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An experimental study was carried out to investigate the performance of fibrous filters in the transition flow regime, where the fiber radius is of the same order of magnitude as the mean free path of gas molecules. Filter media with the mean fiber diameter of 0.21–0.72 μm and the packing density of 0.053–0.08 were used in this study. The transition flow conditions were achieved by reducing the gas pressure in the filter test apparatus. Experiments were performed in the pressure range of 0.1–1.0 atm using monodisperse particles of 0.04–0.45-μm diameter range. The particles were generated by the electrostatic classification technique. The particulate penetration through the filter and the corresponding pressure drop were measured at face velocities ranging from 6 to 19 cm/s. Experimental results showed that the penetration decreased by three to four orders of magnitude as the pressure was reduced from 1.0 to 0.1 atm. It was found that the most penetrating particle size increased slightly as the gas pressure was reduced. The pressure drop across the filter was also found to decrease significantly as the pressure was reduced.

INTRODUCTION

Fibrous filters have been widely used for gas purification and aerosol sampling. A fibrous filter is an assembly of fibers with orientation generally normal to the direction of gas flow. Particulates in the gas are removed when they collide and adhere to the fiber surface. Filtration studies generally are concerned with two problems: the collection efficiency E and the pressure drop ΔP. The collection efficiency of a filter is the ratio of number of particles collected by the filter to that entering the filter,

$$E = \frac{N_{up} - N_{down}}{N_{up}} \tag{1}$$

where N_{up} is the number concentration of particles upstream of the filter and N_{down} is the number concentration downstream. Another parameter, the fractional penetration P is also used to characterize filter performance where

$$P = 1 - E \tag{2}$$

The collection efficiency of a filter depends on the diameter of fibers D_f, the packing density α, the face velocity U, and other parameters, such as the thickness of the filter L, the temperature, the external electric field, etc. The packing density of a filter is defined by

$$\alpha = \frac{\text{the volume of fibers}}{\text{the total volume of filter mat}} \tag{3}$$

The face velocity U is the velocity of the approaching flow at the face of a filter. It is

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equal to

$$U = \frac{Q}{A} \tag{4}$$

where Q is the volumetric flow through a filter and A is the effective area of a filter exposed to gas flow.

Particles in the gas stream are generally removed by the following mechanisms: Brownian diffusion, direct interception, inertial impaction, gravitational sedimentation, and deposition due to external forces, such as the electrostatic forces (Fardi and Liu, 1990). In the absence of the external forces, Brownian diffusion, direct interception, and inertia interception are the three primary collection mechanisms. The particle deposition depends on not only the properties of the particle but also the characteristics of the gas flow through the fiber. A dimensionless parameter, Kn, the Knudsen number is used to characterize the flow regime for the gas flow around the fibers.

$$Kn = \frac{2\lambda}{D_f} \tag{5}$$

where the λ is the mean free path of the gas molecules. According to the classification of Deviene (1958), the flow regimes can be divided as follows,

1. Continuum flow regime $Kn < 0.001$
2. Slip flow regime $0.001 < Kn < 0.25$
3. Transition flow regime $0.25 < Kn < 10$.
4. Free molecule flow regime $Kn > 10$.

For $Kn < 0.001$, the mean free path of the gas molecules is much smaller than the diameter of the fiber, and the gas can be treated as continuum fluid, thereby ignoring its molecular structure. The majority of filtration studies (e.g., Friedlander, 1957; Kirsch and Fuchs; 1968; Lee and Liu; 1982), were made for flow in the continuum regime, where the factors affecting filter efficiency and filter resistance are well understood.

If the mean free path of gas molecules is comparable to the fiber diameter, $0.001 < Kn < 0.25$, the continuum assumption is no longer valid because the fluid may slip over the surface of the fibers owing to its molecular structure. In the slip flow regime, filtration theories (e.g., Natanson, 1962; Pich, 1978) were developed by modifying the continuum theories to take into account of the slip effect. Kirsch and Stechkina (1978) investigated the filter efficiency and the flow resistance characteristics in the slip flow. Yeh and Liu (1974) studied the problem by using a numerical approach. In those authors' study, the flow field around a fiber was derived from the Kuwabara (1959) model by taking into account the slip effect. In Rubow's work (1981), the filtration model developed by Lee and Liu (1982) was revised to include the slip effect. The slip flow regime theories predicted an increase in filter efficiency with increasing the Knudsen number. However, because of technological limitations in fiber fabrication and for efficiency measurement, all of these studies were restricted at relatively small Knudsen numbers ($Kn < 0.25$).

With the development of the fine fiber fabrication technology, commercial fibers as small as 0.1 μm are now available. Such fine fibers give rise to a Knudsen number of 1.33 at atmospheric pressure. Because the filter efficiency increases with decreasing fiber size, it can be expected that filter media made of ultrafine fibers with $D_f < 0.1$ μm will play an increasingly important role in air filtration in the future. In addition, fibrous filters made of submicrometer fibers are often operated at reduced pressures. Under such conditions, the fluid flow around a fiber is in the transition regime, also known as the Knudsen regime. Knowledge of air filtration in the transition regime is more limited both in theory and by experiment. Fundamental studies are therefore needed to extend aerosol filtration studies into this regime.

Kirsch and Stechkina (1978) and Monson (1984, 1988) investigated the flow resistance characteristics of fibrous filter in the Knudsen regime, but experimental studies of the filtration efficiency in the Knudsen regime have not been reported. This study was conducted to improve our understanding of aerosol filtration by fibrous filters in this important and interesting regime.

EXPERIMENTAL STUDY

To perform filtration experiments in the transition flow regime, two problems need to be solved. First, to obtain the Knudsen flow the filter media must be made of ultrafine fibers. Secondly, the experimental evaluation of the filter must be performed at a low pressure in order to cover a wide range of the Knudsen regime. The objectives of the study include: (1) developing techniques for preparing ultrafine fiber filter media ($D_f \approx 0.15$ μm); (2) developing an experimental apparatus for testing filters at reduced pressures; and (3) performing filtration experiments at reduced pressures.

Preparation of Ultrafine Fiber Media

The mean fiber diameter of the current generation of commercially available high efficiency particulate air filter (HEPA) and the ultralow penetration air filter (ULPA) is ~ 0.5 μm. On the other hand, the lowest pressure at which the experiment can be performed was found to be 0.1 atm owing to the limitation of the condensation nucleus counter (CNC) for operation at lower pressures (Zhang and Liu, 1991). Because the mean free path of the air molecules is 0.66 μm at 0.1 atm, the largest Knudsen number obtainable in the HEPA and ULPA filters is 2.64. In order to investigate the filtration mechanisms at higher Knudsen numbers, filters made of ultrafine fibers need to be fabricated.

Three groups of fibers from Johns-Manville company with the mean diameter $\langle D_f \rangle = 0.145$ μm and geometric standard deviation (GSD) = 1.69, $\langle D_f \rangle = 2.73$ μm and GSD = 1.76, and $\langle D_f \rangle = 10$ μm and GSD = 1.72, were selected for preparing the test filter media. Coarse fibers of $\langle D_f \rangle = 2.73$ μm and $\langle D_f \rangle = 10$ μm were used to increase the porosity of the filter media. For each sample media, 120 mg of the fibers was mixed with 200 ml of water in a rotating blender to break up the fiber clumps to form a slurry. In that some tiny lumps can not be effectively dispersed in the blender, a device shown in Figure 1 was used to disintegrate these clumps. The dispersing system consisted of a dispersion tank, a piezoelectric transducer, an ultrasonic power supply, an orifice, a flow control valve, and a collection tank. The slurry formed in the blender was forced through the orifice. The ultrasonic transducer generated a highly concentrated ultrasonic beam that was focused directly on the orifice. Fiber clumps passing through this orifice were broken up by the ultrasonic oscillation. The flow control at the outlet of the container was used to maintain an adequate flow through the orifice. Too high a flow rate would result in incomplete disintegration of fibers and too slow a flow would lead to blockage. The slurry exiting the dispersion tank was collected in the collection tank, then reintroduced into the dispersion tank. This process was repeated four times to completely disperse fibers. The slurry produced by means of this process was poured into a container with a screen on the bottom. The water was slowly drained out. The fibers formed a mat on the screen. The mat was dried in an oven at the temperature of 100°C.

Experimental System and Procedure

Figure 2 shows a schematic diagram of the experimental system developed for use in the present study. The generating system for producing the monodisperse test aerosols is shown within the dashed lines. Monodisperse dioctyl phthalate (DOP) aerosols were generated and diluted with clean air at atmospheric pressure ($P = 1$ atm). The aerosol is then expanded into a low pressure envi-

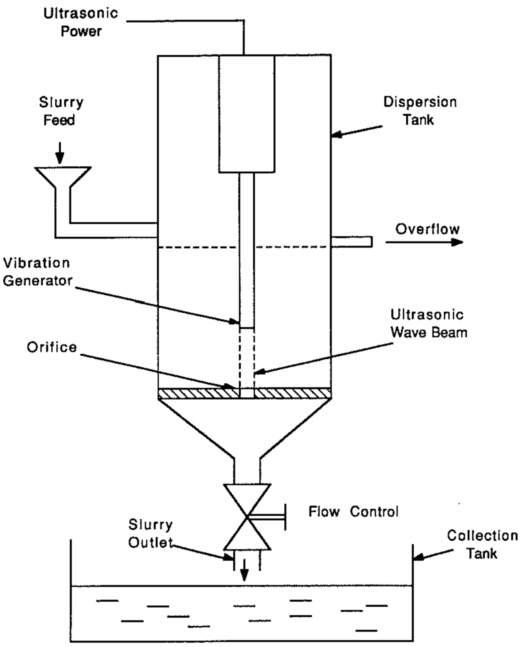

FIGURE 1. Schematic diagram of the apparatus for dispersing fibers.

ronment through an orifice that controls the pressure in the test filter housing. For a given flow rate, the pressure control orifice was selected such that the desired pressure can be obtained in the downstream side of the orifice. For example, if the desired pressure was 0.2 atm, and the volumetric flow through the filter was 10 L/min, then an orifice of a size capable of maintaining 2 L/min of flow was selected to obtain the desired pressure.

Two different pressure adjusting methods were tested in our preliminary experiments. In the first method, a needle valve was used for pressure adjusting. In the second method, an orifice was used. The testing results are shown in Figure 3. The penetration curves obtained with the first method were found to be discontinuous at low pressure conditions. The discontinuity in penetration curves at larger particle size was attributed to particle loss by impaction and turbulent deposition onto the small opening of the valve.

It is known that particle loss by impaction generally would increase with increasing particle diameter. Because the aerosol obtained from the differential mobility analyzer (DMA) is not completely monodisperse and shows some small size variation within a narrow range, as the valve opening decreases, the large particles would be lost in greater amounts in the valve by impaction than the small particles. Therefore, the actual median diameter of the aerosol downstream of the valve may become smaller as pressure is reduced. This change in particle size would result in changes in penetration. This effect would become more pronounced as the particle size is increased and as the valve opening is decreased. In contrast, penetration curves obtained using the orifice as the pressure control were smooth, indicating that the particle loss was minimized with the use of orifices. In the remainder of the paper, all data presented were obtained with the orifice as pressure adjusting device.

An absolute vacuum gauge (Wayless & Tiernan, Belleville, NJ), was placed upstream of the filter holder, indicated in Figure 2, to monitor the pressure in the filter housing. Two model 3760 CNCs (TSI, Inc., St. Paul, MN) were used to measure the aerosol concentrations upstream and downstream of the filter. To ensure the accuracy of the measurement, the CNCs were cross-checked. Particle penetrations through the empty filter housing were measured over the pressure range of 0.1–1.0 atm. In all cases, the fractional penetrations were found to be between 0.95 and 1.05, showing that the counting efficiencies of the two CNCs were in good agreement with each other.

An IBM-PC computer equipped with the Model 3704 interface board (TSI, Inc.) was connected to the condensation nucleus counters. A program called SINGFAST (TSI, Inc.) was used for data acquisition, which enables one to directly read the particle counts during a given sampling period. Thus, the aerosol penetration P through the filter was simply determined by taking the ratio of

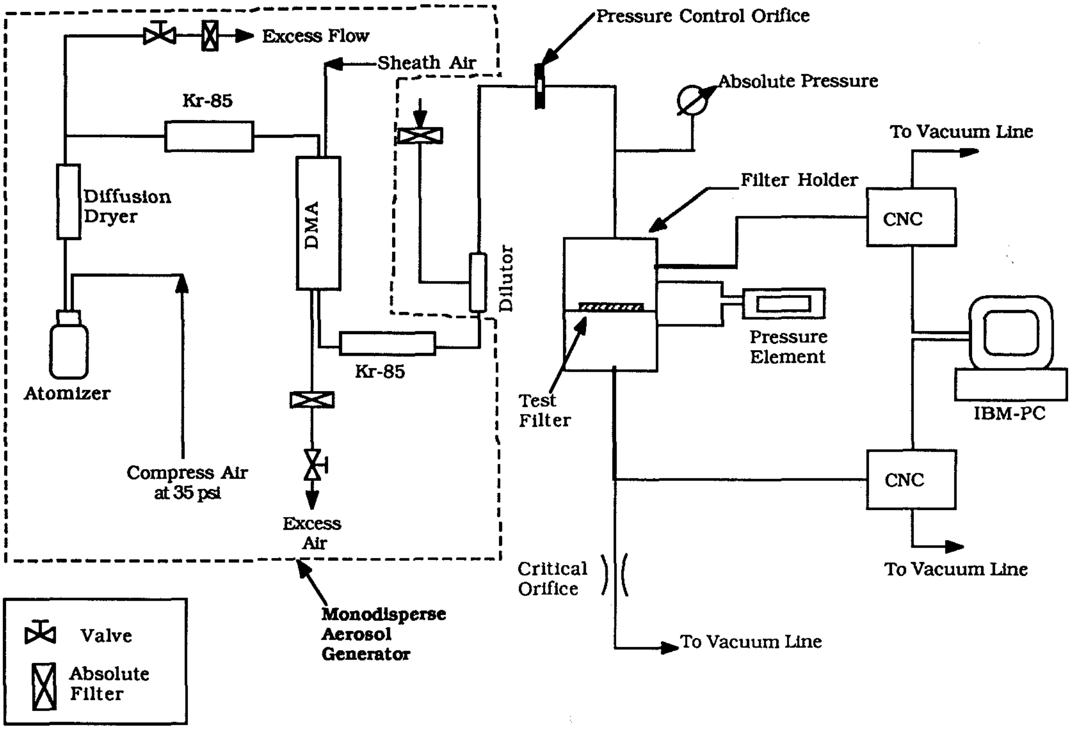

FIGURE 2. Schematic diagram of the experimental system for testing filters at reduced pressures.

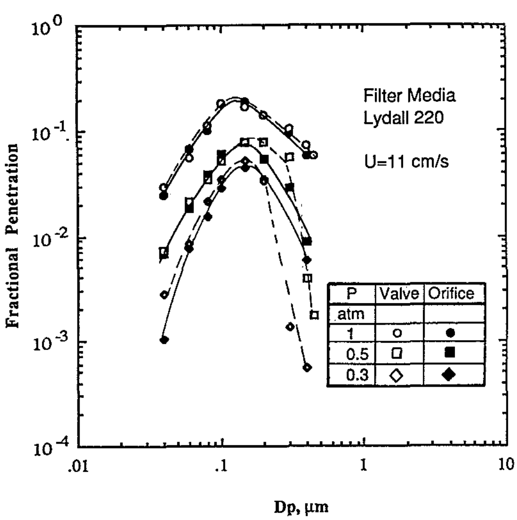

FIGURE 3. Comparisons of the penetrations obtained with the different pressure control devices.

the upstream particle counts C_{up} to the downstream particle counts C_{down}.

$$P = \frac{C_{down}}{C_{up}} \tag{6}$$

The TSI Model 3760 CNC is able to measure very low particle concentrations, as low as 0.0001 particles/cm^3. The ability to detect low concentrations was essential for our experiment because at low pressure conditions the aerosol penetration through a filter could be very low. The downstream particle concentration can be measured only if the particle counter is able to detect very low concentrations.

The pressure drop across a filter was measured using a differential pressure element comprised of a high accuracy pressure transducer (Type 398-HD-00100, MKS Instruments, Inc., Boulder, CO) and a high accuracy electronic display unit (Type 270B, MKS Instruments, Inc.). This pressure element can measure the pressure drop up to 100 cm H_2O with the precision of 0.01 cm H_2O, or up to 10 cm H_2O with the precision of 0.001 cm H_2O.

The face velocity of the filter was controlled by a critical orifice the downstream of the filter and the critical orifices of the CNCs. The pressures at the upstream and downstream of the orifices were monitored throughout the tests. For all cases of this study, the ratio of the upstream pressure to the downstream pressure was found to be greater than 4, showing that the face velocity was well controlled throughout the experiments.

In the experiments, three kinds of filter media were used. They are the Lydall 220, Lydall 258, and the ultrafine fiber filter medium prepared by us using the method described above. The filter medium prepared by us will be referred to as the UM filter in this article. Table 1 shows the characteristics of these three types of filter media. DOP solutions of concentrations between 0.005% and 0.1% by volume were made up to produce particles ranging from 0.035 to 1.0 μm. The face velocity U varied from 6 to 19 cm/s. The data was taken until the observed variation of the particle concentration in upstream of the filter was within $\pm 1\%$.

TABLE 1. Characteristics of Filter Media Used in This Study

	Filter media		
	Lydall 220	Lydall 258	UM
Thickness, L (cm)	0.0406	0.040	0.030
Packing density, α	0.078	0.080	0.053
Mean fiber diameter, $<D_f>$ (μm)	0.72	0.42	0.21
GSD, σ_g	2.38	2.20	2.34
Effective fiber diameter, D_{fe}(μm)	0.83	0.49	0.25

EXPERIMENTAL RESULTS

Particulate Penetration

The Lydall 220 filter medium was first tested. Particle penetrations through the filter were measured at face velocities of 6 and 11 cm/s, and the pressure varying between 3.15 and 29.5 in Hg. The test results at various conditions are plotted against the particle diameter in Figure 4. As illustrated in the figures, particle penetrations decreased significantly with decreasing pressures (or increasing the Knudsen number), showing the significant increase in filter efficiency as pressure is reduced.

The same experimental apparatus was used for testing the Lydall 258 and the UM filters. Tests were performed at the face velocities ranging from 6 to 19 cm/s, and the pressure between 0.106 and 1.0 atm. Again, the fractional penetrations are shown as a function of the particle diameter in the Figures 5 and 6.

The penetration curves for all three filters tested are similar in shape regardless of at different pressures and face velocities. The aerosol penetration through a filter is found to first increase with increasing particle size, showing the influence of particle diffusion on fiber performance. The penetration then reaches a maximum, before decreasing with further increase in particle size as the aerosol filtration enters into the interception and inertial impaction dominated regime. In all cases, the maximum penetration was found to shift slightly to larger particle size as the pressure decreased. This implies that the diffusion mechanism becomes more effective at reduced pressure, whereas the enhancement of interception and impaction mechanisms was relatively small at reduced pressures.

Pressure Drop

Table 2 shows the pressure drops across the filters at the atmospheric pressure. The normalized pressure drop, $\Delta P/\Delta P_0$, i.e., the

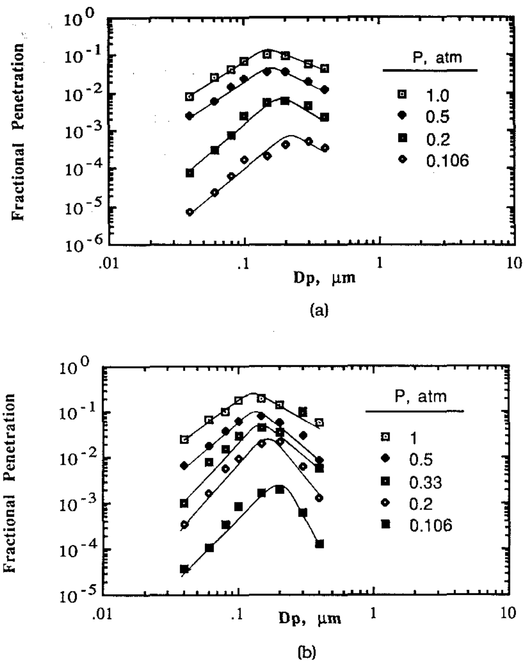

FIGURE 4. Fractional penetrations of the Lydall 220 medium at various pressures: (*a*) $U = 6$ cm/s; (*b*) $U = 11$ cm/s.

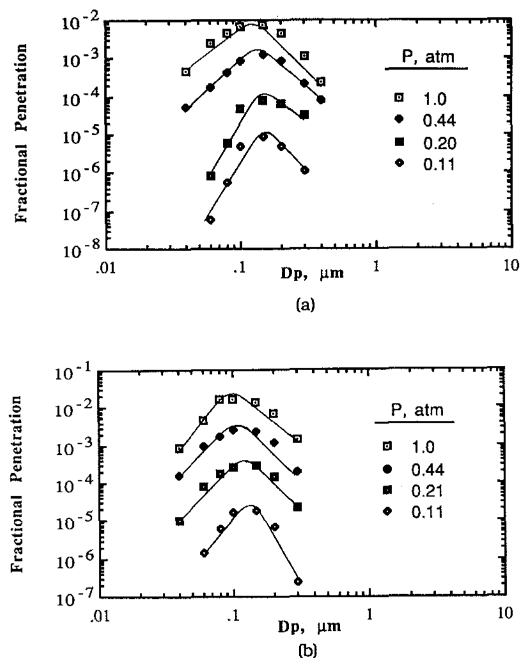

FIGURE 5. Fractional penetrations of the Lydall 258 medium at various pressures: (*a*) $U = 6$ cm/s; (*b*) $U = 19$ cm/s.

ratio of pressure drop at reduced pressure ΔP to that at the atmospheric pressure ΔP_0, was plotted as a function of pressure in Figure 7 for Lydall 220, Lydall 258, and UM filters, respectively. It is seen that the pressure drop decreases with the reduction of the pressure, showing that the gas slip effect became more and more important with decreasing the pressure. It was also observed that the correlation of $\Delta P/\Delta P_0$ versus the pressure was independent of the face velocity.

CONCLUSIONS

The primary objective of this study was to experimentally investigate the aerosol filtration by fibrous filters in the transition flow regime. In this work, the transition flow conditions were achieved by performing the experiments at reduced pressures and using filters made of fine and ultrafine fibers. Three types of the filter media, Lydall 220, Lydall 258, and the media prepared at the Particle Technology Laboratory, University of Minnesota (UM filters) were used in the study. The mean fiber diameter of the filter media used was in the range of 0.21–0.72 μm, while the packing densities of the media varied between 0.053 and 0.08. Experiments were carried out over the pressure range of 0.1–1.0 atm. and the face velocity range of 6–19 cm/s. Monodisperse DOP particles of 0.04–0.45 μm in diameter were used as the challenge agents.

An experimental apparatus has been developed to measure the particulate penetration through and pressure drop across filters at the reduced pressures (0.1 atm $< P <$ 1.0 atm). The apparatus enables one to perform the filtration studies over a relatively wide range of the Knudsen numbers. This CNC-

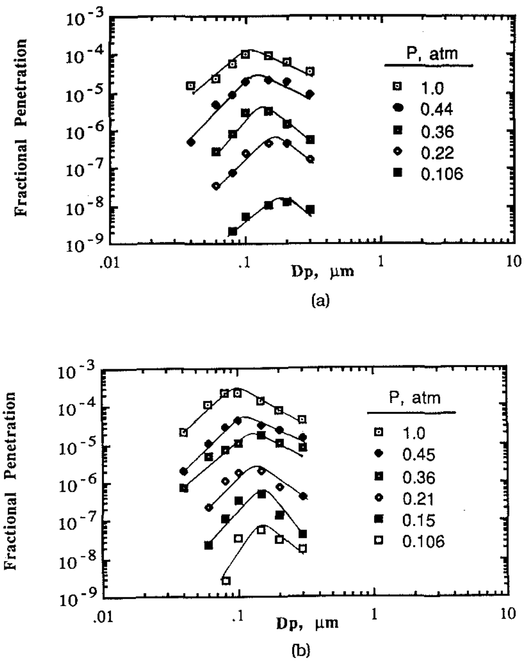

FIGURE 6. Fractional penetrations of the UM medium at various pressures: (*a*) $U = 11$ cm/s; (*b*) $U = 19$ cm/s.

TABLE 2. Pressure Drop Across Filter at Atmospheric Pressure, ΔP_0

	Pressure drop (cm H_2O)		
Face Velocity (cm/s)	Lydall 220	Lydall 258	UM
6	0.95	3.36	3.86
11	1.79	6.37	7.22
19	—	11.46	13.36

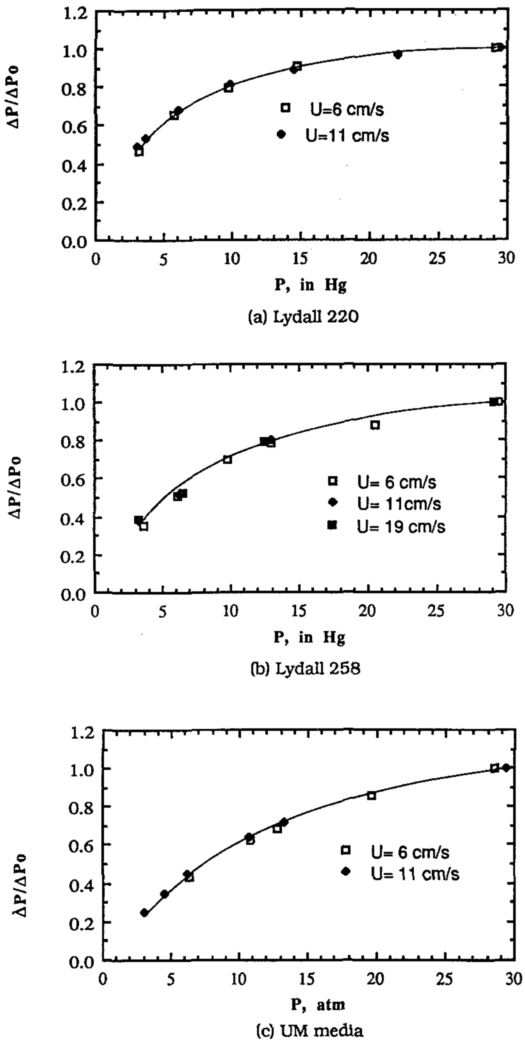

FIGURE 7. Normalized pressure drop, $\Delta P/\Delta P_0$, at different pressures (ΔP_0 = pressure drop at 1 atm): (*a*) Lydall 220 medium; (*b*) Lydall 258 medium; (*c*) UM medium.

based system was highly sensitive, capable of measuring the penetration as low as 10^{-9} with good accuracy.

The results of the penetration measurements showed that the particle penetration through a fibrous filter decreased significantly with decreasing the pressure or increasing the Knudsen number. For example, at the face velocity of 11 cm/s, the peak penetration of the Lydall 258 media decreased from 10^{-2} at the pressure of 1 atm to 10^{-5} at 0.11 atm. It was also observed that the most penetrating particle size shifted slightly to larger particle size as pressure is reduced. The pressure drop across the filter was found to decrease with decreasing absolute pressure, indicating enhanced slip effect at low pressures. The ratio of pressure drop at reduced pressure to that at 1 atm was found to be independent of the face velocity, showing that the slip effect is independent of the flow velocity.

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