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Effect of slip flow on pressure drop of nanofiber filters

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ABSTRACT

The slip flow effect is often brought out to explain the reduction in pressure drop for nanofiber filters. Kirsch, Stechkina, and Fuchs (1973) studied the slip flow effect on the pressure drop of fibrous filters consisting of micron fibers, and proposed an empirical equation to predict the dependence of the dimensionless drag, F, on the Knudsen number, Kn, with considering non-uniformity of fiber packing. However, their empirical equation was derived based on the experiments with filters consisting of micron fibers so that the empirical equation is not yet verified for nanofiber filters. In the present work, we used various commercially available nanofiber filters with various physical properties, and the pressure drop was measured at low pressures in order to examine the validity of the empirical equation. As a result, we found that the empirical equation is valid even for nanofiber filters with a large inhomogeneity factor at a large Kn up to 20.

1. Introduction

Air filters play important roles in various fields such as air cleaning, particle sampling, and respiratory protection due to its high collection efficiency, simple structure, and economical cost as well as a low pressure drop (Choi, Park, Kim, Kim, & Lee, 2015; Leung & Hung, 2012; Li et al., 2015; Sambaer, Zatloukal, & Kimmer, 2011; Wang & Otani, 2013; Zhang et al., 2010). The initial filtration performance is evaluated by the filter quality factor, q_F, defined as the ratio of logarithm of particle penetration to the pressure drop (Hinds, 1999):

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

where, P is the particle penetration, and $\triangle p$ is the pressure drop across the filter media. Since, a good filter media has a high collection efficiency and a low pressure drop (Bao et al., 2016; Hung & Leung, 2011), it has a higher value of q_F. Therefore, air filters made of nanofibers have attracted a great attention because they may simultaneously achieve a high collection efficiency due to diffusion and interception and a low pressure owing to the slip flow effect (Bao et al., 2016).

The flow around a fiber is classified into three regimes, namely, molecular flow regime, transitional flow regime and continuous flow regime, according to the Knudsen number, $Kn = 2\lambda/d_f$, where λ is the mean free path of air and d_f is the fiber diameter (Brown, 1993; Barhate & Ramakrishna, 2007; Pich, 1971). When a fiber diameter is small and comparable to the mean free path of air,

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Knudsen number becomes close to unity and the air flow around a fiber behaves like a rarefied gas. In the transitional regime, the boundary condition of flow velocity on the fiber surface is assigned as a non-zero velocity (slip flow condition), which results in a lower pressure drop (Bao et al., 2016; Barhate & Ramakrishna, 2007; Sambaer et al., 2011). Although the slip flow effect is commonly accepted in the aerosol filtration, there have been few studies on the influence of slip flow on the pressure drop. Kirsch et al. (1973) measured the pressure drop at low pressures using micron-fiber filters and proposed an empirical equation to predict the dependence of the dimensionless drag, F, on the Knudsen number, Kn, accounting for the non-uniformity of fiber packing and the packing density. However, their empirical equation was obtained based on the experiments with filters consisting of micron fibers so that the validity of proposed empirical equation is not assured for nanofiber filters.

In the present work, we prepared the nanofiber filters with various physical properties, and the pressure drop was measured at low pressures in order to examine the validity of empirical equation proposed by Kirsch et al. (1973).

2. Slip flow effect on the pressure drop of fibrous filters - Kirsch et al. (1973)

As the fiber size decreases to nanometer-scale, the slip flow on the fiber surfaces becomes significant and the pressure drop is expected to be low compared to that without the slip flow. Kirsch et al. (1973) experimentally investigated the influence of slip flow on the dimensionless drag, F, for real filters, proposed the following empirical equation:

$$F^{-1} = F_0^{-1} + \frac{\tau\varphi}{4\pi}(1-\alpha)Kn \tag{2}$$

where, F_0, is the dimensionless drag without the slip flow ($Kn = 0$), $\tau = 1.43$ is the slip coefficient, φ the function of filter structure, and α the packing density. Furthermore, they empirically determined $\varphi = \delta^{1/2}$ as a function of the inhomogeneity factor, δ. The inhomogeneity factor, δ, is defined as the ratio of dimensionless drag of a fan model filter, FMF, to that of a real filter with same packing density at $Kn = 0$:

$$\delta = \left(\frac{F^{\mathrm{m}}}{F^{\mathrm{r}}}\right)_{Kn=0} \tag{3}$$

$$F^{\mathrm{m}} = 4\pi/k \tag{4}$$

$$k = -0.5\ln\alpha - 0.52 + 0.64\alpha + 1.43(1-\alpha)Kn \tag{5}$$

where, k is the hydrodynamic factor, and the superscripts m, r represents “model” and “real” respectively.

Table 1 shows the physical properties of filters studied by Kirsch et al. (1973). As shown in the table, the fiber diameter studied was larger than 3 μm since there existed no nanofiber filters in 1970's. They measured the pressure drop at various low pressures (760 to 7 mmHg), and calculated the dimensionless drag of filter, F, by the following equation:

$$F = \frac{\Delta p}{\mu u l(1-\alpha)} \tag{6}$$

$$l = \frac{4\alpha L}{\pi d_f^2} \tag{7}$$

where l is the fiber length in unit filter area, u the filtration velocity, L the filter thickness, and d_f the fiber diameter. Fig. 1 shows how they obtained the empirical equation of Eq. (2). They plotted the reciprocal of experimental dimensionless drag of filters No. 1−4 (the same fiber mat but with different packing densities) calculated by Eq. (6) against Knudsen number (Fig. 1(a)), and the slopes of these lines, which corresponds to $\tau\varphi(1-\alpha)/4\pi$ are plotted against $1-\alpha$ (Fig. 1(b)) so as to find that the coefficient of Kn is proportional to $1-\alpha$. Then the slope divided by $1-\alpha$, which corresponds to $\tau\varphi$, was plotted against δ to find $\varphi = \delta^{1/2}$ (Fig. 1(c)).

However, the empirical equation of Eq. (2) was based on the experimental data for microfiber filters so that the validity for nanofiber filters should be examined. In the present work, we measured the pressure drop of nanofiber filters at various low pressures

Table 1
Physical properties of test filters in the previous work (Kirsch et al., 1973).

Test filter	Fiber diameter, d_f [μm]	Thickness, L [mm]	Packing density, α [dimensionless]	Inhomogeneity factor, δ [dimensionless]
1	14	5.8	0.04	1.39
2	14	3.3	0.07	1.43
3	14	2.3	0.10	1.41
4	14	2.8	0.14	1.40
5	18.1	2.4	0.11	2.03
6	14	2.4	0.03	1.30
7	14	3.5	0.038	1.30
8	13.2	2.4	0.08	2.20
9	7.14	2.1	0.035	1.13
10	7.14	2.5	0.063	1.90
11	3.14	1.5	0.017	1.08