Advanced Powder Technology xxx (2018) xxx–xxx

Contents lists available at ScienceDirect

Advanced Powder Technology

journal homepage: www.elsevier.com/locate/apt

Original Research Paper

Investigation of a double shrouded probe for particle sampling in high velocity airflows

Nae-Gang Heo [a], Sang-Hee Woo [a], Jun-Hyung Lim [a], Se-Jin Yook [a,*], Kang-Ho Ahn [b]

[a] School of Mechanical Engineering, Hanyang University, Seoul 133-791, Republic of Korea
[b] Department of Mechanical Engineering, Hanyang University, Ansan, Kyunggi-do 425-791, Republic of Korea

ARTICLE INFO

Article history:
Received 24 August 2017
Received in revised form 2 December 2017
Accepted 25 January 2018
Available online xxxx

Keywords:
Isokinetic sampling
Sampling probe
Shrouded probe
Aspiration ratio
PM_{10}
$PM_{2.5}$

ABSTRACT

An accurate forecast of the concentration of fine dust in the atmosphere is critical because of the negative public health impacts associated with high concentrations of particulate matter. To achieve an accurate forecast, large volumes of data need to be collected over a wide range of regions to act as forecast model boundary conditions. Therefore, the concentration of fine particles should be measured at both fixed observatories and from a range of moving monitoring stations, including cars, trains, and aviation vehicles. To accurately record particulate concentrations at flow velocities up to 200 km h^{-1}, this study proposed a double-shrouded probe design based on the widely used single-shrouded probe. Using the double-shrouded probe, isokinetic sampling for $PM_{2.5}$ was achieved at velocities up to 200 km h^{-1}, and for PM_{10} at velocities up to 75 km h^{-1}. When flow velocities exceeded these values and particle sizes increased, particulate concentrations were overestimated. However, as compared to the single-shrouded probe, the double-shrouded probe reduced the level of overestimation markedly.

1. Introduction

Aerosol particles, or Particulate Matter (PM) 2.5 and PM10, can have a significant impact on the environment and public health [1–3]. There are various sources of particles that are harmful to the human body. For example, exhaust gases such as nitrogen oxide (NO_x), sulfur oxides (SO_x), carbon monoxide (CO), and ozone (O_3) from the burning of fossil fuel in power plants, incineration plants, and factories, can combine to create particles that reach diameters of up to micron size in the air [4–6]. In October 2013, fine particulate matter was classified as a Category 1 carcinogen by the World Health Organization, drawing the attention of the public and researchers alike. Recent reporting by the Financial Times highlighted that Seoul, the capital of the Republic of Korea, was designated as one of the top three cities in the world in terms of severe air pollution. As such, it is important for Korea to accurately monitor the number and mass concentrations of fine airborne particles in real time. Many monitoring stations across Korea, run by the Korea Environment Corporation (www.keco.or.kr), measure the concentration of airborne particles and disclose the results in real time. This data is useful for forecasting particle concentrations; however, forecast accuracy is low due to boundary condition limitations caused by the small number of monitoring stations. Mobile monitoring facilities, including vehicles, such as cars, trains, vessels, drones, and unmanned aerial vehicles, can provide a more accurate forecast by providing two- and three-dimensional boundary conditions for forecast models. To facilitate mobile air pollution monitoring, it is necessary to develop a probe which can effectively sample particles at varying velocities.

Isokinetic sampling condition means that a representative sample of aerosol flows into a sampling tube when aerosol sampling is performed in a moving aerosol stream. Therefore, meeting isokinetic sampling conditions is critical to accurate measurement of the number and mass concentrations of particles in the atmosphere. In most cases, isokinetic sampling can be completed when the flow into the probe is controlled [7,8]. However, to achieve this, pressure also needs to be regulated. Several means of controlling the pressure within the probe and meeting the isokinetic sampling conditions have been evaluated by using either a hot wire near the probe inlet or by raising the temperature of the air current around the probe using electric heating [9,10]. The anisokinetic nozzle with a shroud was developed so that nuclear fuel storage facilities can continuously sample for radionuclide aerosols released through stacks [11]. Later, the advantage of the shrouded probe was proven when compared to the unshrouded isokinetic sampler [12]. More recently, sampling probe technology advanced in order

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* Corresponding author.
E-mail address: ysjnuri@hanyang.ac.kr (S.-J. Yook).

https://doi.org/10.1016/j.apt.2018.01.025
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Please cite this article in press as: N.-G. Heo et al., Investigation of a double shrouded probe for particle sampling in high velocity airflows, Advanced Powder Technology (2018), https://doi.org/10.1016/j.apt.2018.01.025

to sample aerosol particles using airplanes [13]. However, each type of sampling probe is limited in that there is a boundary for the airflow velocity possible for isokinetic sampling in accordance with the intake flow. Additionally, there has been research on an omnidirectional sampling probe, which can conduct particle sampling from various directions [14,15]. However, this probe requires a relatively slow air flow velocity, and is only applicable when a large intake flow is available.

This research aims to develop a sampling probe, which is not sensitive to the outside air velocity and as such can be used to accurately measure the aerosol particle concentration from various types of vehicles. To achieve this, a sampling probe is proposed with double-shroud structure, based on the shape of the single-shrouded sampling probe described by Gong et al. [16]. Results are compared with the experimental results of Chandra [17] to demonstrate the prediction accuracy of the numerical analysis method used in this study. We find that a sampling probe with double-shroud structure can provide accurate isokinetic fine particle sampling for velocities up to 200 km h^{-1}.

2. Numerical methods

An estimation of the aspiration ratio of the sampling probe within a high-speed flow was conducted using a three-dimensional simulation. Firstly, in order to establish the numerical method, we followed the probe design described by Gong et al. [16] as shown in Fig. 1. This probe sets the isokinetic sampling conditions at the mouth of the sampling tube by lowering the flow velocity using differential pressure through single-shroud. According to Gong et al. [16], the length and external diameter of the shroud are 176 and 58 mm, respectively, and its internal diameter (a) is 52 mm. The internal and external diameters of the sampling tube are 15 and 44.5 mm respectively, and the intake flow is 56.6 L min^{-1}. Hence, the average speed of the air within the sampling tube is $U_{st} = 5.34$ m s^{-1}. The distance between the shroud inlet and the sampling tube is 90 mm. Two cases ($U_0 = 8.9, 21.0$ m s^{-1}) for the freestream velocity outside of the shroud were considered. Temperature and pressure were set at 15 °C and 101.3 kPa, respectively.

This study used the *ANSYS FLUENT Release 16.1* for air flow analysis, which is a commercial computational fluid dynamics package, to solve continuity, momentum, and energy equations. Air flow was assumed to be three-dimensional, steady, incompressible, and turbulent. Following the numerical approach of Gong et al. [16], the standard k-ε turbulence model was employed. The calculation domain and boundary conditions for air flow analysis are described in Fig. 1b. We conducted a grid-dependence test and set the diameter and length of the cylindrical calculation domain as 180 and 776 mm, respectively. Approximately 1.8 million mesh elements were created. Velocity inlet, pressure outlet, and symmetric conditions to the entrance, exit, and side of the cylindrical calculation domain were used as boundary conditions. The velocity outlet, which was added to the exit of the sampling tube, facilitated air flow into the sampling tube at 56.6 L min^{-1}.

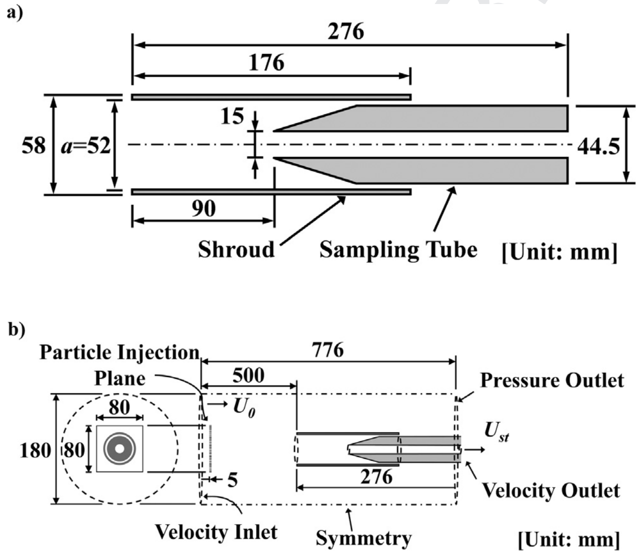

Fig. 1. Calculation domain for the analysis of single-shrouded probe: (a) design of single-shrouded probe; (b) boundary conditions and particle injection scheme.

Particle trajectory was analyzed through DPM (Discrete Phase Models) code built in FLUENT. We considered the particle aerodynamic size based on the assumption that the particle shape is spherical with a density of 1000 kg m^{-3}. Drag, gravity, Brownian force, and Saffman lift force were considered as forces acting on the particles [18]. In order to revise the drag magnitude, this study applied a slip correction factor [19]. It set a particle injection plane with a shape of 80 × 80 mm^2, 495 mm ahead of the shroud, and made 250,000 equally-spaced particles flow at the same speed and in same direction as the freestream. These particles were assumed to be trapped when they hit the wall. Among the flowing particles, we counted how many particles passed through the sampling tube outlet and assessed the aspiration ratio (A) using the following equation:

$$A = \frac{C_{st}}{C_0} = \frac{N_{st}}{N_0} \cdot \frac{Q_0}{Q_{st}} = \frac{N_{st}}{N_0} \cdot \frac{U_0}{U_{st}} \cdot \frac{a_0}{a_{st}} \qquad (1)$$

Here, C_{st} is the particle number concentration at the mouth of the sampling tube and C_0 is the particle number concentration in the freestream. Isokinetic sampling refers to a situation where a representative sample of aerosol in a moving aerosol stream comes into the sampling tube [20]. As a result, when the aspiration ratio is one, that is $A = 1$, isokinetic sampling has occurred. N_{st} and Q_{st} are the number of particles per unit time and the flow rate of air flowing into the mouth of the sampling tube, and thus $N_{st}/Q_{st} = C_{st}.N_0$ and Q_0 are the number of particles per unit time and the flow rate of air through the particle injection plane, resulting in $N_0/Q_0 = C_0$. U_{st} and U_0 are the average velocity of air flowing through the sampling tube and the particle injection plane, respectively, while a_{st} and a_0 are the cross-sectional areas of the flow path in the sampling tube and the particle injection plane.

Fig. 2 shows the shape of the double-shrouded probe proposed in this study, having double-shroud structure based on the existing single-shrouded probe. For the measurements of the shape of the double-shrouded probe, "a" refers to the size of the inner shroud, and "b," "c," and "d" determine the size of the outer shroud. In particular, d is the location of the outer shroud opening from the mouth of the inner shroud. The outer shroud opening is located higher than the inner shroud inlet when the value is negative, lower when the value is positive, and at the same height when $d = 0$. It should be noted that the downstream end of the outer shroud creates an isolated structure. This structure is connected to the outer wall of the sampling tube, meaning that air flow is released in the opposite direction to the freestream through the outer shroud opening immediately after passing through a narrow space between the inner shroud and the sampling tube. Because the shape and size of the sampling tube is the same as those of the original shrouded probe of Gong et al. [16], we analyzed the air flow and particle trajectory, and assessed the aspiration ratio while changing the size of a, b, c, and d. The calculation domain and boundary conditions were the same as those mentioned above. In order to determine the particle sampling characteristics within

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