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Collection efficiency and interstage loss of nanoparticles in micro-orifice-based cascade impactors

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HIGHLIGHTS

► Nanoparticle loss occurs in lower stages of the micro-orifice cascade impactors.
► Nozzle plates with step-shape nozzle results in possible nozzle clogging.
► New NMCI with nozzles of smooth nozzle shape prevents nozzle clogging.
► New NMCI can facilitate accurate mass size distribution measurement of aerosols.

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ABSTRACT

In this study, two micro-orifice-based cascade impactors, including the micro-orifice uniform deposit impactor (MOUDI, MSP Model 110) and the NCTU micro-orifice cascade impactor (NMCI), were tested for the collection efficiency and interstage loss of nanoparticles. In the NMCI, new nozzle plates with smooth nozzle shape made by the LIGA (Lithography, Electroplating, and Molding) process were used to replace the 7th–10th stages in one of the MOUDI. Test results show that after adjusting proper S/W ratios (S: jet to plate distance, W: nozzle diameter) to 2.52, 3.01, 13.44, and 24.75 for the 7th, 8th, 9th and 10th stage of the NMCI, respectively, and 5.56, 11.18, 9.3, and 10.9 for the 7th, 8th, 9th and 10th stage of the MOUDI, respectively, the cutoff aerodynamic diameters (d_{pa50}) are close to the nominal values given in Marple et al. (1991). Different S/W ratios are needed due to differences in the nozzle shape and nozzle diameter between two cascade impactors. Total interstage loss of nanoparticles from the inlet to the 6th–10th stage of the MOUDI exists due to the convection-diffusion mechanism, which increases with decreasing d_{pa}. For the MOUDI, total loss is 2.9–15.3 % (d_{pa}: 105.8 to 15.4 nm) for the inlet to the 6th stage and it increases to 20.1–26.1 % (d_{pa}: 23 to 15.4 nm) for the inlet to the 10th stage, respectively. Similar but slightly lower loss also exists in the NMCI. Field comparison tests in the ambient air show that mass size distributions measured by the MOUDI agree well with those of the NMCI. Finally, nozzle clogging tests using high concentration incense smokes indicate that the NMCI has a much less tendency for particles to clog in the nozzles than the MODUI.

1. Introduction

Cascade impactors are used to measure aerosol mass size distributions and the collected samples can further be analyzed for chemical compositions (Chen et al., 2010; Kim et al., 2012; Kudo et al., 2012; Wang et al., 2010; Zhu et al., 2010, 2012). Traditionally, the smallest cutoff aerodynamic diameter (d_{pa50}) of a cascade impactor is around 0.5 μm, which leads to a poor size resolution of submicron particles and nanoparticles. To obtain a lower d_{pa50}, improved cascade impactors have been developed, such as the micro-orifice uniform deposit impactor (MOUDI) (Marple et al., 1991), the low pressure impactor (LPI) (Hering et al., 1979) and the electric low pressure impactor (ELPI) (Keskinen et al., 1992). Among them, the MOUDI is the most widely used device (Chow and Watson, 2007) because of its relatively smaller interstage pressure drop as compared to low pressure impactors which reduces potential evaporation of volatile aerosol species. Recently, a novel inertial filter was also developed and equipped at downstream of a four stages cascade impactor for classifying nanoparticles with much lower pressure drop to avoid more loss of volatile components (Otani et al., 2007; Furuuchi et al., 2010).

There are three major concerns when using cascade impactors: solid particle bounce, overloading of collected particles on the

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impaction plate and interstage loss (Marple et al., 2001). Many efforts have been made to resolve these problems. For example, different types of impaction substrates such as oil-coated substrates (Turner and Hering, 1987; Pak et al., 1992; Peters et al., 2001; Liu et al., 2011; Tsai et al., 2012), porous substrates (Huang et al., 2005, 2001) and specially designed substrates (Chang et al., 1999; Tsai and Cheng, 1995) were used to reduce solid particle bounce. In case that uncoated substrates are needed to avoid interference with chemical analysis of collected samples, Chen et al. (2011) suggested to condition the relative humidity (RH) of the incoming aerosols of the MOUDI to be higher than 75 or 65%, respectively, for uncoated aluminum foil or Teflon filter substrates. Similar conclusion was also found in Vasiliou et al. (1999). For increasing the particle loading capacity on impaction substrates, rotating substrates (Marple et al., 1991; Tsai et al., 2012), oil-soaked Teflon filters (Turner and Hering, 1987; Tsai et al., 2012) and impaction plates of special designs (Tsai and Cheng, 1995) provide possible solutions.

Besides collection efficiency, interstage loss data are also critical to complete the calibration of a cascade impactor since it may result in the shift of the collection efficiency curve to the smaller particle size (Liu et al., 2011) or even lift the left tail end of the curve (Hillamo and Kauppinen, 1991). The interstage loss in the MOUDI was measured during its initial development (Marple et al., 1991). However, the loss for nanoparticles with the diameter smaller than the d_{pa50} of each of the lower stages was not tested. In addition, the loss of nanoparticle can occur in the upstream stages before a certain lower stage, which is hard to measure because the loss per stage is small unless the test is conducted from the inlet to a specific lower stage. In Virtanen et al. (2001), particles with the size from 10 to 400 nm were used to measure the loss for the 5th to 12th stage of the ELPI with the corresponding d_{pa50} ranging from 260 nm to 6.7 μm. However, only particles (silver particles: 10–40 nm, DOS particles: 40–400 nm) which were smaller than d_{pa50} and deposited on the impaction plates of the stages were considered as particle loss while particles might also deposit between stages. In addition, particle loss in the lower 1st–4th stages with d_{pa50} smaller than 260 nm was not measured.

Another practical problem needs to be addressed is particle clogging in the nozzles due to long-term or high particle concentration sampling, which may often be ignored by many users since this problem develops slowly. The clogged nozzles may result in an increase in the pressure drop across the cascade impactor and eventually a decrease in the d_{pa50} values of the lower stages (Ji et al., 2006). Therefore, dirty nozzle plates need to be cleaned regularly. For the lower 7th–10th stages of the MOUDI, the nozzles may be clogged easily due to its step-shaped structure with abrupt contraction, as shown in Fig. 1a–c, in which the cross sectional view, top views at the depth of 0 μm and 150 μm, respectively, are shown for the 9th stage nozzle of the MOUDI as an example (MSP Model 110). The larger dashed circle in Fig. 1c shows the circumference of the step before the nozzle hole where particles may deposit easily resulting in possible nozzle clogging. In addition, since the bottom part of the nozzle used to determine the nozzle diameter is thin and fragile, cleaning by ultra-sonication is not recommended for fear that possible nozzle fracture may occur (MSP, 2006). Otherwise, ultra-sonication is an effective way to dislodge particles deposited in the nozzle.

In this study, the original 7th–10th stages in one of the MOUDI were replaced by the new nozzle plates with smooth nozzle shape fabricated by the LIGA process (Lithography, Electroplating, and Molding). The cascade impactor is hereafter referred to as the NMCI (NCTU micro-orifice cascade impactor). The cross sectional view, top views at the depth of 0 μm and 120 μm of the new nozzle can be seen in Fig. 1e–g. Furthermore, the bottom views of the nozzle of the MOUDI and the NMCI shown in Fig. 1d and h, respectively, indicate that the latter is closer to a perfect round shape than the former. In the laboratory, the particle collection efficiency curves of the 7th–10th stages of the NMCI and those of the MOUDI were obtained to ensure d_{pa50} values match with the nominal values given in Marple et al. (1991). After that, the total interstage loss of nanoparticles from the inlet to each lower stage (7th–10th) of both NMCI and MOUDI was measured. The comparison test of the collocated NMCI and MOUDI was also conducted in two ambient air monitoring stations. Finally, to examine if nozzle clogging occurs in both cascade impactors, the pressure drop across the inlet to the 9th stage of the cascade impactors was monitored during sampling of high concentration incense smokes. After the test, nozzle was examined under a microscope for possible nozzle clogging.

2. Experiment methods

The experimental setup for measuring particle collection efficiency and nanoparticles loss is shown in Fig. 2. Monodisperse liquid dioctyl sebacate (DOS) particles with the aerodynamic diameter (d_{pa}) from 15 to 500 nm were generated by the atomization and electrostatic classifier technique for the test. Polydisperse particles were first generated by the constant output atomizer (TSI Model 3076) from the DOS solution with the concentration from 0.001 to 0.1 % (v/v). The aerosol flow was passed through a tubular furnace (Lindberg/Blue, Model HTF55322C, USA) at a fixed temperature of 300 °C to produce a relatively narrow size distribution by the evaporation-condensation process. Monodisperse, singly charged particles were then generated by the electrostatic classifier (EC, TSI Model 3080) equipped with the nano-differential mobility analyzer (DMA, TSI Model 3085) or the long-DMA (TSI Model 3081). To minimize the effect of multiple charges on the monodispersity of the classified particles (Pui and Liu, 1979), only particles larger than the count median diameter (CMD) were classified. When calibrating the particle collection efficiency of a single lower stage, a ball valve was used to simulate the pressure drop created by all previous upstream stages. The following equation was then used to calculate the particle collection efficiency (η) or interstage loss (L) as:

$$\eta \text{ or } L = \left(1 - \frac{I_2}{I_1}\right) \times 100 \quad (1)$$

where the I_1 and I_2 are the aerosol currents at the inlet or outlet of the tested impactors measured by the TSI 3068 aerosol electrometer (AE) equipped with a home-made faraday gage which is similar to that in the original TSI AE except that a larger tube for the aerosol flow (inner diameter is 7.3 mm compared to 3.1 mm of the original one) is used inside it to reduce the pressure drop.

After the laboratory tests, field comparison and nozzle clogging tests were conducted. For the field comparison test, the NMCI and the MOUDI were collocated to measure ambient aerosol mass size distributions at the Jhongshan and Jhudong air monitoring stations, Taiwan. These two sampling sites were chosen because they are ideal urban sites with typical bimodal mass size distributions, where the distances from the stations to the nearest main road are 15 and 300 m for the Jhongshan and Jhudong stations, respectively. Silicone grease (KF-96-SP, Topco Technologies Corp., Taiwan) coated aluminum foils were used as the impaction substrates in the 0th–10th stages to reduce solid particle bounce, and Teflon filters (Zefluor P5PJ047, Pall Corp., New York, USA) were used as the after filter. Before weighing, the substrates were conditioned in an environmental conditioning room where the RH and temperature were kept at 40 ± 2% and 21 ± 1 °C, respectively. A microbalance (Model CP2P-F, Sartorius, Germany) was used for weighing, in