Journal of Aerosol Science 95 (2016) 43–53

Contents lists available at ScienceDirect

Journal of Aerosol Science

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

A prototype personal aerosol sampler based on electrostatic precipitation and electrowetting-on-dielectric actuation of droplets

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ARTICLE INFO

Article history:
Received 4 August 2015
Received in revised form
2 December 2015
Accepted 13 January 2016
Available online 23 January 2016

Keywords:
Aerosol collection
Electrostatic precipitator
Electrowetting-on-dielectric
EWOD
Personal sampler

ABSTRACT

An electrostatic precipitator (ESP) based personal sampler with a laboratory based electrowetting-on-dielectric (EWOD) concentrator could provide a high concentration rate personal aerosol sampler system. A prototype system has been developed based on the concept of a lightweight personal ESP collecting aerosol particles onto a hydrophobic surface followed by the use of an EWOD actuated droplet system to transfer the deposited sample into a microlitre size water droplet.

A personal sampler system could provide military or civilian personnel with a wide area biological monitoring capability supplying information on who has been infected, what they have been infected with, how much material they were exposed to and possibly where and when they were infected. Current commercial-off-the-shelf (COTS) personal sampler solutions can be bulky and use volumes of water to extract the sample that are typically a thousand times greater than the proposed method.

Testing of the prototype ESP at a sample flow rate of 5 L min^{-1} demonstrated collection efficiencies greater than 80% for sodium fluorescein particles larger than 4 μm diameter and of approximately 50% at 1.5 μm. The ESP-EWOD system collection efficiency measured for *Bacillus atrophaeus* (BG) spores with an air sample flow rate of 20 L min^{-1} was 2.7% with a concentration rate of 1.9×10^5 min^{-1}. This was lower than expected due to the corona ions from the ESP affecting the hydrophobicity of the collection surface and hence the EWOD efficiency. However, even with this low efficiency the concentration rate is more than an order of magnitude higher than the theoretical maximum of the best current COTS personal sampler. For an optimised system, ESP-EWOD system efficiency should be higher than 32% with a comparable increase in concentration rate.

1. Introduction

Personal samplers have been used for many years in fields such as occupational hygiene to measure individual exposures to toxic materials. A description of a range of personal samplers is given by Vincent (2007) and results from laboratory

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http://dx.doi.org/10.1016/j.jaerosci.2016.01.007

testing of a range of samplers are presented in Gorner, Simon, Wrobel, Kauffer, and Witschger (2010) and Sleeth and Vincent (2012). However, personal samplers are still not widely used by the military to collect samples to confirm a soldier's exposure to potentially dangerous aerosol such as biological warfare agents (BWAs). Using personal samplers to inform whether soldiers or civilian personnel have been exposed to hazardous levels of BWAs is particularly challenging. This is because the infectious or toxic thresholds of some materials of interest are very low and the equipment used to detect the sampled agents in the field may have relatively high limits of detection.

1.1. High concentration rate personal sampler concept

Biological agents can have very low infectious doses. For example, for *Yersinia pestis*, the causative agent of plague, it is 100 to 500 organisms, and for the smallpox Variola virus, 10 to 100 organisms (Franz, Jahrling, & Friedlander, 1997), meaning that someone can become infected following a very limited exposure. The probability of detection is a function of both the limit of detection or sensitivity of the sensor and the concentration of the target biological agent presented to the sensor. To improve the likelihood of a personal sampler based detection system indicating whether a person has been exposed to a biological agent, it is important that the concentration of the liquid sample is as high as possible. This can be achieved through a high air sample rate or by producing a small output liquid volume. Personal samplers tend not to be suitable for very high flow rate sampling due to physical size constraints and the requirement to run from batteries for long periods; therefore a small liquid output volume is required.

The concentration rate, R_c [min^{-1}] used in the paper is as defined by Han, An, and Mainelis (2010) and is given by

$$R_c = \frac{Q}{V}\eta_s, \tag{1}$$

where Q [$\text{m}^3\,\text{s}^{-1}$] is the air sample flow rate, V [m^3] is the volume of the final liquid sample produced and η_s [dimensionless] is the total system efficiency which includes any efficiencies associated with the collection of the sample or the transfer of the sample into liquid.

The theoretical maximum concentration rate is calculated by assuming all the efficiencies of the sampler are 100%. For a fixed sampling period and mean airborne concentration, a higher value of R_c leads to an increased liquid concentration.

Most COTS personal samplers operate at low air flow rates ($<5\,\text{L min}^{-1}$). For example the Institute of Occupational Medicine (IOM) personal inhalable aerosol sampler (SKC Inc., PA, USA) operates at $2\,\text{L min}^{-1}$ and the Button personal inhalable aerosol sampler (SKC Inc., PA, USA) operates at $4\,\text{L min}^{-1}$. There are some exceptions such as the recently discontinued BioBadge® (FLIR®, Arlington, VA, USA) which samples at $40\,\text{L min}^{-1}$, and the CIP 10-M (developed by Institut National de Recherche et de Sécurité (INERIS)) and the Personal Environmental Monitor (SKC Inc., PA, USA) which both operate at up to $10\,\text{L min}^{-1}$.

All COTS personal samplers require or use greater than 1 mL volumes of liquid either to collect the sample into or to wash the collection media. The CIP 10-M uses 2 mL to 2.5 mL (Gorner, Fabries, Duquenne, Witschger, & Wrobel, 2006), BioBadge® uses 5 mL (Ryan, Wright, & Gloster, 2009) and the IOM uses 10 mL (SKC).

The high concentration rate ESP-EWOD concept is based on a lightweight personal ESP to collect aerosol particles onto a removable hydrophobic surface. After the sample has been collected, the hydrophobic surface is placed in an EWOD droplet actuation system. The EWOD system transfers the collected sample into a microlitre size water droplet (2 µL to 3 µL) that is actuated across the surface (Jonsson-Niedziolka et al., 2011), providing a highly concentrated sample for analysis. Table 1 compares the operating parameters of a range of COTS, discontinued or advanced development personal samplers to the ESP-EWOD concept. Two rows are included for the ESP-EWOD concept to show concentration rate when it is operated at $5\,\text{L min}^{-1}$ or $20\,\text{L min}^{-1}$. It shows that the theoretical maximum concentration rate for the ESP-EWOD concept is several orders of magnitude higher than that of the next highest sampler. It should, however, be noted that the prototype ESP-

Table 1
Operating characteristics for a selection of personal samplers. The concentration rate figures are theoretical maximum values assuming $\eta_s = 100\%$.

Sampler	Air sampling rate/L min^{-1}	Liquid collection volume /mL	Theoretical maximum concentration rate/min^{-1}	Source of information
BioBadge®	40	5	8.0×10^3	Ryan et al. (2009) and Flir (2014)
CIP-10-M	10	2	5.0×10^3	Gorner et al. (2006) and Arelco (2014)
IOM	2	10	2.0×10^2	SKC
SKC button sampler	4	10	4.0×10^2	Air sample rate (SKC, 2014a). Liquid volume estimated.
Personal environmental monitor	10	10	1.0×10^3	Air sample rate (SKC, 2014b). Liquid volume estimated.
Ilochip	0.12–0.14	0.025	5.2×10^3	Christensen et al. (2009)
ESP-EWOD	5	0.0029	1.7×10^6	This paper
	20	0.0029	6.9×10^6	