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Laboratory Measurements to Quantify the Effect of Bypass on Filtration Efficiency

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ABSTRACT

The issue of filter bypass has long been a topic of much interest in the HVAC industry, but to date, there has been limited work that quantifies the effect of bypass on filtration efficiency. In this research, an ASHRAE 52.2 compliant test loop was used to study bypass. A matrix consisting of filters ranging from MERV 2 to MERV 14, different gap geometries, and gap sizes was completed. The results show that the efficiency degradation effects of filter bypass are more pronounced with increasing filter efficiency, as well as increasing gap size. For the first set of tests, the pressure drop across the test filter was held constant with and without bypass. It is recognized that this assumption is not realistic in all field installations. As a result, a second set of tests was developed and completed where fan speed was held constant with and without filter bypass. The results suggest that filter bypass can cause significant and predictable degradation of filter efficiency and an assessment of bypass is essential for high-performance filtration.

INTRODUCTION

In the HVAC industry, the focus has migrated towards improving respiratory health and protection of building occupants from contaminants. This has lead to the development and marketing of higher efficiency filters and equipment. However, the fact is that no matter how efficient the filter is, without proper installation, it will not perform up to its full potential. One of the key components to proper installation is the elimination of filter bypass. It is widely known that filter bypass can have a major effect on efficiency, but minimal effort has been exerted on quantifying this effect. Ward and Siegel (2005) developed an analytical model to predict the effects of bypass on filter efficiency. This study employed a mathematical model developed to estimate pressure driven air flow through cracks in building envelopes. A range of gap sizes, geometries, and filter efficiencies were analyzed, but model validation using field studies was not performed. In this work, we provide validation experiments for a wide variety of gap geometries and filter efficiencies. Furthermore, a critical assumption used when applying the model is that the pressure drop and volumetric airflow through the filter is the same with and without bypass. Although this assumption allows the model to be directly applied to existing data, it does not replicate what is found in many field installations. For this reason, a second group of tests were performed where fan speed remained unchanged during the test, regardless of the presence of bypass. This work presents the results from the constant pressure drop and constant fan speed tests and analyzes the differences between the two types of tests.

Experimental Method

To conduct this research on filter bypass, a test apparatus designed to ASHRAE Standard 52.2-2007 was used. This standard provides a methodology for testing standard 24 in.× 24 in. (0.61 m × 0.61 m) filters for initial efficiency as well as efficiency after five incremental dust loadings. The methodology for measuring the efficiency of the test filter consists of injecting potassium chloride (KCL) particles into the test apparatus and measuring the concentration of the particles upstream and downstream of the test filter using a laser particle counter. These concentrations were then used to determine the efficiency of the test filter at twelve individual particle size ranges from 0.3-10 μm. The efficiency was also measured after injecting ASHRAE dust upstream of the filter. The dust

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was used to increase the resistance of the filter and simulate the loading effect that particulate has on a filter over time. Dust was injected five times throughout the test until the final pressure drop of the test filter was attained.

The standard also provides a means of quantifying the performance of a filter with a single value. This corresponds to the minimum efficiency reporting value or MERV. This value is determined based on the calculated efficiencies obtained after performing a full ASHRAE 52.2 test (initial efficiency and five dust loading efficiency measurements). The minimum efficiencies from the six efficiency measurements are averaged for each range shown below in Table 1. The three average minimum efficiencies for each of the ranges are then used to determine the MERV value of the test filter using the lookup table below.

Four filter efficiency values MERV 2, MERV 7, MERV 11, and MERV 14 were selected for this research. These were chosen to cover a range of filters commonly found in HVAC applications. The bypass gaps that were chosen were 0.25, 0.75, and 1.25 in. (6.4, 19.1, 31.8 mm). Based on Ward and Siegel (2005), it was decided that any bypass gap smaller than 0.25 inch (6.4 mm) would most likely cause a smaller change in efficiency than the uncertainty of an ASHRAE Standard 52.2 test.

In order to incorporate bypass into the duct using standard filters, modifications to the test rig were implemented. The main modification involved replacing one of the test filter access doors with a custom designed filter bypass door which provides adjustable bypass on only one side of the filter. This door contains a pocket for the filter to slide into resulting in a bypass gap between the filter and the wall of the duct, opposite to the door. The door also contains a clamping mechanism which prevents the filter from moving during a test. A sketch of this setup is indicated in Figure 1 below.

In addition to an adjustable bypass gap on one side of a filter, several bypass gap geometries were tested. The first of these is straight bypass where air flows straight through the bypass gap. The second configuration involves the installation of a U-shaped channel on the bypass side of the duct which is intended to resemble a filter rack. In this configuration, the filter is held centered within the channel, and the bypass air flows through the U-shaped channel and past the filter. When examining field installations, however, the filter is usually not centered but rather pushed towards the back edge of the channel by the pressure of the airflow. As a result, a second U-shaped bypass configuration was developed to realistically simulate a field installation. The U-shaped and U-shaped real configurations are shown below in Figure 2.

The different filter types, bypass configurations and gap sizes discussed above were organized into a constant pressure drop filter bypass test matrix as shown below in Table 2. This

Table 1. Minimum Efficiency Reporting Value Table from ASHRAE Standard 52.2-2007

Standard 52.2 Minimum Efficiency Reporting Value (MERV)	Average Particle Size Efficiency, % in Size Range		
	Range 1 0.30—1.0 µm	Range 2 1.0—3.0 µm	Range 3 3.0—10 µm
1	n/a	n/a	$E_3<20$
2	n/a	n/a	$E_3<20$
3	n/a	n/a	$E_3<20$
4	n/a	n/a	$E_3<20$
5	n/a	n/a	$20 \le E_3<35$
6	n/a	n/a	$35 \le E_3<50$
7	n/a	n/a	$50 \le E_3<70$
8	n/a	n/a	$70 \le E_3$
9	n/a	$E_2<50$	$85 \le E_3$
10	n/a	$50 \le E_2<65$	$85 \le E_3$
11	n/a	$65 \le E_2<80$	$85 \le E_3$
12	n/a	$80 \le E_2$	90vE_3
13	$E_1<75$	$90 \le E_2$	$90 \le E_3$
14	$75 \le E_1<85$	$90 \le E_2$	$90 \le E_3$
15	$85 \le E_1<95$	$90 \le E_2$	$90 \le E_3$
16	$95 \le E_1$	$95 \le E_2$	$95 \le E_3$

constant pressure drop matrix consists of 61 tests which were labeled either with the letter B, N, or F. The letter B corresponds to an initial efficiency test with bypass while the letter N corresponds to an initial efficiency test with no bypass. The letter F refers to a full ASHRAE 52.2 test with five dust loadings. The majority of the tests in this matrix are initial efficiency tests, while only several are full tests. The results of the tests within the same box were then compared to determine the effects of bypass on the efficiency of a particular filter with a particular bypass configuration and gap size. U-shaped real 1.25 inch (31.8 mm) tests were not included in this matrix because the edge of the filter on the bypass side would extend beyond the edge of the channel. This would not represent a U-shaped real configuration, but rather a straight bypass configuration which is already tested in this matrix.

There are two types of test procedures used in this research. For a “no bypass” test, the filter is installed into the duct in either a straight, U-shaped, or U-shaped real configuration, set to a prescribed bypass gap, and sealed with tape on all four sides of the filter to prevent any bypass. The test is then performed at a target airflow rate of 2000 CFM (53.3 m^3/min) and a “no bypass” efficiency curve is generated. For a bypass test, the filter is installed using the same bypass configuration and gap size with tape only used on three sides of the filter. The bypass side is not sealed with tape allowing air to flow through the bypass gap between the filter and the duct wall. The airflow rate is then increased until the pressure drop across the filter is identical to the pressure drop with “no bypass”. The test is then performed at this new increased airflow rate. This is done to compare the results to the analytical model, where the pressure drop is held constant with and without bypass.

After completing the constant pressure drop matrix, the constant fan speed matrix was developed. The constant fan

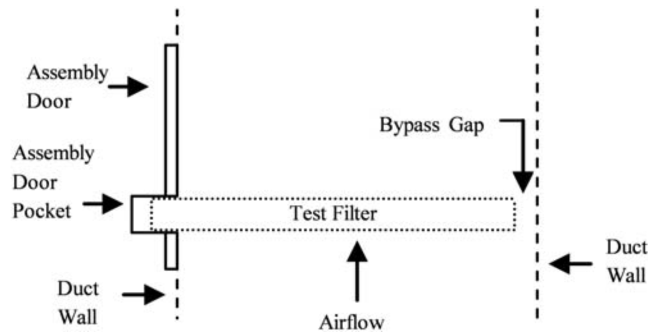

Figure 1 *Top view of a filter installed in the duct with bypass using the assembly door.*

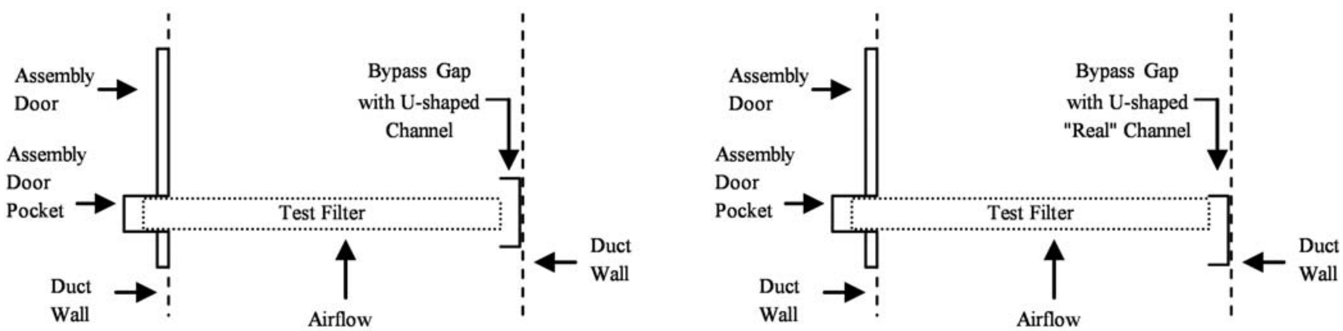

Figure 2 *U-shaped and U-shaped real bypass configurations for filter bypass testing.*

Table 2. Constant Pressure Drop Filter Bypass Test Matrix

Filter MERV Rating	Straight Bypass			U-Shaped Bypass			U-Shaped Real Bypass	
	Gap: 0.25 in. (6.4 mm)	Gap: 0.75 in. (19.1 mm)	Gap: 1.25 in. (31.8 mm)	Gap: 0.25 in. (6.4 mm)	Gap: 0.75 in. (19.1 mm)	Gap: 1.25 in. (31.8 mm)	Gap: 0.25 in. (6.4 mm)	Gap: 0.75 in. (19.1 mm)
2	B N	B N	B N	B N	B N	B N	B N	
7	B N	B N F	B N	B N	B N	B N	B N	B
11	B N	B N	B N	B N	B N	B N	B N	B
14	B N F	B N	B N	B N	B N	B N	B N	B

speed test matrix shown below in Table 3 consists of 30 tests. This matrix is smaller than the constant pressure drop test matrix because after reviewing the results from the first test matrix, it was determined that it was not necessary to include all test parameters. In particular, the MERV 2 filter had a very low efficiency that varied considerably and was removed from this matrix. In addition, the 0.25 inch (6.4 mm) gap tests from the constant pressure drop matrix had minimal effect on efficiency and were also removed. The full filter tests were also removed from this matrix because they were difficult to perform due to the bypass gap (elevated downstream particle counts due to dust re-suspension).

The tests were performed using the same methods from the constant pressure drop tests with the exception that the fan speed was held constant for the bypass tests. After performing several 0.75 inch (19.1 mm) and 1.25 inch (31.8 mm) “no bypass” tests, where the gap was set and all sides of the filter were sealed with tape, negligible differences in efficiency were detected. Therefore, all of the 0.25 inch (6.4 mm) “no bypass” tests from the constant pressure drop matrix as well as the 1.25 inch (31.8 mm) “no bypass” tests for the constant fan speed matrix were not performed.

RESULTS AND DISCUSSION

Constant Pressure Drop Test Results

After completing all of the relevant tests in the constant pressure drop matrix, the results were plotted showing removal efficiency versus particle size. The MERV 7, MERV 11, and MERV 14 results are plotted together and organized by bypass configuration and gap size. The MERV 2 filter is not presented because it failed to provide consistent results, although it should be pointed out that a user of such a low efficiency filter would likely not be concerned with bypass. The “no bypass” curves are also presented as benchmarks for efficiency, which are used to determine the reduction in efficiency due to bypass for each of the filters.

The first plot shown in Figure 3 shows the results from the constant pressure drop straight bypass tests. The results show some interesting trends. The MERV 14 efficiency curves show significant reductions in efficiency for increasing gap sizes. Also, the MERV 14 results show reductions in efficiency that are mostly consistent and fairly independent of particle size. The MERV 11 results show less efficiency reduction than the MERV 14, but the reductions show a dependency on particle size. For the smaller size particles (< 1 μm), the efficiency differences are negligible. For particles > 1 μm, the curves show increasing differences in efficiency. This trend is generally true as well for the MERV 7 data, but the overall filter efficiency is considerably lower, as expected. In general, the lower the efficiency of the filter, the less efficiency reduction that is evident for the smaller particle size ranges. There are several explanations for this behavior. First, the pressure drop for lower MERV filters is lower. This results in less bypass gap airflow, and as a result, less efficiency degradation. Second, the lower MERV filters, by definition, are much less efficient for the smaller size particles, so the particles are less likely to be removed by the filter. Therefore, the effect of a bypass gap is less pronounced.

The next graph shown in Figure 4 plots the results from the constant pressure drop U-shaped bypass tests. When compared to the straight bypass results of Figure 3, there are some notable differences. In general, there is less efficiency degradation for filter types and gap sizes. This is due to the presence of the U-shaped channel in the bypass gap. This channel adds a restriction and impedes airflow, reducing the effect of the bypass. For the MERV 14 results, there is much less difference between the “no bypass” and 0.25 inch (6.4 mm) bypass curves for the U-shaped bypass configuration. For the MERV 11 tests, there is slightly less difference between curves when compared to the straight bypass data. This statement is also true for the MERV 7 data, with the exception of the 1.25 inch (31.8 mm) bypass curve, which shows significantly more degradation than the smaller gap sizes.

Figure 5 depicts the results from the constant pressure drop U-shaped real bypass tests. When compared to the two previous plots, it is apparent that the efficiency degradation for the U-shaped real bypass configuration is much less than the other configurations. This is due to the U-shaped real bypass configuration where the back edge of the filter is inline with the back edge of the channel. The filter overlaps the back edge of the channel for the 0.25 inch (6.4 mm) bypass tests effectively forming a seal and eliminating most bypass air. For the 0.75 inch (19.1 mm) bypass tests, a 0.125 inch (3.175 mm) gap is present between the filter and the channel which allows air and particles to bypass the filter. For the MERV 7 and

Table 3. Constant Fan Speed Filter Bypass Test Matrix

Filter MERV Rating	Straight Bypass		U-Shaped Bypass		U-shaped Real Bypass
	Gap: 0.75 in. (19.1 mm)	Gap: 1.25 in. (31.8 mm)	Gap: 0.75 in. (19.1 mm)	Gap: 1.25 in. (31.8 mm)	Gap: 0.75 in. (19.1 mm)
7	B N	B N	B N	B N	B N
11	B N	B N	B N	B N	B N
14	B N	B N	B N	B N	B N

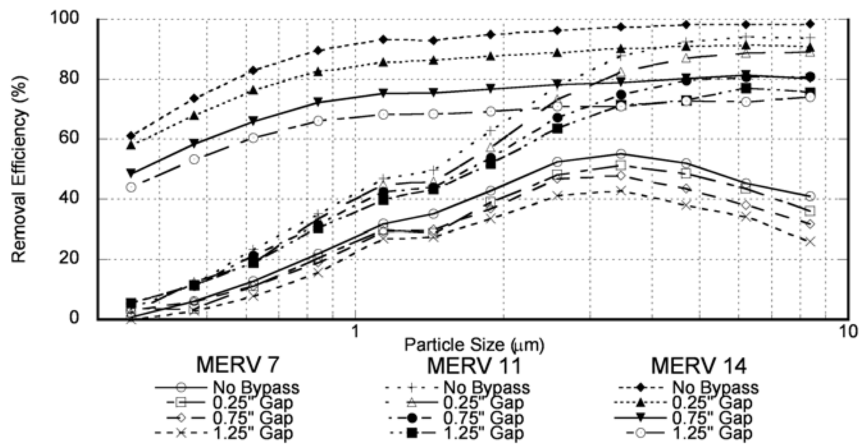

Figure 3 *Straight bypass constant pressure drop results.*

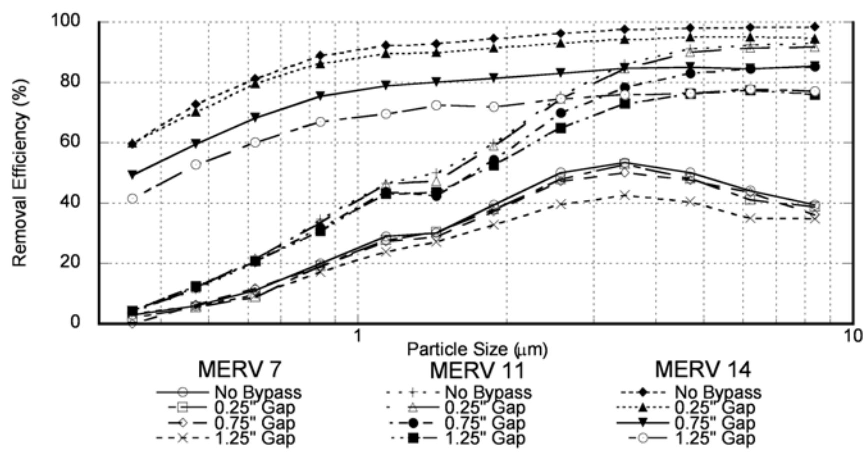

Figure 4 *Constant pressure drop results for U-shaped bypass.*

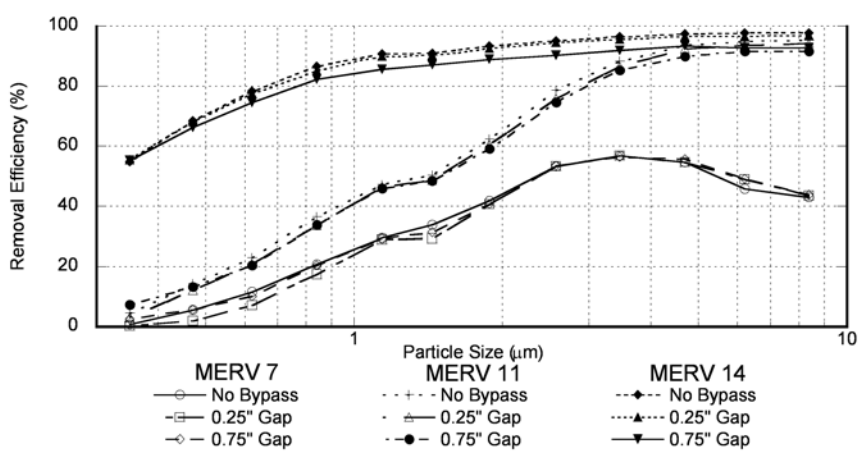

Figure 5 *Constant pressure drop results for U-shaped real bypass.*

MERV11 tests, the difference in efficiency for the various gap sizes is negligible. Only when the MERV14 filter is tested do we see any major difference, that being with the 0.75” bypass gap. This is likely due to the high pressure drop across the filter, which leads to high gap air flow, and more particles bypassing the filter.

Constant Pressure Drop—Full Tests

In addition to the initial efficiency tests, two full tests were performed. The first test was a MERV 7 filter with 0.75 inch (19.1 mm) straight bypass, while the second test was a MERV 14 filter with 0.25 inch (6.4 mm) straight bypass. The results of both tests are shown below in Figure 6. The initial curves represent the initial efficiency of each clean filter. The remaining five curves for each filter represent the efficiencies after successive dust loadings. For the MERV14 filter, the filtration efficiency for particle sizes <1µm shows consistent improvement for each dust loading efficiency curve. For particle sizes >1µm, minimal changes in efficiency are shown. This is due to the fact that the filter is a high efficiency filter, and already has an efficiency > 80%, so loading of the filter has minimal effect. For the smaller particle sizes, the efficiency is much less, and the addition of ASHRAE dust loads the media, resulting in an increase of efficiency. The MERV 7 filter exhibits similar behavior for particle sizes < 3µm, with increasing efficiency for each dust loading. For particle sizes > 3µm, we see a reduction in efficiency for each successive dust loading. This is the opposite of what is normally seen during full filter tests. This behavior is likely due to the re-suspension of larger size ASHRAE dust through the bypass gap. The larger particles are re-suspended, flow through the bypass gap, and result in elevated downstream particle counts. This re-suspension may be caused by filter vibration during testing.

Constant Fan Speed

The next set of results is from the constant fan speed test matrix. The results from these tests are presented in the same manner as the constant pressure drop test results. Figure 7 shows the results from the constant fan speed straight bypass tests. The MERV 7 curves show fairly consistent reduction in efficiency with increasing gap size. The MERV 11 data shows significant efficiency degradation at larger particle sizes, with less degradation at the smaller sizes. For the MERV 14 filter, major efficiency reduction is shown for a 0.75 inch (19.1 mm) bypass gap, and further reduction for the 1.25 inch (31.8 mm) gap size. When comparing this plot to the analogous constant pressure drop plot, the trends are very similar.

Figure 8 shows the results from the constant fan speed U-shaped bypass tests. These curves show the same trends as the previous plot, but with slightly less efficiency degradation. This is due to the addition of a restriction to the bypass gap. Instead of the bypass air following a straight path, it has to change directions through the U-shaped channel, which reduces air flow, and therefore reduces the effect of bypass on efficiency.

Figure 9 shows the constant fan speed U-shaped real bypass tests. The MERV 7 data indicates virtually no difference between the “no bypass” and 0.75 inch (19.1 mm) bypass tests. This is due to the minimal gap that exists in the U-shaped real configuration, and the low pressure drop of a MERV 7

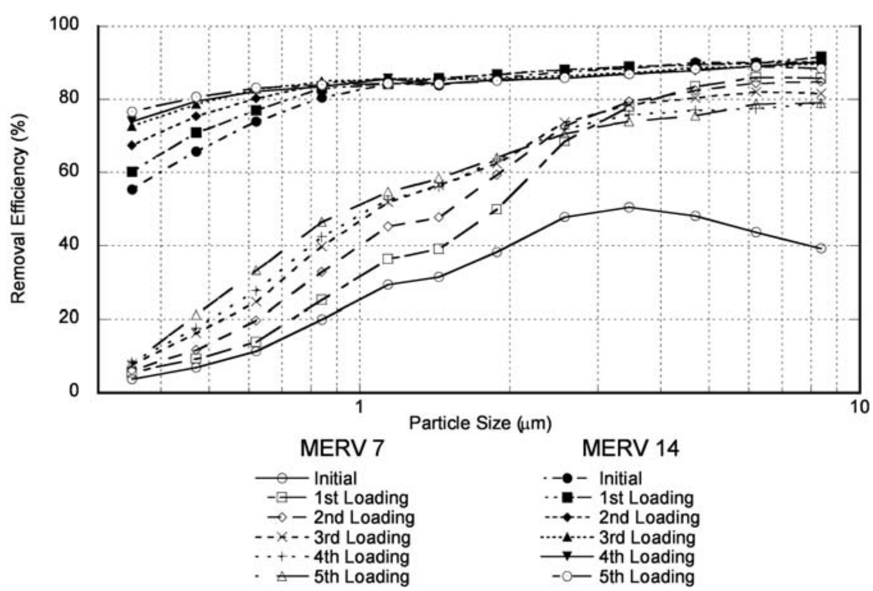

***Figure 6** Constant pressure drop - MERV 7 and MERV 14 full test results.*

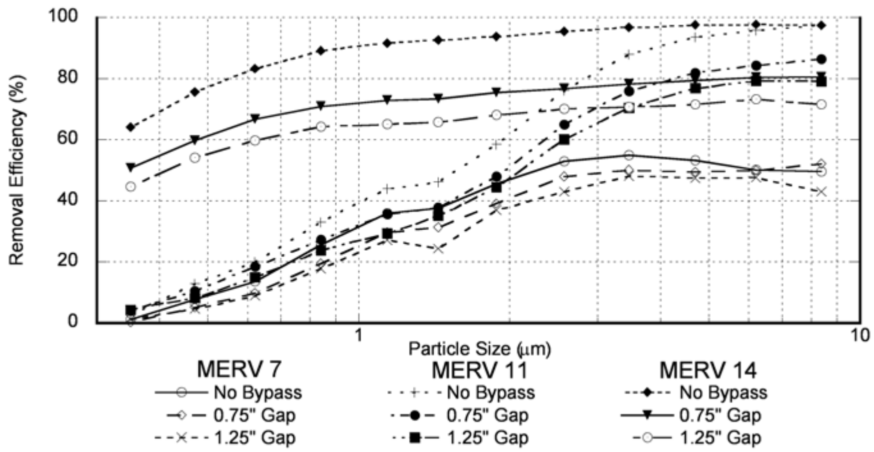

Figure 7 *Constant fan speed results for straight bypass.*

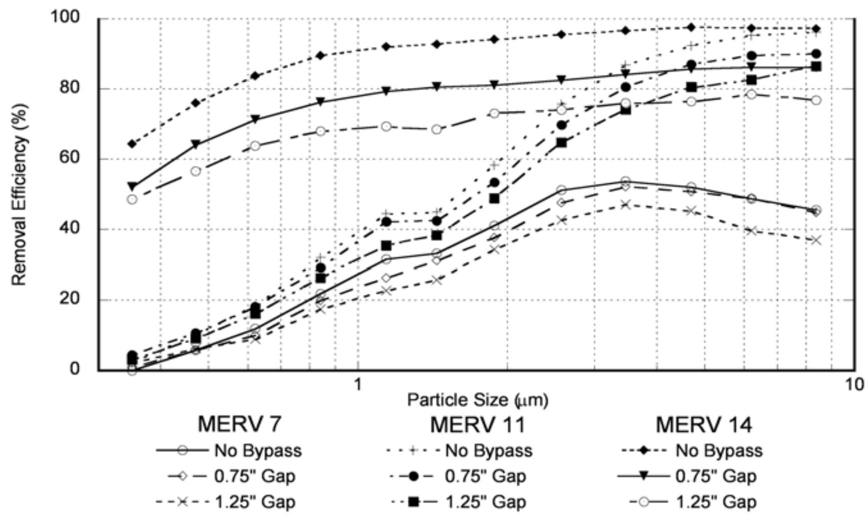

Figure 8 *Constant fan speed results for U-shaped bypass.*

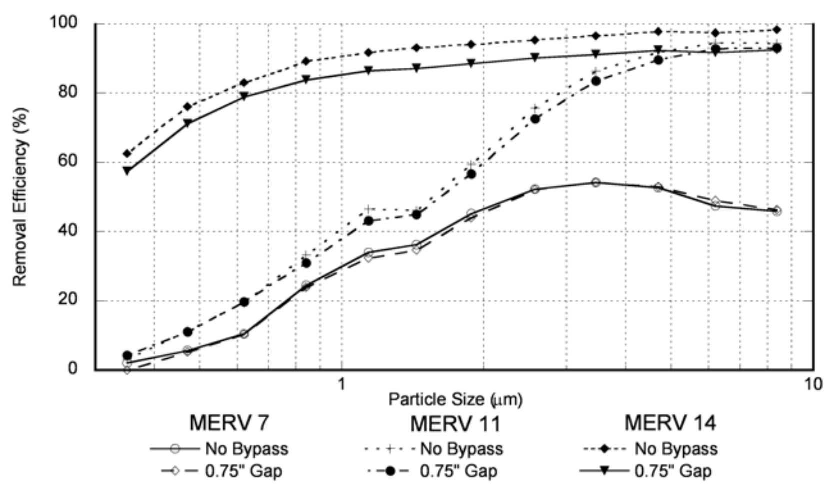

Figure 9 *Constant fan speed results for U-shaped real bypass.*

filter. A similar situation exists for the MERV 11 tests, but with a visible difference between the efficiency curves, especially for larger particle sizes. In the case of the MERV 14 filter, a relatively consistent reduction in efficiency is apparent throughout all particle size ranges. Again, this is caused by the higher flow through the bypass gap due to the increased pressure drop across the filter.

Constant Pressure Drop Initial Efficiency Reporting Values (IERV)

As discussed earlier a minimum efficiency reporting value (MERV) can be determined using ASHRAE Standard 52.2-2007. Since the tests shown above are initial efficiency only, the term initial efficiency reporting value (IERV) will be used to summarize the bypass effects. The initial efficiency reporting values for these tests are shown below in Table 4. The “no bypass” IERV values shown in the table for each filter are benchmarks for the straight, U-shaped, and U-shaped real configurations and are used to determine how much efficiency is reduced with increasing gap size. It should be noted that the “no bypass” IERV values for the MERV 7 and MERV 14 filters are not the same for each bypass configuration. This is because the IERV value is determined based on three efficiency ranges found in the lookup table shown in Table 1. If one of the ranges is not satisfied a lower value is chosen until the all three ranges meet the conditions in the table. For MERV 7 straight and U-shaped “no bypass” tests, range 3 was only a few percentage points away from satisfying the conditions of an IERV 7, but instead the value dropped to an IERV 6. Likewise, range 1 for the MERV 14 U-shaped real “no bypass” test was close to satisfying the conditions of an IERV 14, but instead became an IERV 13. In addition, it can be seen in the table below that the MERV 14 filter with 0.75 inch (19.1 mm) U-shaped bypass has two values. This is because the ranges do not satisfy all the conditions of an IERV 11 or IERV 12. Instead, the value is in between an 11 and a 12.

Despite the reduction of efficiency of the MERV 7 filter with bypass, the table shows that the IERV did not change for the straight, U-shaped, and U-shaped real configurations with increasing gap size. The MERV 11 filter decreased from an IERV 10 to an IERV 8 for the 1.25 inch (31.8 mm) straight and U-shaped bypass tests. The MERV 14 filter decreased the most from an IERV 14 to an IERV 8.

Constant Pressure Drop Full Test Minimum Efficiency Reporting Values (MERV)

The full tests can also be analyzed by determining the initial efficiency and minimum efficiency reporting values. Since these two tests were full tests with dust loadings, we can calculate actual MERV ratings for the filters with bypass. It should be noted that Table 1 is used for determining both IERV and MERV. The MERV 7 filter used in one of the full tests performed as an IERV 6 with 0.75 inch (19.1 mm) straight bypass as shown in Table 5 below. The value did not change when determining MERV for this filter. This is because the efficiency for each of the particle size ranges was found to be the minimum during the initial efficiency measurement. The MERV 14 filter with 0.25 inch (6.4 mm) straight bypass had an initial efficiency value of 12. The MERV was between an 11 and 12. This slight drop in value was caused by the reduction in efficiency for particle size ranges >1μm as a result of dust shedding through the bypass gap. This ASHRAE dust that migrates downstream of the test filter causes elevated downstream counts, and therefore reduces efficiency values. This caused some of the dust loading efficiencies to drop below the initial efficiency of the filter. Since the minimum efficiencies are used to determine MERV, the value was reduced.

Table 4. Constant Pressure Drop Initial Efficiency Reporting Values.

Filter Type	MERV 7				MERV 11				MERV 14			
Bypass Gap	No Bypass	0.25 in. (6.4 mm)	0.75 in. (19.1 mm)	1.25 in. (31.8 mm)	No Bypass	0.25 in. (6.4 mm)	0.75 in. (19.1 mm)	1.25 in. (31.8 mm)	No Bypass	0.25 in. (6.4 mm)	0.75 in. (19.1 mm)	1.25 in. (31.8 mm)
Straight	6	6	6	6	10	10	8	8	14	12	8	8
U-Shaped	6	6	6	6	10	10	8	8	14	13	11/12	8
U-Shaped Real	7	7	7	—	10	10	10	n/a	13	13	12	—

Table 5. IERV and MERV for Constant Pressure Drop Full Tests

Filter Type	IERV	MERV with Bypass
MERV 7	6	6
MERV 14	12	11/12

Table 6. Constant Fan Speed Initial Efficiency Reporting Values

Filter Type	MERV 7			MERV 11			MERV 14		
Bypass Gap	No Bypass	0.75 in. (19.1 mm)	1.25 in. (31.8 mm)	No Bypass	0.75 in. (19.1 mm)	1.25 in. (31.8 mm)	No Bypass	0.75 in. (19.1 mm)	1.25 in. (31.8 mm)
Straight	7	7	6	10	8	8	14	8	8
U-Shaped	7	6	6	10	10	8	14	11/12	8
U-Shaped Real	7	7	---	10	10	n/a	14	12	---

Constant Fan Speed Initial Efficiency Reporting Values (IERV)

The initial efficiency reporting values for the constant fan speed tests are shown below in Table 6. For the MERV 7 filter, IERV is reduced from a 7 to a 6 for the straight and U-shaped bypass tests. The value did not change for the U-shaped real bypass test. The MERV 11 filter reduced from an IERV 10 to an IERV 8 for the straight and U-shaped bypass tests. The value also did not change for the U-shaped real bypass test. The MERV 14 filter was affected most by change in IERV. For the straight and U-shaped bypass tests, IERV was reduced from a 14 to an 8. The U-shaped real bypass test reduced from an IERV 14 to and IERV 12.

Comparison of Constant Pressure Drop and Constant Fan Speed Test Results

We hypothesized that the constant pressure drop tests would demonstrate greater efficiency degradation when compared with the constant fan speed tests. The reasoning behind this prediction was that the constant pressure drop tests with bypass were performed at an increased airflow rate in order to hold the pressure drop constant. This would suggest that the airflow through the bypass gap was higher for the constant pressure drop tests than the constant fan speed tests and would allow more particles to flow through the bypass gap resulting in greater efficiency degradation. After comparing the constant pressure drop plots with the constant fan speed plots, these trends were not seen, likely because of small differences in pressure drop and fan speed between the two test conditions.

Some differences in IERV were present between matrices. These include the MERV 7 filter with 0.75 inch (19.1 mm) straight bypass and the MERV 11 filter with 0.75 inch (19.1 mm) U-shaped bypass. The initial efficiency reporting value for the MERV 7 constant pressure drop test was a 6, while the value was a 7 for the constant fan speed test. For the MERV 11 filter, the constant pressure drop test resulted in an IERV 8, while the constant fan speed resulted in an IERV 10. These differences would imply that our hypothesis was correct about the constant pressure drop tests demonstrating greater efficiency degradation than the constant fan speed tests. However, these are the only two differences in the initial efficiency reporting values for the tests with bypass. As a result, we were not able to determine a trend between these two test methods.

CONCLUSION

The results from this research show that bypass air is capable of significantly reducing the filtration efficiency of a filter. The magnitude of reduction is based on several factors including the type of filter that is used, the bypass gap size and configuration, pressure drop, and airflow. The results show that filters which are more restrictive degrade more in efficiency with bypass than filters that are less restrictive when bypass is present. As the bypass gap size increases, degradation in efficiency increases. When comparing the three different types of bypass configurations, the most pronounced effect is shown with straight bypass where IERV can be reduced by as much as six points for the MERV 14 filter with a 1.25 inch (31.8 mm) gap. When the U-shaped channels were used, degradation due to bypass was reduced, where the smallest reduction of efficiency occurred for the U-shaped real tests. In general, when adding restrictions in the bypass gap, such as the U-shaped channels, the airflow through the gap is reduced. This results in less particles flowing through the gap thereby improving filtration efficiency. When comparing the constant pressure drop tests with the constant fan speed tests, noticeable trends were not identified. Despite this, the magnitude of efficiency reduction due to bypass was still apparent for both types of tests.

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