Comparison of Experimental and Theoretical Efficiencies of Residential Air Filters

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ABSTRACT

A variety of residential air filters are commercially available including the standard fibrous mat filters which have been used for years as well as recently developed filters which incorporate electrostatic fibers (electrets) to enhance particulate removal and carbon-impregnated filters to enhance removal of organic vapors. In this study, eleven different commercially available filters were evaluated to determine their characteristics and the particulate removal efficiencies of the filters in the range of 0.5 to 4.0 μm. The 50.8 X 50.8 cm^2 (20 X 20 in^2) filters were evaluated in a simulated home heating system at velocities of approximately 450 to 750 fpm to determine their initial efficiencies prior to loading. An optical particle counter with a multichannel analyzer was used to simultaneously measure the concentration of particles in six particle size increments.

The measured efficiencies of the filters were then compared to values predicted by using filtration theory and the measured filter characteristics (fiber diameter, thickness, packing density, and filtration velocity). The equations used in the filtration model are summarized and the results are presented. In general, the residential filter efficiencies ranged from 0-32% at 0.5 μm up to 35-86% at 4 μm. Based on the filtration theory, the primary removal mechanism was inertial impaction, thus explaining the low observed efficiencies at the smaller particle sizes.

INTRODUCTION

A variety of air filters are now commercially available for use in residential heating/ventilation systems. These include the conventional low efficiency fibrous mat filters which have been used for years to remove lint and large particles in order to protect the heating system, as well more efficient filters such as pleated filters and filters which incorporate electrostatic fibers (electrets) to enhance particulate removal and carbon-impregnated filters to enhance removal of organic vapors. In support of the university's research efforts in the area of indoor air quality, a study was conducted on eleven different commercially available filters to determine their filtration characteristics including the pressure drop and the particle removal efficiencies of the filters in the range of 0.5 to 4.0 μm. The 50.8 X 50.8 cm^2 (20 X 20 in^2) filters, were evaluated in a simulated home heating system at velocities of 2.34 to 3.83 m/s (461 to 753 fpm) to determine their initial efficiencies prior to loading. An optical particle counter with a multichannel analyzer was used to simultaneously measure the concentration of particles in six particle size increments.

The initial characterization included studying the effect of velocity on the pressure drop and efficiency, and the effect of edge leaks around the filters which are typically installed without a positive edge seal other than the seal provided by the suction of the filter frame against the flange of the filter holder.

The observed results were also compared to existing equations used to predict the pressure drop and efficiency of filter media to determine the applicability

of the equations to residential filters which operate at relatively high velocities.

DESCRIPTION OF TEST METHODS

Description of Indoor Air Quality Test Stand

The filters studied herein were tested in an indoor air quality test stand as shown in Figure 1. The stand was constructed to hold a nominal 50.8 X 50.8 cm^2 (20 X 20 in^2) air filter. The actual filter area is actually 45 X 45 cm^2 (18 X 18 in^2) excluding the frame of the filter. The aluminum duct contained a variable speed fan at the outlet which was capable of producing velocities at the entrance of 2.34, 2.99, and 3.83 m/s (461, 588, and 753 fpm). The velocities were determined by conducting velocity transverses using an Alnor Thermoanememometer. The 45 X 45 cm^2 (18 X 18 $in^{2)}$ duct opening was divided into 25 equal areas. The minimum and maximum velocity at the center of each square was recorded. The average of these velocities was then summed for all squares and divided by the number of areas (25) to obtain the average velocity.

A probe mounted in the center of the duct downstream of the filter was used to extract a sample of the flow into an optical particle counter to measure the particle concentrations. Upstream concentrations were obtained by removing the filter such that the laboratory air passed, unfiltered into the test duct. The filter was then replaced and the concentration was measured downstream of the filter. Due to the low pressure drop of the indoor air filters, and the lack of any particulate loading on the filters, the velocity at the face of the duct remained relatively constant with or without the filters in place. Mounting of filters to the duct was done by either 1) taping the filters to the duct such that there were no edge leaks or 2) simply placing the filters against the flange, and allowing the airflow to hold the filters in-place, in which there was a natural, but small edge leak, similar to that which occurs in an actual residential filter holder. The technique varied depending on the objective of the study (i.e to study the effect of edge leaks).

All tests were conducted at a temperature of 24-26°C (≈76-78°F), and at atmospheric pressure. The particles used in the test were those which naturally occurred in the air quality laboratory in which the tests were conducted. While the concentration varied with time, it was sufficiently stable during any one test to obtain upstream and downstream concentrations which could be used to determine the filtration efficiency.

Description of Particle Counting

The particle counter used in this study was a Climet Model 208 optical particle counter (OPC) capable of measuring particle sizes of 0.5-10 μm. Each particle which passes through the counter scatters light at an intensity which is related to its particle size. The intensity is amplified and creates a voltage pulse ranging from approximately 50 mv to 10 volts for particles of 0.5- 10.0 μm, respectively. As originally purchased, and as is typical of many commercially available counters, the counter was set up to measure particles greater than any one of five preset sizes ranging form 0.5-5.0 μm. In order to obtain simultaneous counts at each particle size of interest, the signal from the OPC was processed by a multichannel analyzer card (MCA) which processed the signal into 1028 channels in the 0-8 volt range. The card, a Nucleus Personal Computer Analyzer card (PCA-II) (Oxford Instruments, Oak Ridge, TN) was mounted in an IBM compatible 486 SX personal computer.

The OPC/MCA

The software associated with the MCA allows the user to specify the region of interest (ROI) in which the counts are to be summed. In this case, the ROIs were set to sum the number of particles in narrow ranges centered about 0.5, 1.0, 1.5, 2.0,

3.0, and 4.0 μm, respectively. The concentration of particles in the laboratory greater than 5.0 μm was insufficient to obtain accurate efficiency values across the filters.

The OPC/MCA was calibrated by generating monodispersed latex spheres of known size in an ASTM 1215 Test Stand. Sizes used in the calibration included 0.60, 0.99, 2.02, 2.99, and 5.30 μm. Once the calibration curve was generated, the channels corresponding to each size of interest were interpolated from the curve.

DESCRIPTION OF FILTRATION MODELS

Prediction of Pressure Drop

While there have been numerous equations developed for the prediction of pressure drop, the authors have chosen a specific equation derived from Kuwabara flow theory and reported by Davies[1] and later modified by Liu and Rubow[2] to use in this study. The equation is as follows:

$$\Delta P = \frac{16 c \mu_g V}{K D_f^2 \epsilon} \qquad (1)$$

where

ΔP = pressure drop (nt/m^2)
c = packing density
μ_g = viscosity (kg-s/m^2)
V_f = face velocity (m/s)
L = thickness of filter (m)
K = Kuwabara hydrodynamic factor
D_f = diameter of fibers (m)
ε = inhomogeneity factor (1.0 for a randomly packed filter)

The Kuwabara factor is

$$K = -\frac{1}{2}\ln c - \frac{3}{4} + c - \frac{c^2}{4} \qquad (2)$$

In general all of the above parameters can be measured except for the packing density, c. The packing density can be determined by gravimetrically measuring W_f, the areal density (kg/m^2) of the filter, and using the following equation:

$$c = \frac{W_f}{\rho_f L} \qquad (3)$$

where ρ_f is the density of the fibers in kg/m^3.

Equation 1 was reported by Liu and Rubow[1] to overpredict the pressure drop for polyester filters which they studied by a factor of 1.6 due to the inhomogeneity of the fibers. While this factor, ε, may vary due to the type of material and method of manufacture, the factor of 1.6 was applied in this study as well.

Prediction of Efficiency

The efficiency of particle removal across fibrous filters is generally assumed to be a combination of three removal mechanisms which operate concurrently within the filter: diffusion, interception, and inertial impaction.[1] At low velocities, diffusion and interception have been shown to dominate, while at high velocities, inertial impaction of particles onto the fibers becomes more dominant. As a first approximation, the fractional efficiency of removal of a single particle approaching a single fiber, η_s, can be represented by the equation

$$\eta_s=\eta_D+\eta_R+\eta_I \tag{4}$$

where the subscripts D, R, and I represent the efficiencies due to diffusion, interception, and inertial impaction, respectively for a given particle size. The overall efficiency, η_o, of the filter for a specific particle size is

$$\eta_o=1-e^{-\eta_s S} \tag{5}$$

where S is referred to as the solidarity factor and is calculated as follows:

$$S=\frac{4cL}{\pi D_f} \tag{6}$$

Liu and Rubow[2] reported that the following equation was found to be adequate for the prediction of the single fiber removal efficiencies for diffusion and interception:

$$\eta_s=\frac{2.58}{\epsilon}\left(\frac{1-c}{K}\right)^{\frac{1}{3}}P_e^{-\frac{2}{3}}+\frac{1}{\epsilon}\left(\frac{1-c}{K}\right)\frac{R^2}{1+R} \tag{7}$$

where the first term is η_D and the second term is η_R. The term, P_e, is the Peclet number defined as

$$P_e=\frac{VD_f}{D} \tag{8}$$

and R is the interception parameter

$$R=\frac{D_p}{D_f} \tag{9}$$

In the above equations, D is the diffusivity of the particle (m^2/s) and D_p is the diameter of the particle (meters). A value of ε equal to 1.6 was again recommended for the inhomogeneity factor. Liu and Rubow[2] recommended that equation 7 be used for particle diameters in the range of 0.034-1.3 μm, and velocities of 0.01-0.3 m/s where diffusion and interception would dominate.

In the case of higher velocities and larger particles where inertial impaction is important, an equation is needed to approximate the efficiency of inertial impaction, η_I. Whitby[3] developed an approach that can be used to approximate the efficiency for the inertial impaction component of the single particle/single fiber efficiency for Reynolds numbers (Re) greater than or equal to 0.5 and for velocities of 0.2-3.0 m/s. These higher velocities are more typical of residential indoor air filters. The equation, which plots as a straight line on log-probability paper is as follows:

$$\eta_I=0.5+0.5erf\left[\frac{\ln(\Psi/\Psi_M)^{1/2}}{(2)^{1/2}\ln\sigma}\right] \tag{10}$$

where Ψ is the inertial impaction parameter defined as

$$\Psi=\frac{\rho_p D_p^2 VC_f}{18\mu_g D_f} \tag{11}$$

and "erf" is the error function. In equations 10 and 11, ρ_p is the particle density (kg/m^3) and C_f is the Cunningham Correction Factor. For $0.2 < Re < 150$, Ψ_M is the value of the inertial impaction parameter which yields a fractional single fiber collection efficiency of 0.5 and has a value of

$$\Psi_M = 1.57 Re^{-0.137} \qquad (12)$$

with a geometric standard deviation, σ, of 1.65. For $Re < 0.2$, the value of Ψ_M is 1.96. As an alternative to solving for the error function in equation 10, a linear graph can be constructed on log probability paper by first calculating $\Psi_M^{0.5}$ using equation 12. The value of $\Psi_M^{0.5}$ is plotted at the 50th percentile point and the value 1.65 X $\Psi_M^{0.5}$ is plotted at the 84.15 percentile, after which a linear curve is constructed using these two values. Once the graph is constructed, and the squared root of the value of Ψ is calculated, the efficiency, η_I, can be read from the probability scale in percent.

In this study, equations 7 and 10 were used to determine the single particle/single fiber fractional collection efficiencies. The value of η_I predicted by equation 10 was also divided by the inhomogeneity factor of 1.6. The efficiencies were then summed in equation 4, after which equation 5 was used to determine the overall efficiency.

RESULTS

Efficiency as a Function of Particle Size and Velocity

Eleven different commercially available residential air filters were tested to determine the efficiency of the clean (as-received) filters as a function of particle size in the 0.5-4.0 μm range. The filters ranged from a standard filter that has been commercially available for a number of years (Filter 3), to electrostatically enhanced filters (polypropylene/polyurethane layers) such as Filter 6, and a pleated electret filter (Filter 1).The physical characteristics of the filters are summarized in Table 1. In some cases, i.e. Filters 4, 5, 6, 7, and 10, the filters were layered. In these cases, an effort was made to separate the layers and characterize each layer. Physical measurements were made of the thickness, fiber diameter (microscopic analysis), and the areal density (gravimetric). The fiber density was determined by identifying the chemical structure of the fibers; the packing density, c, was determined by calculation using equation 3.

In the first series of tests that were conducted, the filters were mounted on the test stand and held in-place by the suction of the airflow. These tests simulated the typical manner in which the filters would have been installed in a residential system. Three efficiency tests were conducted and the values were averaged for each filter. Figures 2 and 3 show the results which were obtained at a face velocity of 2.34 m/s (461 fpm). It should be noted that while a face velocity of 2.34 m/s was used for all filters, the actual velocity through the pleated filters was actually lower due to the increased surface area. Table 1 lists the actual velocity that occurred at the filter surface when a face velocity of 2.34 m/s was applied. The measured efficiencies at 0.5 μm ranged from nearly zero for the least efficient filters up to 32% for the pleated electret filter (Filter 1). In all cases, the efficiency increased as the particle size was increased indicating that inertial impaction was the dominant mechanism at this velocity. At 4.0 μm, the efficiencies ranged from a low of approximately 35% to a high of 86%.

Each of the filters was also tested in triplicate at velocities of 2.99 and 3.83 m/s (588 and 753 fpm). While it is beyond the scope of this paper to present all of the results, Figure 4 presents the results obtained on Filter 4 and illustrates the typical trends which were observed. Tests were also conducted on this filter at velocities of 0.91 and 1.42 m/s (180

and 280 fpm) to provide more insight into the effect of velocity. As shown in the figure, the efficiency at 0.5 μm remained low and was relatively unaffected by increases in velocity since inertial impaction is not significant on sub-micron particles. For the particle sizes greater than or equal to 1.0 μm, the efficiency generally increased as the velocity was increased from 0.91 to 3.83 m/s.

The measured efficiency values obtained on each filter were also compared to the values predicted using equations 7 and 10 above. Figure 5 illustrates a comparison of the predicted and measured efficiencies for Filter 4 for the 0.5, 1.5, and 4.0 μm particle sizes, and is typical of the results of the other filters. The equations tended to simulate the smaller particle sizes reasonably well, however, tended to overpredict the efficiency for the larger particle sizes and higher velocities. The predicted efficiencies for all of the filters at 0.5 μm ranged from 0-7.8%. Figures 2 and 3 show that the measured values at 0.5 μm are in the range of zero to 18.9%, with the exception of Filter 1 which was the electret filter. The electret filter had the highest measured efficiency with a value of 32%, while the predicted efficiency was only 3.8%, due to the absence of an electrostatic mechanism in the efficiency equations. At the largest particle size studied (4.0 μm), the measured efficiencies ranged from 36.0-86.8% while the predicted efficiencies ranged from 63.0-98.9%.

One possible explanation for the overprediction at the larger particle sizes is that the high velocities used in residential filters may result in a loss of particles due to particle bouncing as the particles strike the fibers. The filtration theory discussed herein assumes that the particle sticks to the fiber once it makes contact and does not account for any loss due to bouncing or lack of adherence. In the study by Whitby[3], he also noted that the inertial impaction equations tended to overpredict the efficiency at particle sizes greater than 5 μm at normal velocities of 25-250 fpm. At the higher velocities used in this study, this effect would become more pronounced. It should be noted, however, that when the inertial impaction mechanism is removed from the efficiency equations, that the equations which included only the diffusion and interception terms (Equations 5 and 7) resulted in a substantial underprediction of the efficiency of each filter. For example, at 4.0 μm, predicted efficiencies at 2.34 m/s with only these two mechanisms ranged from 1-5% for all of the filters, while the measured values ranged from 36.0-86.8%. The actual efficiency at these higher velocities lies somewhere in between the values predicted by the two sets of equations (one with only diffusion and interception, the other with all three mechanisms). Additional studies are on-going in an attempt to modify the above equations to account for particle bounce by applying a correction factor based on the particle momentum.

A second series of tests was conducted to determine if edge leakage affected the results obtained on the filters as shown in Figures 2 and 3. In this series of tests, the filters were taped to the air duct in order to ensure no edge leakage. The results of one taped test run were compared to the average of the runs with out the tape (the three runs from the previous velocity series plus one run done at the same time as the tape run). In general, the results showed that edge leakage was not a significant factor for the new, non-loaded filters. Figure 6 shows a comparison of Filters 1, 3, and 10 with and without the edges taped. The difference in the efficiencies is relatively small and within the errors of the tests. While edge leaks were not significant on any of the filters tested, the effect of edge leaks may become more significant as the filters become loaded with dust and acquire a higher resistance to flow. Further investigation is on-going to determine the significance of loading on the edge effects.

Comparison of Measured and Predicted Pressure Drops

The pressure drop across each filter was measured at the three different flowrates to which each filter was subjected using Dwyer Magnehelic gauges (0-4 and 0-0.5 in. H_2O). Table 2 summarizes the measured pressure drops for each filter at the three velocities. Figure 7 shows a comparison of the measured values to the predicted values when the filter characteristics listed in Table 1 were used in Equation 1 to predict the pressure drop. Filters 6 and 10 were excluded from this analysis since these contained polyeurathane layers which were not fibrous in nature. While the general trend of agreement is apparent, the best fit line showed that the predicted pressure drop was less than the measured value and that the correlation coefficient, R^2, was only 0.61. This is likely due to the wide variety of the types of filters tested, variations in fiber diameter and packing density within each filter, and the fact that the inhomogeneity factor in Equation 1 was assumed to be a constant value of 1.6. In retrospect, it appears that a smaller value of the inhomogeneity factor would have been more appropriate and would have reduced the magnitude of the underprediction. However, it would not affect the relative large scatter since it is a linear correction.

CONCLUSIONS

The overall study has characterized the initial, clean performance of eleven different filters which are commercially available as residential air filters, including standard, electrostatically enhanced, and electret filters. The particulate removal efficiencies of the filters ranged from nearly 0-32 % at 0.5 μm to 35-86% at 4.0 μm. Existing filtration theory was reviewed and the predictive equations for pressure drop and efficiency were compared to the measured pressure drops and efficiencies of the filters. For the sub-micron particles, the efficiency equations were in general agreement with the measured values. However, for particles greater than 1.0 μm, the equations progressively overpredicted the efficiency as the particle size was increased. In general, the measured efficiency was observed to be greater than the predicted efficiency when only the diffusion and interception mechanisms were used, but less than the efficiency predicted when the inertial impaction mechanism was included in the equations.

In a second series of tests, it was shown that the efficiencies of the filters were not significantly affected by the manner in which the filters were installed. Results on tests in which the filters were sealed by a natural seal (the suction of the filter against a flange) were similar to those obtained when the edges of the filter were sealed by taping then to the housing with no edge leak.

Additional studies are on-going to evaluate the importance of edge leakage as filters become loaded and to improve on the ability of existing filtration theory to predict the efficiency of filters, such as filters used in residential filtration, where high velocities and larger particle sizes are of concern.

REFERENCES

1. Davies, C. N., Air Filtration. Academic Press, London, 1973.

2. Liu, B. Y. H., and K. L. Rubow, "Air Filtration in Fibrous Media," Fluid Filtration: Gas, Vol. 1. ASTM STP 975. 1986, pp 1-12.

3. Whitby, K., "Calculation of the Clean Fractional Efficiency of Low Media Density Filters," ASHRAE JOURNAL. pp 56-64, September, 1965.

Table 1. Summary of Filter Characteristics

Filter	Effective Velocity m/s	Filter Density g/cm³	Polymer Type[1]	Structure	Filter Surface Area cm²	Fiber Diameter (D_f) cm²	Actual Density (W_f) g/cm²	Filter Media Thickness (L) cm	Packing Density[2] (c)
1	1.217	0.91	PP	Pleat	3892	14.4	0.00778	0.50	0.0171
2	1.01	1.38	PET	Pleat	4680	15.8	0.00981	0.45	0.0158
3	2.34	1.15	N	Flat	2025	48.2	0.0123	2.30	0.0047
4	2.34	1.38	PET white	Flat	2025	26.6	0.0163	2.30	0.0051
	2.34	1.38	PET green	Flat	2025	26.6	0.0114	1.20	0.0069
5	2.34	1.38	PET white	Flat	2025	24.4	0.0049	0.40	0.0089
	2.34	1.38	PET green	Flat	2025	29.2	0.0107	0.50	0.0155
	2.34	1.38	PET black	Flat	2025	40.9	0.0313	0.80	0.0284
6	2.34	0.91	PP	Flat	2025	316	0.0152	0.20	0.0835
	2.34	1.30	PU	Flat	2025	111	0.0194	0.91	0.0164
	2.34	0.91	PP	Flat	2025	316	0.0152	0.20	0.0835
7	2.34	0.91	PP	Flat	2025	316	0.0178	0.20	0.0978
	2.34	1.38	PET white	Flat	2025	25.0	0.0083	1.00	0.0060
	2.34	1.38	PET blue	Flat	2025	25.0	0.0086	1.00	0.0062
	2.34	0.91	PP	Flat	2025	316	0.0178	0.20	0.0978
8	2.34	1.22	cellulose	Flat	2025	218	0.0718	2.10	0.0280
9	2.34	1.22	cellulose	Flat	2025	186	0.0906	2.56	0.0290
10	2.34	1.30	PU	Flat	2025	94.6	0.0139	0.50	0.0241
	2.34	1.38	PET	Flat	2025	25.9	0.0156	1.10	0.0103
11	1.75	1.15	N	Pleat	2707	15.1	0.0089	0.30	0.0258

[1] PP indicates polypropylene electret, PET indicates polyester, N indicates nylon, and PU indicates polyurethane.
[2] Effective filtration velocity at a face velocity of 2.43 m/s.

Table 2. Summary of Measured Pressure Drops

Filter	Pressure Drop (inches H_2O)[1]		
	2.43 m/s	2.99 m/s	3.83 m/s
1	0.35	0.45	0.60
2	0.20	0.28	0.40
3	0.10	0.13	0.18
4	0.35	0.45	0.55
5	0.20	0.30	0.45
6	0.25	0.35	0.50
7	0.35	0.45	0.60
8	0.05	0.11	0.15
9	0.06	0.10	0.16
10	0.30	0.45	0.60
11	0.30	0.40	0.50

[1]Pressure drop of the filters was conducted at the three air velocities 2.34, 2.99, and 3.83 m/s (461, 588, and 753 fpm).

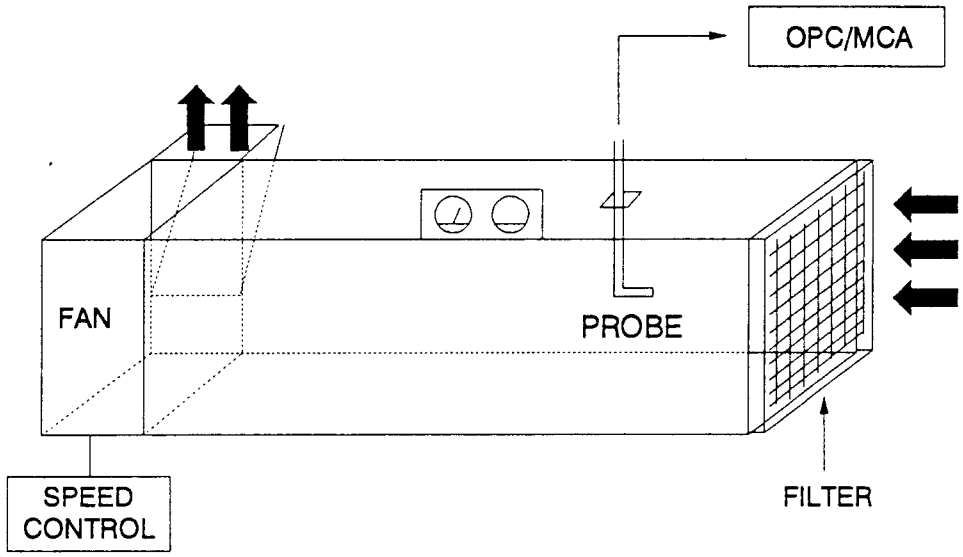


Figure 1. Schematic of Indoor Air Quality Test Stand.

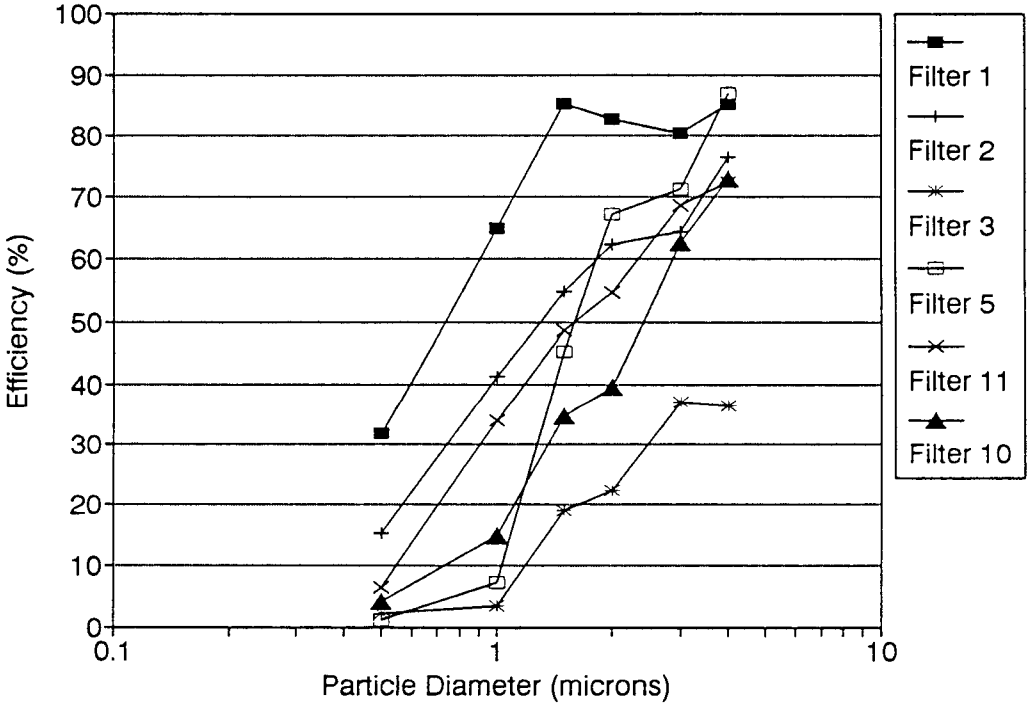


Figure 2. Efficiency of Residential Filters at 2.34 m/s.

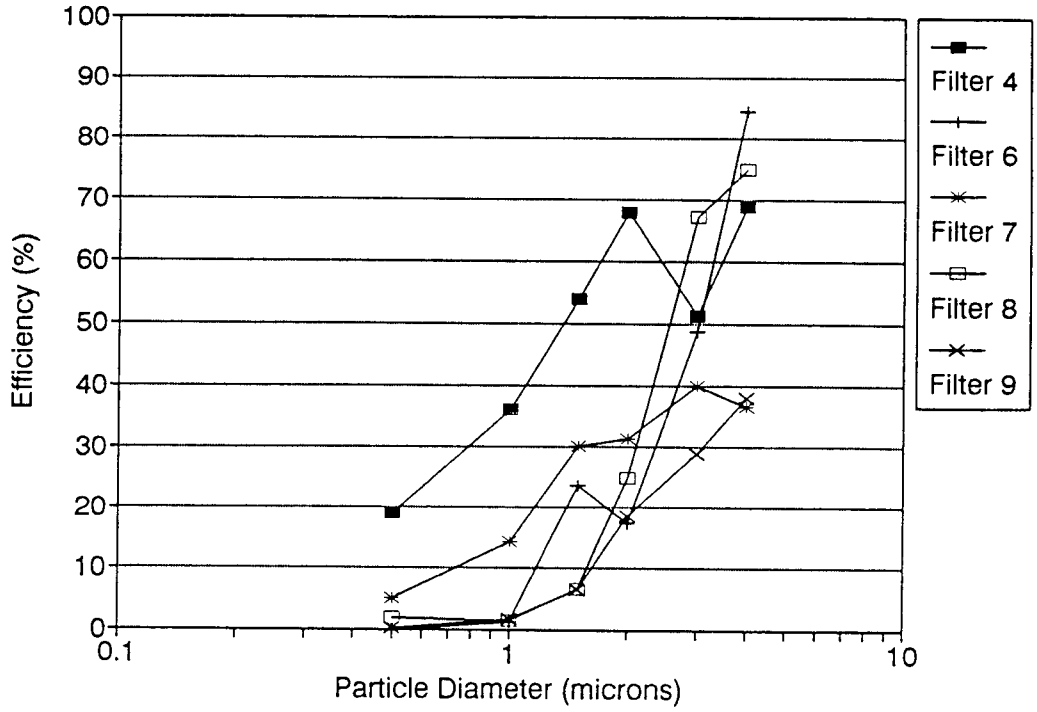


Figure 3. Efficiency of Residential Filters at 2.34 m/s. (cont.)

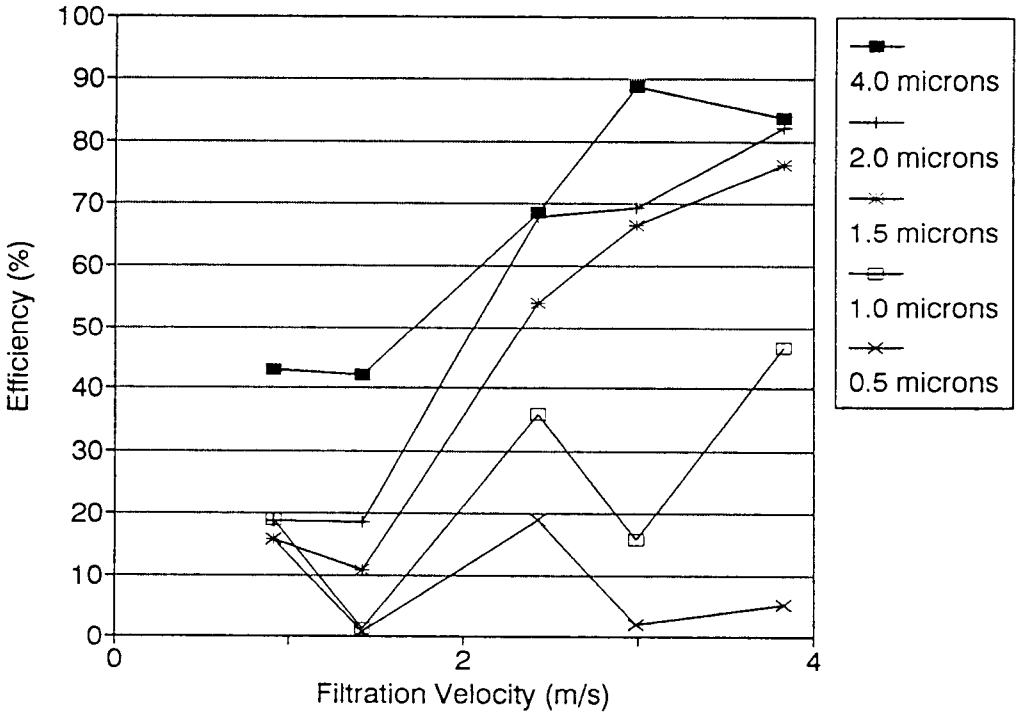


Figure 4. Efficiency of Filter # 4 as a Function of Velocity.

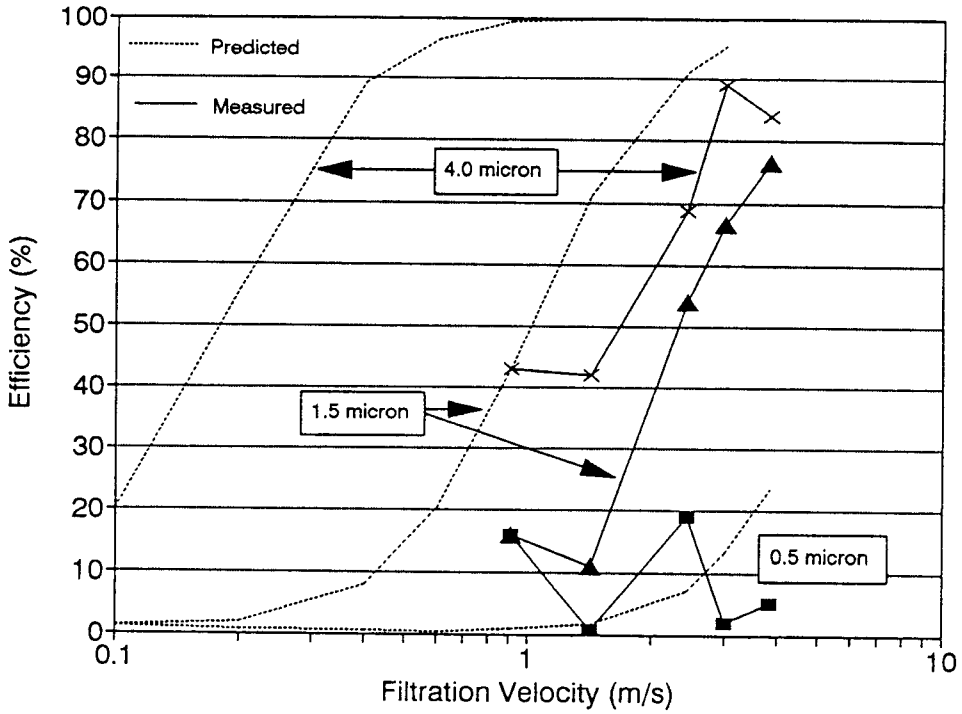


Figure 5. Comparison of Predicted and Measured Efficiencies for Filter 4.

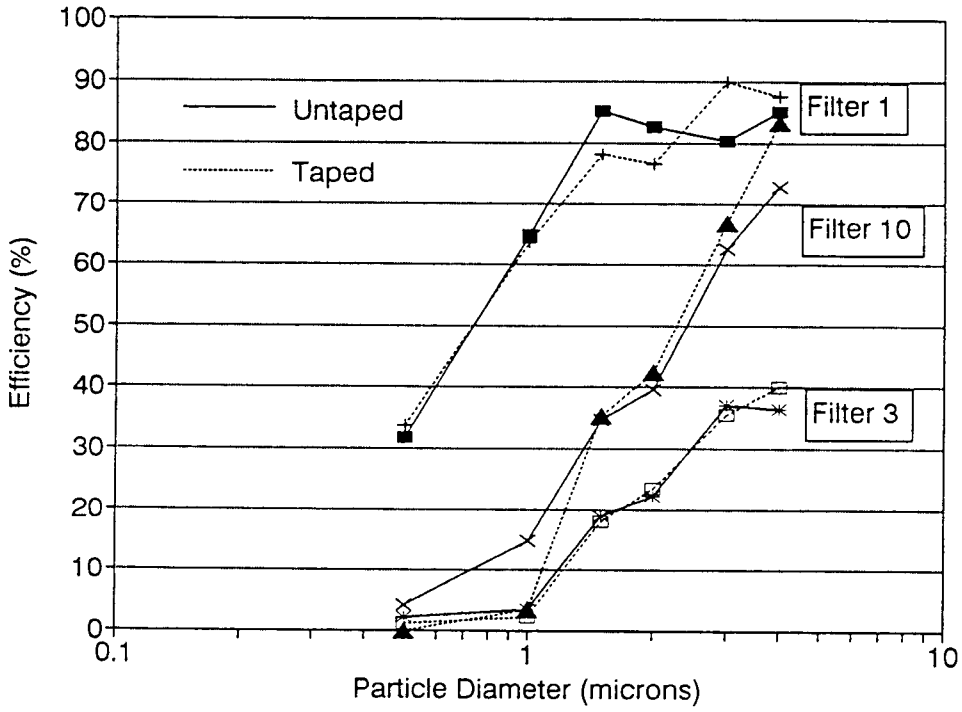


Figure 6. Comparison of Efficiency With and Without Edge Leaks.

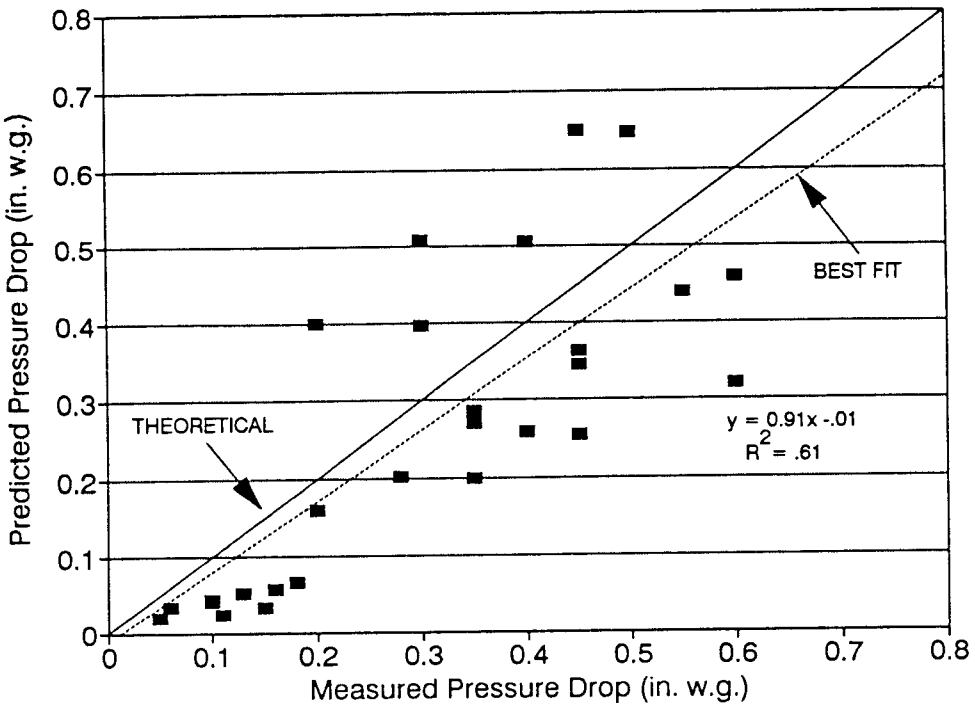


Figure 7. Predicted versus Measured Pressure Drop.