Building and Environment 95 (2016) 13–20

Contents lists available at ScienceDirect

Building and Environment

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

Enhanced performance of pocket-sized nanoparticle exposure monitor for healthy indoor environment

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A R T I C L E   I N F O

Article history:
Received 11 June 2015
Received in revised form
27 August 2015
Accepted 9 September 2015
Available online 11 September 2015

Keywords:
Airborne nanoparticles
Cantilever resonator
Integrated system
Electrophoretic sampler

A B S T R A C T

An electrophoretic cantilever-based nanoparticle (NP) sensor was described and evaluated for personal monitoring of occupational exposure at indoor environment. Measurements performed under defined NP concentrations in a conditioned chamber confirmed the feasibility of the measurement principle. For the first laboratory sample of the sensor cyclic switching between NP sampling and frequency tracking revealed settling times of 5 min and 1.5 min, respectively, until stable conditions were reached. Using an enhanced design of the sampling head this response time was considerably reduced to 20 s. With a total device volume of 540 cm^3, weight of 375 g, and power consumption of 1.25 W the fully integrated pocket-sized system can be easily held or worn, e. g., by workmen in nanotechnology industry during their working shifts.

1. Introduction

Airborne nanoparticles (NPs), which are ubiquitous in many indoor workplaces and environment, can affect health and well being of workmen [1]. In case of accident high concentrations of hazardous nanoparticle (NP) may be set free and inhaled unless exposed persons do not leave immediately the room. For the normal rooms (e.g., fitness centers), the indoor air pollutants may also be also present during the physical activity where the measured maximum mass concentration levels are in the range of ~20 μg/m^3 and ~10 μg/m^3 for PM2.5 and PM1, respectively [2]. Nevertheless, occupational exposure limits for NPs are not yet established and available expert NP monitoring systems are expensive or not directly readable. Therefore, low-cost, direct-reading/real-time NP monitors are required, which must be sensitive and unspecific for various engineered NP aerosols, easy to operate, and small/lightweight enough to be wearable in the work clothing. Furthermore, the selected metric should be traceable to the SI, considering that air quality standards are given as mass concentrations [2,3]. Diffusion chargers (DCs), which are based on unipolar NP charging and two sensitive electrometer stages, can measure average number concentration and size of airborne NPs [4]. The Partector DC (Naneos, Switzerland) fulfills many of the above requirements (pocket-sized, 440 g, μSD memory card, universal serial bus (USB) charger) but still costs about €5000 to €10,000 [5]. Correspondingly, production of a second commercial DC (Nanotracer, Philips, Netherlands) was stopped in 2012 [6]. A low-cost optical particle counter (OPC) based on the commercial Dylos Air Quality Monitor, which is available at < $300, is based on optical scattering (650 nm), i.e., NPs with diameters of less than 300 nm cannot be detected [7]. Furthermore, calculation of mass concentrations c_m from measured NP number concentrations requires knowledge on their shape and density.

With respect to the World Health Organization (WHO) air quality standards given in μg/m^3 [8] [9], direct gravimetric methods are preferable but difficult to implement due to the very small masses of NPs. A sufficient limit of detection (LOD) is provided by the tapered element oscillating microbalance (TEOM), where airborne particles are collected on a filter/impactor mounted on an oscillating hollow tube through which particle-laden air is flown. However, commercially available stationary instruments for PM2.5 are heavy (34 kg) and expensive ($24,600) [10]. A portable version of TEOM developed for personal dust monitoring in coal mines still has a weight of 2 kg (PDM3700 Personal Dust Monitor, Thermo

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http://dx.doi.org/10.1016/j.buildenv.2015.09.013
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Fisher Scientific Inc., https://www.thermoscientific.com/en/product/p-43308.html).

For gas sensing micro/nano electromechanical systems (M/NEMS) have shown highest mass sensitivity in ambient air down to the femtogram and attogram scales for MEMS and NEMS devices, respectively [11–13]. Correspondingly, M/NEMS-based resonant mass balances can detect single NPs. Furthermore, MEMS technology is an enabling technology for low-cost miniaturized sensors for advanced smartphone applications like the Internet of Things (IoT). Therefore, future participatory airborne NP monitoring networks based on low-cost, portable, and wireless-connected sensors may rely on such M/NEMS-based devices providing mass-concentrations rather than number or surface concentrations. However, their active area is small and efficient self-actuation and sensitive self-detection as prerequisite to mobile operation are a challenge [14]. Correspondingly, nano string resonators on which NPs can be trapped by impaction still require external vibration excitation using a shaker and detection using a laser Doppler vibrometer [15]. Furthermore, the impaction process of NPs on a MEMS resonator needs partial vacuum for large-enough air flow velocity (1350 m/s), which so far can only be realized using external pumps [16].

Much lower air flow velocity about 1 m/s, which can be provided by a miniature fan, is sufficient, if the collection of NPs is supported by electro- or thermophoresis. In case of the used electrophoretic sampling method, the charged NPs driven by an electrical field are extracted from the flowing air and directed to a MEMS cantilever mass sensor, which have been demonstrated using a commercial instrument (Nanometer Aerosol Sampler 3089, TSI Inc., USA) [17]. The neutral NPs are then polarized and pulled to the cantilever where it has a negative polarity. To support the personal use, in this work, a laboratory prototype of a miniaturized electrophoretic sampling head was employed (Fig. 1). Meanwhile, a closed-loop frequency tracking circuit was added to enable direct read out of trapped NP mass during real-time/online measurements. Characterization of this first direct-reading, electrophoretic (EP) MEMS-based NP sampling head under defined conditions using carbon nanoparticle aerosols exhibited an LOD of 25 μg/m^3 within a response time of 8 min. However, important issues remain open considering the dynamic behavior and long-term stability of the sampling head. Excessive loading with carbon NPs after 43.5 h of operation under typical workplace ambient conditions was found to lead to unstable performance, which was related to resuspension of agglomerates of NPs from the cantilever to the ambient. This effect can be expected, if the external moments/forces acting on NPs, e. g. due to aerodynamic drag by the air flow or NP acceleration by the cantilever vibration, exceed the moments/forces of adhesion [18]. In this contribution, the sampling head and its redesign are addressed in detail, as well as the performance comparison of two designs of the cantilever-based NP detector (Cantor). Here, we did not consider volatile NPs which we addressed previously with vapor condensates from e-cigarettes [19].

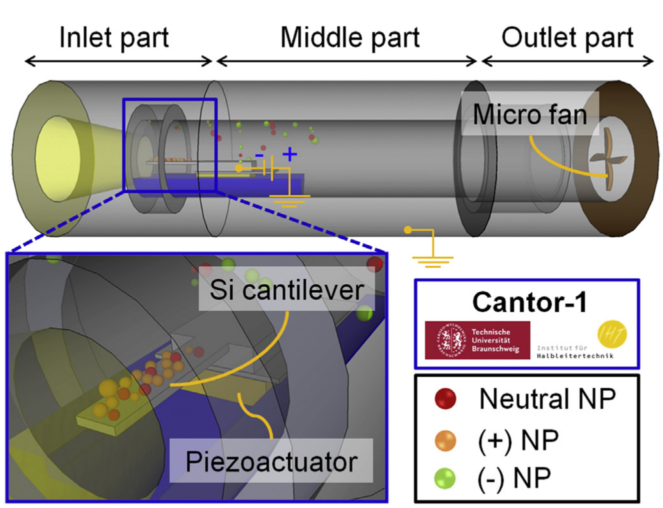

Fig. 1. 3-D schematic of MEMS-based electrophoretic (EP) nanoparticle NP sampler head of Cantor-1.

2. Partially integrated portable system

2.1. Experimental details

The first generation of the MEMS-cantilever-based EP NP monitor prototype “Cantor-1” is shown in Fig. 2(a). NP-laden air is flown through a small-size tube of outer dimensions of 20 mm in diameter and 45 mm in length using a micro fan (MF10A03A, SEPA Europe). At its inlet a membrane filter of a pore size of 2.5 μm is fixed to separate coarse particles from the air flow (Fig. 2(b)). A silicon cantilever adhesively attached and wire-bonded to a small printed circuit board (PCB) serves as the NP detector (Fig. 2(c) and (d)). Fabrication of the cantilever of a mass of $m_0 = 32$ μg and the coarse particle filter of a pore diameter of 2.5 μm was performed using deep reactive ion etching (DRIE). The cantilever die is mounted onto two prototype external PCBs comprising a DC–DC amplifier for EP voltage supply (V_{EP}) and a closed loop frequency tracking circuit based on a phase-locked loop (PLL), respectively [19]. In the preliminary implementation of Cantor-1 a fast (ms) and low-cost (few tens of €) automatic control switch (microcontroller, Arduino Uno with relay shield V1.0, Seedstudio) is used. The tracked frequency measured by a digital multimeter (HP 34401A) is read out to a notebook computer using a LabVIEW-based software.

For real-time measurement of aerosol NP mass concentrations, the sensor is switched between two operating modes, i.e., a NP *sampling mode* and a *frequency-tracking mode*. During the *sampling mode*, the cantilever is negatively biased by $V_{EP} = -0.5$ kV leading to a field strength up to ~6.5 kV/mm to attract positively charged

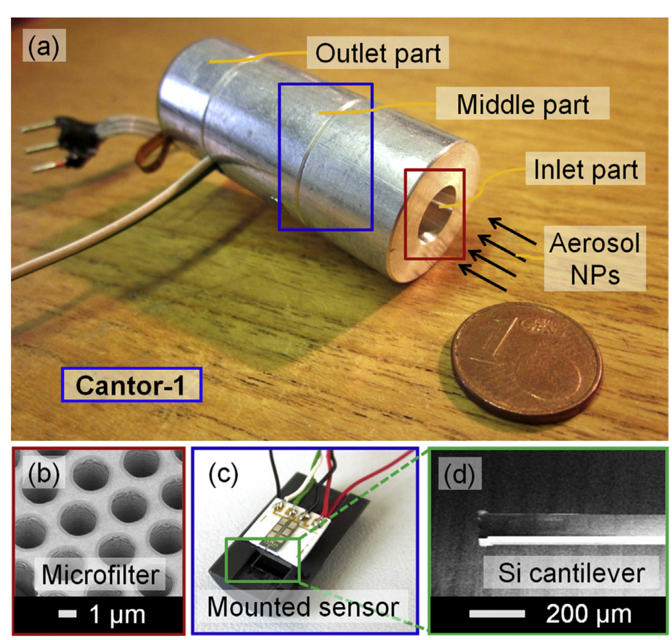

Fig. 2. (a) MEMS-based EP NP sampler head of Cantor-1 showing its (b) microfilter, (c) mounted sensor with piezoactuator, and (d) silicon cantilever.