Modeling Filter Bypass: Impact on Filter Efficiency

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ABSTRACT

Current models and test methods for determining filter efficiency ignore filter bypass, the air that circumvents filter media because of gaps around the filter or filter housing. In this paper, we develop a general model to estimate the size-resolved particle removal efficiency, including bypass, of HVAC filters. The model applies the measured pressure drop of the filter to determine the airflow through the bypass cracks and accounts for particle loss in the bypass cracks. We consider a particle size range of 0.01 to 10 µm, nine typical commercial and residential filters in clean and dust-loaded configurations, and a wide range of bypass gaps typical of those found in real filter installations. The model suggests that gaps on the order of 1 mm around well-seated filters have little effect on the performance of most filters. For high pressure drop filters, small gaps decrease filter performance and large gaps substantially decrease filter performance. Because higher efficiency filters also typically have a larger pressure drop, bypass tends to have a larger effect on high performance filters. The results provided here suggest that bypass can dramatically affect filter performance.

INTRODUCTION

Filtration in HVAC systems is the most widely used method for protecting people and equipment from airborne particulate matter. To aid in filter selection, there are several standards that address HVAC filtration efficacy including ASHRAE Standard 52.2: Method of Testing General Ventilation Air-Cleaning Devices for Removal Efficiency by Particle Size (ASHRAE 1999) and ASHRAE Standard 52.1: Gravimetric and Dust-Spot Procedures for Testing Air-Cleaning Devices Used in General Ventilation for Removing Particulate Matter (ASHRAE 1992). The result of an ASHRAE Standard 52.2 test includes the Minimum Efficiency Reporting Value (MERV), which classifies filters according to their efficiency. Standard 52.2, as well as most other filter test methodologies, are tests of the filter media, rather than the installed filter system. When applied to real systems, filter test results implicitly assume that no bypass exists around filters. Examination of most residential and commercial HVAC systems suggests that this is not a good assumption: both small and large gaps are common. The purpose of this paper is to simulate the effect of filter bypass on common filters.

HVAC filtration has been widely studied, and several studies have measured particle-size resolved efficiencies for a variety of filters (e.g. Hanley *et al.* 1994; Raynor and Chae 2003). Filter efficiency curves are typically U-shaped with very small particles (<0.05 µm) removed by Brownian diffusion and very large particles (>5 µm) removed by inertial mechanisms. Although most measurements have been made with filter bypass intentionally sealed, there are numerous anecdotal reports of particle bypass. Braun (1986) reported that catastrophic filter bypass led to fouling of an evaporator coil. Ottney (1993) and several others suggest that eliminating filter bypass is an important component of achieving acceptable indoor air quality. Siegel (2002) simulated filter bypass and suggested that even moderate amounts of filter bypass could dramatically increase HVAC heat exchanger fouling.

Despite its obvious importance, we know of no existing mathematical models for filter bypass and decision-makers have limited information available on the effect of bypass. In this paper we present a model of filter bypass that predicts the amount of air that will bypass a filter, and the effect on overall filter efficiency. The most important independent parameters are the size (i.e. gap width) and geometry of the gaps around the filter and the efficiency and pressure drop of the filter. We report several parameters including the volumetric airflow that bypasses the filter (Q_B) and the effective filter efficiency as a function of particle diameter (η_{eff}) for the filter system (filter + bypass). We apply our model to a variety of commonly used HVAC filters in order to understand the interplay between filter efficiency, pressure drop, and bypass. From these simulations, we calculate the effective MERV ($MERV_{eff}$) that accounts for bypass. The results are intended to provide additional assistance when selecting filters and to quantify the benefits associated with eliminating bypass.

METHODOLOGY

An effective filtration efficiency that includes bypass can be derived by differentiating bypass flow from filtered flow. Knowledge of both the bypass flow rate and the removal of particles in the gap, as well as the flow through the filter and the particle removal by the filter, are needed to implement the model. In order to quantify bypass flow, a quadratic relationship is employed to relate flow to pressure drop in a rectangular sharp-edged crack such as are present in HVAC filter holders or slots. Flow through the filter and filter efficiency are determined from measured data in the literature.

The flow through an HVAC filter system (Q) can be considered as the sum of the flow passing through the filter media (Q_F) and the flow bypassing the filter (Q_B). The effective particle removal efficiency of the filter can then be written in terms of the penetration fraction of particles passing through the filter (P_F) and the penetration fraction of particles bypassing the filter (P_B) as shown in Equation 1.

$$\eta_{eff} = 1 - \left[\frac{P_F Q_F + P_B Q_B}{Q} \right] \tag{1}$$

P_F is equal to one minus the measured particle removal efficiency, η_F, of a filter with the gap sealed ($Q_B = 0$). Hanley *et al.* (1994) measured P_F and Q for various filters with different dust loadings and pressure drops. They eliminated bypass in their experiments, so Q equals Q_F for their work. The results of Hanley *et al.* (1994) and the measurements of filters from a major manufacturer by an independent laboratory provide values of P_F and Q_F for our model.

We estimated Q_B by using an expression, derived by Baker *et al.* (1987), that relates airflow to pressure drop through a rectangular-shaped crack in terms of the crack dimensions. Equation 2 is the Baker *et al.* (1987) expression applied to a bypass crack around a filter. This expression accounts for both laminar and turbulent flow and is directly applicable to the sharp-edged, rectangular gap between a filter and the filter frame or slot that holds the filter in place.

$$\Delta P = \frac{12\mu L}{WH^3} Q_B + \frac{(1.5+n)\rho}{2W^2H^2} Q_B^2 \tag{2}$$

where ΔP is the pressure drop across the filter, Q_B is the flow rate of air bypassing the filter, L is the length of the crack longitudinal to the flow, W is the width of the crack perpendicular to flow, H is the height of the crack, n is the number of right angle bends ($n < 3$ for Equation 2 to be valid) in the path of bypass flow, μ is the dynamic viscosity of air, and ρ is the density of the air. Baker *et al*. (1987) experimentally validated their model for ΔP between 0.1 and 100 Pa, and they demonstrated that, for ΔP up to 200 Pa, their model is superior to the power law relationship between pressure drop and flow. The results of Baker *et al.* (1987) show strongest agreement with measured data for higher Reynolds numbers and large gaps, conditions typical of those around HVAC filters. Equation 2 can be solved for Q_B, as shown in Equation 3:

$$Q_B = \frac{\left[-\frac{12\mu L}{WH^3} + \sqrt{\left(\frac{12\mu L}{WH^3}\right)^2 + \frac{2(1.5+n)\rho\Delta P}{W^2H^2}} \right]}{\left(\frac{(1.5+n)\rho}{W^2H^2}\right)} \tag{3}$$

Several researchers have studied deposition of particles traveling through cracks (Liu and Nazaroff 2001; Mosley *et al.* 2001; Carrie and Modera 2002). To account for P_B, we adapted the model of Liu and Nazaroff (2001) for particle penetration efficiency through a building envelope crack. As shown in Equation 4, Liu and Nazaroff (2001) modeled particle penetration through a rectangular crack as the product of penetration due to individual particle removal mechanisms.

$$P_B = P_g \times P_d \times P_i \approx P_g \times P_d \quad (4)$$

P_g, particle penetration due to gravitational settling, is assumed to be independent of P_d, particle penetration due to diffusion, since these two particle removal mechanisms are significant for different sized particles. P_i, particle penetration due to impaction, and P_g are not independent, and particles with enough inertia to be removed by impaction usually are removed by gravitational settling. Therefore, we have neglected P_i in order to avoid over-estimating the removal of larger particles in the gaps. The model of Liu and Nazaroff was intended for cracks in buildings where ΔP is less than 10 Pa, whereas the ΔP across an HVAC filter can be greater than 100 Pa. However, Liu and Nazaroff's reasoning should extend to HVAC filter gaps because it is based on the Baker *et al.* (1987) relationship between Q_B and ΔP, which was validated for ΔP up to 100 Pa and applies theoretically for higher ΔP. Liu and Nazaroff (2003) later experimentally validated their model.

Model Parameters

The model was applied to ten different HVAC filters with particle size, pressure drop, and gap shape varied. The face velocity (and hence Q_F) was held constant for each filter. Table 1 summarizes the descriptions of each filter.

Table 1: Filter characteristics

Filter Name	Filter Depth (m)	Filter Face Area (m^2)	Face velocity (m/s)	Display Element
Furnace Filter[a]	0.025	0.372	1.30	Fig. 2
Self-Charging Panel Filter[a]	0.025	0.372	1.30	Fig. 3
Pleated Panel Filter[a]	0.025	0.258	1.87	Fig. 4
Panel Electronic Filter[a]	0.025	0.372	1.30	Fig. 5
Pleated Paper-Media Filter[a]	0.150	0.372	1.30	Fig. 6
Pocket Filter[a]	0.560	0.372	1.30	Fig. 7
MERV 6[b]	0.127	0.315	1.50	Fig. 8
MERV 11[b]	0.102	0.330	2.50	Fig. 9
MERV 15[b]	0.051	0.372	2.50	Fig. 10

a: Data from Hanley *et al.*. (1994)
b: Data from independent test lab

Effective particle removal efficiency, η_{eff}, was compared for each filter with five gap shapes while ΔP and Q_F were held constant. The gap configurations were characterized as follows: the first was the no bypass case; the second, H = 1 mm and n = 2, was chosen to represent the lower bound on Q_B in which a filter is well seated around its perimeter in a U-shaped slot; the third, H = 1 mm and n = 0, was chosen to represent a well-seated filter with a straight-through crack; the fourth gap configuration, H = 10 mm and n = 2, was chosen to represent a poorly seated filter with a U-shaped gap; the final, H = 10 mm and n = 0, was chosen to represent the upper bound on Q_B in which the filter is poorly seated against a flange with no bends in the path of the air bypassing the filter. For all gap configurations, W is equal to the distance around the perimeter of the filter, and L (the distance a particle travels as it bypasses the filter) is equal to the depth (short dimension) of the filter plus 20 mm added for each bend (each flange adds 20mm to L.). Table 2 summarizes the bypass gap dimensions for each case considered.

Table 2: Bypass gap descriptions

Dimension	No bypass	U-shaped 1 mm gap 2 bends	Straight-through 1 mm gap 0 bends	U-shaped 10 mm gap 2 bends	Straight-through 10 mm gap 0 bends
H	0	1 mm	1 mm	10 mm	10 mm
L	0	Filter depth + 2×20 mm	Filter depth	Filter depth + 2×20 mm	Filter depth
W	0	Filter perimeter	Filter perimeter	Filter perimeter	Filter perimeter

RESULTS

This section presents model simulation results for each of the nine filters described in Table 1. Crack height (H), pressure drop (ΔP), and, to a lesser extent, the number of bends (n) significantly affected the bypass flow rate (Q_B). The Penetration fraction (P_F) and Q_B significantly affected the effective filtration efficiency (η_{eff}), but the bypass penetration fraction (P_B) only slightly affected η_{eff}.

Impact of bypass on flow

Model simulations indicate that Q_B increases significantly as gap size (H) or pressure drop (ΔP) increase. Further, effective fractional particle removal efficiency (η_{eff}) decreases significantly with Q_B and increases with the number of bends (n) for every particle size. To illustrate the relationship between bypass flow, pressure drop, and gap shape, Q_B/Q has been plotted as a function of ΔP for a 0.51 m × 0.51 m × 0.025 m filter with a 1.87 m/s face velocity for several gap shapes. Figure 1 shows that Q_B/Q increases parabolically with ΔP and that both gap size (H) and the number of bends (n) are important. Bypass flows are small (i.e. less than 5% of total flow) for a 1 mm gap and increase to 25-35% for a 10 mm gap. For a given gap size, increasing the number of bends decreases the bypass flow, and thus decreases the bypass flow ratio.

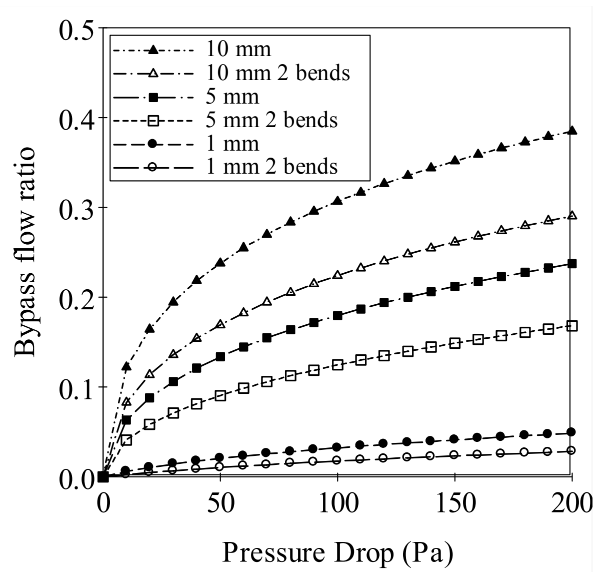


Figure 1: Relationship between pressure drop and bypass flow

Another factor that affects ΔP, and hence Q_B/Q, is the age or the amount of dust built up on the filter. A clean filter will have a lower pressure drop than at any other time during its life. Hence, the smallest bypass flow occurs when a filter is clean. Table 3, which presents Q_B/Q for each combination of clean filter and gap shape, shows that the ratio of bypass flow to total flow for clean filters ranges from 1-27%.

Table 3: Ratio of initial bypass flow to total flow rate for each clean filter

Filter	Clean ΔP (Pa)	Q_F (m^3/s)	U-shaped 1 mm gap 2 bends	Straight-through 1 mm gap 0 bends	U-shaped 10 mm gap 2 bends	Straight-through 10 mm gap 0 bends
Furnace Filter	10	0.484	0.3%	0.7%	9.8%	14.3%
Self-Charging Panel Filter	35	0.484	1.0%	1.9%	17.0%	23.8%
Pleated Panel Filter	68	0.483	1.3%	2.5%	19.2%	26.7%
Panel Electronic Filter	50	0.484	1.3%	2.5%	19.6%	27.2%
Pleated Paper-Media Filter	40	0.484	0.5%	0.6%	17.7%	24.7%
Pocket Filter	50	0.484	0.2%	0.2%	18.8%	25.6%
MERV 6	26	0.472	0.3%	0.4%	14.1%	20.0%
MERV 11	88	0.826	0.7%	1.0%	15.2%	21.5%
MERV 15	92	0.929	0.9%	1.5%	14.7%	20.9%

Table 4, which presents Q_B/Q for each combination of dust-loaded filter and gap shape, shows that the ratio of bypass flow to total flow ranges from 1-38% for dirty filters.

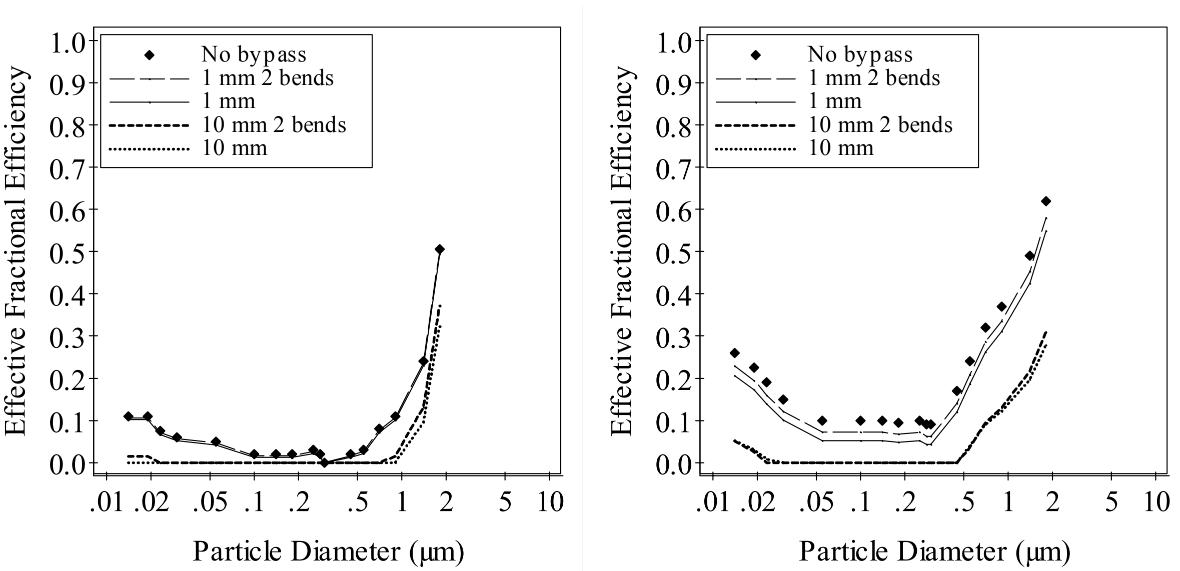
Table 4: Ratio of bypass flow to total flow rate for each dust-loaded filter

Filter	Dirty ΔP (Pa)	Q_F (m^3/s)	U-shaped 1 mm gap 2 bends	Straight-through 1 mm gap 0 bends	U-shaped 10 mm gap 2 bends	Straight-through 10 mm gap 0 bends
Furnace Filter	125	0.484	2.5%	4.4%	27.9%	37.2%
Self-Charging Panel Filter	125	0.484	2.5%	4.4%	27.9%	37.2%
Pleated Panel Filter	125	0.483	2.1%	3.7%	24.4%	33.1%
Panel Electronic Filter	125	0.484	2.5%	4.4%	27.9%	37.2%
Pleated Paper-Media Filter	125	0.484	1.3%	1.7%	27.8%	36.9%
Pocket Filter	125	0.484	0.5%	0.5%	27.2%	36.0%
MERV 6	150	0.472	1.6%	2.2%	28.5%	37.8%
MERV 11	128	0.826	0.9%	1.3%	17.8%	24.9%
MERV 15	156	0.929	1.3%	2.2%	18.4%	25.6%

Impact of bypass on filter efficiency

The effective efficiency, η_{eff} is plotted as a function of particle size for each clean (Figures 2a-10a) and dust-loaded (Figures 2b-10b) filter. The five gap configurations discussed above are presented in each figure. The no-bypass case comes from measured data of Hanley *et al.* (1994) and from an independent test lab. The lines represent simulated effective filter efficiencies for each gap. These figures delineate the bounds of the influence of bypass on efficiency for a range of typical filters. In general, a 1 mm gap slightly lowered the fractional efficiency for every particle size, and a 10 mm gap significantly lowered fractional efficiency. Gaps with two bends lowered fractional efficiency less than gaps with no bends. Fractional efficiency was lowered by about the same amount for particles less than 1 µm. For particles larger than 1µm, fractional efficiency was lowered less as particle size increased. This indicates that particles larger than 1µm deposit in the gap but particles smaller than 1 µm are not appreciably removed in the gap.

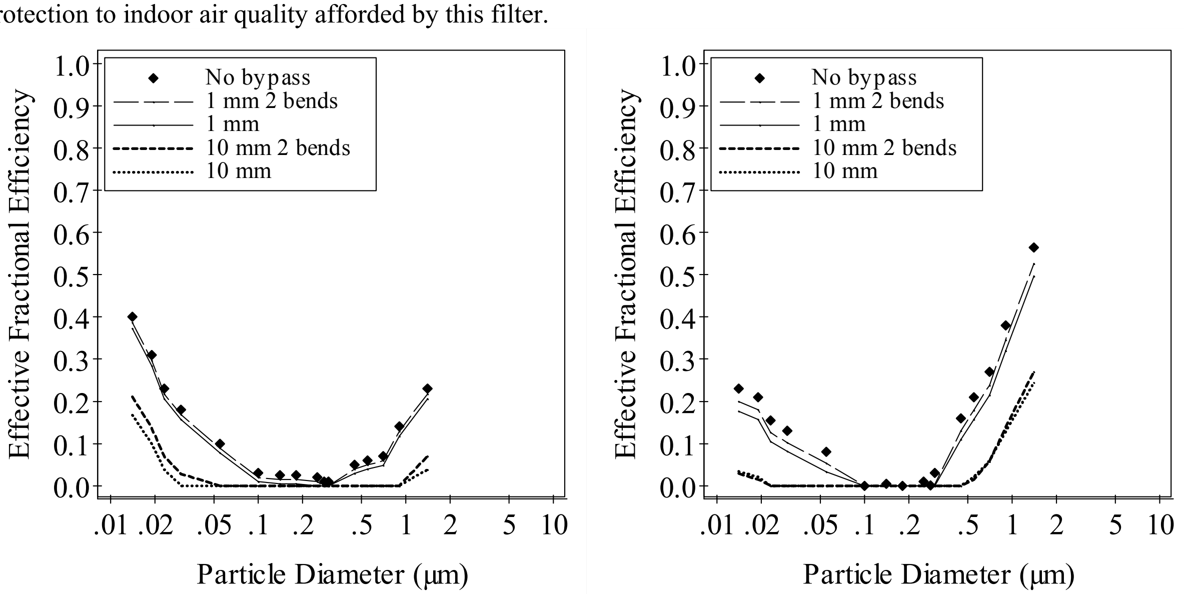
For most of the filters, a 10 mm gap completely negates the added efficiency from dust loading, and a clean filter with no gap performs better than a loaded filter with a 10 mm gap. For relatively low pressure drop filters, such as the clean Furnace Filter (Figure 2a), the bypass flow, Q_B, is quite small. For the 1 mm gaps, the effective efficiency, η_{eff}, is very close to the filter efficiency, η_F. For the larger 10 mm gaps, the effective efficiency is close to zero for all submicron particles. Figure 2b shows the same filter when loaded with test dust to 125 Pa. The larger pressure drop causes more bypass flow, which in turn causes an increased reduction in η_{eff}. Overall efficiency reductions are 2-5 percentage points for 1 mm gaps and 10-30 percentage points for 10 mm gaps.



(a) **(b)**

Figure 2: Effective particle removal efficiency for a clean (a) and dust-loaded (b) Furnace Filter with pressure drops of 10 and 125 Pa, respectively

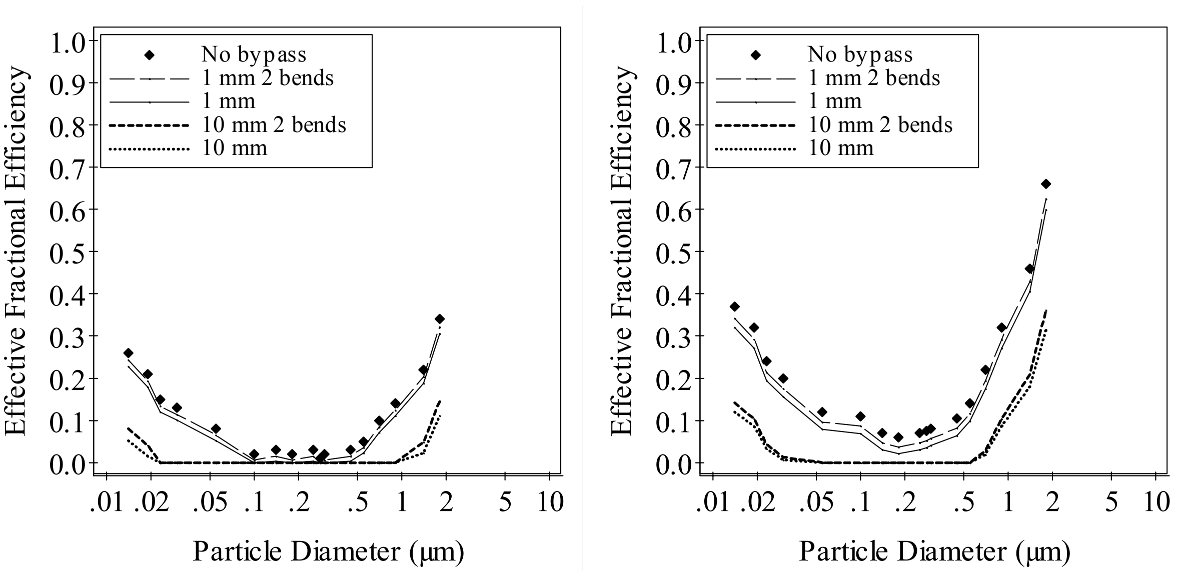
Figure 3 shows η_{eff} for a Self-Charging Panel Filter. Bypass decreases η_{eff} by about one percentage point for a 1 mm gap to about 20 percentage points for a 10 mm gap. For the Self-Charging Panel Filter with a large gap, η_{eff} is zero for the most respirable range of particle size. This observation indicates that bypass could negate most protection to indoor air quality afforded by this filter.



(a) **(b)**

Figure 3: Effective particle removal efficiency for a clean (a) and dust-loaded (b) Self-Charging Panel Filter with pressure drops of 35 and 125 Pa, respectively

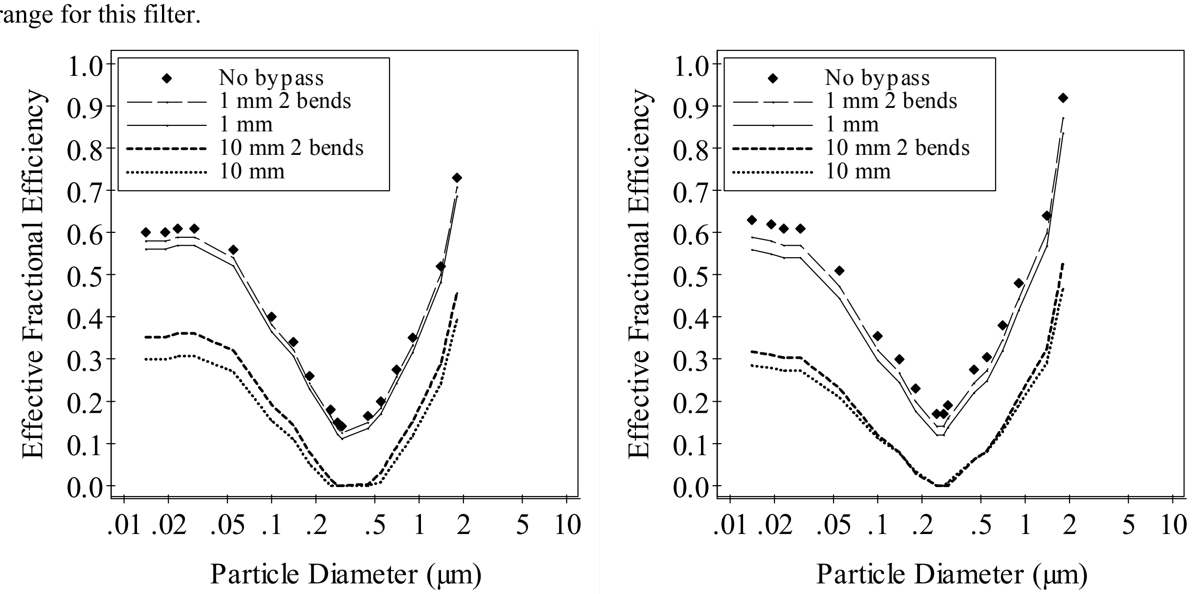
Like the Furnace Filter (Figure 2) and the Self-Charging Filter (Figure 3), the Pleated Panel Filter (Figure 4) offers no protection from most respirable particles when large bypass gaps are present. Bends begin to play a significant role in this filter with a difference of five percentage points for 0.02 µm particles.



(a) **(b)**

Figure 4: Effective particle removal efficiency for a clean (a) and dust-loaded (b) Pleated Panel Filter with pressure drops of 68 and 125 Pa, respectively

The number of bends in the bypass gap is important for the Panel Electronic Filter (Figure 5). Two bends decrease efficiency by two to three percentage points for a clean filter with small gaps to about six percentage points for large gaps. Bypass decreases efficiency much more for the smallest and largest particles than for the middle range for this filter.



(a) **(b)**

Figure 5: Effective particle removal efficiency for a clean (a) and dust-loaded (b) Panel Electronic Filter with pressure drops of 50 and 125 Pa, respectively

Figures 6 and 7 show the effective efficiency of the Pleated Paper-Media Filter and the Pocket Filter, respectively. Bypass has a similar impact on both of these filters. The 1 mm gap causes almost no change in the effective efficiency, and the number of bends is unimportant. For the 10 mm gaps, the effective efficiency degrades by 20 - 40 percentage points for the clean Pleated Paper-Media Filter and 30 - 40 percentage points for the Pocket Filter. When loaded to 125 Pa, the effective efficiency of the Pleated Paper-Media Filter decreases by 30 – 50 percentage points and the Pocket Filter shows a similar degradation of 30 - 40 percentage points. Note that when loaded, and with no bypass, the Pocket Filter has a measured efficiency of over 90% for the entire particle size range measured by Hanley *et al*. (1994). With a 10 mm bypass crack, the effective efficiency drops to between 50 and 60% over the same range. Another interesting observation about the Pleated Paper Media Filter and the Pocket Filter is that decreased efficiency is fairly uniform over the range of particle sizes.

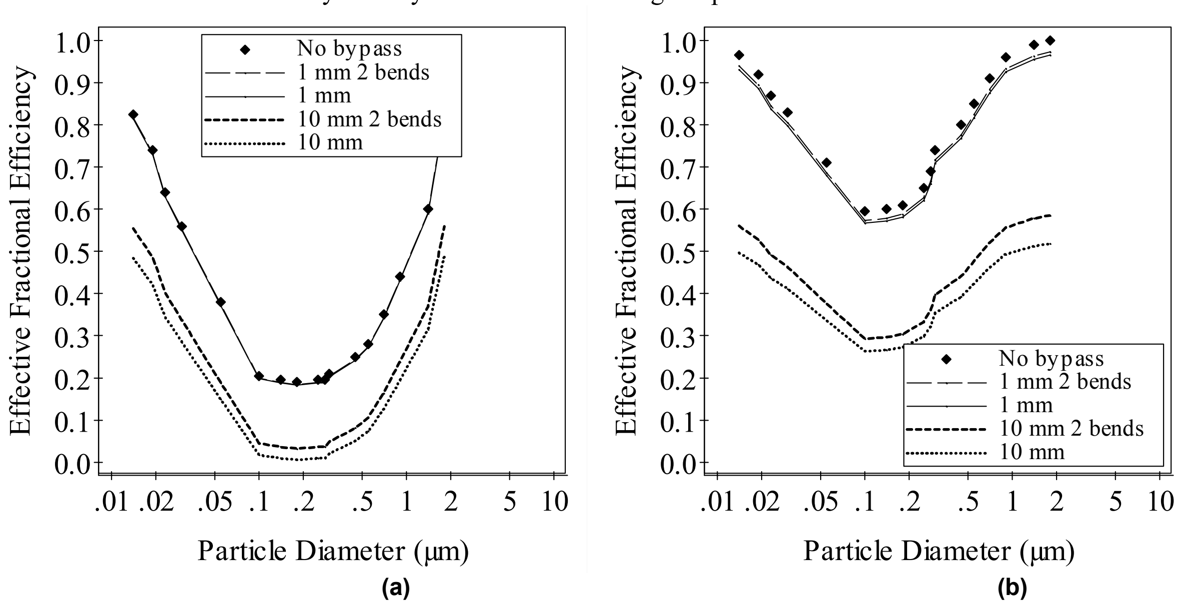


Figure 6: Effective particle removal efficiency for a clean (a) and dust-loaded (b) Pleated Paper-Media Filter with pressure drops of 40 and 125 Pa, respectively

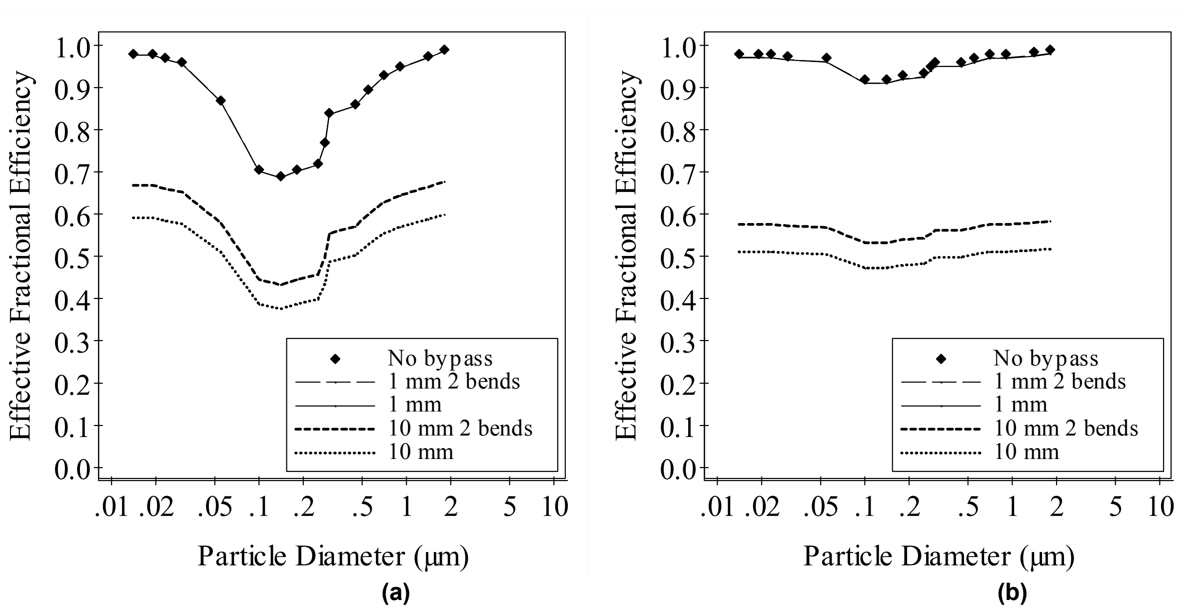


Figure 7: Effective particle removal efficiency for a clean (a) and dust-loaded (b) Pocket Filter with pressure drops of 50 and 125 Pa, respectively

The MERV rated filters show data for a particles ranging from 0.3 – 10 μm as opposed to the range used in Figures 2 – 7. The different range is representative of the fact that this data was produced as part of an ASHRAE Standard 52.2 test. This particle size range shows that bypass has a greater influence on efficiency as particle size increases. The MERV filters should not be compared to the other filters in this study without noting differences in face velocity, flow rate, filter area, and filter depth.

For most of the filters, a 10 mm gap completely negates the added efficiency from dust loading, and the clean filter with no gap performed better than the loaded filter with a 10 mm gap. However, for the MERV 6 (Figure 8) filter dust loading increases efficiency by more than the 10 mm gap lowers efficiency, and this dust-loaded filter with a 10 mm gap performs better than the clean filter with no gap.

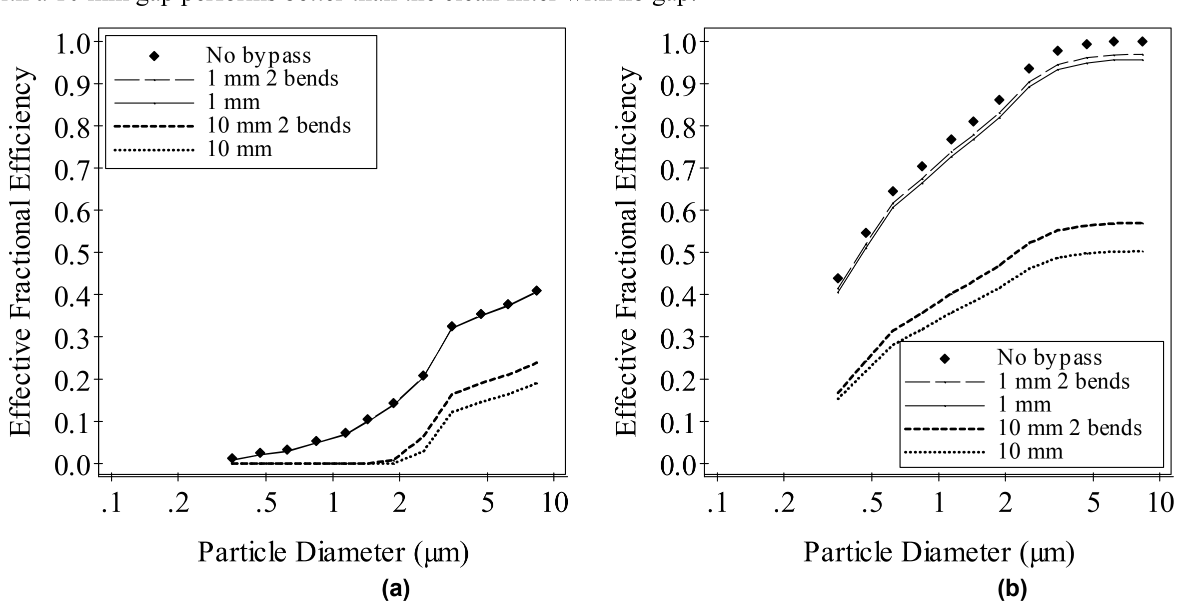


Figure 8: Effective particle removal efficiency for a clean (a) and dust-loaded (b) MERV 6 filter with pressure drops of 26 and 150 Pa, respectively

For the MERV 11 filter (Figure 9), the importance of bends increases as particles increase in size up to 2 μm, after which, the number of bends no longer increases in importance. Also, for the MERV 11 filter, a gap height of 1 mm makes almost no effect on efficiency.

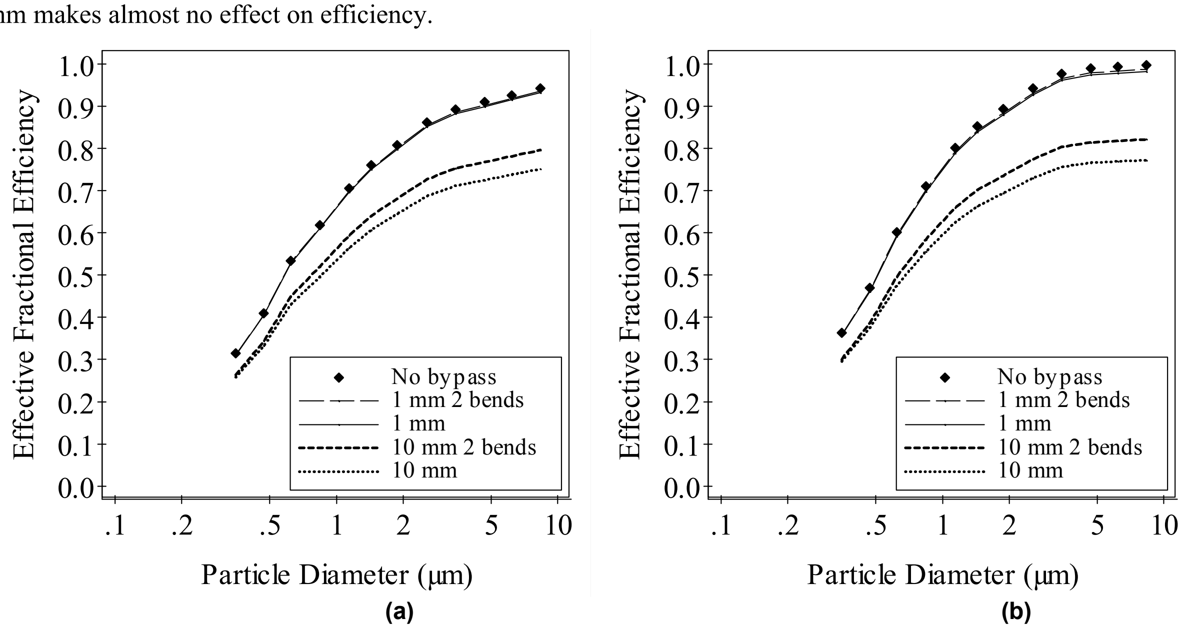
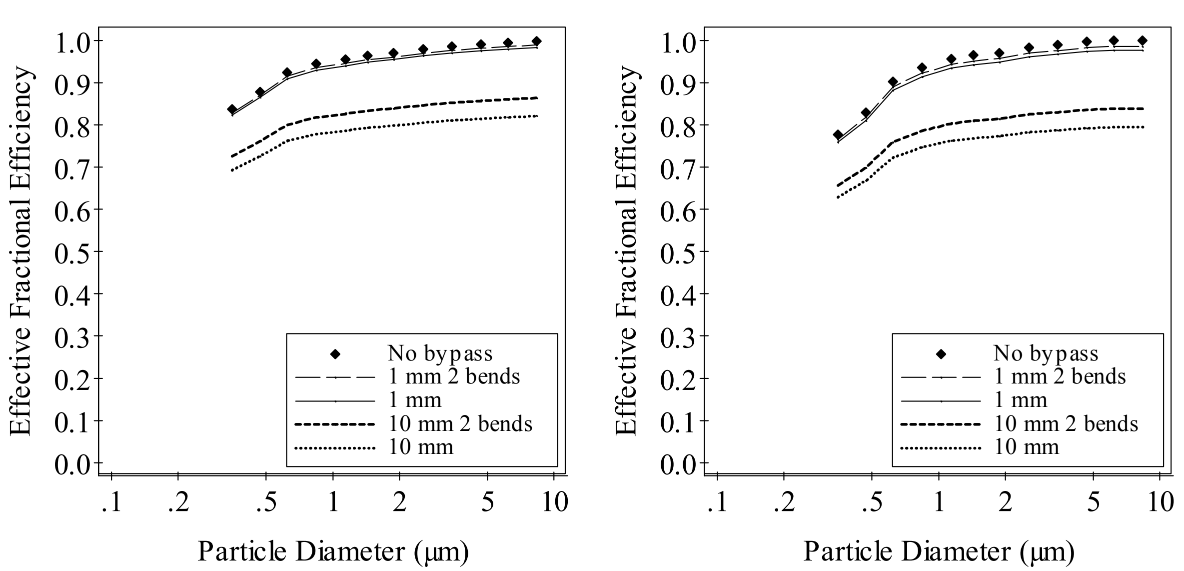


Figure 9: Effective particle removal efficiency for a clean (a) and dust-loaded (b) MERV 11 filter with pressure drops of 88 and 125 Pa, respectively

The MERV 15 filter (Figure 10) has the largest clean pressure drop, ΔP, of any of the other filters and, not surprisingly, it has the least difference in efficiency between clean and dust loaded. Bypass lowers efficiency by 10 – 20 percentage points for 10 mm gaps with 2 bends to 15 – 26 percentage points for 10 mm gaps with no bends.



(a) **(b)**

Figure 10: Effective particle removal efficiency for a clean (a) and dust-loaded (b) MERV 15 filter with pressure drops of 92 and 156 Pa, respectively

Impact of bypass on MERV rating

Effective MERV ratings ($MERV_{eff}$) that include the effect of bypass were calculated for the three MERV rated filters. For the MERV 15 filter, a small gap (H = 1 mm) caused the $MERV_{eff}$ rating to decrease by one point. A small gap did not decrease the rating of the MERV 11 or the MERV 6 filter. A large gap decreased the rating of the MERV 15 filter by seven points, the MERV 11 filter by three points, and the MERV 6 filter by one point. Except for the MERV 6 filter, bends did not make large enough differences to change the $MERV_{eff}$ rating. Table 5 summarizes these results.

Table 5: Effective MERV ratings with bypass included

Filter	1 mm gap, 2 bends	1 mm gap, 0 bends	10 mm gap, 2 bends	10 mm gap, 0 bends
MERV 6	6	6	5	<5
MERV 11	11	11	8	8
MERV 15	14	14	8	8

DISSCUSSION AND CONCLUSIONS

The results have important implications for the understanding filter performance. They suggest that most HVAC filters with sizeable bypass gaps actually perform worse with age, which is opposite to the assumption of conventional knowledge. Moreover, high efficiency filters may not justify their expense if they have sizable gaps. For example the loaded Pleated Paper-Media Filter with no gap performs better than the loaded Pocket Filter with a 10 mm gap. In other words any economic analysis seeking to optimize the cost effectiveness of filtration must either include costs for minimizing bypass or account for reduced efficiency caused by bypass. The data presented in this paper can provide a basis for such analyses.

The results also show that respirable particles are not appreciably removed in the gap, which means that bypass is significantly detrimental to indoor air quality. An HVAC design that employs high efficiency filters to prevent health problems associated with indoor fine particles may fail to perform as intended due to bypass. The results presented in this paper can provide a basis to quantify the effect of bypass on indoor air quality.

For all of the simulations, we assumed that volumetric flow through the filter (Q_F) was constant. In some HVAC systems, it would be more correct to hold the total flow (Q) constant. The analysis of bypass would thus involve an iterative procedure where the flow is allocated between the filter and the bypass crack until the pressure drop through both flow paths was equal. We did not complete this procedure because we did not have efficiency data for the reduced filter face velocities that would result, but this effect should be included in future measurements of bypass.

While the model simulations presented in this paper provide a quantitative account of bypass, they do not substitute for experimental data and the results should be verified experimentally both in a laboratory apparatus with controlled parameters and in real HVAC systems. Also, the bypass results coupled with full HVAC deposition models can provide a comprehensive accounting of HVAC systems' influence on indoor particulate matter with an ability to relax the usual assumption that the particle removal efficiency is equal to the rated filter efficiency. Finally, the authors hope that this work will motivate methods to detect bypass in the field and to create HVAC designs that reduce bypass.

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