Journal of the Taiwan Institute of Chemical Engineers 000 (2017) 1–9

Contents lists available at ScienceDirect

Journal of the Taiwan Institute of Chemical Engineers

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

Development and collection efficiency of an electrostatic precipitator for in-vitro toxicity studies of nano- and submicron-sized aerosols

Ta-Chih Hsiao[a,*], Hsiao-Chi Chuang[b], Chun-Wan Chen[c], Tsun-Jen Cheng[d], Ya-Chien Chang Chien[a]

[a] Graduate Institute of Environmental Engineering, National Central University, No. 300 Jhongda Rd., Jhongli City, Taoyuan County 32001, Taiwan
[b] School of Respiratory Therapy, Taipei Medical University, No. 250 Wu-Hsing Street, Taipei City 11031, Taiwan
[c] Institute of Labor, Occupational Safety and Health, Ministry of Labor, No. 99, Lane 407, Hengke Rd., Sijhih District, New Taipei City 22143, Taiwan
[d] Institute of Occupational Medicine and Industrial Hygiene and Department of Public Health, National Taiwan University, No. 17, Shiujou Rd., Taipei 10055, Taiwan

ARTICLE INFO

Article history:
Received 24 April 2016
Revised 8 December 2016
Accepted 9 January 2017
Available online xxx

Keywords:
Nanoparticle exposure
Air-liquid interface
Dosimetry
Electrostatic precipitator (ESP)
Electrospray

ABSTRACT

The direct air-liquid interface (ALI) *in vitro* exposure method are used for high-throughput screening of nanoparticle toxicity, due to the relatively low capital required and the low cost of labor compared to animal and *in vivo* experiments. In this study, a new ALI exposure chamber using an electrostatic precipitator (ESP–ALI) was designed to improve the nano- and submicron-sized particle collection efficiency on the air-liquid exposure interface. Particle penetration tests were performed to characterize the performance under different operating conditions. The effects of different geometric dimensions and operating conditions were explored, and the similarity-scaling process was applied to reveal the hidden effects underlying the experimental data. The penetration results show that the developed electrostatic precipitator is able to efficiently collect particles with a size of up to 300 nm under a DC electric field of 5.0 kV/cm and at a flow rate of up to 1.5 lpm. The electrospray charging technique was also tested with this ESP–ALI system and proved to enhance the ALI collection efficiency without ozone generation. In addition, the particles collected on the exposure interface are uniformly distributed under various operating conditions, as supported by consistent dimensionless precipitation densities.

1. Introduction

Nanotechnology has tremendous promise in various applications, such as medical imaging and drug delivery technologies. Numerous engineered nanoparticles, such as silver nanoparticles, have been manufactured and widely used in consumer and industrial products, as well as other novel technological applications, due to their physiochemical properties [1–5]. However, there are concerns about the potential adverse effects on the human body, when exposed to nanoparticles [1,2,6,7]. Therefore, research on nanotoxicity has gained considerable attention in recent years. To determine the toxicity of nanoparticles, the three methods of the exposure experiment has generally been used to evaluate the exposure-dose-response relationships: (1.) animal/*in vivo* testing, (2.) *ex vivo* studies of cells of bronchial lavage or biopsies, and (3.) *in vitro* systems of exposure of lung cells to pollutants under controlled conditions [8,9]. Although the *in vitro* system lacks the ability to clarify complex interactions between the different types of cells in their natural environment, this method enables investigators to examine the effects of inhaled toxins on specific cell types. The *in vitro* test thus offers valuable information that can be used to determine the potential cellular mechanisms mediating these responses [10]. In addition, *in vitro* tests are relatively inexpensive, compared to *ex vivo* studies or animal/*in vivo* experiments, and avoid the ethical issues surrounding animal testing. Therefore, *in vitro* tests are often used to study the health effects of particulate matter at the cellular and molecular level [11]. In a recent review of *in vitro* cell exposure studies by Paur et al., they further concluded that cell-based *in vitro* exposure studies might offer a new avenue for the toxicity screening of novel nanoparticles [12].

For inhalable particles exposure experiments meant to assess toxicity in the lungs, the most widely used *in vitro* method involves directly pipetting the particle suspension into the cell culture, which is then immersed in a fluid culture medium within a culture flask or within a culture dish on a supporting microporous membrane (transwell). The particle suspension is either a commercial product or made by suspending ambient-collected or lab-made aerosol particles in liquid. The exposure dosage, which is critical

* Corresponding author.
E-mail addresses: tchsiao@ncu.edu.tw, tchsiao@gmail.com (T.-C. Hsiao).

http://dx.doi.org/10.1016/j.jtice.2017.01.003
1876-1070/

for establishing the exposure-dose-response relationships of active substances, relates to the concentration of particles in the suspension [13–16]. However, it is unknown which fraction of the suspended particles will interact with the submersed cells cultured as a monolayer (Cohen et al. 2013).

For primary contact organs such as the lungs, skin, or eyes, the aforementioned traditional *in vitro* testing method represents an unrealistic way of exposure, as the *in vivo* exposure occurs at the air-liquid interface instead of in fully immersed (submerged) conditions [17]. In addition, the process of pipetting particle suspensions sometimes allows cells to be exposed to all the particles at once, resulting in a very high dosage per unit time [18]. Moreover, the physiochemical properties of the particles, such as the size, surface area, morphology, and chemical composition, would be significantly altered during the suspension preparation and/or filter collection process. The physiochemical characteristics of aerosol particles are crucial for determining their toxic effects when in contact with cells [7,19,20]. Particle-cell interactions then shall be changed [21]. To avoid the potential issues arising from traditional *in vitro* exposure methods, the air-liquid interface (ALI) system, which directly guides the aerosol particles to deposit on the exposure surface/air-liquid interface without changing their intrinsic physiochemical properties, was suggested as a system that more realistically represents the actual exposure scenario.

The reported ALI systems can be classified into two categories based on their particle-collection mechanisms: the aerodynamic ALI system and the electrostatic precipitating ALI (ESP–ALI) system. The aerodynamic ALI system primarily utilizes air flow to deliver particles that are deposited on the air-liquid interface (exposure interface). Gravitational settling, inertial impaction, and Brownian diffusion are the major particle-collection mechanisms. Among the different designs proposed previously [20–26], Tippe et al. is one of few research groups that has proposed a dosimetric method to quantitatively determine the convective transport and deposition due to Brownian diffusion and sedimentation [21]. In Tippe's aerodynamic ALI, it was found that the collection efficiency is fairly constant but low (~2%) for the particles with sizes ranging from 50 to 500 nm [27]. For the commercialized ALI system, CULTEX® module, it is only about 0.7% for 200 nm aerosol particles [18,28]. Although the collection efficiency of nano- and submicron-sized particles could be enhanced by increasing the working flow rate, it could place additional cellular stress on the culture cells and may even result in apoptosis. Therefore, aerodynamic ALI systems may not be suitable candidates for performing cell exposure tests for nano- or submicron-sized particles.

By introducing an additional electrostatic force, ESP–ALI systems could dramatically improve the collection efficiency of nano- and submicron range particles. ESP–ALI systems also offer a slower deposition velocity towards the collection interface and alleviate the potential extracellular stress in exposure experiments [29]. The ESP–ALI system is only functional for charged particles and requires an added charging device. The external electric field in ESP and the charge release during particle deposition are generally not expected to affect *in vitro* cell tests. As suggested by Savi, Kalberer, Lang, Ryser, Fierz, Gaschen, Ricka and Geiser [18], under the typical exposure concentration of challenging aerosols (about 10^4 particles/cm^3), the resulting charge current due to particle deposition is in the sub-femtoampere range, which is much smaller than the typical threshold to damage the cells based on electroporation experiments. For the electric field, several ALI studies [11,18,30,31] have applied 1 to 5 kV/cm on cell cultures and do not observed any adverse effect. In addition, the controlled cell exposure units are operated in parallel to determine unknown influences. Several designs of ESP–ALI that can be used to collect nano- and submicron-sized particles efficiently on the exposure interface have been proposed recently [11,18,29,30,32]. Savi et al. designed a co-direction ESP–ALI system with an AC electric field. The experimental results showed that the overall particle collection efficiency increased to 15–30%, with lower efficiencies for the smallest (50 nm) and largest (600 nm) particles [18]. To further increase the fraction of charged nanoparticles and improve the collection efficiency, the ESP–ALI systems reported by Sillanpää et al., Bruijne et al., and Volcken et al. incorporated an unipolar corona charger instead of a bipolar Kr^{85} charger [11,29,30]. Sillanpää et al. demonstrated that the collection efficiency can be greater than 90% for particles larger than 20 nm under a DC electric field of 5.3 kV/cm. Bruijne et al. reported an approximately 90% collection efficiency for "all particles" between 19 and 882 nm. In addition, compared to the low flow rates used in the ESP–ALIs with a Kr^{85} neutralizer (167 cm^3/min for EPDExS and 50 cm^3/min for Savi's ESP–ALI), the corona charging ESP–ALIs system was operated at a higher flow rate (1.0~4.0 lpm) while maintaining a good collection efficiency. It is noteworthy that these corona-charging based ESP–ALIs allow the direction of the electric field to be perpendicular to the direction of aerosol flow, which may induce non-uniform deposition on the exposure interface. However, few studies [17,27] have addressed the issue of the spatial uniformity of particle deposition over the exposed interface and its potential consequences. Moreover, Volckens et al. have reported the corona charging process releases ozone into the particle flow at a concentration of approximately 80 ppb in their system. The ozone released by the corona charger could introduce another significant confounding interference in exposure experiments.

In this study, a new ESP–ALI exposure chamber was designed to operate at a moderate to high flow rate range (0.6~1.5 lpm). The effects of different geometric dimensions and the operating conditions of the ESP–ALI chamber, such as the applied voltage, electrode spacing, and flow rate, were explored. The uniformity of the particle deposition pattern on the exposure interface was investigated by means of inspecting the deposition pattern of fluorescein salt. At last, instead of corona charging, the novel electrospray charging technique were applied to prevent the ozone generation in this ESP–ALI system.

2. Materials and methods

Two experimental methods, the penetration test and the fluorescein tracing, were conducted to characterize the performance of the new ESP–ALI exposure chamber and to investigate the effects of different electrode spacing and operating conditions. The penetration test was implemented to evaluate the overall collection efficiency, which is a key performance indicator for ALI systems. However, as noted earlier, the regional wall losses inside the ALI chamber had not been taken into account, which may have led to overestimation of the exposure dose. In this study, the fluorescein tracing method was performed to inspect the fraction of particle deposition in different regions inside the ESP–ALI chamber and to quantify the uniformity of deposited particles.

2.1. Design of the new ESP–ALI exposure chamber

The new ESP–ALI chamber is main component of the overall ESP–ALI system. It is a co-direction design with a DC electric field, and its schematic diagram is shown in Fig. 1a. The initial flow direction and the DC electric field are parallel, although the flow direction would be bended and perpendicular to the electric field near the surface of the collection media. This co-direction design was expected to preserve the uniformity of particle deposition on the exposure interface comparing to the cross-direction ESP–ALI design. The prototype basically consists of 4 coaxial components: the upper cylinder with an expansion inlet, the body cylinder, the

Please cite this article as: T.-C. Hsiao et al., Development and collection efficiency of an electrostatic precipitator for in-vitro toxicity studies of nano- and submicron-sized aerosols, Journal of the Taiwan Institute of Chemical Engineers (2017), http://dx.doi.org/10.1016/j.jtice.2017.01.003