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Experimental and modeling study of pressure drop across electrospun nanofiber air filters

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ABSTRACT

Electrospun nanofiber air filters can achieve high $PM_{2.5}$ removal efficiency with a relatively low pressure drop because of the slip effect. They may therefore be applied in buildings to reduce indoor exposure to $PM_{2.5}$ with lower energy consumption. This study first fabricated 25 nylon nanofiber filters with different filter parameters of fiber diameter, filter thickness, and packing density. The pressure drop across each nanofiber filter was measured under five different face velocities. This study then developed a method for modeling the pressure drop across electrospun nanofiber air filters using the filter parameters. 125 sets of experimental data were obtained for the model development, and a semi-empirical model was developed to predict the pressure drop across nylon electrospun nanofiber filters. The results showed that the pressure drop was proportional to the face velocity and filter thickness. The product of drag coefficient and Reynolds number was a function of both packing density and Knudsen number. The semi-empirical model reasonably predicted the pressure drop across the nylon electrospun nanofiber filters with a median relative error of 4.3%.

1. Introduction

The Global Burden of Diseases Study reported that outdoor $PM_{2.5}$ (particulate matter with an aerodynamic diameter of less than 2.5 μm) was the fifth-ranking mortality risk factor in 2015 [1]. Exposure to outdoor $PM_{2.5}$ caused 4.2 million deaths in 2015, representing 7.6% of total global deaths [1]. Numerous epidemiologic studies have also revealed strong associations between exposure to outdoor $PM_{2.5}$ and various adverse health effects, such as heart failure [2], asthma [3], and lung cancer [4]. Although these particles are generated from outdoor sources, they can enter indoor environments through ventilation and infiltration [5–11]. As people spend most of their time indoors [12], the majority of exposure to $PM_{2.5}$ of outdoor origin occurs in indoor environments [13]. Furthermore, many indoor sources can generate $PM_{2.5}$ and lead to elevated indoor exposure [14–25]. It is therefore crucial to mitigate indoor exposure to $PM_{2.5}$ to reduce the associated health risks.

Filtration is the most popular and effective approach to reduce the exposure to $PM_{2.5}$ in indoor environments [26–32]. High efficiency particulate air (HEPA) filters can be installed in the heating, ventilation, and air-conditioning (HVAC) systems to remove the $PM_{2.5}$ from the incoming outdoor air. However, although HEPA filters exhibit very high particle removal efficiency, they usually lead to a large pressure drop, which may increase the energy consumption in certain HVAC systems. For example, Zaatari et al. [30] compared the fan energy consumption from using different filters classified by the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) Standard 52.2 Minimum Efficiency Reporting Value (MERV) and found that the fan power for units with fan speed control with high efficiency filters (MERV 13/14) was 11%–18% greater than for those with low efficiency filters (MERV 8). It is therefore worthwhile to develop novel air filters with high $PM_{2.5}$ filtration efficiency but low pressure drop.

In past decades, micro- and nanotechnologies have brought great benefits to society in many aspects [33–39]. One promising nanofiber approach is the electrospinning technique, which can be used to fabricate nanofiber air filters for $PM_{2.5}$ capture. For example, Liu et al. [40] developed a polyacrylonitrile (PAN) transparent air filter with a $PM_{2.5}$ filtration efficiency of 96.1% and a pressure drop of 133 Pa. They proposed to use the transparent nanofiber filter as a window screen to prevent the entry of outdoor $PM_{2.5}$ during natural ventilation. Zhang et al. [41] fabricated polyimide (PI) air filters with high-temperature stability to be used to remove $PM_{2.5}$ from vehicle exhaust gas. Bian

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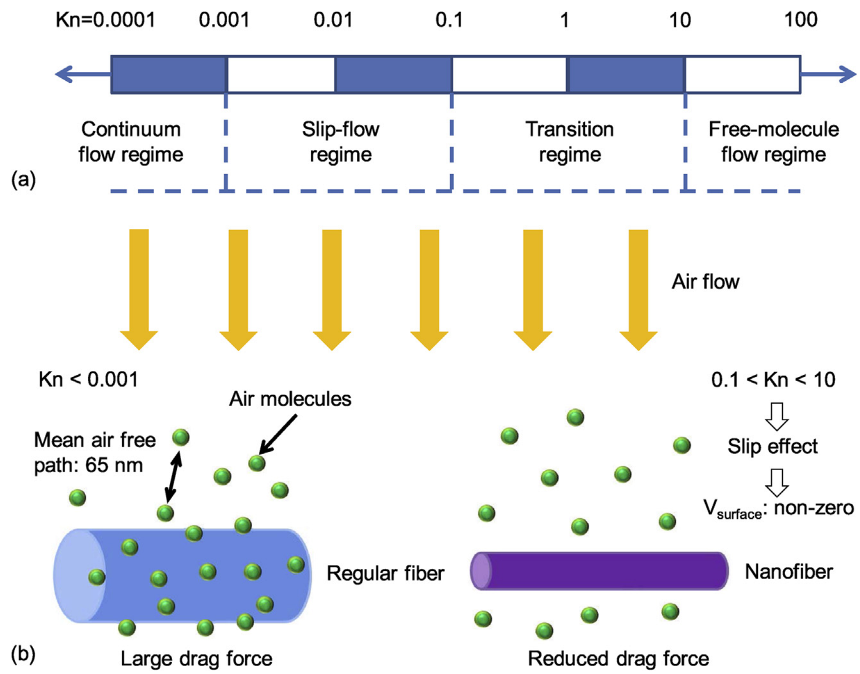

Fig. 1. (a) Flow regime in terms of the Knudsen number; (b) schematic of large drag force associated with a regular fiber and reduced drag force associated with a nanofiber because of the slip effect (modified based on Fig. 2 of Xia et al. [44] and Zhao et al. [45]).

et al. [42] developed a hybrid silk fibroin and polyvinyl alcohol (PVA) air filter with a $PM_{2.5}$ removal efficiency of 98.97% and a pressure drop of 50 Pa. Zhang et al. [43] developed a composite polysulfone/polyacrylonitrile/polyamide-6 (PSU/PAN/PA-6) air filter with an extremely high $PM_{2.5}$ removal efficiency of 99.992%. These novel nanofiber air filters are considered promising candidates for use in buildings to mitigate exposure to $PM_{2.5}$ in indoor environments.

One of the main advantages of the nanofiber filters is the relatively low pressure compared with conventional HVAC filters. Xia et al. [44] systematically compared the pressure drops of 122 nanofiber filters reported in the literature with those of conventional HVAC filters. The median quality factor of the collected nanofiber filters was 116% higher than that of the collected traditional HVAC filters, mainly because of the gas slip effect, as illustrated in Fig. 1. Usually, the diameters of electrospun nanofibers (d_f) are comparable with the mean free path of air molecules (λ). Therefore, the Knudsen number, which is defined as $Kn = 2\lambda/d_f$, can achieve a high value, normally ranging from 0.1 to 10 [45]. In this transition flow regime, the gas slip effect is significant. The air velocity at the nanofiber surface is non-zero, so the drag force on the air can be significantly reduced; hence, a relatively low pressure drop can be achieved with nanofiber air filters.

Although nanofiber filters are capable of achieving a low pressure drop, it remains unclear how the filter parameters—fiber diameter, filter thickness, and packing density—affect the pressure drop across a nanofiber filter. Therefore, this study developed a method for modeling the pressure drop across electrospun nanofiber air filters. Experiments were conducted to obtain a database for the model development. A semi-empirical model was then developed to establish the relationship between the pressure drop and filter parameters (fiber diameter, filter thickness, and packing density). The developed model can be used to analyze the influence of filter parameters on the pressure drop across electrospun nanofiber filters.

2. Methods

2.1. Theoretical model

Based on the drag theory, the following expression for the pressure drop across a conventional fibrous filter, ΔP (Pa), is derived [46]:

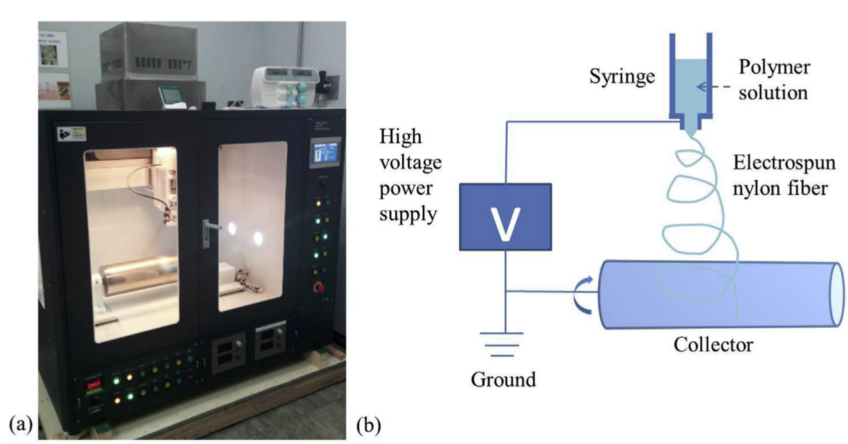

Fig. 2. (a) Photographs and (b) schematic of the experimental setup for the electrospinning process.