Journal of Aerosol Science 79 (2015) 61–71

Contents lists available at ScienceDirect

Journal of Aerosol Science

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

Airflow resistance and bio-filtering performance of carbon nanotube filters and current facepiece respirators

Zhuanglei Zou [a], Maosheng Yao [a,b,*]

[a] State Key Joint Laboratory of Environmental Simulation and Pollution Control, College of Environmental Sciences and Engineering, Peking University, Beijing 100871, China

[b] State Key Laboratory of Pathogen and Biosecurity, Beijing Institute of Microbiology and Epidemiology, People's Liberation Army (PLA) Academy of Military Medical Sciences, Beijing 100071, China

ARTICLE INFO

Article history:
Received 4 May 2014
Received in revised form
7 October 2014
Accepted 7 October 2014
Available online 16 October 2014

Key words:
Respiratory mask
Carbon nanotube filter
Filtration efficiency
Airflow resistance
Aerosol particle

ABSTRACT

This study aimed to study airflow resistance of carbon nanotube (CNT)-based filtration material and compare its bioaerosol filtering performances with commercially available facepiece respirators. Firstly, we developed a manikin-based system to evaluate the filtering performances of six respiratory masks for biological aerosol particles using an Ultraviolet Aerodynamic Particle Sizer (UV-APS). Secondly, CNT filters with a base filter with a pore size of 10 μm were prepared using single-walled carbon nanotube (SWNT) loadings of 0.05, 0.1 and 0.2 mg/cm^2. In addition, mask filter membranes were also made by manually cutting the materials of the tested respiratory masks, and their filtration efficiencies and pressure drops were measured and compared with those of CNT-based filters.

Results indicated that most of the studied respirator masks achieved a practical protection efficiency of $>90\%$, while N95 types obtained more than 99% absolute protection efficiency under fully sealed conditions. Increasing CNT loading was shown to increase the quality factor (QF) for the CNT filter given all the sizes considered. For the loading of 0.2 mg/cm^2, CNT filters achieved 87% filtration efficiency against indoor viable bioaerosols and 70% for outdoor aerosol particles; and its QF was significantly higher than those of base filter, activated carbon and surgical mask filters. Different from other mask filters, CNT filters were observed to have higher biological aerosol particle filtration efficiencies than the total aerosol particles. Future work in improving air permeability of CNT filter and CNT distribution on filter support would lead to next generation respiratory mask.

1. Introduction

Airborne particulate matter (PM), consisting of both biological and non-biological materials, when inhaled can cause respiratory, cardiovascular and lung diseases (Kampa & Castanas, 2008; Dockery, 2009; Raaschou-Nielsen et al., 2013). Recently, an association between a decrease of 10 μg/m^3 in the concentration of $PM_{2.5}$ and an increase in mean life expectancy of 0.35 years was detected (Correia et al., 2013). With the rapid progress of modernization, atmospheric

* Corresponding author at: State Key Joint Laboratory of Environmental Simulation and Pollution Control, College of Environmental Sciences and Engineering, Peking University, Beijing 100871, China. Tel.: +86 1062767282.

E-mail address: yao@pku.edu.cn (M. Yao).

http://dx.doi.org/10.1016/j.jaerosci.2014.10.003
0021-8502/

pollution has become one of the serious environmental problems in China (Chan & Yao, 2008; Kan et al., 2012; Matus et al., 2012) and in the rest of the world. For example, in many parts of China, air quality has been characterized by heavy haze with increasing frequency and duration in recent years (Liu et al., 2013; Kang et al., 2013; Zhang et al., 2008). During haze days, PM concentrations can increase to levels much higher than usual. For example, 220 μg/m^3 mass concentration of $PM_{2.5}$ was reported in a study investigating regional haze in Beijing (Liu et al., 2013). Another study showed that increasing PM concentration also resulted in increased abundances of allergenic and pathogenic materials (Cao et al., 2014). Recently, dust collected by an automobile air conditioner filter in Beijing was found to harbor significant amounts of bacteria, fungi and endotoxin, which was shown to be re-aerosolized into the automobile cabin upon use of the air conditioner (Li et al., 2013). On another front, healthcare providers, e.g., in a respiratory clinic, and the public also face increased threats of pathogenic aerosol exposure arising from frequent outbreaks of infectious diseases such as SARS in 2003, H1N1 in 2009 and H7N9 in 2013 (World Health Organization, 2003, 2009; Gao et al., 2013). Correspondingly, there is a great interest for developing better personal inhalation exposure protection measures.

Among many approaches, filtering facepiece respirators (FFRs) are widely used to prevent inhalation of harmful substances from the air (Rengasamy et al., 2004). Wearing a respiratory mask is considered to be one of the most affordable and effective methods to reduce exposure to airborne pollutants. For various commercially available respirators, N95 FFRs, surgical mask and activated carbon mask are widely studied in the literature (Grinshpun et al., 2009; Loeb et al., 2009). N95 FFRs, certified by National Institute for Occupational Safety and Health (NIOSH), are described to achieve more than 95% filtration efficiency for 0.3 μm particles under certain test conditions (National Institute for Occupational Safety and Health, 1997). Qian et al. (1998) found that N95 respirators can achieve at least 95% protection against airborne particles in the absence of face leakage. However, relevant results varied greatly under different experimental conditions. When treated with airborne viruses and nanoparticles, the penetration of N95 FFRs can exceed 5% (Bałazy et al., 2006a, 2006b). Lee et al. (2008) also showed that N95 masks may not offer expected protection against bacteria and viruses. On the other hand, surgical masks are widely used in the hospital and operating rooms for protecting wounds from infection (Lipp & Edwards, 2012), and their protective efficiency against airborne microbes attracts much attention. To further enhance the performance of biological protection, some novel masks were designed, e.g., an anti-influenza face mask containing copper oxide could filter above 99.85% of aerosolized influenza viruses (Borkow et al., 2010).

Despite the practicality of these respiratory masks, they often fall short of fully protecting healthcare professionals as well as the civilians from the pathogenic infection due to improper wearing and/or facial leakage. For example, a randomized trial for the nurses in Ontario tertiary care hospitals found that Influenza infection occurred in 23.6% participants wearing surgical masks and 22.9% in N95 respirator wearing group due to face leakage (Loeb et al., 2009). Nonetheless, surgical masks were found to have equal protection rates with N95 masks (Loeb et al., 2009). In addition to the failure of achieving desired protection efficiency, breathing resistance increases the wearing discomfort such as 'heat' and water moisture inside the mask. As a result of the breathing discomfort of those masks, people are often reluctant to wear them for a sustained time period, thus increasing the risks of respiratory infection especially during an infectious disease outbreak or a flu season. The pressure drop of a filtering material is closely related to the breathing resistance. A recent study indicated that the pressure differential (ΔP) was significantly greater across the N95 respirator compared with all face masks tested (Skaria & Smaldone, 2014). Arising from the difference of breathing resistance, lower heart rate was observed among the group wearing surgical masks than those wearing N95 masks (Li et al., 2005). In addition, it was also shown that N95 FFR dead-space has higher carbon dioxide and lower oxygen levels than the ambient workplace standards, respectively (Roberge et al., 2010). In developing more comfortable respiratory masks, an exhalation valve on the N95 respirator is being adopted and is shown not to affect the respiratory protection, while contributing to reducing the breathing resistance (Lee et al., 2008). In another work, a nanofiber mask was evaluated and it was found to have lower breathing resistance, even when sealed to the face (Skaria & Smaldone, 2014). Overall, higher protection efficiency often comes at the price of losing breathing comfort, and better respiratory filtration material is certainly needed.

As one of the most studied nanomaterials (Harris, 2009; Popov, 2004), carbon nanotube (CNT) is shown to have a gas permeability of several orders of magnitude higher than current available filtration materials (Cooper et al., 2003; Viswanathan et al., 2004). Over the past decade, a significant number of studies were conducted to prepare CNT-based filters (Park and Lee, 2006a, 2006b; Karwa et al., 2012) and also water-borne inactivation and removal of biological agents such as bacteria and viruses by carbon nanotubes (Arias & Yang, 2009; Vecitis et al., 2011). It was found that direct cell contact with single-walled carbon nanotubes (SWNTs) can lead to severe membrane damage and subsequent cell inactivation (Kang et al., 2007). Vecitis et al. (2011) prepared multi-walled carbon nanotube (MWNT) filter by depositing MWNTs onto a 5 μm PTFE membrane, and then used the filter to remove and inactivate viruses (MS2) and bacteria (*Escherichia coli*) in the water. Results showed that without electrolysis, the MWNT filter was effective in completely removing bacteria by sieving and multi-log removal of viruses by depth-filtration (Vecitis et al., 2011). Brady-Estévez et al. (2008) used SWNT-based filters with different concentrations ranging from 0.3 to 0.8 mg/cm^2 in water purification, and found that the SWNT filter exhibited high antibacterial and antivirus activity. Compared with applications in water treatment, research of CNT applied in gas-phase filtration is scarce. Viswanathan et al. (2004) presented a filter media by depositing MWNTs onto cellulose fiber filters to filter airborne particulate matters; the results indicated that the prepared MWNT filters achieved over 99.9% filter efficiency for 0.3 μm particles even for low MWNT coverage (0.07 mg/cm^2). Most recently, CNT-based filters were used to remove biological aerosols (Guan & Yao, 2010; Xu & Yao, 2011; Park et al., 2011). The results have shown that use of 0.64 mg/cm^2