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The influence of nozzle throat length on the resolution of a low pressure impactor—An experimental and numerical study

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ABSTRACT

This study investigates the effect of the nozzle throat length on the resolution of the low pressure impactor (LPI). Two basic nozzle geometries, rectangular slit and round nozzle with 25 nm cutpoint were investigated both experimentally and by numerical simulation. A new impactor stage with variable nozzle throat length and jet-to-plate distance was designed, built and tested. The impactor was calibrated at four different configurations with monodisperse dioctyl sebacate (DOS) aerosol. A very good agreement between the simulated and the experimental resolutions and cutpoints were found. The main conclusions are that (a) the length of the nozzle is a crucial parameter affecting the resolution and (b) it is possible to achieve a better resolution with a rectangular slit type impactor than with a round nozzle type LPI. The best observed resolution was achieved with the slit type LPI with a nozzle throat length to width ratio of only 0.33. Compared to similar cutpoint impactor stages of commercially available LPIs, the resolution of the new stage is by far the highest.

1. Introduction

Impactors have been used since the end of the 19th century in aerosol science to classify particles according to their size. One widely used method is to use impactor stages in a cascade configuration to measure the size distribution of the particles. In cascade impactors, several impactor stages with varying cut points are placed in series. To achieve lower cutpoints, low pressure impactors (LPI) have been introduced. In cascade low pressure impactors the pressure is reduced either by having a separate pressure reducing stage (e.g. Hering et al., 1978, 1979) or by gradually reducing the pressures by using high jet velocities (e.g. Berner, 1972; Vanderpool et al., 1990). Besides the size classification of particles, LPIs have been employed in some less conventional applications such as studying the particle properties (Friedlander, 1999; Virtanen et al., 2010).

Resolution of the single impactor stage is defined as the steepness of the collection efficiency curve. Having a high resolution for a single impactor stage would allow the cutpoints of individual stages to be brought closer to each other without significant overlap in the kernel functions. This way more channels can be added to the same size range in the distribution measurement. In addition, this gives opportunity to control the impaction conditions of the particles more closely. For example, the impaction velocities of the particles inside an LPI stage will be more uniform. The resolution of an impactor stage is affected by many parameters such as geometry and flow conditions.

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The first numerical studies where the steepness of the collection efficiency has been studied are Marple & Liu (1974) and Marple et al. (1974). They investigated the effect of geometry and Reynolds number on the impactor resolution. Their studies showed that with decreasing Reynolds number the resolution may be deteriorated and shortening the throat length may have the opposite effect. However, Marple's studies have been made during 70's and therefore the size of the computation grids were quite limited. Jurcik & Wang (1995) studied the effect of nozzle entrance geometry on the resolution of the impactor. They found out that the straight nozzle geometry focuses particles towards the axis of round nozzle, and this may cause the "tail" of the collection efficiency curve. Like Marple et al. showed earlier, also Jurcik & Wang observed that the resolution decreases when the Reynolds number is decreased below 100. All these studies assumed constant fluid properties for the flow. Supersonic and hypersonic impactors have been studied by numerical methods in Abouali & Ahmadi (2005), Abouali et al. (2011) and Zare et al. (2007). Their results show that the resolution of these extremely large pressure ratio impactors (upstream/downstream pressure ratio is in the order of magnitude 100) seems to be lower than for example the lowest cutpoint stages of well known Berner LPI (Hillamo & Kauppinen, 1991). Result implies that the resolution of the supersonic impactor is about the same as for subsonic LPI.

Marple & Liu (1975) made analysis on how to reach the ideal impactor collection efficiency, i.e. impactor that has a step functional collection efficiency curve. The idea was that if the impactor flow field solution is dependent only on the normal distance from the collection plate and the velocity distribution of particles at the nozzle exit plane is uniform, the collection efficiency curve shape is ideal. Conclusion of the paper was that with small nozzle Reynolds numbers the collection efficiency curve steepness decreases because of boundary layer development at the nozzle walls. Developed boundary layer causes particles to have an uneven velocity profile at the nozzle exit plane. Their analysis was based on numerical simulation results of LPI by Marple & Liu (1974). De la Mora et al. (1990) investigated experimentally the operation of the transonic LPI at moderate Reynolds number. They chose the investigated nozzle geometry in order to prevent the deterioration of resolution by the possible boundary layer development. This was accomplished by using a wide nozzle compared to its length. The ratio of the nozzle length (T) to the diameter (W) was 0.15. The nozzle consisted of a converging section followed by a straight nozzle with a total length of 0.554 mm. Gómez-Moreno et al. (2002) studied the turbulent transition in the impactor jet. This was performed by observing the resolution of the LPI as a function of the Reynolds number. Results showed that when the jet-to-plate distance is two times greater than the diameter of the nozzle, the flow experiences the laminar to turbulent transition at Reynolds number in an order of 1000. When the transition occurs also the resolution is deteriorated significantly. Also Arffman et al. (2011) investigated the effect of turbulence on LPI resolution by numerical simulations. They found out that when the Reynolds number is less than 1500 the turbulence does not have strong deteriorating effect on the resolution of LPI. In the applied flow range the simulated and measured resolutions had a good correlation, and therefore the simulation approach they presented can be used in studying the resolution at low Reynolds numbers.

The focus of this study is on improving the resolution of a single LPI stage by experiments and numerical simulations. Idea on how to improve the resolution of LPI is inspired by the previous studies of Marple et al. (1974) and De la Mora et al. (1990) and also by the considerations of steady impaction conditions presented in the previous study of authors (Arffman et al., 2011). We investigate the effect of the ratio of nozzle throat length (T) to the width of the nozzle (W, the width or the diameter of the nozzle corresponding round and slit nozzles) on the collection efficiency curve steepness by numerically and experimentally. Also the resolutions produced by rectangular slit and round nozzle LPIs are compared. Simulations are made using methods presented in Arffman et al. (2011). Resolution is studied experimentally by building a new LPI stage with exchangeable nozzle length and shape. Collection efficiency of the stage is measured using monodisperse vacuum oil particles.

2. Simulations

Effect of different geometrical parameters on the shape of impactor collection efficiency curve were simulated using methods presented in the preceding paper by Arffman et al. (2011). Briefly, the flow field was first simulated using ANSYS Fluent 12.1 software, and the particle tracking and collection efficiency computation was carried out with a separate Matlab script. All simulations were made in two dimensions (axi- and planesymmetric equations) with compressible flow effects included. Meshes were rectangular and included roughly 50,000–100,00 computation cells. Boundary layer was created for the collection plate and the mesh was densed inside the nozzle and at outlet of the nozzle. Flow was modeled as a turbulent flow using the SST-$k-\omega$-turbulence transfer model and the advanced wall treatment of ANSYS Fluent. Although it did not have much practical effect in the simulations, because the Reynolds numbers were in order of few hundred, and the turbulent viscosity values were negligible compared the dynamic viscosity of the gas. Second order upstream discretization scheme was used in the discretizations of the flow equations. Boundary conditions were fixed pressures at the inlet and outlet boundaries of the domain. These are listed in the Table 1. Particles were released from the nozzle inlet plane and the aerodynamic focusing effect at the inflow was not included in the simulations. The focusing effect drives particles towards the axis of the nozzle and tends to steepen the collection efficiency curve. On the other hand, when the particles are packed in a confined space the Coulombic repulsion and the diffusion spread the particles radially, that inhibits the focusing effect.

It has been pointed out in previously (Arffman et al., 2011) that at least with the nozzle counts of ELPI impactor the effect of the nozzle count on the accuracy of simulation is very small. For example, the 17 nm cutpoint stage of ELPI has