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Energy Implications of Filtration in Residential and Light-Commercial Buildings

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ABSTRACT

Higher-efficiency HVAC filters generally have a higher pressure drop and are widely assumed to increase energy consumption in smaller air conditioning systems. To explore the effects of filters in real buildings, we monitored 17 residential and light-commercial forced air cooling systems in Austin, TX. Measurements were made once per month for one year at each site with filters from three different MERV range categories. Measured parameters included system airflow, fan power draw, outdoor unit power draw, cooling capacity, pressure drops across filters and coils, and duct leakage. Higher-efficiency (MERV 11-12) filters generally had a small impact on parameters related to cooling energy consumption in the residential and light-commercial test systems when compared to lower-efficiency (MERV 2) filters. The median energy consequence of higher-efficiency filtration in the test systems was estimated as a decrease of approximately 16 kWh per ton of nominal capacity (4.6 kWh per kW) per month of cooling season operation, albeit with large variation, with most of these small savings coming from fan energy reductions. These results suggest a weak link between higher-efficiency filters and energy use in residential and light-commercial systems and that other factors should govern filter selection.

INTRODUCTION

High-efficiency filtration in forced air heating, ventilating, and air-conditioning (HVAC) systems is used to protect building equipment and occupants, but can also influence building energy use. Filters with a high MERV (Minimum Efficiency Reporting Value, as defined by ASHRAE Standard 52.2-2007) typically have a greater pressure drop than a filter with a lower MERV. The energy consequences of a greater pressure drop due to filtration are well known for large commercial systems, where fan and motor controls typically maintain required airflow rates. A higher pressure drop filter causes the fan motor to draw more power to overcome the pressure drop and deliver the required amount of air, thus increasing energy consumption (Chimack and Sellers 2000; Fisk et al. 2002). This association between energy use and filter pressure drop is widely assumed to hold true for smaller residential and light-commercial systems, but operational differences between small and large systems suggest very different energy consequences.

The central difference is that increasing the pressure drop of a filter in most residential HVAC systems generally causes diminished airflow, although evidence is limited. Parker et al. (1997) measured a 4 to 5% airflow rate reduction when replacing standard disposable filters with high-efficiency pleated filters in residential air conditioner field tests. Diminished airflow generally decreases cooling capacity, power draw of the compressor, and system efficiency. Parker et al. (1997) predicted by computer simulations and laboratory tests that a 5% reduction in airflow from a value recommended by most manufacturers of 400 CFM ton^{-1} (193 $\text{m}^3\cdot\text{h}^{-1}\cdot\text{kW}^{-1}$) to 380 CFM ton^{-1} (184 $\text{m}^3\ \text{h}^{-1}\cdot\text{kW}^{-1}$) would decrease sensible cooling capacity by approximately 2%. This suggests that a system would run 2% longer to meet the same cooling load. In laboratory experiments, Rodriguez et al. (1996) tested 3.5-ton (12.3 kW) air conditioners and reported approximately 6 to

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7% reductions in efficiency and total capacity associated with a 10% reduction from the recommended airflow rate. Palani et al. (1992) measured the impacts of low airflow on a 3-ton (10.5 kW) air conditioner in a series of laboratory tests as well and found similar reductions in capacity for comparable reductions in airflow. The same studies showed that more drastic energy consequences occur when flow reductions are extreme. Parker et al. (1997) reported that system cooling energy consumption could increase by 20% if flow diminishes approximately 40% from 400 CFM ton^{-1} (193 m^3·h^{-1}·kW^{-1}).

The previous investigations show that if the presence of a higher-efficiency filter diminishes airflow, sensible cooling capacity will decrease, suggesting an increase in energy consumption due to increased system runtime. However, fan and compressor power draw also generally decrease, potentially limiting negative energy impacts. In addition, a change in filter pressure drop can affect duct leakage by changing the pressure around duct leaks. Although we know of no direct research of the implications of filtration on duct leakage, there is extensive literature on the energy consequences of duct leakage in residential and light-commercial systems (e.g., Modera 1989; Modera 1993; Parker et al. 1993; Jump et al. 1996; Walker et al. 1998; Withers and Cummings 1998; Siegel et al. 2000; Francisco et al. 2006).

One of the central challenges of associating energy consequences with filtration is the complexity of these interacting effects. The magnitudes, and even the signs, of many of these effects are not well characterized, but are likely very system-dependent and are affected by such parameters as the fraction of the system pressure drop associated with the filter, the fan-speed setting, and the intersection point of the fan and the duct curves. To explore these effects in real systems, we monitored residential and light-commercial forced air cooling systems at multiple sites in Austin, Texas. Measured parameters included system airflow rate, power draw, cooling capacity, pressure drops across filters and coils, and duct leakage. Periodic measurements were made over the course of a year at each site with readily available filters with different MERV categories, as rated by the filter manufacturer. The purpose of this research was to assess how filter MERV and the corresponding measured pressure drop impact energy use in smaller air-conditioning systems. The specific goal is to allow system designers and users to evaluate the consequences associated with higher-efficiency filtration.

METHODOLOGY

Site Selection and Descriptions

Seventeen systems were selected as a sample of convenience based on the willingness of the building owners and residents to have monitoring equipment installed and frequent visits from the field personnel. Table 1 summarizes the 17 test sites. The first eight sites were residential buildings and the remaining nine were light-commercial buildings. The light-commercial buildings were all office spaces with some also serving a limited retail function. Each system served less than 2000 ft^2 (186 m^2) of floor area and rated air conditioner cooling capacities ranged from 1.5 to 5.0 tons (5.3 to 17.6 kW). Sites 1 to 15 had typical permanent split capacitor (PSC) fans and Sites 16 and 17 had electronically commutated motor (ECM) fans. Most ductwork was located in unconditioned attics, with a few systems with ducts in other locations. Filters were located in return grilles or at the air handler. All of the test systems relied on infiltration for fresh air, rather than dedicated outdoor air ventilation.

Test Methodology

The test sites were visited once a month for a year, during which time three categories of filtration efficiency typically used in residential and light-commercial systems were installed: low (MERV 2), medium (MERV 6-8), and high (MERV 11-12). Each MERV category filter was left in place for three months and monitored four times: initially on the day of installation and after one, two, and three months of usage. The final three-month period was used to repeat an installation of one of the MERV categories to assess variation in the measurements. Unlike the other sites, Site 12 had only high-efficiency filters installed over the duration of the project because of a request by the building owner.

During each monthly visit, measurements were made in the fan-only mode by activating the switch at the thermostat. Pressure measurements were made using an Energy Conservatory DG-700 handheld digital manometer (uncertainty ±1% of reading), including the pressure drop across the filter(s) and cooling coil and the pressure differential between the occupied space and the supply and return plenums. A custom-built data-logging box was then launched to record the pressure drop across the filter(s) and cooling coil and the power draw of the air handler fan in the fan-only mode for approximately 15 minutes at 10-second intervals. The data-logging box consisted of a Continental Control Systems (CCS) Wattnode AC true power meter (uncertainty ±0.45% of reading and ±0.05% of full-scale), two Setra pressure transducers (uncertainty ±1% of full-scale) connected to an Onset Flexsmart (uncertainty ±1% of full-scale), and an Onset HOBO Energy Logger Pro. The box was connected to pressure taps, voltage taps, and 0 to 20 Amp CCS current transducers (uncertainty ±1% of reading) that remained installed for the duration of the one-year test period.

During each monthly visit in the cooling season, measurements were made with each system in fan-only mode, then the equipment was left to monitor and log for approximately 24 hours with the thermostat operated normally by the building occupants. Also, during the cooling season visits, additional continuous measurements were made of the power draw of the outdoor unit using the same instrumentation as described above and Onset HOBO U12 dataloggers for temperature and relative humidity measurements (uncertainty ±0.4°C (±0.7°F) and ±2.5% from 10% to 90% RH; 6-minute response time). Temperature and relative humidity measurements were taken

Table 1. Test Site Characteristics

Site	Building Use	Floor Area, ft^2 (m^2)	Rated Cooling Capacity[1], tons (kW)	Ductwork Location	Air Handler Location	Number of Filters	Filter Location[2]
1	Residential	1830 (170)	4.0 (14)	Attic	Closet	1	Slot
2	Residential	1430 (133)	3.0 (11)	Attic	Garage	1	Slot
3	Residential	1080 (100)	2.5 (9)	Between floors	Closet	3	Grilles
4	Residential	320 (30)	1.5 (5)	Attic	Attic	1	Grille
5	Residential	1140 (106)	2.5 (9)	Attic	Attic	1	Grille
6	Residential	1500 (139)	3.0 (11)	Attic	Attic	1	Grille
7	Residential	1200 (111)	3.0 (11)	Between floors	Closet	1	Slot
8	Residential	1350 (125)	3.0 (11)	Attic	Garage	1	Slot
9	Commercial	1300 (121)	5.0 (18)	Attic	Attic	2	Grilles
10	Commercial	1300 (121)	3.5 (12)	Attic	Attic	2	Grilles
11	Commercial	1320 (123)	3.5 (12)	Attic	Attic	2	Grilles
12	Commercial	1860 (173)	5.0 (18)	Attic	Attic	3	Grilles
13	Commercial	1430 (133)	3.5 (12)	Attic	Closet	1	Slot
14	Commercial	980 (91)	3.0 (11)	Attic	Closet	1	Slot
15	Commercial	1000 (93)	2.5 (9)	Attic	Closet	2	Slot
16	Commercial	760 (71)	1.5 (5)	Outdoor	Outdoor closet	1	Grille
17	Commercial	280 (26)	1.5 (5)	Conditioned space	Closet	1	Slot

[1] Cooling capacity corresponds to the nominal capacity of the outdoor unit.

[2] Slot = Filter slot at the air handling unit, Grille(s) = Return grille(s).

outdoors, in the zone that contained the majority of the duct work (often the attic), inside the return plenum, inside the supply plenum, and at a single supply register.

Duct leakage and airflow measurement tests were conducted during one visit over the course of the year long monitoring period. Duct leakage was measured using an Energy Conservatory Duct Blaster (uncertainty ±3% of flow reading) and Model 3 blower door in accordance with ASHRAE Standard 152-2004. The Duct Blaster alone was used to make total (interior + exterior) leakage measurements and the blower door was added to make exterior leakage measurements. The tests were repeated with the return side of the system sealed off to separate supply and return leakage. Monthly estimates of duct leakage were assessed by correcting for changes in the supply plenum operating pressure observed during each visit and using a power-law flow-leakage approximation following the procedure in the Duct Blaster manual. System airflow rates were measured with an Energy Conservatory TrueFlow metering plate and DG-700 digital manometer (uncertainty ±7% of reading). Monthly corrections were made based on changes in the supply plenum pressure measured during each visit following the calculation procedure in the instrument manual. Table 2 summarizes the equipment used in the field tests and the manufacturer-reported accuracies of each device.

Calculation of Energy Consequences

Previously, similar studies have relied on the metrics of capacity (sensible and latent) and the coefficient of performance (i.e., efficiency) in attempts to address the complicated relationship between flow changes, system runtime, and overall energy consumption. We used the same metrics to describe the cooling performance of the systems using the measured data. The total capacity, q_t (Btu/h, W), calculation is shown in Equation (1). The first term defines sensible capacity and the second term defines latent capacity.

$$q_t = Q_{fan}\rho(C\Delta T + \Delta W h_{fg}) \tag{1}$$

where

Q_{fan} = volumetric flow rate of air (ft^3/h, m^3/s) flowing through the cooling coil;
ρ = air density, assumed constant (0.075 lb$_m$/ft^3, 1.2 kg/m^3);
C = specific heat of air, assumed constant (0.24 Btu/(lb$_m$·°F), 1.005 kJ/(kg·K);
ΔT = temperature difference across the cooling coil (°F, K);
ΔW = humidity ratio difference across the cooling coil (lb$_m$/lb$_m$, kg/kg); and
h_{fg} = latent heat of vaporization for water, assumed constant (970 Btu/lb, 2257 kJ/kg).

The coefficient of performance, COP, calculation is shown in Equation (2).

$$\mathrm{COP} = \frac{q_t}{W_{ou} + W_{fan}} \tag{2}$$

where

W_{ou} = power draw of outdoor unit, including the compressor (W); and
W_{fan} = fan power draw (W).

Table 2. Field Instrumentation

Measurement	Units, IP (SI)	Equipment	Accuracy
Logged Measurements			
Pressure	IWC (Pa)	Setra 265 Transducer	±1% FS[1]
Power draw	V	CCS Wattnode	±0.45% of reading and ±0.05% FS
	A	CCS Current Transducer	±1% of reading
	W	Onset Energy Logger Pro	±1.5%[2]
Temperature	°F (°C)	Onset HOBO U12	±0.7°F (±0.4°C)
Relative Humidity	%	Onset HOBO U12	±2.5% from 10% to 90% RH
Periodic Measurements			
Pressure	IWC (Pa)	Energy Conservatory DG-700	±1% of reading or 0.0006 IWC (0.15 Pa)
Airflow	CFM (m^3/h)	Energy Conservatory TrueFlow Plate	±7% of reading[3]
Duct Leakage	CFM (m^3/h)	Energy Conservatory Duct Blaster	±3% of reading or ±1 CFM (± 2 m^3/h)

[1] Three models of pressure transducers were used in the field measurements with full-scale ranges of 0.25 IWC (62 Pa), 0.50 IWC (125 Pa), and 1.0 IWC (249 Pa).

[2] Voltage and amperage accuracies added in quadrature produced an uncertainty of ±1.2% in the power draw measurements. The estimated uncertainty was rounded to ±1.5% for use in this study because of unknown uncertainties associated with higher-order harmonics.

[3] Manufacturer's literature reports 7%, but conversations with the manufacturer suggest that a higher accuracy is appropriate for repeated measurements of flow differences, which led to the 5% uncertainty determination used in this work.

The cooling capacities were calculated during each recorded cycle only when the systems reached a period of steady-state operation. Measured observations were flagged in the analysis as steady-state when the supply plenum temperature did not vary for a period of at least 2 minutes by more than 0.9°F (0.5°C) from the lowest temperature recorded during a cycle. Steady-state cycles also had to be at least 6 minutes long due to the response time of the temperature and relative humidity instrumentation.

Although the capacity and efficiency calculations in Equations (1) and (2) assess the cooling performance of a system, little is known about how changes in sensible capacity actually translate to thermostat readings to ultimately affect runtime and energy consumption. To address this, we also measured the energy consumption and runtime of the test systems. The amount of energy consumed during an air conditioning cycle, E_{cyc} (watt-hours), is defined in Equation (3) as the total power draw of a cycle times the length of a cycle, l_{cyc} (hours).

$$E_{cyc} = (W_{ou} + W_{fan})l_{cyc} \tag{3}$$

DATA ANALYSIS

Counting each visit where a filter replacement occurred as two separate tests (one test with a 3-month-old filter followed immediately by a test with a brand new filter) and one missed visit each at Sites 11 and 12, a year of monthly tests at 17 sites resulted in 270 total visits. Approximately 43% of these visits occurred during the cooling season. The resulting dataset was analyzed to answer three specific research questions:

1. What is the impact of filtration efficiency (MERV) on airflow and parameters related to system energy use?
2. How do airflow and energy consequences relate directly to filter pressure drop?
3. What is the range of cooling energy consequences of filtration that is likely in residential and light-commercial buildings?

The analysis and statistical procedures for each question are described below.

1. **Impacts of Filtration Efficiency (MERV).** Dependent variables in this analysis that are potentially associated with energy consequences include: system airflow rate, power draw of the air handler fan, supply and return duct leakage to the exterior, fan efficacy (i.e., the volumetric flow per unit of power), power draw of the outdoor unit, total capacity, sensible capacity, latent capacity, coefficient of performance, sensible heat ratio, and duct delivery efficiency. To address the impact of filter MERV on these quantities, each of these dependent variables were first averaged for each site visit then averaged again across a given filter MERV category, treating periods of repeated filter installations separately. To assess statistical variation between filter MERV categories, both a paired two-tailed t-test and a Wilcoxon signed-ranked (non-parametric) test were conducted. The tests compare the mean values of each dependent variable at each site between: (1) high- and low-MERV filters, (2) high- and mid-MERV filters, and (3) mid- and low-MERV filters. Statistical significance was assessed as $\alpha < 0.05$. Any significant findings were further explored by comparing the absolute magnitude of the differences with instrumentation uncertainty and comparing repetitions at the same site with the same MERV-category filter.
2. **Impacts of Filter Pressure Drop.** Filter pressure drop can be only weakly correlated with MERV category, particularly for used filters with increased pressure drop due to loading. To assess the impact of a change in filter

pressure drop, regardless of MERV category, each dependent variable was first averaged for each visit at each site, then the change in each dependent variable was calculated and normalized to the value that was measured when a clean low-MERV filter was installed. A linear regression of each normalized dependent variable versus the measured filter pressure drop was performed, in which the filter pressure drop was also normalized to that measured with a clean low-MERV filter. The regression slope estimates the expected variable change due to an increase in filter pressure drop. Significance of the regression slope was determined when the 95% confidence interval did not contain zero, establishing upper and lower bound estimates on the expected variable change due to a change in filter pressure drop.

3. **Estimation of Energy Consequences during Cooling Mode.** The first two research questions attempt to isolate the effects that filters have on changes in individual energy-related parameters. In this analysis, the range of changes in actual cooling energy consumption (in kWh) due to filters was estimated according to changes measured in fan power draw, power draw of the outdoor unit, and system runtime. These parameters will, in theory, capture any changes in other energy-related parameters, including duct leakage effects. This approach was taken with only low- and high-MERV filters to assess the maximum possible impact of filters in the measured systems. Forty-five cooling visits occurred with low-MERV filters installed and fifty-four cooling visits occurred with high-MERV filters installed.

RESULTS AND DISCUSSION

This section first details the field measurements, then summarizes the results from each of the three research questions.

Field Measurements

Figure1a and 1b display the pressure drops measured across the filters, the corresponding airflow rates, and the filter MERV category installed during each field visit while operating in fan-only mode. Figure 1(A) shows measurements made at the residential systems and Figure 1(B) shows the commercial systems. Filter pressure drop values are averaged over the length of each fan-only operation period (typically about 15 minutes) and airflow rates are based on the supply plenum pressure measured at the beginning of each visit. Each bar represents a monthly site visit and filter changes are marked by an "X" on the x-axis. Error bars denote the larger of either the standard deviation of the measurements or the accuracy of the instrumentation. Due to limited access for sensor placement, Sites 9 and 12 report the pressure drop measured in the return plenum, not the pressure drop directly across the filter.

Filter pressure drop generally increased with each month of filter life as filters were loaded over time, although a few sites (e.g., Sites 1, 3, 8, and 17) sometimes show an unexpected decrease. This decrease can be caused by several factors including uncertainty in pressure drop measurements or complex turbulent airflows and other interference around pressure taps positioned in the airstream before and after the filter. High- and mid-MERV category filters revealed generally higher filter pressure drops than low-MERV category filters, but little difference existed between high- and mid-MERV categories themselves. The median pressure drop across low-, mid-, and high-MERV filters at all sites (excluding Sites 9 and 12) during the fan-only mode was 0.137 IWC (34 Pa), 0.213 IWC (53 Pa), and 0.221 IWC (55 Pa), respectively. The median airflow rate with low-, mid-, and high-MERV filters at all sites (excluding Site 12) during the fan-only mode was 939 ± 47 CFM (1595 ± 80 $m^3 \cdot h^{-1}$), 988 ± CFM (1679 ± 84 $m^3 \cdot h^{-1}$), and 888 ±44 CFM (1509 ± 75 $m^3 \cdot h^{-1}$), respectively. The fan-only

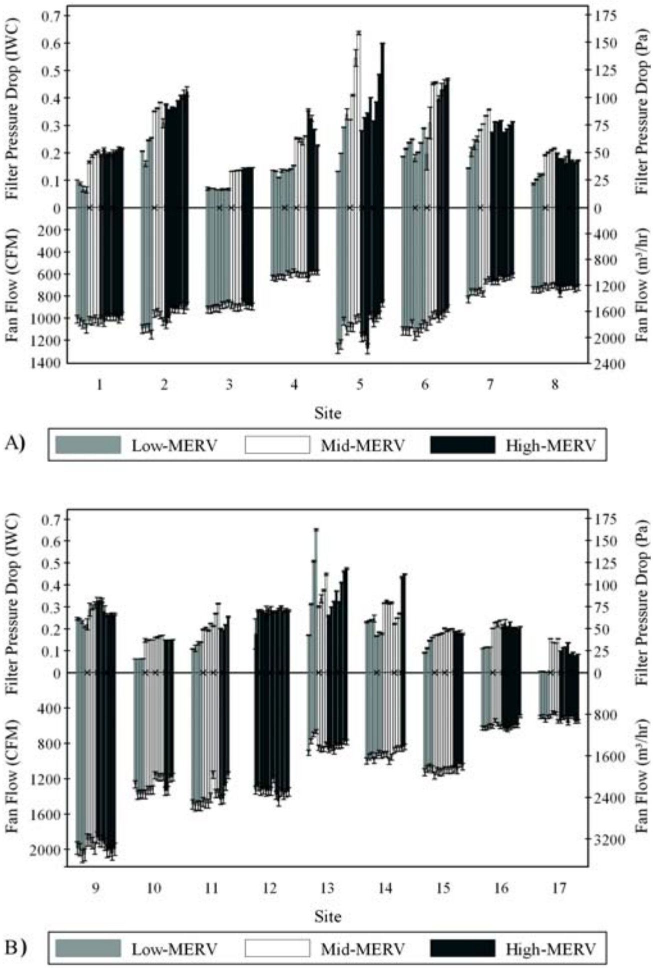

Figure 1 *Filter pressure drop and system airflow in (A) residential systems and (B) commercial systems operating in fan-only mode. Sites 9 and 12 measure the pressure drop through the entire return system and not just the filter pressure drop.*

airflow rates were much lower in Sites 16 and 17 because they had ECM fans while all the others had PSC fans.

The fan-only conditions shown in Figure 1(A) and (B) existed at every site visit, but measurements were also conducted at the test sites during the cooling season. Cooling season measurements accounted for approximately 43% of the monthly visits, producing a dataset of 115 total visits in cooling mode, 55 in residential systems and 60 in light-commercial systems. Figure 2 displays the fan and outdoor unit power draw of each system during the cooling season, averaged over the visits with low- and high-MERV filters installed. The amount of power draw of the fan and outdoor unit are important parameters in characterizing system energy usage. Figure 2 also displays the average airflow rate reduction measured with high-MERV filters versus low-MERV filters during the cooling season. Each bar represents between 1 and 5 visits made with a particular MERV category installed and the error bars represent one standard deviation from the mean.

The residential and light-commercial systems generally drew similar amounts of total power. On average, the power draw of the outdoor unit dominated total system power draw, accounting for approximately 85% of total power draw in the residential systems and 80% in the light-commercial systems. Most of this difference was because the light-commercial system fans drew approximately 40% more power while having approximately 35% higher airflow rates, on average, than the residential sites. The median system had an approximately 9% lower airflow rate in the cooling mode with high-MERV filters installed versus low-MERV filters. Site 13 was the only system to have a greater airflow rate with high-MERV filters installed, most likely because low-MERV filters were installed during a time of high system usage and the filter eventually became loaded enough to have a greater pressure drop than any high-MERV measurement at that site, as seen in Figure 1(B).

In addition to outdoor unit and fan power draw, system runtimes and cycle lengths are also important in assessing system energy consumption. The residential and light-commercial systems behaved similarly in terms of system runtime. The median cycle length was approximately 8 minutes for both residential and light-commercial systems. The commercial sites showed greater variation and longer runtimes overall but the residential and light-commercial systems generally behaved similarly. Approximately 25% of the recorded cycles were under 6 minutes long and had to be dropped from some of the analysis because they were shorter than the response time of the temperature and relative humidity sensors.

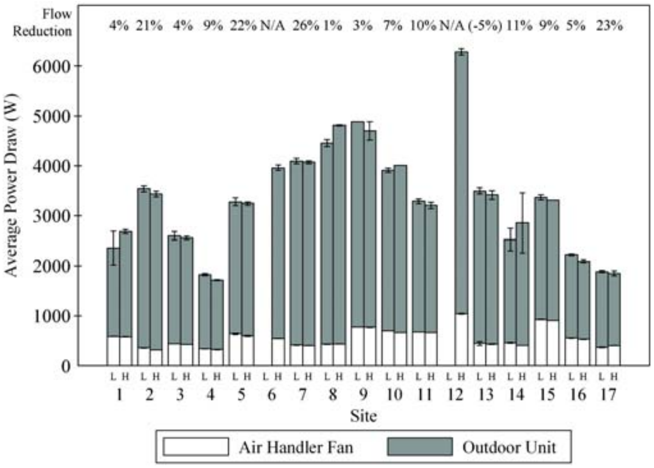

Figure 2 *Average fan and outdoor unit power draws and flow reductions during the cooling season at each site with low-MERV (L) and high-MERV (H) filters installed. Sites 6 and 12 did not have a low-MERV filter installed during any cooling visits and Site 14 received an outdoor unit replacement during this study. Average flow reductions are shown as high-MERV values relative to low-MERV values. Higher average airflow rates were measured with high-MERV filters only at Site 13.*

Research Question 1: What is the impact of filtration efficiency on the measured parameters?

The goal of this analysis is to compare low-MERV, mid-MERV, and high-MERV filters and see how filter efficiency influences parameters related to energy use in the test systems. Table 3 shows those dependent variables for which there are statistically significant differences between filter MERV categories. Table 3 Impacts of Filter Efficiency on Measured Variables 3 also shows both a median percentage difference and a median absolute difference between each filter type, along with the number of systems, *n*, used in the statistical tests. Comparisons between mid- and high-MERV filters are not shown because the only significant difference in fan-only mode was a small change in duct leakage and there were only two or three sites to compare in cooling mode. No significant differences existed between mid- and low-MERV filters in cooling mode, likely because of the small sample size.

The results in Table 3 show that high-MERV filters introduced an approximately 45% greater pressure drop than low-MERV filters. High-MERV filters caused median airflow rates to decrease by approximately 4% in the fan-only period and by 10% in the cooling mode, relative to low-MERV filters. High-MERV filters decreased fan power draw by approximately 1% in the fan-only mode and 4% in the cooling mode relative to low-MERV filters. The net result of the changes in airflow and fan power is that high-MERV filters supplied approximately 4% less volumetric airflow per unit of power in the fan-only mode and 5% less in the cooling mode. Supply and return duct leakage flows both decreased in the presence of high-MERV filters, although the magnitudes of these changes are small and not always significant. The magnitude of flow reductions seen with higher-efficiency filters generally agrees with the flow reductions measured in Parker et al. (1997).

Table 3. Impacts of Filter Efficiency on Measured Variables

		High-MERV vs. Low-MERV			Mid-MERV vs. Low-MERV		
	Dependent Variable, IP (SI)	**[%][1]**	**Absolute[1]**	***n*[2]**	**[%][1]**	**Absolute[1]**	***n*[2]**
Fan-Only Mode	Fan Power, W	**–1.1***	**–5***	16	–1.2	–5	16
	Filter Pressure Drop, IWC (Pa)	***+45****	***+0.096 (24)****	16	***+47****	***+0.11 (26)****	16
	Fan Flow, CFM (m^3·h^{-1})	***–4.2****	***–59 (100)****	16	***–5.3****	***–40 (68)****	16
	Fan Efficacy, CFM·W^{-1} (m^3·h^{-1}·W^{-1})	***–3.9****	***–0.08 (0.14)****	16	*–4.4*	*–0.09 (0.15)*	16
	Supply Duct Leakage Flow, CFM (m^3·h^{-1})	–16	–8 (14)	14	***–44****	***–31 (53)****	14
	Return Duct Leakage Flow, CFM (m^3·h^{-1})	–14	–3 (5)	13	–44	–11 (19)	13
Cooling Mode	Fan Power, W	***–4.0****	***–15****	11	+4.9	+24	2
	Filter Pressure Drop, IWC (Pa)	***+43****	***+0.13 (31)****	11	–9.6	–0.037 (9.3)	2
	Fan Flow, CFM (m^3·h^{-1})	***–10****	***–96 (160)****	11	–0.3	–54 (92)	2
	Fan Efficacy, CFM·W^{-1} (m^3·h^{-1}·W^{-1})	*–5.4*	*–0.11 (0.19)*	11	–5.5	–0.13 (0.22)	2
	Supply Duct Leakage Flow, CFM (m^3·h^{-1})	***–14****	***–24 (41)****	9	+3.8	+5 (9)	3
	Return Duct Leakage Flow, CFM (m^3·h^{-1})	***–19****	***–7 (12)****	8	+7.6	+11 (19)	2

[1] **Asterisk (*) and bold indicate $p < 0.05$ from paired t-test.** *Italics indicate $p < 0.05$ from Wilcoxon matched-pairs sign-rank test.*

[2] The maximum number of systems used in the filter comparison tests is 16 because one system (Site 12) required high-MERV filters be installed at all times. Three sites were excluded from supply duct leakage testing and four sites were excluded from return duct leakage testing due to scheduling conflicts with one building owner and because some ductwork was located within conditioned space, thus having no exterior leakage.

During cooling periods, median sensible capacity and outdoor unit power draw, although not statistically significant, decreased by 10 and 2%, respectively, in systems with a high-MERV filter relative to a low-MERV filter. The magnitude of the decreases in sensible capacity and outdoor unit power draw generally agrees with values seen in the literature with flow reductions of 10%. The reductions in fan power draw, outdoor unit power draw, and duct leakage may reduce the increase in energy consumption expected with a decline in cooling capacity, although the measured reductions approach the bounds of instrument uncertainty, especially in fan-only mode.

All of the variables related to the non-fan-only portion of air conditioner energy performance, including cooling capacity and outdoor unit power draw, did not show any statistically significant differences between filters and thus are not reported in Table 3. One limitation of this analysis is that the cooling mode tests do not take into account climatic and behavioral conditions. Outdoor temperature and evaporator entering wet-bulb temperature are two climatic conditions that are known to affect capacity, power draw, and system runtime. Thermostat settings by occupants are behavioral parameters that affect air conditioner energy consumption as well. Since these conditions were unable to be controlled in the field tests, a binned analysis was conducted to attempt to isolate their effects from those possibly attributed to changes in filter MERV categories. The binned analysis compared data at both 6 and 12 ranges of similar outdoor dry bulb and indoor entering wet bulb conditions and revealed no significant relationships, although this was likely due to the fact that there were very few possible comparisons of two different filters at the same site with the same outdoor and indoor conditions.

We have some confidence that neither a significant relationship nor a bias exists in the cooling mode data because filter type was only weakly correlated with outdoor temperatures. The median outdoor dry-bulb and evaporator entering wet-bulb temperatures at which systems with low-MERV filters operated was approximately 2.5°F (1.4°C) and 0.9°F (0.5°C) greater, respectively, than those recorded with high-MERV filters. Also, a nonparametric extension of the Wilcoxon rank-sum test reveals that there appears to be no statistical trend in outdoor temperatures across MERV categories, which suggests that low-MERV filters and high-MERV filters were installed during similar outdoor temperature conditions. The same test, however, does reveal a significant, but slight, apparent trend in evaporator entering wet bulb temperatures across MERV categories. This suggests a possible bias regarding thermostat settings and that low-MERV filters were installed during periods of higher thermostat settings or higher indoor wet-bulb temperatures, although the magnitude is small.

Repeated tests at the same site with the same MERV filter did not have a statistically different filter pressure drop, but did reveal some statistically significant differences in fan-only mode parameters. Median fan power decreased 3% and median airflow decreased approximately 5% within filter MERV repetitions. Supply- and return- duct leakage flows both increased 26%. These values are all similar to the magnitude of the effects shown in Table 3, thus the impacts of filter efficiency on energy-related parameters were generally small enough to be in the noise of variations of filters, installations, and other factors. This suggests that the actual energy implications of filter MERV may be small as well.

Research Question 2: How does filter pressure drop relate directly to the measured parameters?

The goal of this analysis is to normalize the pressure drop across filters in each system, regardless of MERV category, and see how pressure drop influences parameters related to energy consumption. The analysis ignores Sites 9 and 12 because only the return plenum pressure drops were measured in the field (not the true filter pressure drops). The normalization approach for each dependent and independent variable (1) subtracts the average variable measured with a clean low-MERV filter from the average variable measured at any monthly visit and (2) divides the average variable by the average variable measured with a clean low-MERV filter.

Table 4 summarizes significant results and shows the slope of the regression for all statistically significant changes in dependent variables, with upper and lower bounds according to a 95% confidence interval, and the number of data points (i.e., monthly site visits), *n*, used in the regression. A slope is taken to be significant ($\alpha < 0.05$) if the 95% confidence interval does not contain zero. A negative value in Table 4 means that the variable decreased as filter pressure drop increased and a positive value means the variable increased. The larger the absolute value of the slope, the stronger the relationship.

According to the regressions, a doubling of the filter pressure drop (due either to loading or replacement with a higher-efficiency filter) would likely result in an 6 to 8% decrease in system airflow during fan-only operation and 7 to 10% during cooling operation. Other significant differences due to an increase in filter pressure drop include fan power, fan efficacy, and duct leakage flows. These differences generally agree with the results based on filter efficiency described in Table 3. A doubling of filter pressure drop would likely result in a 1 to 3% decrease in fan power draw during fan-only periods and a 4 to 6% decrease in fan power draw during cooling modes, suggesting a potential energy benefit when switching from a low to a higher pressure drop filter. As filter pressure drop doubles, both supply- and return-side leakage airflow rates in the fan-only mode measured statistically significant decreases of 19 to 27% and 10 to 15% in the cooling mode, suggesting further potential energy benefits of higher-efficiency filters. However, since system airflow rates also diminished, the magnitude of changes in duct leakage fractions, which are the important parameters for duct efficiency in ASHRAE Standard 152-2004, is less than 1%. Finally, latent capacity decreased 7 to 25% in the field systems with a doubling of filter pressure drop. Much of this decrease can be attributed to decreases in system airflow [(see Equation (1)].

The significant decrease in latent capacity could also be attributed to indoor and outdoor temperatures and sensible and latent cooling loads, as climatic conditions are not considered in this analysis. No significant changes in sensible capacity, total capacity, or outdoor unit power draw were detected. However, similar to the filter efficiency analysis, measured filter pressure drop is very weakly correlated with outdoor temperature and entering wet bulb temperature (correlation coefficients = –0.11 and –0.10, respectively), suggesting a minimal bias between filter installations and climatic conditions. However, relative filter pressure drop is more strongly correlated with indoor wet bulb temperature (correlation coefficient = –0.28), suggesting that the significant decrease in latent capacity measured with higher pressure drop filters could be biased towards measurements made with lower indoor wet bulb temperatures and lower latent cooling loads.

Table 4. Impacts of Filter Pressure Drop on Measured Variables

	Normalized Dependent Variable, Compared to Clean High-MERV	Regression Slope ± 95% CI (%)[1]	*n*
Fan-only Mode	Fan Power	–1.8 ± 1.1	218
	Fan Flow	–6.7 ± 0.9	218
	Fan Efficacy	–4.6 ± 1.1	218
	Supply Duct Leakage Flow	–23 ± 3.6	169
	Return Duct Leakage Flow	–23 ± 3.4	201
Cooling Mode	Fan Power	–4.7 ± 0.8	91
	Fan Flow	–8.6 ± 1.4	83
	Fan Efficacy	–4.3 ± 1.3	83
	Supply Duct Leakage Flow	–12 ± 1.9	77
	Return Duct Leakage Flow	–13 ± 2.1	70
	Latent Capacity	–16 ± 8.9	73

[1] The regression slope refers to the change in dependent variable associated with a doubling of filter pressure drop.

Research Question 3: What is the range of energy consequences of filtration that is likely in residential and light-commercial buildings?

The goal of this analysis is to explore any possible connections between filter MERV category and energy consumption in the test systems. In theory, the decline in system airflow and therefore sensible capacity caused by high-efficiency filters would cause a system to run longer and consume more energy. At the same time, fan and outdoor unit power draw may decline to minimize additional energy consumed because of lengthened operation time. Although a significant reduction in system airflow occurred between low- and high-MERV filters in the test systems, identifying a statistical difference in cycle lengths due to filters proved difficult. Many statistical tests are not valid because unequal amounts of tests in the cooling season were conducted at different sites at different conditions, leading to a lack of independent comparisons. Thus, this analysis relies only on a summary approach of the cycle lengths and power draw measurements made in the test systems, first on a site-by-site basis and second on an overall statistical basis.

The median length for all cycles recorded at all sites (excluding Sites 6, 12, and 14) was 7.3 minutes with a low-

Table 5. Impacts of Filter MERV on Duty Cycle and Power Draw

	Duty Cycle, hours day^{-1}			Normalized Total Power, W ton^{-1} (W·kW^{-1})			Change in Daily Energy Consumption[3]
Site[1]	Low-MERV	High-MERV	Change[2]	Low-MERV	High-MERV	Change[2]	kWh·ton^{-1}·day^{-1} (kWh·kW^{-1}·day^{-1})
1	3.65	5.13	+1.49	550 (156)	671 (191)	+120 (+34)	+1.4 (+0.41)
2	3.25	2.31	–0.94	1180 (337)	1140 (325)	–40 (–11)	–1.2 (–0.34)
3	3.11	2.30	–0.82	1060 (301)	1010 (288)	–50 (–13)	–0.97 (–0.27)
4	5.77	7.14	+1.37	1210 (343)	1160 (330)	–50 (–13)	+1.3 (+0.38)
5	6.14	12.0	+5.90	1330 (379)	1280 (364)	–50 (–16)	+7.2 (+2.1)
7	3.41	6.21	+2.80	1360 (387)	1350 (385)	–10 (–2)	+3.8 (+1.1)
8	7.69	8.19	+0.50	1480 (421)	1600 (456)	+120 (+35)	+1.7 (+0.50)
9	5.71	5.27	–0.44	963 (274)	949 (270)	–14 (–4)	–0.50 (–0.14)
10	3.51	4.37	+0.86	1110 (315)	1150 (328)	+40 (+13)	+1.2 (+0.33)
11	10.3	10.7	+0.36	935 (266)	900 (256)	–35 (–10)	0.03 (0.01)
13	14.3	8.65	–5.62	956 (272)	953 (271)	–3 (–1)	–5.4 (–1.5)
15	11.2	4.01	–7.17	1370 (389)	1320 (376)	–50 (–13)	–10 (–2.8)
16	5.22	3.21	–2.02	1480 (420)	1400 (398)	–80 (–22)	–3.2 (–0.92)
17	6.98	1.80	–5.17	1250 (356)	1250 (355)	0 (0)	–6.5 (–1.8)
Mean	6.44	5.8	–0.63	1160 (330)	1150 (328)	–10 (–2)	–0.80 (–0.23)
Median	5.74	5.2	–0.04	1190 (340)	1160 (329)	–24 (–7)	–0.26 (–0.07)
Std. Dev.	3.40	3.2	3.48	255 (72.5)	241 (68.6)	62 (18)	4.4 (1.3)

[1] Sites 6, 12, and 14 are excluded from this analysis.

[2] Change is calculated as high-MERV values minus low-MERV values.

[3] Daily energy consumption for each filter MERV is calculated as the average daily duty cycle multiplied by the normalized total power draw.

MERV filter installed and 8.3 minutes with a high-MERV filter installed. However, cycle lengths were distributed over a wide range due in part to the variety of equipment and occupant behavior that produced a large amount of scatter in the field data. Comparing only individual sites, median cycle lengths were longer with a high-MERV filter in six of the fourteen applicable sites, longer with a low-MERV filter in seven sites, and approximately equal in one site.

Another useful comparison of cycle lengths is the measure of duty cycle, or the hours per day that the cooling system is running. Table 5 displays the average duty cycle measured at each site with low- and high-MERV filters installed, combined with the total power draw ($W_{fan} + W_{ou}$) measured at steady state operation, normalized by nominal cooling capacity to weight differently sized systems equally. Fundamentally, the measures of total power draw and system runtime will capture any energy consequences of changes in airflow, capacity, or duct leakage due to high-efficiency filters. Also in Table 5 is the average change in energy consumption during one day of cooling operation, calculated as high-MERV values minus low-MERV values at each site. The observed change in daily energy consumption (kWh·ton^{-1}·day^{-1}, kWh·kW^{-1}·day^{-1}) is calculated from the average duty cycle and normalized power draw values for each MERV filter in Table 5, with high-MERV values minus low-MERV values, which means a negative value represents energy savings with high-MERV filters installed.

Excluding Sites 6, 12, and 14, duty cycle lengths were longer with high-MERV filters in seven sites and shorter in seven sites. The median difference in duty cycles due to high-MERV filters was –0.04 hours, or under three minutes in a 24-hour day. Median normalized total power draw was approximately 24 W·ton^{-1} (7 W·kW^{-1}) lower with high-MERV filters relative to low-MERV filters. Although it is important to note that both mean and median daily energy consumption decreased slightly in the presence of high-MERV filters, the extreme values and the very large standard deviations in Table 5 reflect considerable scatter due to other dominating factors (i.e., climate and occupant behavior) that is not uncommon for field measurements.

The differences in duty cycle were greatest at Sites 5, 13, 15, and 17. Long cycle lengths with high-MERV filters at Site 5 were dominated by occupant thermostat settings, as the minimum return air temperature was approximately 4°F (2.2°C) lower than that measured with low-MERV filters. Longer cycle lengths occurred at Site 13 with low-MERV filters primarily because both outdoor temperatures were greater and thermostat settings were lower, although a large amount of filter loading with low-MERV filters installed caused average airflow rates to actually be 9% lower with low efficiency filters than with high-MERV filters. Site 15 was an old system that ran a large portion of the workday and since a large amount of bypass prevented filters from changing airflow rates dramatically, changes in energy consumption were entirely due to outdoor temperatures and thermostat settings. Site 17 was affected primarily by greater outdoor temperatures recorded with low-MERV filters installed.

The differences in normalized total power draw were greatest at Sites 1, 8, and 16. Site 1 had a variable speed compressor that adjusted to an average outdoor temperature that was 2.7°F (1.5°C) higher with high-MERV filters installed. Maximum outdoor temperatures reached 97°F (36°C) at Site 8 during some cycles with high-MERV filters compared to 91°F (33°C) with low-MERV filters, causing the outdoor unit to draw more power. Similarly, the average outdoor temperature at Site 16 was 91.4°F (33°C) with low-MERV filters installed compared to 81.5°F (27.5°C) with high-MERV filters installed.

The median change in daily energy consumption at the test sites was a decrease of 0.26 kWh·ton^{-1}·day^{-1} (0.07 kWh·kW^{-1}·day^{-1}) with high-MERV filters installed, suggesting potential small energy savings associated with higher-efficiency filters. However, the large standard deviation suggests that filters had a small impact on these systems in comparison with other factors. Similar to differences in duty cycle lengths and total power draw, the extreme values in Table 5 are explained by differences in outdoor temperature and thermostat settings in the field data. An example of this is that five of seven residential systems showed an increase in energy consumption with high-MERV filters (positive values in Table 5) and five of seven light-commercial systems showed a decrease in energy consumption (negative values in Table 5). Given the scatter in the data, it is difficult to make a firm assessment, but it may be that differences in the indoor conditions and the operation of these two types of buildings are important factors that govern the sign and magnitude of the energy implications of filters. For example, light-commercial systems operated longer than residential systems, on average, regardless of filter installation. Longer operation can be due to lower thermostat settings in light-commercial buildings or the time of day that light-commercial systems operate (in general, the light commercial buildings use cooling more during the hotter portions of the day while residences are unoccupied).

Given the complexity of interacting effects, we have limited confidence in the reliability of directly associating changes in energy consumption with filter efficiency in the field data, especially given the small magnitude of these effects and the large amount of scatter in the overall dataset. Instead, we defined a statistical matrix (Table 6) to estimate the range of possible energy consequences of high and low efficiency filtration using the distributions of total power draw and system runtime in Equation (3), extrapolated to a hypothetical month during the cooling season. Table 6 was constructed from the values in Table 5 that compares the differences of normalized total power draw and duty cycle fractions measured between high- and low-MERV filters at the 14 test sites with available data.

The top row in the matrix is from the distribution of the variable that compares the difference in normalized total power draw with high- and low-MERV filters at each site. The left-hand column in the matrix is from the distribution that compares the duty cycle between the two filter categories at each site. The cell values in Table 6 are the values from the power draw distribution multiplied by values from the duty cycle distribution, then multiplied by the number of hours in a 30-day month (720 hours), with low-MERV values subtracted from high-MERV values. The result is an estimate of the likely change in energy consumption during one month of cooling operation in the test systems, normalized by nominal cooling capacity. Table 6 is intended to provide data over the entire range of conceivable energy consequences of filters according to our test systems but does not reflect actual measured changes in energy consumption.

Table 6. Expected Change in Energy Consumption (Comparing High- to Low-MERV)

ΔkWh per Ton (ΔkWh per kW) of Capacity per Month of Cooling[1]						
		Change in Duty Cycle				
Change in Normalized Filter Impact on Total Power Draw, W·ton^{-1} (W·kW^{-1})		5th percentile	25th percentile	50th percentile	75th percentile	95th percentile
		–7.2 h d^{-1}	–2.0 h d^{-1}	–0.04 h d^{-1}	1.4 h d^{-1}	5.9 h d^{-1}
5th percentile	–78 (–22)	–330 (–93)	–97 (–28)	–32 (–9.0)	+44 (+13)	+230 (+66)
25th percentile	–45 (–13)	–270 (–75)	–77 (–22)	–23 (–6.6)	+40 (+11)	+200 (+56)
50th percentile	–24 (–7)	–210 (–59)	–60 (–17)	–16 (–4.6)	+34 (+10)	+160 (+45)
75th percentile	–3 (–1)	–210 (–59)	–58 (–17)	–13 (–3.7)	+39 (+11)	+170 (+48)
95th percentile	+120 (+35)	–300 (–86)	–78 (–22)	+0.2 (+0.1)	+88 (+25)	+310 (+87)

[1] Changes in power draw, duty cycle, and energy consumption due to filters are calculated as the value measured with a high-MERV filter installed minus that measured with a low-MERV filter installed.

Table 6, in accordance with Table 5, reveals that the median system from systems similar to those in our study would draw 24 W per ton (7 W per kW) less power and have a shorter duty cycle of approximately 0.04 hours per day. Projecting the values to a hypothetical 30-day month, the median system would likely consume approximately 16 kWh per ton (4.6 kWh per kW) less electricity with a high-MERV filter than with a low-MERV filter during a month of cooling operation, suggesting that the energy implications of filter selection are minor. Given the results described above for the other research questions and the large variations, this small savings is not likely to be statistically significant. Table 6 does suggest that in the extreme, higher-efficiency filters can have large energy impacts, although that impact is slightly biased towards saving energy (using less energy with a higher pressure drop filter) rather than using more energy.

The range of likely effects on energy consumption is large for both filter efficiency categories, which suggests the changes are affected mostly by other climatic and behavioral factors. The bottom quartile of systems ran less often during the cooling season with a high-MERV filter and higher-efficiency filters had decreased energy consumption. The top quartile of systems ran more often during the cooling season with high-MERV filters and higher-efficiency filters appear to have increased energy consumption. However, this is not a site-by-site analysis and the sites that experienced changes in power draw were not the same sites that observed changes in duty cycle lengths. Table 6 represents only the range of potential energy consequences using the statistical distributions of power draw and duty cycles in the measured field data.

Given the results in Table 6, the systems at the extreme ends of both variables merit exploration. As previously mentioned, the sites in Table 5 that showed the largest difference of duty cycles between filters were affected most by varied occupant thermostat settings and somewhat by varied outdoor temperatures. The sites in Table 5 that showed the largest difference in total power draw between filters were dominated by outdoor unit power draw values measured at different outdoor temperatures (e.g., Sites 5 and 7 had high-MERV filters installed at higher outdoor temperatures). Nevertheless, a decrease in energy consumption at the median values suggests that higher-efficiency filters, on average, had a small and likely energy-saving effect for these systems.

It is important to describe the major limitations of this investigation. The magnitude of energy consequences of filters seen herein was generally small, but the analysis does not capture the effects of filtration on other potentially important parameters like refrigerant charge or extremely low airflow rates. For example, if a poorly maintained system has low refrigerant charge or is already operating at very low airflow rates with low-efficiency filters, the additional, albeit small, decrease in airflow rate introduced by a higher-efficiency filter could be large enough to have more serious performance effects like ice formation on the evaporator coil. The sample size of this investigation was limited, but given the cost of field measurements and the fact that some significant findings were found, the sample size appears reasonable. The sample was never intended to be representative of all small systems in the U.S., but the system characteristics generally concur with those found by others (i.e., Parker et al. 1997; Downey and Proctor 2002). The test systems also varied widely in age, size, efficiency, and operational characteristics. Thermostats were controlled by the building occupants and the test sites were only visited once per month. Although this introduced confounding factors, such as uncontrolled climatic conditions and thermostat operation, it also provides a more realistic assessment of the factors that really affect energy use associated with filters. To avoid these issues, we have conducted further research that continuously monitored the performance of two air conditioning units at a controlled test house for several months. The results of the study will be available in a forthcoming publication and generally confirm the results presented here.

This study also focused on cooling system performance. This decision was made because it avoids combustion efficiency issues for non-electric heating and because flow has never been shown to affect heating capacity with the exception of heat pumps (Krafthefter and Bonne 1986), which represent a small proportion of U.S. heating systems (there were none in our sample). Despite these limitations, this investigation clearly suggests a weak and often counterintuitive association between filter efficiency or filter pressure drop and air conditioner energy consumption in small residential and light-commercial systems.

CONCLUSION

Smaller residential and light-commercial systems do not behave like large commercial systems and the energy consequences of filters are consequently more complex. Field measurements of 17 residential and light-commercial forced air cooling systems were conducted in Austin, Texas to assess the energy implications of higher-efficiency filtration. Three ranges of commonly available filters were installed: low (MERV 2), medium (MERV 6-8), and high (MERV 11-12), as rated by the manufacturers. The results described herein suggest that higher-efficiency filters do not appear to have much of an impact on energy consumption in smaller forced air cooling systems and that the magnitudes of effects seen with filters are small in comparison to the effects of more important parameters like thermostat settings, climatic conditions, refrigerant charge, and duct leakage. Many of the energy consequences of filter efficiency were small enough to be in the noise of variations of filters and installations.

The primary findings of the investigation include:

- Median airflow rates were approximately 4 to 5% lower during fan-only operation for 16 of the sites and 10 to 11% lower during cooling operation for 11 of the sites with high-efficiency filters (MERV 11-12) installed versus low-efficiency filters (MERV 2);

- The median fan power draw decrease was approximately 1% during fan-only operation and 4% during cooling operation with high-MERV filters installed;
- Median supply and return duct leakage airflow rates decreased in the presence of high-MERV filters, although the change in leakage fractions were very small;
- Median cycle lengths were longer with a high-MERV filter in six of the fourteen applicable sites, longer with a low-MERV filters in seven sites, and approximately equal in one site;
- Likely energy consequences of high-MERV filters suggest a median energy reduction of 16 kWh per ton (4.6 kWh per kW) per month when compared to low-MERV filters, albeit with considerable scatter;
- Many of the impacts of filters measured in the test sites were within the range of instrument uncertainty and repeated filter tests had similar impacts in many cases as different filter efficiency installations did; and
- Climatic variation and factors relating to system operation, installation, and maintenance appear to be considerably more important than the small energy consequences associated with different filter pressure drops.

We hope that these results will assist decision makers in assessing the positive and negative implications when designing and selecting filters for residential and light-commercial buildings.

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