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Verification of slip flow in nanofiber filter media through pressure drop measurement at low-pressure conditions

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ABSTRACT

Slip flow phenomena are of great concern in aerosol filtration because of their ability to develop low-pressure drops and high collection efficiency air filters by using nanofibers. However, it is a difficult task to verify the slip flow effect on the reduction in pressure drop because the inhomogeneity in fiber packing also results in a decrease in pressure drop. In the present work, we propose pressure drop measurements at low pressures to verify the slip flow effect by distinguishing the effects of filter inhomogeneity. We found that the experimental dimensionless drag at low-pressure conditions, which was obtained with correction by the inhomogeneity factor measured at atmospheric pressure, followed the theoretical prediction that includes the slip flow correction (Kirsch and Stechkina, 1978) for both conventional PTFE and newly developed fluororesin nanofiber filter media. Because the dimensionless drags of both nanofiber filters decreased inversely proportional to the Knudsen number, we concluded that these nanofiber filters have low-pressure drops because of slip flow effects.

1. Introduction

The increasing demand for energy savings in air conditioning has encouraged the inevitable development of high-performance filters [1]. A good filter should have high particle collection efficiency, low pressure drop, and a long lifetime. Filters are typically characterized by their filter quality factor, q_F [2]:

$$q_F = -\frac{\ln P}{\Delta p}, \tag{1}$$

where P is the particle penetration and Δp is the pressure drop. The conventional filtration theory predicts that the single fiber collection efficiency resulting from inertia, interception, and Brownian diffusion increases with reducing fiber diameter and that the drag acting on the fibers would decrease by enhancing slip flow effects. To date, commercially available filters are mostly made of glass fibers, which have large diameters (~500 nm) with non-uniform packing. Non-uniform packing of fibers leads to both a low pressure drop and low collection efficiency, and therefore the reduction in pressure drop is not well acknowledged. The use of nanofibers with diameters around 100 nm with uniform packing as a filter media may achieve a low pressure drop through slip flow phenomena and high collection efficiency at the same time, because particle capture can be done through interception and diffusion processes [6–8]. However, the lifetime of nanofibrous filters still needs to be improved. Both efficiency of collection and pressure drop are intimately related to the linear velocity of sampling, filter porosity, fiber diameter, and mat thickness [9,10]. Therefore, development of new nanofiber media is necessary for longer lifetimes whilst simultaneously maintaining low pressure drops via slip flow phenomena on the fiber surface.

To obtain a high-quality factor filter, we have developed a fluororesin nanofiber medium with beaded fiber-like morphology and significantly thinner diameters than commercial filters. The pattern of gas flow structure around fibers depends on thermodynamic conditions such as gas pressure and temperature. It can also be seen from the Knudsen number, $Kn = 2\lambda/d_f$, that the size of fibers also influences the gas flow structure [11]. When Kn is small because the fiber diameter (d_f) is larger than the average mean free path of the carrier gas, i.e. air, $\lambda = 0.065$ µm, continuous

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air flow will be formed around the fiber and leads to a fluid speed on the fiber surface of zero. In contrast, nanofibers with smaller diameters than the average mean free path result in large *Kn* and transform the air flow around the fiber to transitional flow. The fluid speed on the fiber surface is increased and results in a lower pressure drop [12]. This phenomenon is called "slip flow" and its effect is remarkable for sufficiently large Knudsen numbers. However, the pressure drop along nanofibers is not only affected by slip flow but also the inhomogeneity of the fiber packing [13]. Consequently, it is difficult to verify the slip flow effect on the decrease in pressure drop [4,14–16]. Although some have recognized the decrease in filter pressure drop with the use of nanofibers [17,18], there has been no research that has proven the presence of slip flow theory thus far. Hence, it is highly necessary to develop a method for pressure drop measurement for identifying the slip flow effect.

Here, we introduce a pressure drop measurement under low pressure conditions corresponding to high Knudsen numbers. In this work, λ is increased proportionally with a reduction in absolute pressure, and causes an increase in the Knudsen number, *Kn*. The filtration properties of various tested filter media are summarized in Fig. 1. High-efficiency particulate air (HEPA) filters consisting of a conventional PTFE fibrous medium and another with a newly developed fluororesin fibrous medium with ultra-low pressure drop and a long lifetime [19–23] were investigated. A commercially available fiberglass filter was selected as a reference for comparison. This is the first report demonstrating the slip flow phenomena effect on filter pressure drop based on fiber morphology. The general filtration performance as indicated by the efficiency, pressure drop, and lifetime were measured under atmospheric pressure. In addition, pressure drop was also measured under low pressure conditions. In these measurements, the inhomogeneity of fiber packing under atmospheric pressure was defined and used to obtain the experimental value of the dimensionless drag force, based on the measured pressure drop under low pressure conditions. The measured value was then compared with the theoretical value of dimensionless drag force and corrected by *Kn* after considering the slip flow. The slip flow effect of the nanofiber was experimentally verified through this method.

2. Experimental

2.1. Filter media samples

Three filter media with different properties were used for slip flow evaluation. The physical properties and scanning electron microscopy (SEM) images of the tested filters are shown in Table 1 and Fig. 2, respectively. Sample A is a commercial fiberglass filter (S-320M Lot 4281(4-8-22-588C); Hokuetsu Industries Co., Ltd., Tokyo, Japan) typically used as a HEPA filter medium. This type of filter has an efficiency ⩾99.99% at 0.3 μm and a pressure drop of around 260–300 Pa at 5.3 cm/s.

Sample B is a conventional PTFE nanofiber (13HL1 Lot T140418-04L; Daikin Industries, Ltd., Osaka, Japan/AAF International) with a lower pressure drop of around 130–160 Pa at 5.3 cm/s and a similar efficiency (⩾99.99% at 0.3 μm) compared with those of commercial fiberglass filter media. Because the off-gassing properties of dopant (boron, phosphorus) are negligible and the acid resistance is excellent in sample B, it is typically installed in semiconductor cleanrooms and equipment. Fiber arrangement in this conventional PTFE filter medium is dense and very thin, which may cause fast clogging because the dust particles are collected by surface filtration. Product development is therefore necessary to overcome the short lifetime and to expand the use of PTFE filter media. The low-density, thick film alternative structure offers a depth filtration that may become an effective nanofiber filter medium.

Sample C is a newly developed nanofiber (Lot T140117-08L; Nippon Muki Co., Ltd., Tokyo/Daikin Industries, Ltd., Osaka, Japan/AAF International). It is an improvement over Sample B and performs with better dust holding capacity compared with the conventional PTFE nanofiber [1,2,6,7]. This newly developed fluororesin nanofiber was synthesized using a new raw material (fine powder) and suitable conditions for fibrillization, such as by control of extrusion, calendar, and stretching processes, and by controlling the ratio of fibril to node. This strategy enables the improvement of the collection mechanism for the filter media from surface filtration to depth filtration. Consequently, the filter media lifetime may be extended by maintaining a low pressure drop and a high efficiency. Sample C HEPA filter media has larger fiber diam-

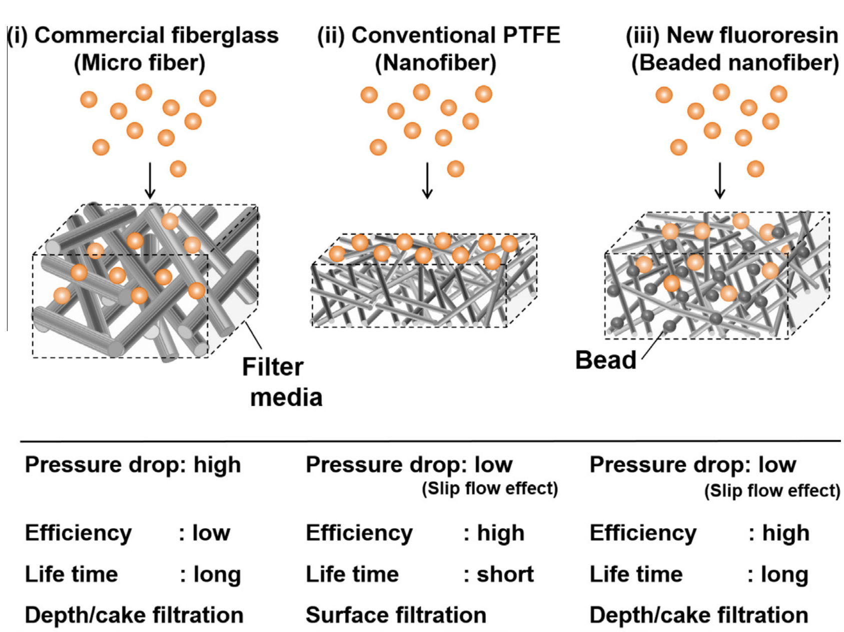

Fig. 1. Outline of various tested HEPA filter media.