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The effect of sheath flow rate on the particle trajectory inside an optical cavity with direct flow configuration

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ABSTRACT

In order to obtain the optimized flow condition inside an optical cavity with direct flow configuration, we conducted numerical simulations using commercial computational fluid dynamics (CFD) code Fluent 15.0 solver. The average residence time of particles, the width of particle beam, and particle loss rate were calculated from the particle trajectories that were obtained using Discrete Phase Model (DPM). Also, the Discrete Random Walk (DRW) was used to consider the effect of turbulence on the particle. It was found that particle loss rate and the residence time of particles can change according to the sheath flow rate. Increasing the sheath flow rate has the effect of reducing the particles loss rate and the size of the recirculating particles. It was found that using sheath flow with a flow rate over 0.7 L/min was an effective way to prevent particles from recirculating, which causes particle loss inside an optical chamber. However, an increase in sheath flow rate increases the pressure drop and reduces the residence time of particles. Furthermore, as the size of particle becomes smaller, the average residence time of particles above 3 μm decreases. By contrast, due to the turbulent dispersion of particles, the residence time of particles below 3 μm increases as the size of particle becomes smaller. For 1–10 μm, the Brownian motion of particles can be neglected compared to the turbulent dispersion of particles. In addition, flow visualization experiments were conducted to validate our CFD simulation results and experimental results were in good agreement with numerical predictions. Overall, in the design of particle detection devices, it is important to consider the influence of the sheath flow on the particle trajectory through numerical simulation.

1. Introduction

Airborne microorganisms including bioaerosols, such as viruses, bacteria, and fungal spores, are major components of atmospheric aerosols. Those components can cause harmful health effects for people and animals (Kang, Lee, Kim, Bae, & Jung, 2014). Many studies have reported that airborne microorganisms can cause damage to the lungs and respiratory system and thus lead to human disease and public health problems, such as allergies or asthma (Kim, Jahan, & Kabir, 2013; McCormack et al., 2011; Shah et al., 2013). Also, vehicular traffic and fossil combustion activities produce harmful aerosol particles and those aerosol particles can affect air quality, ecosystem, and climate (Fuzzi et al., 2015; Li et al., 2009). From the military view, bioaerosols can be used as harmful bioagents resulting in serious incidents (Kovář, Farka, & Skládal, 2014). Particles of the size range of 1–10 μm are well known to be maximally effective, since particles smaller than 1 μm tend to be expelled from the lungs, while particles larger than 10 μm settle quickly in the air within a very short period of time (Primmerman, 2000). In this context, considering that airborne aerosol

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particles are related to the abovementioned public health and environmental and military problems, it is essential to find effective methods for detecting aerosol particles and measuring their concentration (Zhang et al., 2013).

For this reason, several studies have been conducted on the detection of aerosol particles. The optical detection method is an efficient way to detect aerosol particles in real time (Taketani et al., 2013). Once aerosol particles are lit by a light source, they start scattering this light in all directions. In Optical Particle Counter (OPC), a laser-diode is normally used as a light source. A photo detector measures the scattered light of particles as an electrical signal. The amplitude of electrical signal is determined by the particle size and the size distribution of particles can be derived by measuring the intensity of scattered light from individual particles (Giechaskiel et al., 2014).

Another way for detecting aerosol particles in real time is using the Time-of-Flight (TOF) method. Aerodynamic Particle Sizer (APS, Model 3320 and Model 3321, TSI Inc., St. Paul) is used to measure particle size distribution of particles sized from 0.3 to 20 μm in the aerodynamic diameter based on the time-of-flight (TOF), an aerodynamic property, and optical property (Armendariz & Leith, 2002; Peters & Leith, 2003). The nozzle part of APS consists of two coaxial converging nozzles: the outer nozzle and the inner nozzle. The outer nozzle thoroughly encases the inner nozzle. Aerosol flow entering the outer nozzle has the flow rate of 5 L/min and the flow is separated into two lines, i.e., 4 L/min flow and 1 L/min flow. The 4 L/min flow that passes through a high-efficiency filter located at the outer nozzle is used as a sheath flow. Remaining 1 L/min flow traverses the inner nozzle and is recombined with 4 L/min particle-free sheath flow at the exit of the inner nozzle (Volckens & Peters, 2005). The recombined 5 L/min flow is accelerated in a converging nozzle and is focused into the center by sheath air. Then, particles pass through two laser beams. The distance between two laser beams is well defined and the transition time of particle can provide aerodynamic diameter with a suitable calibration (Hinds, 1999).

While both OPC and APS can provide physical properties such as concentration and particle size, they do not provide data on the biological and chemical characteristics of aerosols (Cheng, 1999). Ultraviolet laser-induced fluorescence (UV-LIF) can be a useful method for detecting bioaerosols in real time (Pan et al., 2003). Numerous types of instruments, including Ultraviolet-Aerodynamic Particle Sizer (UV-APS), Fluorescence Aerodynamic Particle Sizer (FLAPS), Biological Agent Warning Sensor (BAWS), and Single Particle Fluorescence Analyzer (SPFA), have been developed for the detection of bioaerosols. Those instruments have a laser as an excitation source inside them (Agranovski, Ristovski, Hargreaves, Blackall, & Morawska, 2003; Eversole et al., 2001; Ho, 2002). However, using a conventional laser as a light source has several limitations, such as high costs, large power consumption, and frequent maintenance requirement (Cabalo, Sickenberger, Underwood, & Sickenberger, 2004).

In recent years, due to the disadvantages of using the conventional laser as a light source, many studies have focused on using a light emitting diode (LED) as a light source (Ryškevič et al., 2010). LED light sources have been used due to low cost and low power consumption. Due to the demand of compactness and low cost of field monitoring systems, the LED light source is attractive as an alternative to the UV-Laser light source. However, the low sensitivity of LED still needs to be improved. In order to overcome the limitation, it is necessary to increase the time period during which particles are exposed to the light emitting diode by forming an appropriate flow field around the nozzles inside an optical chamber. Cabalo et al. (2005) used the opposed flow configuration to increase the time period during which particles in the Micro-UV detector optical cavity were excited to a UV light source. In the opposed flow configuration, particles are injected into measurement region through the two nozzles. When the two opposed flows collide, flows spread slowly and perpendicularly to the central axis of two opposed nozzles. However, perpendicularly spread particle flows can cause over-counting of the particles. To avoid the over-counting problem, a specific trigger method such as the Schmitt trigger can be applied. However, the misalignment or unbalanced flow of two opposed nozzles prevents the achievement of the purpose of the opposed flow configuration.

For the direct flow configuration, Stein et al. (2002) performed numerical simulations of the flow field inside APS for the particle size range from 1 to 20 μm. The authors found that the velocity magnitude of recirculating particles passing through the measurement region is smaller than that of the particles that follow a normal pathway. In addition, simulation results reported by Stein et al. (2002) demonstrate that small particles tend to recirculate compared to large particles. Furthermore, in order to measure particles with the diameter of 1–10 μm, Pan, Pinnick, Hill, and Chang (2008) focused on particles in the range of 2–10 μm and used a tapered nozzle of 400 μm in diameter and a double inlet structure. At the downstream of the nozzle, a focused laminar cylindrical aerosol jet was generated. The effective sample flow rate of large particles increased because a tapered nozzle can more effectively focus on large particles ($>$ 3 μm in diameter) than on small particles (1 μm in diameter).

Several previous studies have been conducted on instruments using a laser or LED as a light source for detecting aerosol or bioaerosol (Bridgeman, Baker, Brown, & Boxall, 2015; Davitt et al., 2006; Li et al., 2016; Ryškevič et al., 2010; Zhang et al., 2013). However, those studies did not focus on optimization of flow field inside an instrument but optimization of optical apparatuses and sensors.

Dubey, Ghia, and Turkevich (2014) provided useful parameters to optimize flow field in the flow combination section (FCS) of the Baron fiber classifier focusing on the interaction of sheath and aerosol flows. They found that using a sheath flow could suppress the vortex formation in the FCS and deposition of aerosol on the FCS walls. Also weak recirculation occurs when the ratio of aerosol inlet velocity and the sheath inlet velocity is larger than 50. However, their study does not take account of the effect of turbulent flow on the particle trajectory because the Reynolds number in their study is limited within laminar flow ($Re < 2000$) and the effect of sheath flow rate was not considered because the only aerosol flow rate was varied.

In the present study, we performed three dimensional numerical simulations to optimize flow field around nozzles inside an optical cavity when the direct flow configuration was used unlike TAC-BIO in Cabalo et al. (2005). The injection nozzle used in our simulations has a double inlet structure composed of a tapered inner nozzle and a coaxial outer nozzle. In contrast with the nozzle structure of APS, the outer nozzle encases the upper tapered part of the inner nozzle. Thus, the aerosol flow and sheath flow become