# HVAC filter bypass modelling and experimental validation

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## SUMMARY

To validate an analytic model of filter bypass, an ASHRAE Standard 52.2-2007 compliant apparatus was modified to accept filters with a known bypass gap. The test matrix covered filter efficiencies from MERV 2 through 14, gap sizes up to 32 mm, and straight-through and U-shaped bypass gap configurations. The results show that as the filter efficiency increases, bypass causes a greater decrease in particle removal efficiency. Less efficiency degradation occurs when a flow restriction through the bypass gap is introduced, such as caused by the right angle bends of a U-shaped rack channel. The model is in close agreement (± 5% for all particle sizes) with the experimental results for most cases. However, when more complex filter rack geometries are considered, the model does not predict the effective efficiency as well. The results suggest that the impacts of bypass are significant and can be predicted for many important scenarios.

## KEYWORDS

Particle, Filtration, Filter efficiency, Crack

## 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 (ASHRAE, 2007) and EN 779. The result of an ASHRAE Standard 52.2 test includes the Minimum Efficiency Reporting Value (MERV), which classifies filters according to their efficiency. Standard 52.2-2007, as well as most other filter test methodologies, is a test of the filter in an ideal installation. When applied to real systems, filter test results implicitly assume that no air and particle bypass exists around filters. Examination of most residential and commercial HVAC systems suggests that this is not a good assumption as both small and large gaps are common (Braun, 1986; Ottney, 1993).

Despite the widespread understanding of the importance of filter bypass, it has received limited formal study. Ward and Siegel (2005) presented a mathematical model of filter bypass that suggested that high pressure drop filters experience more degradation than low pressure drop filters. Large filter gaps also led to more bypass when compared to smaller gaps, and even a small gap (1 mm) could lead to measurable efficiency degradations for some filters. Waring and Siegel (2008) used the mathematical model to assess the impact of bypass on filters in residential and commercial HVAC systems and found increased fouling of downstream components when bypass was present as well as decreased filter loading from bypass. Several researchers (as cited in Ward and Siegel, 2005) have anecdotally reported filter bypass in field installations.

The central purpose of this paper is to provide experimental validation of the Ward and Siegel (2005) model. One of the conclusions from that paper was that their results, “do not substitute for experimental data and the results should be verified experimentally.” In this paper we validate the model for a variety of gap sizes and configurations and explore the validity of the model for some cases of more complex and potentially realistic bypass geometries. The central parameter of interest is the effective efficiency which is the particle-size resolved efficiency curve for the filter and the bypass gap. The overall research goal is to understand the strengths and limitations of the model for predicting filter bypass in real buildings.

## MATHEMATICAL MODEL AND EXPERIMENTAL MATRIX

The mathematical model of filter bypass is described in greater detail in Ward and Siegel (2005) and the purpose of this section is to provide an overview of the model, as well as the experimental matrix that was used for verification of the model. The effective filter efficiency including bypass, $\eta_{\mathrm{eff}}$, is defined as:

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

where $P_F$ is the penetration through the filter, $Q_F$ is the flow through the filter, $P_B$ is the penetration through the bypass gap, and $Q_B$ is the flow through the bypass gap. $P_F$ and $P_B$ are particle size dependent, $P_F = 1 - \eta_F$ where $\eta_F$ is the measured filter efficiency with no bypass, and $P_B$ is calculated using the work of Liu and Nazaroff (2001). However for the relatively large 6.4 - 32 mm bypass gap sizes presented in this paper, $P_B \approx 1$ for the entire particle size range considered. $Q_F$ is the measured flow through the filter and $Q_B$ is the bypass flow calculated from the work of Baker et al. (1987) who developed and verified a model of airflow through cracks in buildings. $Q_B$ is a function of the pressure drop across the filter/bypass gap ($\Delta P$), the length, height, and width of the bypass gap, and the number of bends (i.e., a U-shaped gap has two bends). Although designed for a different purpose than the flow around filters, the Baker et al. (1987) model is readily applicable to the problem of filter bypass because of the similar geometry (Ward and Siegel, 2005). The assumptions inherent in the model include $\Delta P \leq 250$ Pa and that there are two or less bends in the bypass gap.

In order to verify the bypass model, validation testing that spanned a wide range of filter efficiencies and pressure drops, bypass gap sizes and configurations, and particle sizes was conducted. Four filter efficiencies (MERV 2, 7, 11, and 14) were considered spanning the range from furnace to high efficiency commercial filters, three gap sizes (6.4, 18, and 32 mm) which refer to the distance between the filter edge and the duct wall, and two gap configurations (straight-through with no bends, and U-shaped with two bends). In addition to the 24 tests described above, six additional tests were completed with a U-shaped configuration, referred to as “U-shaped real”, where the filter was seated against the rear flange and could potentially form a seal or have a smaller gap.

## METHODS

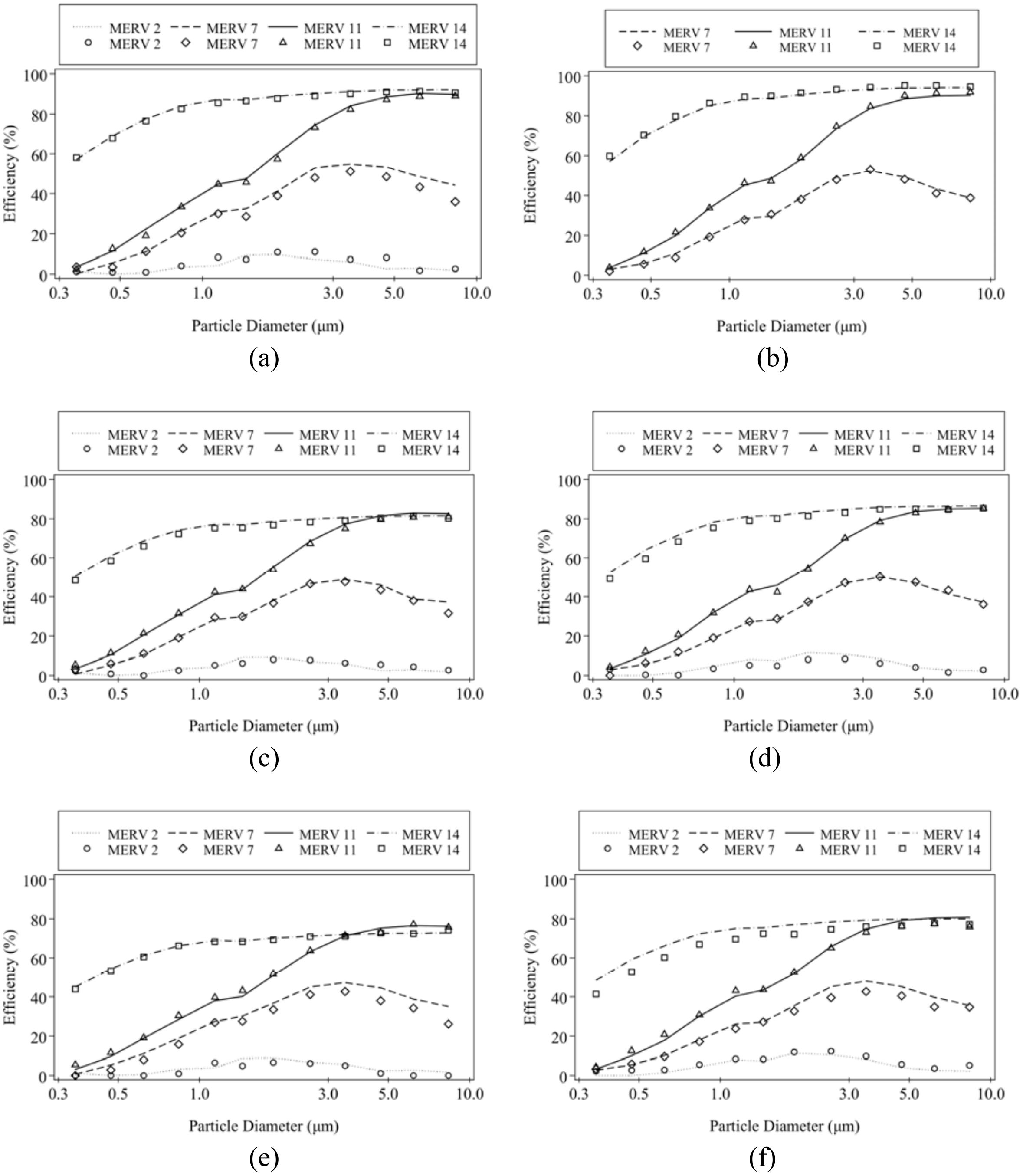
The experimental matrix described above was tested in a fully qualified ASHRAE Standard 52.2 (ASHRAE 2007) test duct located in Chicago, IL, USA. The test duct consists of modular stainless steel duct sections and has been described elsewhere (Nigro et al., 2008). For each cell in the matrix, a filter was installed with the appropriate gap size along one edge of the filter (597 mm from top to bottom). The filter test-section was modified to allow a variable, but precisely spaced, gap. All other filter edges were sealed with masking tape. An ASHRAE Standard 52.2-2007 initial efficiency test was run in which polydisperse potassium chloride particles were generated 3.7 m in front of the filter and particle concentrations were measured upstream and downstream using a Climet Spectro .3 Optical Particle Counter with 12 particle size bins representing the range from 0.3 – 10 μm, as required by the standard. ASHRAE Standard 52.2-2007 has numerous procedures to ensure that the particle concentration in the duct is uniform and that the upstream and downstream concentrations are consistent and all such procedures were followed. The effective filter efficiency, $\eta_F$, was calculated as a function of particle diameter according to the procedures in the standard and an initial efficiency reporting value, IERV, was calculated from Table 12-1 in the standard. IERV is analogous to MERV but is based on the initial efficiency values only. After initial testing of six cells on the matrix confirmed that the values for the filter penetration, $P_F$, were not sensitive to the gap size when the gap was taped, a single $P_F$ value was measured for each filter efficiency. In addition to geometric parameters (length, height, width, and number of bends in the bypass gap), the model also requires the filter/bypass gap pressure drop, $\Delta P$, the flow through the filter, $Q_F$. $\Delta P$ was measured with a Meriam Instruments manometer and $Q_F$ with a flow nozzle and manometer as described ASHRAE Standard 52.2-2007. For comparison to the model, $Q_B$ was calculated by subtracting $Q_F$ from the total measured flow through the filter and bypass gap.

## RESULTS AND DISCUSSION

Filter efficiency as a function of particle size for all tests are shown in Figures 1(a) – (f). In all parts of Figure 1, the experimental results for each of the 12 bins are shown with a symbol and the modeling results are shown with a trace. One test (U-shaped, 6.4 mm gap, MERV 2 filter) was not completed because the experimental results showed substantial variation between runs. In all cases, the model results show very close agreement with the measured bypass results. Some overprediction of efficiency is seen for larger particles, particularly in some cases with the MERV 7 filter (Figures 1 (a), (e), and (f)) as well as for all particle sizes with the MERV 14 filter (most noticeable in Figure 1(f), but also in Figures (c) and (d)). The general trends observed in the data are similar to those predicted by Ward and Siegel (2005) including a strong dependence of efficiency degradation on filter efficiency and pressure drop. Higher pressure drop filters cause more air to be forced through the bypass gap. Because higher efficiency filters usually have higher pressure drop, the decrease in efficiency is greater for these filters. Filter efficiency generally increases in particles size over the 0.3 – 10 μm range considered in ASHRAE Standard 52.2-2007 (ASHRAE, 2007) and MERV 11 and 14 filters are generally very efficient for particles greater than 5 μm, so the impacts of bypass are general most striking for large particles.

In order to determine the range of agreement between the modeled and the measured data, Figures 2(a) – (c) show a comparison of the modeled vs. measured data for the particle size bins centered on 0.62, 1.9, and 6.2 μm particles. These bins were selected because they are the central bins of the sizes ranges that are used to calculate the E1 efficiency (0.3 – 1 μm), E2 efficiency (1 – 3 μm), and E3 efficiency (3 – 10 μm) in ASHRAE Standard 52.2-2007. E1, E2, E3 are used to calculate the MERV/IERV. In Figure 2, the symbol shape indicates the MERV value of the filter with no bypass, the size of the symbol indicates the gap size, and the hollow symbols are used to designate the straight through bypass and the filled symbols are used to designate the U-shaped bypass. Any point that falls on the solid diagonal line represents perfect agreement and the dashed lines indicate ±5 percentage points. For all the particle size bins and for all cases (276 total comparison points), including those not shown in Figure 2, all of the points except for four fell within five percentage points of the model.

Thus, this is a reasonable uncertainty bound for the model and is within the uncertainty in efficiency values that many Standard 52.2 users report anecdotally.



(a) (b)

(c) (d)

(e) (f)

Figure 1. Measured (symbols) and modeled (traces) filter bypass for (a) straight-through 6.4 mm gap, (b) U-shaped 6.4 mm gap, (c) straight-through 19 mm gap, (d) U-shaped 19 mm gap, (e) straight-through 32 mm gap, and (f) U-shaped 32 mm gap.

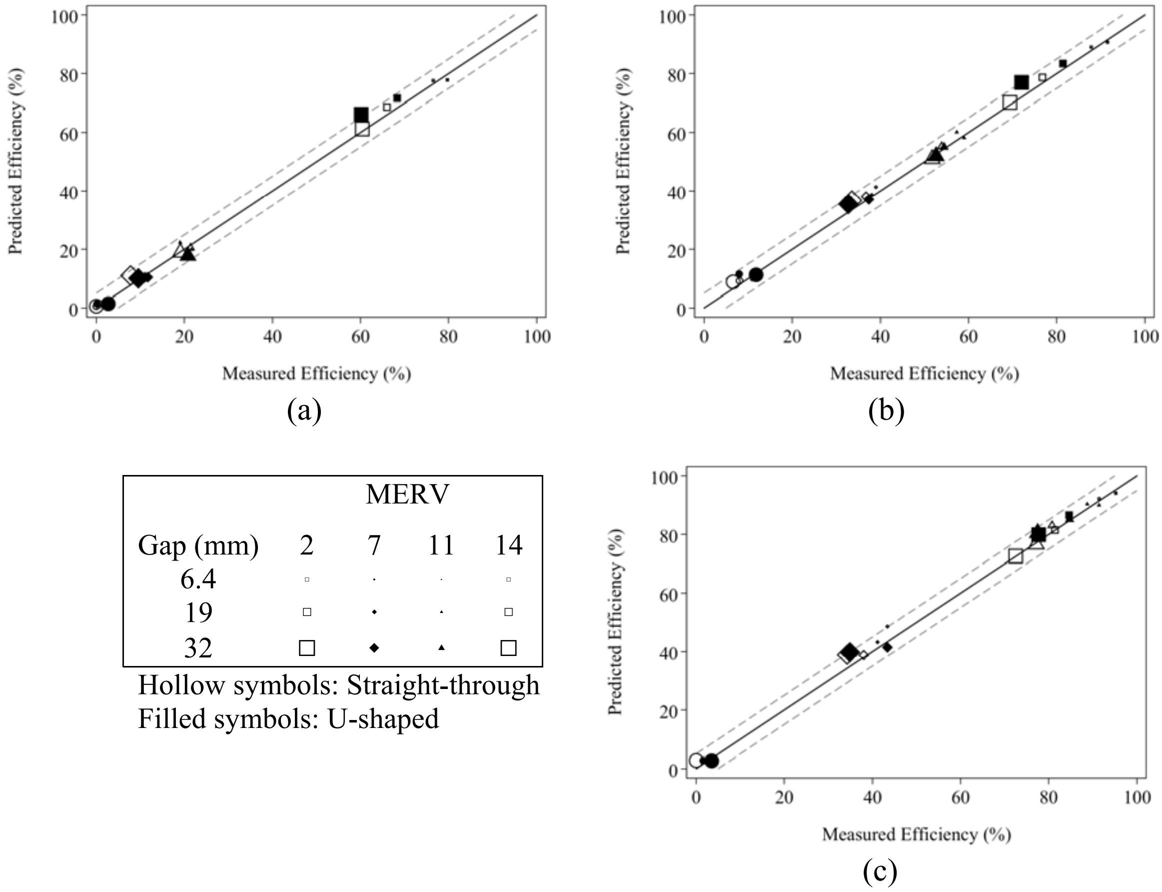


Figure 2. Comparison of modeled and measured efficiency for (a) 0.62 µm, (b) 1.9 µm, and (c) 6.2 µm bins. Dashed lines are five percentage points above and below perfect agreement.

An important question is whether the discrepancy between modeled and measured efficiency is due to an error associated with the model or the measurements. The error in the efficiency measurements has not been calculated at this time. This total error in filter efficiency is difficult to determine because it depends on many factors, including any errors associated with the optical particle counter, particle concentration variation in the duct, air flow non-uniformities, etc. In order to determine if error in the model prediction of bypass flow was causing any discrepancy, the modeled vs. measured comparisons in Figure 2 were repeated, this time using the measured values for $Q_B$. The results in some cases improved, but in other cases got worse. An unweighted comparison of all particle sizes and cases showed no improvement, suggesting that the discrepancy in modeled and measured values was likely not due to the model prediction of flow. Another potential discrepancy is with the calculation of $P_B$, which is based on the work of Liu and Nazaroff (2001). Any difference would represent a bias in the results as the modeled particle deposition in the gap was equal to unity for all considered cases, unlike for the much smaller 1 mm gap modeled by Ward and Siegel (2005). This may serve as a possible explanation for the slight bias towards overprediction of the measured efficiency, as described above. One limitation of this explanation is that any such difference in particle deposition would likely be a function of particle size and, given the large particles considered here, would likely be greater for larger particles. The fact that no such consistent discrepancy was found suggests that uncertainty associated with the measured results is a more probable explanation.

A practical way of summarizing the data is to compare the IERV values between the modeled and the measured data. Using the procedure for calculating MERV values described in Table

12-1 of ASHRAE Standard 52.2-2007, the IERV were calculated for modeled and measured data and are shown in Table 1. Such calculations were not completed for the MERV 2 filters because they require an additional test for low efficiency filters (MERV <4), which was not completed. The MERV values for the modeled and the measured data were in agreement for all cases except for the 6.4 mm U-shaped gap with the MERV 7 filter for which a MERV 7 instead of a MERV 6 was predicted. Examination of Table 12-1 in Standard 52.2 shows that this one discrepancy was caused because of the fact that this filter was very close to the E3 efficiency boundary between MERV 6 and 7 filters.

Table 1. Measured initial efficiency reporting values (IERVs) with and without bypass. Except where indicated, the modeled results agree with the measured values and the U-shaped and straight-through bypass configuration have the same IERV values.

| MERV with No Bypass | Gap Size | | |
|---|---|---|---|
| | 6.4 mm | 19 mm | 32 mm |
| 7 | 6[a] | 6 | 6 |
| 11 | 10 | 8 | 8 |
| 14 | 12/13[b] | 8 | 8 |

[a] Modeled value predicted no decline for U-shaped filter (i.e., MERV 7)

[a] Straight-through = MERV 12, U-shaped = MERV 13

Perhaps most striking about Table 1 is the declines in efficiency that occur. An MERV/IERV 7 filter slightly declines to IERV 6 with any of the three gap sizes. A MERV/IERV 11 filter declines slightly with a 6.4 mm gap, but declines to MERV 8 for both 19 and 32 mm gap. The MERV/IERV 14 filter declines to MERV 13 with a 6.4 mm U-shaped gap and MERV 12 with a 6.4 mm straight-through gap and it also declined to MERV 8 with the larger gap sizes. This suggests that for either of the two larger gap sizes, a MERV 11 and MERV 14 filter will perform similarly. This is similar to that discussed in Ward and Siegel (2005) and is likely caused by the fact that a bigger pressure drop filter pushes more air through the bypass gap.

To further explore applications of the model, the six cases with U-shaped real gaps were compared. As expected, the model did under-predict the measured efficiency, because it does not account for the much smaller gap with the downstream flange of filter rack. We investigated what effective gap size would cause the best agreement between the modeled and the measured results and these results appear in Table 2. The effective gap sizes in Table 2 are much smaller than the nominal gap sizes as expected, indicating that the filters do self-seal to a certain extent. However, there is no obvious trend that would allow prediction of the efficiency degradation for U-shaped real gaps. The MERV 11 and MERV 14 filter do show an opposite trend of effective gap size for the two measured gap sizes in Table 2, suggesting that frame and filter rack shape differences may affect how well a filter seals in this configuration. The results do have implications for the design of filter seals because they suggest that the size of the narrowest section of the gap may govern the overall bypass. Therefore, elaborate seals that seal at multiple places in the direction of flow are likely not warranted.

Table 2. Effective gap sizes for optimal modeled-measured agreement for U-shaped real gaps.

| Filter MERV | Nominal 6.4 mm (mm) | Nominal 19 mm (mm) |
|---|---|---|
| 7 | <1 | <1 |
| 11 | 4 | 7 |
| 14 | <1 | 9 |

## CONCLUSIONS

The results presented here highlight the importance of filter bypass and confirm earlier modeling predictions that the degradation of efficiency due to bypass increases in severity for higher pressure drop filters and larger gap sizes. A mathematical model presented in earlier work (Ward and Siegel, 2005) was validated with experimental results. The model generally predicts the results within five percentage points of the measurements, likely within the range of uncertainty for the measurements. For U-shaped real gaps, the model is not a good predictor of the amount of efficiency degradation and caution is suggested when applying the model to this geometry. It is hoped that the model serves as a useful tool for exploring filter bypass and promotes the development of sealing technologies and filter racks that eliminate bypass.

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