation of collection efficiency with particle diameter at different operating flow rates.

the streamlines and will impact on the impaction plate. In the other hands, smaller particles with insufficient inertia will follow the streamlines and not be collected on the impaction plate. As shown in Fig. 4, the impactor collection efficiency depends on particulate flow rate. It is apparent that the collection efficiency increases between the particulate flow rates of 5 and 15 l/min, because the inertial force acting on the particulate is greater at the higher flow rate.

The flow pattern in the impactor depicted as velocity field and vector plots as well as trajectories of particle entering the impactor when the distance from the acceleration nozzle to the impaction plate varying from 10 to 15 mm with flow rate of 5 l/min is presented in Figs. 5 - 7. The high towards low intensity regions were indicated by red, yellow, green to blue, respectively. Fig. 5 shows velocity field contours in the impactor. Highest velocity intensity appeared around the acceleration nozzle and the impaction plate of the impactor for both cases.

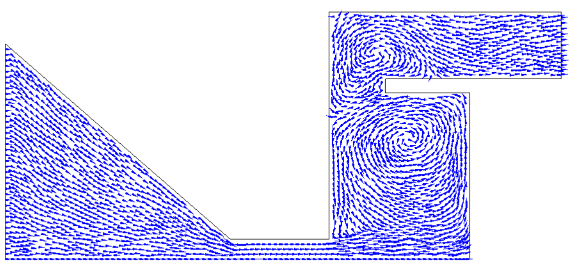


(a) 10 mm

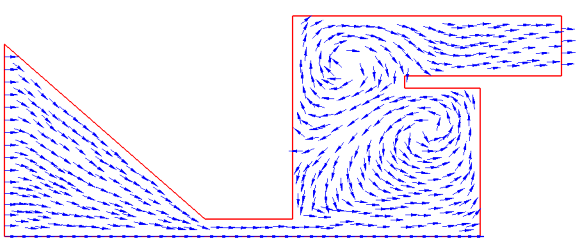


(b) 15 mm

Fig. 5 Velocity contour in the impactor.

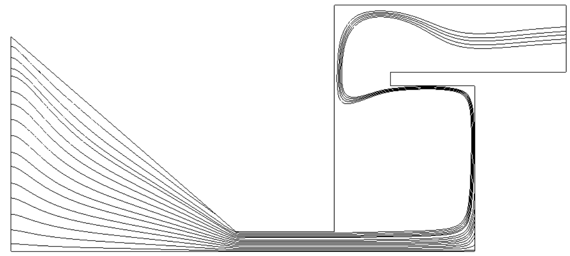


(a) 10 mm

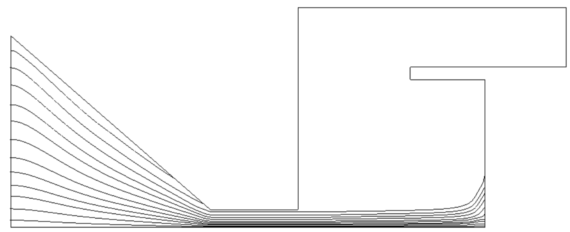


(b) 15 mm

Fig. 6 Vector plots in the impactor.



(a) 10 mm



(b) 15 mm

Fig. 7 Massless particle trajectory plots in the impactor.

It was found that velocity field intensity in case of 10 mm higher than the case of 15 mm. Fig. 6 shows vector plots in the impactor. It was shown that a recirculating flow appeared just downstream of the acceleration nozzle outlet of the impactor for both cases. It was expected that significant particulate loss and particle aggregate due to inertial force. Massless particle trajectory plots inside the impactor for both cases are shown in Fig. 7. In case of 10 mm acceleration nozzle, massless particles are able to follow the streamlines without collected on the impaction plate. In the other hands, massless particles are unable to follow the streamlines and impact on the impaction plate for 15 mm acceleration nozzle. It was expected that the acceleration nozzle to the impaction plate distance should be less than 15 mm.

5. Conclusions

In this paper, a simple and low cost of PM2.5 impactor for airborne particulate matter sampling has been designed and investigated. The design of the inertial impactor was based on the inertial impactor configuration of Marple and Willeke [4]. The cut-off diameter of the PM2.5 impactor was analytically investigated by varying particulate flow rates to predict collection efficiency, flow field and particle trajectory. It was found that the cut-off diameter decreased as the flow rate increased. A numerical model was developed to investigate flow field and particle trajectory inside the impactor to give a better understanding on the operating of the impactor. The modeling results suggest that an optimal operational domain exists for the PM2.5 impactor. Finally, a prototype of the PM2.5 impactor is planned to be constructed and tested, based on the results of this model.

6. Acknowledgement

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7. References

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