Advanced Powder Technology 26 (2015) 868–873

Contents lists available at ScienceDirect

Advanced Powder Technology

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

Original Research Paper

Investigation of collection efficiency of round-nozzle impactors at different atmospheric pressures and temperatures

Chun-Woo Park [a], Gyuho Kim [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 6 December 2014
Received in revised form 6 February 2015
Accepted 23 February 2015
Available online 4 March 2015

Keywords:
Inertial impactor
Collection efficiency
Stokes number
Balloon-borne
ELPI

ABSTRACT

A simulation approach for predicting the collection efficiency of inertial impactors was developed by calculating particle trajectories in a Lagrangian reference frame. When numerically predicted collection efficiencies of the electrical low-pressure impactor (ELPI) were compared with the experimental data found in the literature, the agreement was good and the relative difference in cut-off size was less than 12%. Then, balloon-borne impactors having nominal cut-off sizes of 1 μm, 2.5 μm, and 10 μm were designed, and their collection efficiencies were predicted using the present simulation approach. When volumetric sampling flow rate of air introduced to the single-stage round-nozzle impactors was fixed at varying altitude, the cut-off sizes were predicted to decrease from 0.98 μm, 2.47 μm, and 9.86 μm at sea level to 0.47 μm (by 52.0%), 1.70 μm (by 31.2%), and 7.62 μm (by 22.7%) at 16-km-altitude, respectively. When volumetric sampling flow rate was adjusted, the cut-off sizes of the single-stage round-nozzle impactors were estimated to remain almost unchanged with the variation of less than 5.1%, 7.3%, and 10.6%, respectively, at varying altitude in troposphere.

1. Introduction

Aerosol instruments can be loaded on aircrafts to sample aerosol particles existing at high altitudes [1–4]. The aircrafts usually have large carrying capacities and make it easy to control pressure and temperature for operating the aerosol instruments. The aircraft-borne measurements, however, have weak points such as high cost and limited flight hours. On the other hand, the aerosol instruments can be loaded on balloons for sampling atmospheric aerosol [5–7]. The balloon-borne measurements are less expensive and capable of continuously sampling atmospheric aerosol at a certain altitude. However, the balloon-borne measurements are limited by loading capacity of the balloon, and greatly affected by atmospheric pressure and temperature at high altitudes.

Inertial impactors are frequently used to sample atmospheric particles due to easy operation and simple geometry. Since inertial impactors have strong points such as lightweight and simple operating system, the inertial impactors are appropriate for the balloon-borne aerosol sampling according to altitude. A typical inertial impactor is composed of a nozzle for accelerating aerosol flow and an impaction plate for collecting aerosol particles. While the aerosol flow is accelerated through the nozzle and impinges on the impaction plate, the particles experience curvilinear motion. If a particle has sufficient inertia to deviate from a curvy streamline, then it is collected on the impaction plate. The Stokes number (Stk) is an important dimensionless parameter for characterizing the collection efficiency of inertial impactors and is defined as [8]

$$\mathrm{Stk} = \frac{\rho_p d_p^2 C_c U}{9\mu W}, \quad (1)$$

where ρ_p is the particle density, d_p is the particle size, C_c is the slip correction factor, U is the average jet velocity of air through the nozzle, μ is the viscosity of air, and W is the nozzle diameter.

The ambient pressure becomes lower with increasing altitude. Particle collection characteristics of inertial impactors at low pressure levels were numerically investigated. Leduc et al. [9] simulated the collection efficiency of the electrical low-pressure impactor (ELPI) by using both laminar and turbulent models, i.e., k–ε, RNG k–ε, and RSM turbulent models, to solve flow field, and by employing the discrete random walk (DRW) model provided in the FLUENT software to calculate particle trajectories. When Leduc et al. [9] compared their simulated cut-off sizes with the experimental data of Marjamäki et al. [10], relative error was large

* Corresponding author. Tel.: +82 2 2220 0422; fax:+82 2 2220 2299.
E-mail address: ysjnuri@hanyang.ac.kr (S.-J. Yook).

http://dx.doi.org/10.1016/j.apt.2015.02.014
0921-8831/

for low-pressure stages. According to Arffman et al. [11], stochastic models, e.g., DRW model, might not be accurate with high velocity flows. Therefore, Arffman et al. [11] simulated the collection efficiencies of the ELPI and the quartz crystal microbalance (QCM) impactor for low-pressure stages by using the SST-k–ω turbulent model to solve flow field and by employing no stochastic tracking models. Compared with the ELPI experimental data of Marjamäki [12] and the QCM calibration data of Hering [13], relative error of the simulated cut-off sizes of Arffman et al. [11] was within 25%.

In order to compare the characteristics of atmospheric particles according to altitude, the cut-off size of an inertial impactor needs to be unchanged. However, due to the variation of the atmospheric pressure and temperature according to altitude, the values of the slip correction factor and air viscosity change. This implies from Eq. (1) that the Stokes number becomes different depending on the altitude even for the same particle size and particle density, if the volumetric sampling flow rate, which is proportional to U, remains constant. As a result, the impactor collection efficiency at high altitudes can be dissimilar to that at sea level.

The objective of this study is to design balloon-borne single-stage round-nozzle impactors for collecting particles existing at high altitudes. A numerical approach for precisely estimating the collection efficiency of inertial impactors at varying pressure and temperature is developed, and the collection efficiencies of single-stage round-nozzle impactors are predicted at different altitudes in troposphere. Sampling flow rate is adjusted to keep the cut-off size unchanged at different tropospheric pressures and temperatures, and the numerically estimated cut-off sizes are compared.

2. Numerical

Fig. 1 shows the schematic of the calculation domain for simulating the aerosol flow in a round-nozzle impactor. Radius of the impactor inlet was denoted as R_{in}, nozzle diameter as W, nozzle throat length as L, nozzle-to-plate distance as S, impaction plate diameter as D, pressure at the impactor inlet as P_{in}, pressure near the impaction plate as P_p, and pressure at the impactor outlet as P_{out}. Volumetric flow rate and mass flow rate of air introduced to the impactor stage were denoted as Q_{in} and $\dot{m}_{in}$, respectively. Temperatures (T) at the inlet and walls were set to be the same as the ambient temperature.

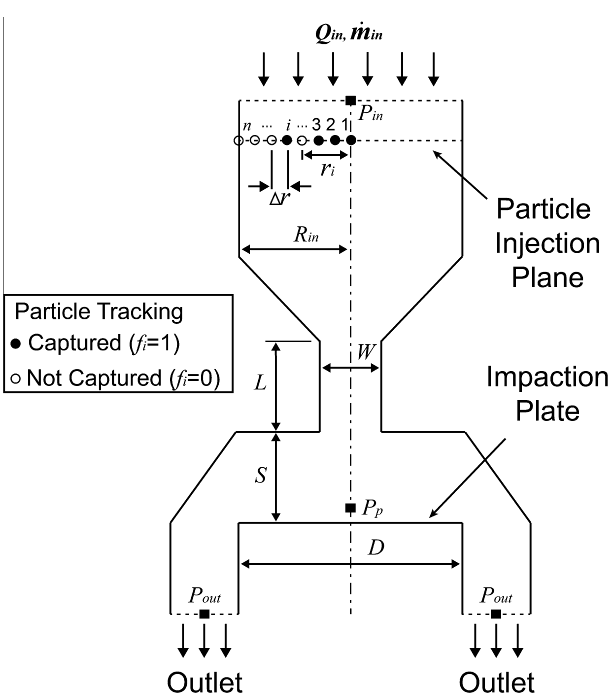

Fig. 1. Simulation domain.

ANSYS® Fluent Release 13.0 was employed to simulate the flow in the inertial impactor. The flow was assumed to be two-dimensional, axi-symmetric, steady, and laminar. The Mach number was calculated from the average jet velocity of air through the impactor nozzle. If the Mach number was smaller than 0.3, then the flow was assumed to be incompressible; pressure-based solver was adopted; the SIMPLE algorithm was used; and boundary conditions were set as velocity inlet at the impactor inlet, pressure outlet at the impactor outlet, symmetry at the axis, and no-slip condition on all walls including the impaction plate. If the Mach number was greater than 0.3, then the flow was presumed to be compressible; density-based solver was employed; the Roe-FDS was selected as the flux type; and boundary conditions were set as mass-flow-inlet at the impactor inlet, pressure outlet at the impactor outlet, symmetry at the axis, and no-slip condition on all walls. For both compressible flow and incompressible flow, double-precision solver was chosen and convergence criterion for iteratively solving continuity, momentum, and energy equations was set at 10^{-6}. Grid independence test was performed and number of cells ranged approximately from 20,000 to 110,000 depending on the impactor nozzle size.

Discrete Phase Models (DPM), incorporated in the FLUENT, was used to simulate particle trajectories in a Lagrangian reference frame. The effects of the gravity and the Stokes drag with slip correction on particle behavior were taken into account. The gravity pointed downward. Because the impactor collection efficiency is affected by the gravity for Reynolds numbers smaller than 1500 [14], the gravitational force was considered in all simulation cases. The influence of particle bounce was not considered, and the particles were assumed to be permanently trapped once they hit the impaction plate.

The impactor collection efficiency was estimated by using the statistical Lagrangian particle tracking (SLPT) approach [15–18]. As shown in Fig. 1, the particle injection plane was located 0.1 mm below the impactor inlet, and n particles of the same size and density were evenly spaced in radial direction. The particles were injected with the same velocity as the airflow velocity at the impactor inlet. Gap between neighboring particles was constant as

$$\Delta r = \frac{R_{in}}{n-1}. \tag{2}$$

Radial position of the ith particle was calculated as

$$r_i = (i-1)\Delta r. \tag{3}$$

Fate of the ith particle (f_i) was determined from particle trajectory simulation using the DPM, that is, $f_i = 1$ if the ith particle was captured on the impaction plate and $f_i = 0$ if not captured. Based on the assumption of a plug flow velocity profile and a homogeneous particle number concentration at the impactor inlet, the impactor collection efficiency (η_c) was predicted as [15]

$$\eta_c = \frac{2\Delta r}{R_{in}^2}\sum_{i=1}^{n} r_i f_i. \tag{4}$$

The effect of n on η_c was checked, and the number of tracked particles was determined as $n = 500$.

3. Results and discussion

The height of the troposphere is approximately 8 km at the poles and reaches up to about 15–18 km at the equator [19].