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ABSTRACT

Occupant concern about indoor air quality (IAQ) issues has led to the increased use of more effective air filters in residential heating and cooling systems. A drawback of improved filtration is that better filters tend to have more flow resistance. This can lead to lower system airflows that reduce heat exchanger efficiency, increase duct pressure that leads to increased air leakage for ducts and, in some cases, increased blower power consumption. There is currently little knowledge on the magnitude of these effects. In this study, the performance of ten central forced air systems was monitored for a year. The systems used either a Permanent Split Capacitor (PSC) or a Brushless Permanent Magnet (BPM) blower. Each system was operated with a range of filter efficiencies ranging from MERV 6 (the lowest currently permitted in ASHRAE Standard 62.2) up to MERV 16. Measurements were recorded every ten seconds for blower power, filter pressure drop, supply and return plenum pressures together with plenum and indoor temperatures. These detailed continuous measurements allowed observation of filter loading effects as well as the initial change in system performance when filters were swapped. The results of the field measurements were used in simulations to examine more general system performance effects for a wider range of climates. The field tests showed that system static pressures were highly influenced by filter selection, filter loading rates varied more from house to house than by MERV rating and overall were quite low in many of the homes. PSC motors showed reduced power and airflow as the filters loaded, but BPM motors attempted to maintain a constant airflow and increased their power to do so. The combined field test and simulation results from this study indicate that for MERV 10-13 filters the effects on energy use are small (<1%) over a wide range of performance conditions and climates. However, using higher efficiency MERV 16 filters leads to problems in terms of potential for significantly increased energy use (>5%) and usability. In systems using low MERV filters that are already close to blower performance limits the addition of a MERV 16 filter pushed the blowers to their performance limits.

INTRODUCTION

Particles are the number one pollutant of concern in homes due to the significant health impacts and their omnipresence in all homes (Logue et al. 2011). ASHRAE Standard 62.2 is considering the addition of filtration requirements to supplement the current dilution and local exhaust approaches to Indoor Air Quality (IAQ). One approach being considered is the addition of high efficiency particle filters to central forced air systems that allow for the removal of both indoor and outdoor sources of particulates. The standard committee needs to balance the additional protection of occupant health due to increased removal of particulates with increases in blower power requirements and other system effects. There is also increasing interest in reducing particulates in indoor air from regulatory bodies, such as the California Air Resources Board who are sponsoring work on the effectiveness of different approaches to filtration in ventilation systems with an interest in having filtration requirements in building codes.

Particles come from both outdoor (e.g., from internal combustion engines) and indoor (e.g., cooking) sources. The migration of outdoor particulates into homes can be reduced by using tight building envelopes combined with supply ventilation air systems that have high levels of filtration. Because we want to address both indoor and outdoor sourced particles, this study focused on filtration in central forced air systems. A drawback of improved filtration is that the better filters tend to have more airflow resistance. This can lead to lower system airflows that reduce heat exchanger efficiency, increase duct pressure differences (leading to increased air leakage for ducts), and increase blower power consumption. Due to a lack of measured data and analysis of energy and performance consequences, there is currently little knowledge on

the magnitude of these effects. There is also no guidance for consumers or contractors purchasing filters regarding the related energy impacts.

Currently, the most common filter rating method is the Minimum Efficiency Rating Value or MERV. MERV ratings are developed from test procedures in ASHRAE Standards 52.2 (2007B). A higher MERV rating means that the filter removes more particles. The MERV rating procedure assesses the particle removal efficiency of a filter over three particle size ranges: 0.3-1 μm , 1-3 μm and 3-10 μm . The higher MERV filters remove more particles in the smaller size ranges. From a health perspective, the literature indicates greater benefits from the removal of particles of 2.5 microns, or less, in diameter (Hinds 1999) – referred to as PM_{2.5} – and thus the two lower particle size ranges are key to particle filtration in homes. The minimum MERV rating to remove 50% of the 1-3 μm size range is MERV 10. A MERV 16 filter captures more than 95% of all three particle sizes, including bacteria and tobacco smoke (Newell, 2006). Therefore, this study used MERV 16 filters as the high-efficiency filters and compared the system performance to filters of lower MERV rating. This study used the manufacturer's MERV ratings as a basis for comparison. It may be interesting in future work to apply the field measurement techniques suggested by Stephens and Siegel (2013) to evaluate the change in filter efficiencies as filters load as a follow-up to the change in energy use as filters load reported here.

Removal of smaller particles generally results in higher air flow resistance (Kowalski and Bahnfleth 2002); however, this is complicated by geometry issues and selection of filtration method and/or medium. Filters come in common depths of 1, 2, 4, 5 and 6 inches with consequent increases in filter media surface area and decreases in airflow resistance for the same filter medium. Another complication is that the two kinds of electric motors used in residential forced air system blowers: Permanent Split Capacitor (PSC) and Brushless Permanent Magnet (BPM), have different responses to pressure difference. In general, PSC driven blowers tend to decrease flow and power with increased pressure difference, whereas BPM blowers maintain flow and increase power.

To estimate the magnitude of these effects, this study performed measurements in ten California houses to determine the effects of changing filter performance on the energy use of the heating and cooling systems. Multiple filters were evaluated in ten homes covering a wide range of filter effectiveness from simple low filtration fiberglass filters, up to high efficiency MERV 16 filters. This included filter designs that are intended to reduce filter pressure drop such as pleated filters and four-inch deep filters. To extend the estimates of filtration impacts sophisticated analysis and simulation tools were used to determine filter impacts for a wide range of parameters and climates. This paper presents a summary of the study results and more details can be found in Walker et al. (2012) and Walker et al. (2013).

System Effects

The added air flow resistance of higher efficiency filters leads to decreased air flow for PSC blowers and increased in blower power for BPM blowers. Lower system airflow results in lower air conditioner efficiencies (a simple method of estimating these changes is given in ASHRAE Standard 152 (ASHRAE 2007)). The coincident system pressure changes also change duct leakage. For supply ducts, any reduction in system air flow will reduce the pressures across supply duct leaks and decrease duct leakage. Conversely, the return duct leakage generally increases because filters are located on the return side of the duct system thus increasing pressure differences in the return. The magnitude of the return duct leak impact will depend on where in the duct system the filters are located. When filters are located at return grilles the entire return duct system is depressurized. When filters are mounted on filter racks near the blower/furnace cabinet then only the blower/furnace cabinet experiences increases in static pressure difference. The leaks in the return ducts themselves may see decreases in static pressure difference if airflow is reduced (similar to the supply ducts). Therefore the energy impact of duct leakage is greater for systems with filters at return grilles.

Filter Loading

Filter pressure drop increases as filters become dirty or fouled. As this pressure drop increases more air goes around the filter instead of through it (called bypass) and does not get filtered, thus reducing the overall filtration effectiveness. There are rough guidelines for changing filters that are usually time based, with a few exceptions that call for more frequent changes such as: unusually dirty ductwork, construction in progress, furniture or drywall sanding, presence of pets or smokers, and if the blower is running continuously. Energy use associated with air filtration is a recognized issue that is mentioned in sales literature of filter manufacturers, however, there is little information on the magnitude of the impacts in typical residential systems, the sensitivity of these impacts to system specifications (e.g., use of different blowers) or how these impacts can be reduced or controlled.

FIELD TESTING OF FILTER IMPACTS ON HVAC SYSTEM PERFORMANCE

Ten homes were tested for this study. They were selected to cover a range of parameters of interest: different filter thicknesses including large four-inch pleated filters, variable speed motors, single speed motors, filters at return grilles, filters at the furnace/blower, filters in both locations, systems with heating only, a multispeed heating system, and systems with both heating and cooling. The houses were located in several California climates including San Francisco Bay Area (including both mild coastal and warm inland), northern California coast, and the California Central Valley. The field-testing had two parts. The first part was diagnostic testing to characterize the home and HVAC system(s). The second part was long-term testing to observe rates of filter loading, changes in filter pressure drop and the associated system performance changes. Diagnostics tests for system air flow and duct leakage were performed for each system and for each filter used. Most of the homes were tested with two levels of filtration: MERV 11 and MERV 16. In three homes initial testing was performed with the filters currently in use by the occupants that ranged from MERV 4 to MERV 13. Approximately four to six months of operation was recorded for each filter. In two homes testing with MERV 16 filters had to be abandoned due to excessive noise because the filters created too much air flow resistance resulting in loud whistling from filter bypass. In one case the filter was almost sucked out of the filter slot after only a few hours of operation. This illustrates potential issues for putting filters into existing systems that were not designed for high MERV filters and their associated air flow resistance and that forced air system design should accommodate low air flow velocities across filters.

Long-Term monitoring

The long term monitoring was over a period of approximately one year. This length of sampling period allowed the evaluation of regular and high efficiency filters for each individual system. The filters loaded due to particles in the air in the homes only - there was no additional artificial loading during the experiments. The system monitoring used a sampling frequency of ten seconds. The data were then averaged for each blower cycle and the blower cycle averages were summarized in timelines so we could observe the step changes in performance as well as changes in time due to filter loading. The pressure drop across the filter, as well as at supply and return plenums and at selected locations in the supply and return duct system, were measured using static pressure probes and digital manometers (Energy Conservatory, DG-700) with a pressure resolution of 0.1 Pa (0.0004 in. water) and an accuracy of $\pm 1\%$. These measurements isolated the components of total system pressure into pressures at the filter, supply ducts, return ducts, and the cooling coil. The power consumption of the blower was measured using true power meters (Continental Control Systems WattNode Power and Energy meters in conjunction with current transformers and voltage readings) to avoid errors associated with low power factor operation (particularly for BPM motors). The uncertainty of the power measurements was $\pm 0.5\%$ of the reading for most measurements, but could be as high as $\pm 4.5\%$ for blower motors with a high power factor. Air temperatures were measured in the supply and return plenum and the occupied space. The temperature sensors were wireless (Point Six Wireless) and the temperatures were recorded by the same computer that recorded all of the data. The accuracy of the temperature measurements was $\pm 0.5^\circ\text{C}$.

Field Test Results

The results are presented in terms of accumulated mass flow of air through the filter (rather than simply changes with time) so that we can account for changes in air flow as the filters foul and for systems that operate at different speeds. Example results are shown for two houses. Figures 1-3 are from House 4 that had a PSC motor and Figures 4-6 are from House 7 that had a BPM motor. For each filter and each mode of operation for multi-speed systems, the changes in pressures, air flow and blower power were assumed to change in a linear fashion with cumulative mass flow. Linear least-squares fits to the measured data are also shown in the figures illustrating that this was a valid assumption. These least square fits were used in the energy modeling. The vertical lines in the plots indicate an important event, usually a filter change or cleaning. These figures show the general trends of increasing system pressures with cumulative mass flow as the filters become loaded, and also the step changes when filters or operating modes are changed. Comparing Figure 1 and Figure 4 shows a key difference between the blower technologies: in Figure 1 the PSC motor shows gradually decreasing air flow and blower power. Figure 4 shows the BPM motor maintaining airflow at the expense of a slight increase in blower power. House 7 had two filter locations in series: one at the ceiling return grille and the other in a filter slot at the furnace (high performance filters were installed in both locations). Figures 5 and 6 show how the filter at the return grille fouled but the one at the furnace did not. This indicates that the first filter was effective at removing particles from the air and hints at the possibility of using inexpensive pre-filters to remove large particles that contribute most to filter loading. This should considerably lengthen the service life of a more costly high-MERV filter.

For PSC motors the airflow generally decreased with filter loading, with low MERV filters averaging a decrease of 5 L/s (11 cfm)/ 10^6 kg, and MERV 16 filters averaging 18 L/s (38 cfm)/ 10^6 kg. For BPM motors the airflow did not change significantly until the blower reached maximum output at which point they decayed at rates similar to PSC motors. No BPM motor using a low MERV filter reached its maximum output. Changing from a low MERV filter to a new clean MERV 16 filter for PSC motors decreased the flow rate by an average of 89 L/s (188 cfm) or 22%. With BPM motors the speed adjusted to keep the flow constant, except at high-speed settings when the maximum speed was reached in the two systems that were already at maximum output before the addition of high performance filters.

Replacing low MERV filters with MERV 10-13 filters has a moderate (< 5%) the effect on blower energy use are over a wide range of performance conditions and climates. Using higher MERV 16 filters leads to problems in terms of potential for significantly increased blower energy use (> 5%) and usability. In systems that are already close to blower performance limits with low MERV filters, the addition of a MERV 16 filter pushed the blowers to their limits. In a couple of cases even BPM driven blowers were unable to maintain airflow because the motors were operating at maximum output before the required airflow rate was met. Other complications for predicting the system performance were that, in one case, a BPM driven blower increased flow with a MERV 16 filter. This shows how the particulars of the BPM control algorithm can confound predictions of performance.

Filter loading rates varied more from house to house more than by MERV rating, and overall were quite low in many of the homes. In seven of the homes the loading effects with a MERV 16 filter were low with filter pressure changes of less than 5 Pa (0.02 in. water) (about 5% of filter pressure). Two homes had a medium rate of loading with pressures changing by about 30 Pa (0.12 in. water) (15% of filter pressure). A single home, with a MERV 8 filter, fouled at what we considered a high rate and saw a pressure change of 40 Pa (0.16 in. water), approximately a 40% change in the filter pressure. Lower MERV rated filters generally had lower loading rates. The physical geometry of the filters – particularly their depth and surface area has an impact on the system effects. Of the filters studied, the four-inch deep filters had an average filter pressure drop of 94 Pa, while the one-inch deep filters had an average filter pressures drop of 110 Pa (0.44 in. water) averaged over all MERV ratings. The four-inch filters also loaded slower with an average rate of 5.6 Pa/ 10^6 kg, whereas the one-inch filters averaged 10.6 Pa (0.04 in. water)/ 10^6 kg. These results indicate that deep pleated filters have significant performance advantages over less deep filters. The highest loading was measured in the house in the most rural setting

(which also had two large hairy dogs), likely due to the higher concentration of large particles in the rural setting as we observed that the particles on the filter were the same color as the earth at that location.

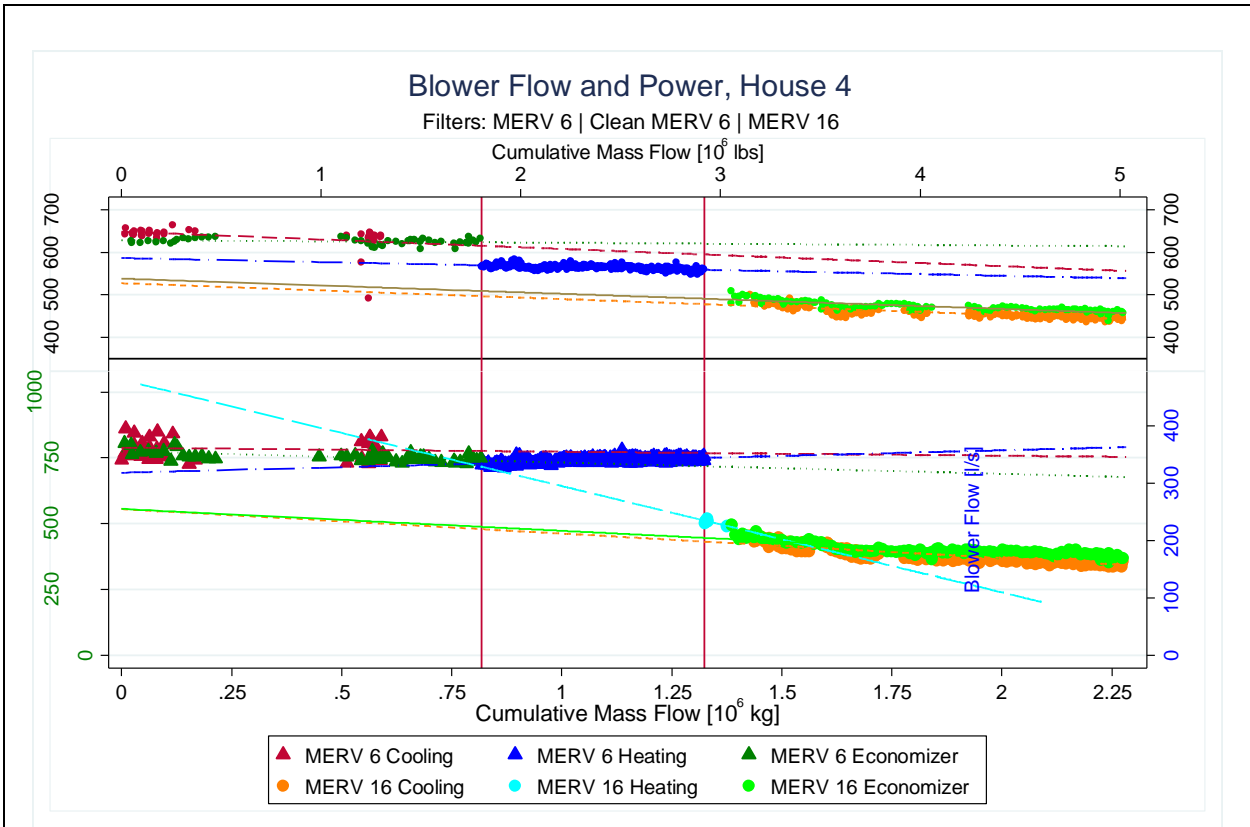


Figure 1 Blower flow and power changes from House 4. The vertical lines show when the MERV 6 filter was replaced with a new MERV 6 filter and then changed to MERV 16. The house had an Economizer in addition to cooling and heating modes.

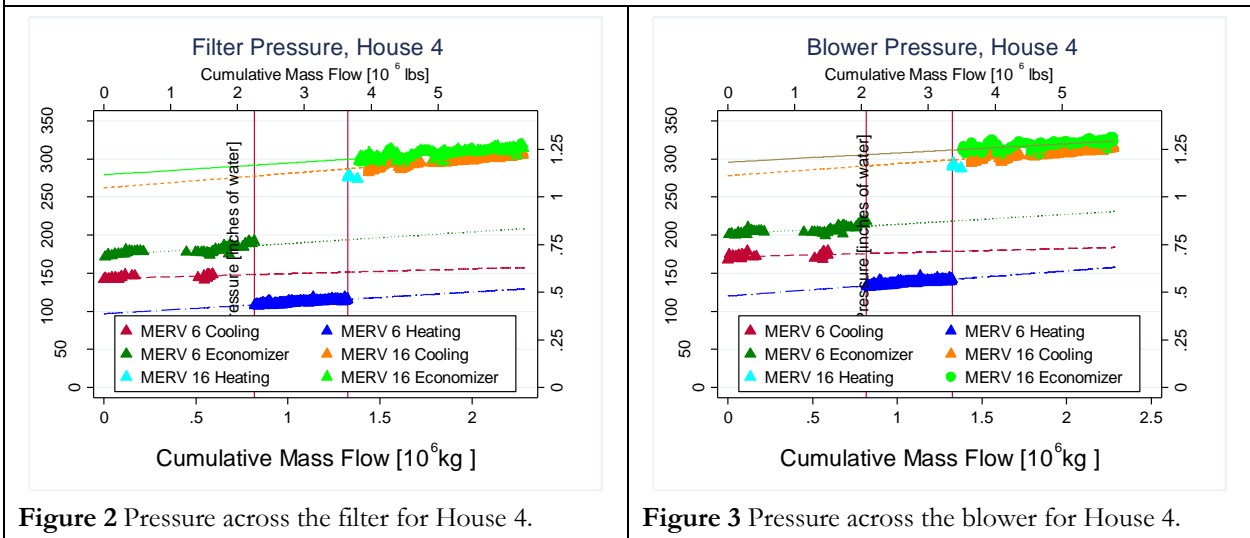


Figure 2 Pressure across the filter for House 4.

Figure 3 Pressure across the blower for House 4.

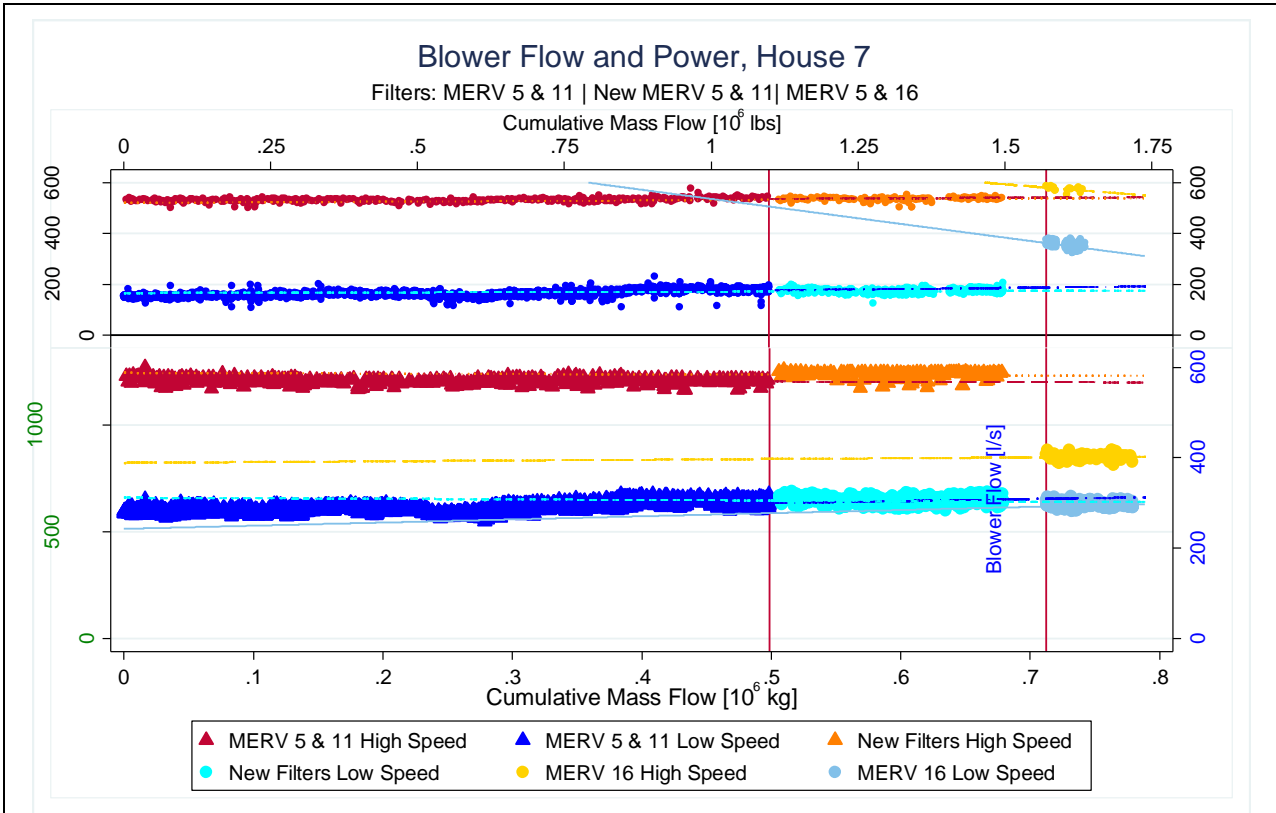


Figure 4 Blower flow and power changes from House 7. There are two filters in series in this house; initially a MERV 5 and 11, which were replaced about half way through with new ones, then these were replaced with a MERV 5 & 16 combination.

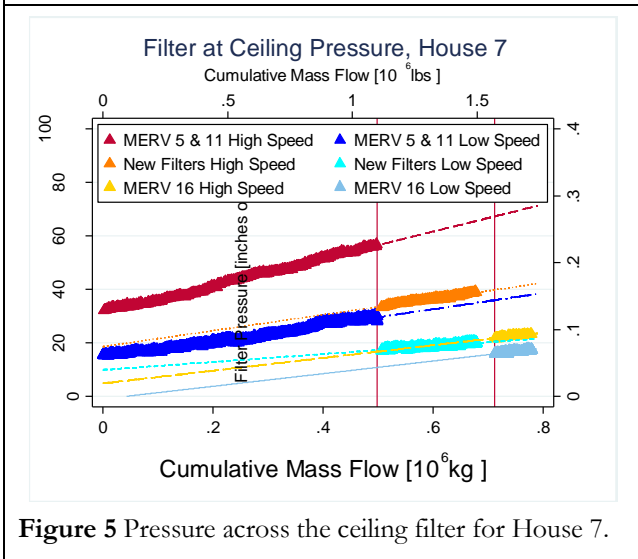


Figure 5 Pressure across the ceiling filter for House 7.

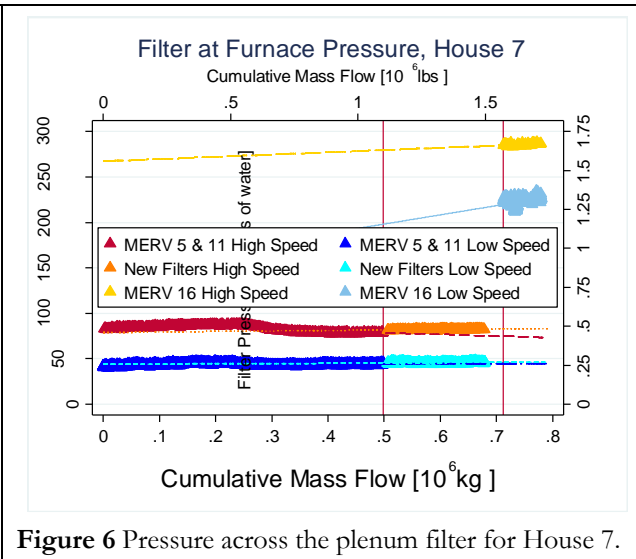


Figure 6 Pressure across the plenum filter for House 7.

The large variability in system installations in terms of the available filter area, filter depth and airflow led to large ranges of measured system pressures. The filters occupants initially had installed before the testing period had MERV ratings ranging from 4 to 13 and had filter pressure drops of 16 to 173 Pa (0.06 to 0.69 in. water) with an average of 71 Pa (0.29 in. water). When these were replaced by MERV 16 filters the pressures ranged from 16 to 300 Pa (0.06 to 0.60 in.

water) with an average of 149 Pa (0.60 in. water). These results indicate that it is *possible* to install MERV16 filters with little change to system pressures (and therefore air flows, air leakage and blower power) – generally the higher performance filters significantly increase the filter pressure drop. Although there is a lot of variability, generally changing to a MERV 16 filter almost doubled the pressure across the filter. Systems with low initial filter pressure drops had dramatic increases in their filter pressures when MERV 16 filters were installed - in one extreme case by over a factor of 10. For comparison, Stephens et al. (2010a) measured pressure drops in 17 residential and light commercial systems that changed from a median of 34 Pa (0.14 in. water) for MERV 2 to 55 Pa (0.004 to 0.22 in. water) for MERV 11, which falls within our range for lower (<MERV 16) filters. Another California field survey (Proctor et al. (2011)) reported a median filter pressure drop (for whatever filters were installed in the study homes) of 38 Pa (0.15 in. water) that corresponds to the results of the lowest MERV filters in our field study.

To convert the blower power and duct leakage effects into energy changes over a year, simulations have been performed (Walker et al. (2012) and Walker et al. (2013)) that used the field test results to model HVAC system performance changes with different MERV filters and filter loading rates. Six California climates were used, ranging from heating dominated Climate Zone 1 (corresponding to DOE Climate Zone 3 Marine) to cooling dominated Climate Zone 15 (corresponding to DOE Climate Zone 2 hot and dry). The other four climates were mixed heating and cooling. In each climate zone a total of 36 cases were simulated accounting for the three higher MERV filter changes, three loading rates, two duct leakage levels, and the two types of blower motor (PSC and BPM). The model included calculations to change the blower power, airflow, return duct leakage (assuming the filter was located at the grille), and air conditioner performance relative to the MERV 5 baseline with no filter loading. In the hottest climates it becomes essential to avoid using MERV 16 filters with leaky ducts and a BPM blower because the energy penalties can get as high as 20%. In many climates the high filter loading cases stood out as having significantly worse performance. This indicates the need for some sort of indicator that a filter is fouled that can be observed by home occupants. The main conclusions from the simulations are:

- The effects of filtration on energy use are about 1% or less, averaged over all climates and loading situations, with the exception of MERV 16 filters with leaky ducts and a BPM blower motor.
- Filtration causes a higher energy penalty in cooling dominated climates than in heating dominated climates mostly due to higher airflow requirements for cooling systems
- In climates that are not dominated by either heating or cooling a PSC motor-driven blower will have energy gains or losses due to power swapping between the air handler and either the furnace or the air conditioner, resulting in a low net energy penalty from filtration
- A BPM blower operates best in heating dominated climates with a low pressure drop system, and shows less variability in total system energy performance with filter loading rate and MERV rating than a PSC blower

The effects of high efficiency filtration on system energy use are small in climates that have both low cooling and heating loads. Note that this needs to be balanced by the fact that the small number of operating hours leads to less particulate removal. For filtration to be effective in these climates the central system may have to be forced to operate when there is no heating or cooling load. This is particularly true for energy efficient homes.

These overall results are comparable with previous studies. For example, Parker et al. (1997) used modeling of airflow reduction effects to estimate about a 2% change in energy use. Stephens et al. (2010a) used periodic field measurements of air conditioner use to examine the change in air conditioner performance when going from low MERV filters to MERV 11 or 12 filters. Taking their median energy reduction of 0.26 kWh/ton/day and the air conditioner capacities and energy use from the current study, implies a change in energy use of about 1%. However, it should be noted that the Stephens et al. study found large variations of ± 4.4 kWh/ton/day (or a variability of about $\pm 15\%$) making comparisons difficult. Springer (2009) tested clean filters rated from MERV 2 (approximately) to MERV 13 and found that filter pressure drop (that ranged from 32 to 130 Pa (0.13 to 0.52 in. water) at a face velocity of 2.5 m/s (490 feet per minute)) was not highly correlated with MERV ratings at a fixed airflow. The airflow reduced by 10% for a PSC blower and did not change for a BPM blower as

MERV increased – but the BPM motor used 10% more power to maintain the airflow. In contrast to conventional wisdom, the Stephens study also reported that extra depth (going from 1 in. to 2 in. deep, or 2 in. to 4 in. deep) only had a marginal effect on the pressure drop from clean filters.

Despite the differences in filtration methodology and MERV ratings of filters it appears that there is a consensus that energy changes are not large on average, and depend very much on individual system characteristics such as duct leakage and initial system air flow resistance. More detailed monitoring of two systems by Stephens et al. (2010b) again showed very small overall impacts for MERV 11 filters that are similar to the results of the current study. It appears that the extension to MERV 16 filters in the current study has shown that energy use issues may only be significant at these higher filtration levels, given the relative agreement between this and previous studies at lower MERV 11 levels.

RECOMMENDATIONS

Due to the large variability in field test results from this and other studies due to the corresponding variability in central forced air system design and installation our recommendations are brief:

1. No energy related requirements are needed for MERV 11 or lower filters
2. General restrictions on MERV 16 filters are:
 - a. A duct leakage test is required and ducts should have 6%, or less, leakage
 - b. Require an alarm to indicate when filter has exceeded its loading limit
3. Require filter manufacturers to label filters with static pressure drop at one or more rating points

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