Modeling the Impacts of Filter Fouling on Energy Consumption

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Abstract

The use of higher efficiency particulate air filters in central heating, ventilating, and air-conditioning (HVAC) systems to improve indoor air quality (IAQ) in homes is continuing to increase. However, as filters are loaded with collected particulate matter and dust, the pressure drop will increase and lead to a variety of direct and indirect energy impacts. The magnitude of energy impacts on fouled, or dirty, filters is not yet known. Therefore, this paper explores the energy impacts of fouled filters on new energy-efficiency homes in multiple climates around the United States by performing whole building energy simulations using BEopt and EnergyPlus. Relevant inputs include filter pressure drop, total pressure drop, HVAC airflow rate, fan efficiency, heating and cooling nominal capacity, and rated airflow rate. The results indicate that annual energy consumption generally increases for permanent split capacitor (PSC) and electronically commutated motor (ECM) fans as the filter gets loaded or dirty over time, although the energy impacts are smaller for ECMs.

Introduction

Central heating and air-conditioning systems account for a significant amount of energy consumption in the United States. Approximately 65% of American households now have a central heating, ventilating, and air-conditioning (HVAC) systems (Sullivan 2010), and the use of higher efficiency particle air filters to improve indoor air quality (IAQ) is continuing to increase. The filter plays an important role in HVAC systems as it prevents the particles and dust from accumulating on the fans and heat exchanger coils that can negatively affect heat transfer (Yang

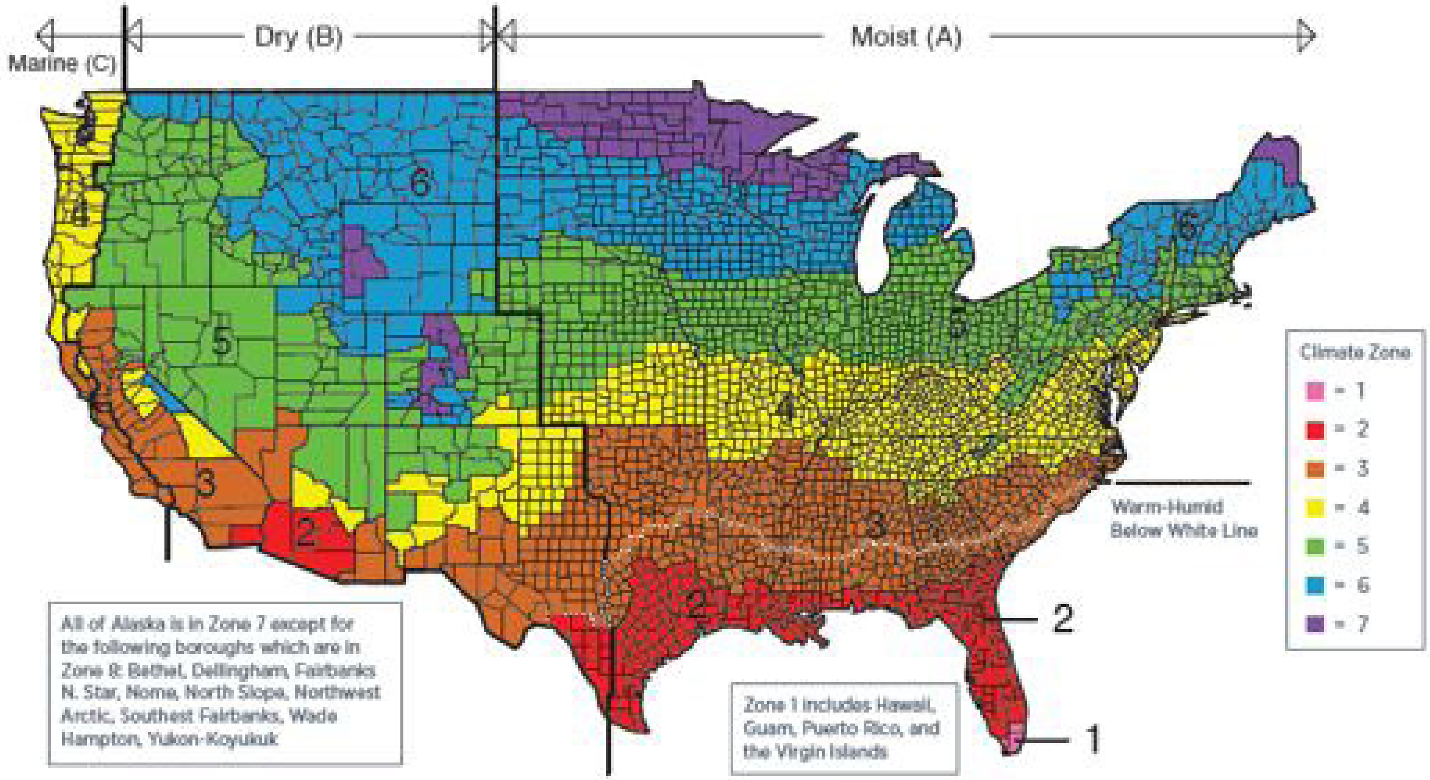

Figure 1. *Climate Zone Map (Figure taken directly from DOE, 2010)*

et al. 2007a, b; Siegel and Nazaroff 2003). With a PSC blower installed in HVAC systems, when the pressure increases, the airflow rate drops, which can lead to higher system runtime, thus increasing the energy consumption. On the contrary, an ECM blower tends to increase the fan speed in order to maintain the same airflow rate and meet the space sensible load requirements when the pressure increases, thus consuming more fan energy for the same amount of runtime. This relationship between energy consumption and filter pressure drop is generally true for smaller residential air-conditioning systems. This study considers a new energy-efficiency home for each climate zone in the United States and explores the energy impacts under various static pressure conditions in residential buildings by performing whole building simulation using BEopt and EnergyPlus.

Methods

Home Selection

Each home represents a climate region shown in Figure 1. All home plans are 2025 sq. ft. and one-story single-family home. Every home is assumed to have a tight building envelope with low infiltration and supplemental mechanical ventilation to increase the ventilation rate. The thermostat setting is 294.8 K (71 oF) in the winter and 297.6 K (76 oF) in the summer. The building characteristics used, which varied among the cities shown in Table 1, were designed to meet the 2009 IECC requirements. Table 1 summarizes the relevant building characteristics in each city.

Identifying pressure drop, airflow rate, fan efficiency, heating and cooling nominal capacities

This paper selected 50 Pa as the baseline static pressure drop where the filter was new and clean. This assumption was made based on the previous work where 62 Pa was introduced by the combination of coils (40 Pa), and registers, grilles, and dampers (22 Pa) (Stephens 2014). From 50 Pa, the increment of 25 Pa was made for each case until 350 Pa where the filter was very dirty. The static pressure drops were used to determine their impacts on fan airflow rates, fan efficiency, and fan power draws using Eq.1 (DOE 2005).

$$W = \frac{\Delta P_{system} \Delta Q_{fan}}{\eta_{fan} \eta_{motor}} \quad \text{(Eq. 1)}$$

	1A - Miami	2A - Houston	2B - Phoenix	3A - Dallas	3B - Los Angeles
Story	1	1	1	1	1
Floor Area (ft^2)	2025	2025	2025	2025	2025
Orientation	Front door faces north	Front door faces north	Front door faces north	Front door faces north	Front door faces north
Floor Construction	Slab, uninsulated	Slab, uninsulated	Slab, uninsulated	Slab, uninsulated	Slab, uninsulated
Number of bedrooms	3	3	3	3	3
Number of bathrooms	2	2	2	2	2
Exterior wall materials	Vinyl, light	Vinyl, light	Vinyl, light	Vinyl, light	Vinyl, light
Wall insulation ($h·ft^2·°F$/ Btu)	R-13 Fiberglass Batt, Gr-1, 2x4, 16 in o.c.	R-13 Fiberglass Batt, Gr-1, 2x4, 16 in o.c.	R-13 Fiberglass Batt, Gr-1, 2x4, 16 in o.c.	R-13 Fiberglass Batt, Gr-1, 2x4, 16 in o.c.	R-13 Fiberglass Batt, Gr-1, 2x4, 16 in o.c.
Wall sheathing	OSB	OSB	OSB	OSB	OSB
Attic insulation ($h·ft^2·°F$/ Btu)	Ceiling R-30 Fiberglass, Vented	Ceiling R-30 Fiberglass, Vented	Ceiling R-30 Fiberglass, Vented	Ceiling R-30 Fiberglass, Vented	Ceiling R-30 Fiberglass, Vented
Window U-value (Btu/ $h·ft^2·°F$)	1.2	0.65	0.65	0.5	0.5
Window SHGC	0.3	0.3	0.3	0.3	0.3
Window area, F B L R (ft^2)	43, 86, 43, 43	43, 86, 43, 43	43, 86, 43, 43	43, 86, 43, 43	43, 86, 43, 43
Duct location	Unfinished attic	Unfinished attic	Unfinished attic	Unfinished attic	Unfinished attic
Duct insulation ($h·ft^2·°F$/ Btu)	R-8	R-8	R-8	R-8	R-8
Duct leakage	7.50%	7.50%	7.50%	7.50%	7.50%
Envelope airtightness	3ACH50	3ACH50	3ACH50	3ACH50	3ACH50
Mechanical ventilation	ERV, 72%	ERV, 72%	ERV, 72%	Supply	ERV, 72%
HVAC equipment	3-ton AC unit 16 SEER 1- stage 98% AFUE gas furnace	3-ton AC unit 16 SEER 1- stage 98% AFUE gas furnace	4-ton AC unit 16 SEER 1- stage 98% AFUE gas furnace	3.5-ton AC unit 16 SEER 1- stage 98% AFUE gas furnace	2-ton AC unit 16 SEER 1- stage 98% AFUE gas furnace
Nominal cooling capacity (W)	10,551	10,551	14,068	12,309	7,034
Nominal heating capacity (W)	10,551	10,551	10,551	10,551	10,551

Table 1. *2009 IECC compliant home characteristics for each city*

	3C - San Francisco	4A - New York	4B - Albuquerque	4C - Seattle	5A - Chicago
Story	1	1	1	1	1
Floor Area (ft^2)	2025	2025	2025	2025	2025
Orientation	Front door faces north	Front door faces north	Front door faces north	Front door faces north	Front door faces north
Floor Construction	Slab, uninsulated	Basement, whole wall R-10 XPS	Slab, 2ft R10 Exterior XPS	Slab, 2ft R10 Exterior XPS	Basement, whole wall R-10 XPS
Number of bedrooms	3	3	3	3	3
Number of bathrooms	2	2	2	2	2
Exterior wall materials	Vinyl, light	Vinyl, light	Vinyl, light	Vinyl, light	Vinyl, light
Wall insulation ($h \cdot ft^2 \cdot {}^oF$/ Btu)	R-13 Fiberglass Batt, Gr-1, 2x4, 16 in o.c.	R-13 Fiberglass Batt, Gr-1, 2x4, 16 in o.c.	R-13 Fiberglass Batt, Gr-1, 2x4, 16 in o.c.	R-13 Fiberglass Batt, Gr-1, 2x4, 16 in o.c.	R-13 Fiberglass Batt, Gr-1, 2x4, 16 in o.c.
Wall sheathing	OSB	OSB	OSB	R-5 XPS	R-5 XPS
Attic insulation ($h \cdot ft^2 \cdot {}^oF$/ Btu)	Ceiling R-30 Fiberglass, Vented	Ceiling R-38 Fiberglass, Vented	Ceiling R-38 Fiberglass, Vented	Ceiling R-38 Fiberglass, Vented	Ceiling R-38 Fiberglass, Vented
Window U-value (Btu/ $h \cdot ft^2 \cdot {}^oF$)	0.5	0.35	0.35	0.35	0.35
Window SHGC	0.3	0.3	0.3	0.3	0.3
Window area, F B L R (ft^2)	43, 86, 43, 43	43, 86, 43, 43	43, 86, 43, 43	43, 86, 43, 43	43, 86, 43, 43
Duct location	Unfinished attic	Unfinished basement	Unfinished attic	Unfinished attic	Unfinished basement
Duct insulation ($h \cdot ft^2 \cdot {}^oF$/ Btu)	R-8	R-8	R-8	R-8	R-8
Duct leakage	7.50%	7.50%	7.50%	7.50%	7.50%
Envelope airtightness	3ACH50	3ACH50	3ACH50	3ACH50	3ACH50
Mechanical ventilation	Supply	Supply	Supply	Supply	Supply
HVAC equipment	2-ton AC unit 16 SEER 1- stage 98% AFUE gas furnace	1.5-ton AC unit 16 SEER 1- stage 98% AFUE gas furnace	2.5-ton AC unit 16 SEER 1- stage 98% AFUE gas furnace	2-ton AC unit 16 SEER 1- stage 98% AFUE gas furnace	1.5-ton AC unit 16 SEER 1- stage 98% AFUE gas furnace
Nominal cooling capacity (W)	7,034	5,275	8,792	7,034	5,275
Nominal heating capacity (W)	10,551	10,551	10,551	10,551	10,551

Table 1. *2009 IECC compliant home characteristics for each city (cont'd)*

	5B - Denver	6A - Minneapolis	6B - Helena	7A - Fargo	7B - Aspen
Story	1	1	1	1	1
Floor Area (ft^2)	2025	2025	2025	2025	2025
Orientation	Front door faces north	Front door faces north	Front door faces north	Front door faces north	Front door faces north
Floor Construction	Slab, 2ft R10 Exterior XPS	Basement, whole wall R-15 XPS	Slab, 4ft R10 Exterior XPS	Basement, whole wall R-15 XPS	Slab, 4ft R10 Exterior XPS
Number of bedrooms	3	3	3	3	3
Number of bathrooms	2	2	2	2	2
Exterior wall materials	Vinyl, light	Vinyl, light	Vinyl, light	Vinyl, light	Vinyl, light
Wall insulation ($h \cdot ft^2 \cdot {}^\circ F/$ Btu)	R-13 Fiberglass Batt, Gr-1, 2x4, 16 in o.c.	R-13 Fiberglass Batt, Gr-1, 2x4, 16 in o.c.	R-13 Fiberglass Batt, Gr-1, 2x4, 16 in o.c.	R-21 Fiberglass Batt, Gr-1, 2x6, 24 in o.c.	R-21 Fiberglass Batt, Gr-1, 2x6, 24 in o.c.
Wall sheathing	R-5 XPS	R-5 XPS	R-5 XPS	OSB	OSB
Attic insulation ($h \cdot ft^2 \cdot {}^\circ F/$ Btu)	Ceiling R-38 Fiberglass, Vented	Ceiling R-49 Fiberglass, Vented	Ceiling R-49 Fiberglass, Vented	Ceiling R-49 Fiberglass, Vented	Ceiling R-49 Fiberglass, Vented
Window U-value (Btu/ $h \cdot ft^2 \cdot {}^\circ F$)	0.35	0.35	0.35	0.35	0.35
Window SHGC	0.3	0.3	0.3	0.3	0.3
Window area, F B L R (ft^2)	43, 86, 43, 43	43, 86, 43, 43	43, 86, 43, 43	43, 86, 43, 43	43, 86, 43, 43
Duct location	Unfinished attic	Unfinished basement	Unfinished attic	Unfinished basement	Unfinished attic
Duct insulation ($h \cdot ft^2 \cdot {}^\circ F/$ Btu)	R-8	R-8	R-8	R-8	R-8
Duct leakage	7.50%	7.50%	7.50%	7.50%	7.50%
Envelope airtightness	3ACH50	3ACH50	3ACH50	3ACH50	3ACH50
Mechanical ventilation	Supply	Supply	Supply	ERV, 72%	ERV, 72%
HVAC equipment	2.5-ton AC unit 16 SEER 1- stage 98% AFUE gas furnace	1.5-ton AC unit 16 SEER 1- stage 98% AFUE gas furnace	2-ton AC unit 16 SEER 1- stage 98% AFUE gas furnace	1.5-ton AC unit 16 SEER 1- stage 98% AFUE gas furnace	2-ton AC unit 16 SEER 1- stage 98% AFUE gas furnace
Nominal cooling capacity (W)	8,792	5,275	7,034	5,275	7,034
Nominal heating capacity (W)	10,551	10,551	14,068	14,068	10,551

Table 1. *2009 IECC compliant home characteristics for each city (cont'd)*

Where the variables are defined as follows:

> Wfan = fan power draw (W);
> Psystem = external static pressures (Pa);
> Qfan = airflow rate (m3s-1);
> ηfan = efficiency of the fan;
> ηmotor = efficiency of the fan motor.

With different types of blowers installed in the HVAC equipment, the airflow rate (Qfan) and overall efficiency (ηfan, ηmotor) will change correspondingly and thus have different effects on fan power draw (Wfan).

Representative fan curves (airflow vs pressure and fan efficiency vs pressure) for single-stage virtual model furnaces for PSCs and two-stage virtual model furnaces for ECMs from the US Department of Energy were referred to find the general average fan curves for both PSCs and ECMs blowers (DOE 2011). Figure 2 and 3 show the fan curves from DOE for PSCs and ECMs blowers respectively. Plotted average fan curves for PSCs and ECMs blowers were shown in Figure 4 and 5 respectively. The plotted graphs were extrapolated to 350 Pa for the sole purpose of this study. The airflow rate and fan efficiency for PSCs and ECMs corresponding to the external static pressures were obtained from the equation of the plotted average fan curve while the fan power draw was the result of multiplication of airflow rate and fan efficiency. The overall efficiency was then calculated using Eq. 1. The relative airflow rate was calculated in order to correlate between airflows and cooling capacities.

The default values for cooling and heating capacities generated by BEopt in IDF were discarded and changed to the cooling and heating capacities commonly found in the United States

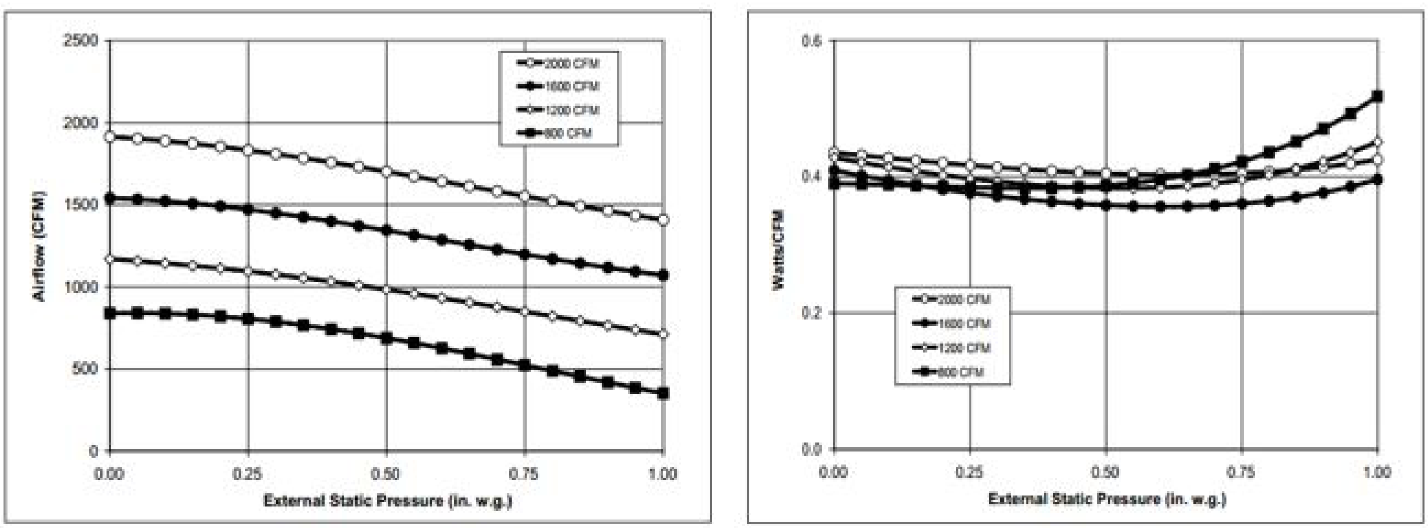

Figure 2. *Fan airflow and fan efficiency curves for PSC blower with four different sizes (Figure taken directly from DOE, 2011)*

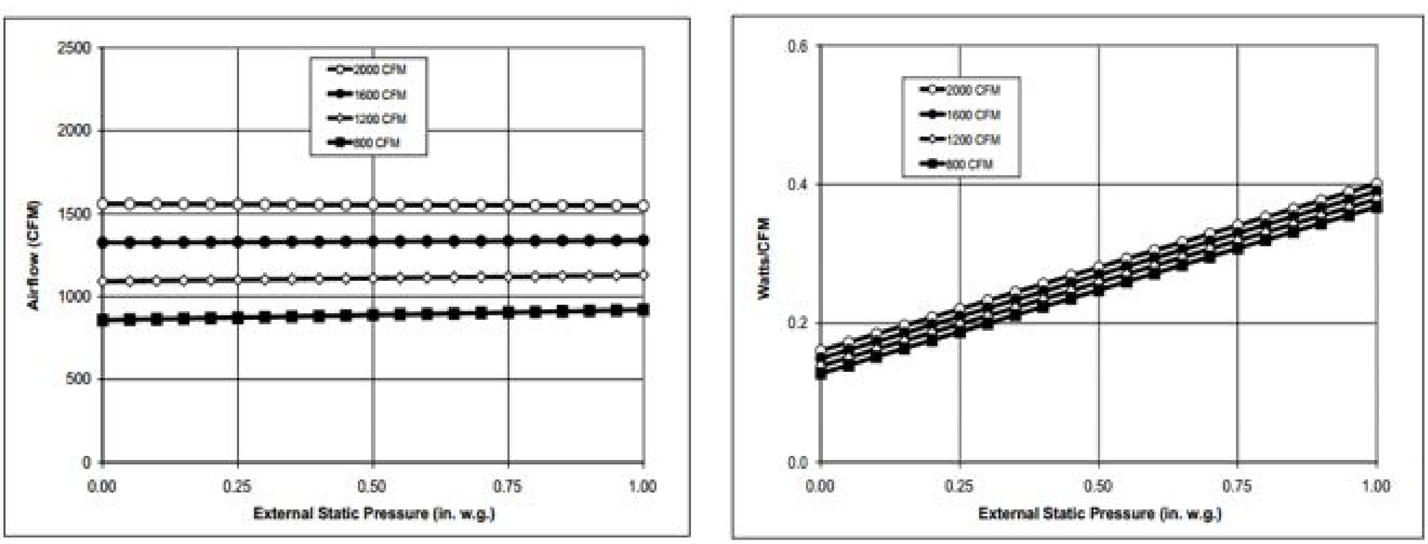

Figure 3. *Fan airflow and fan efficiency curves for ECM blower with four different sizes (Figure taken directly from DOE, 2011)*

for each city. The rated airflow rate for each city was estimated by multiplying the nominal cooling capacity (tons) and cooling flow (400 CFM/tons).

Energy simulation procedures

The modeling tools used in this study were BEopt and EnergyPlus. In this project, fifteen US cities were selected to represent each climate region recognized by ASHRAE (DOE 2010). A total of 390 (13*15*2) simulations were run using thirteen different static pressures, fifteen cities and two types of fan blowers. Once all available inputs were selected in BEopt, a single simulation for each city was run in order to generate the IDF file for EnergyPlus simulations. The IDF was extracted and edited using IDF editor to modify input parameters according to different pressures. Rated airflow rate for HVAC equipment was kept at the maximum value for each case while the designed airflow rate were altered in each case according to different pressures. Airflow rates were changed under Fan:OnOff, Branch, AirLoopHVAC:UnitaryHeatCool, and AirTerminal:SingleDuct:Uncontrolled sections of the IDF. Airflow rates were assumed to be the same for cooling and heating for the ease of use. Fan pressure and efficiency were also changed

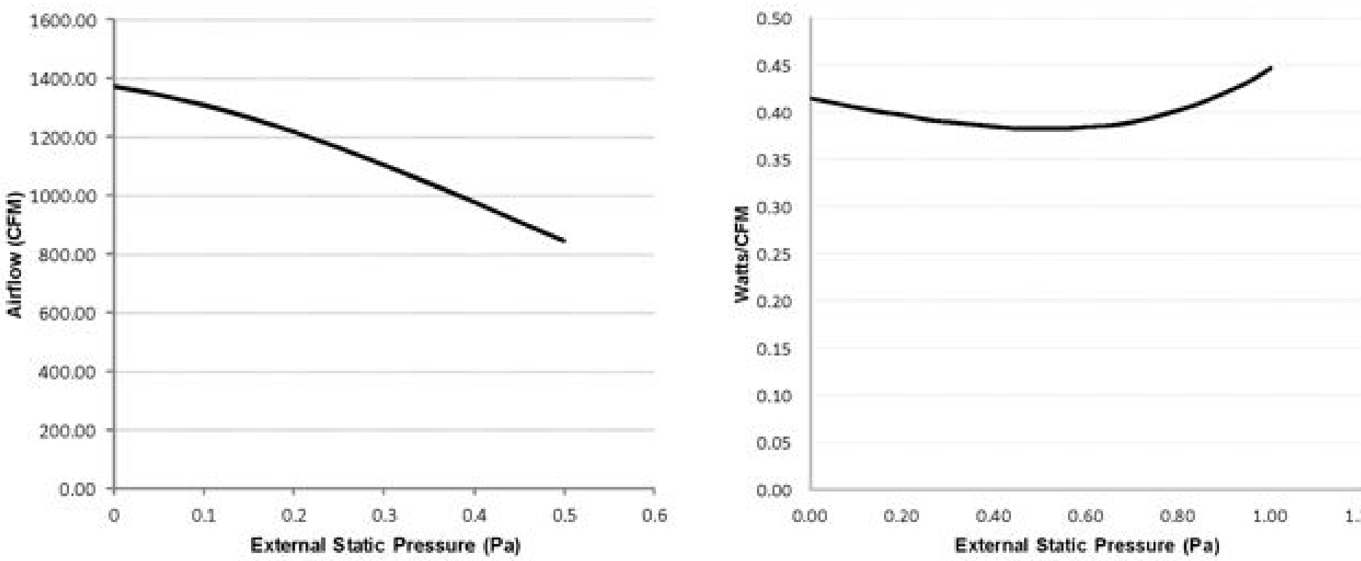

Figure 4. *Average fan airflow and fan efficiency curves for PSC blower*

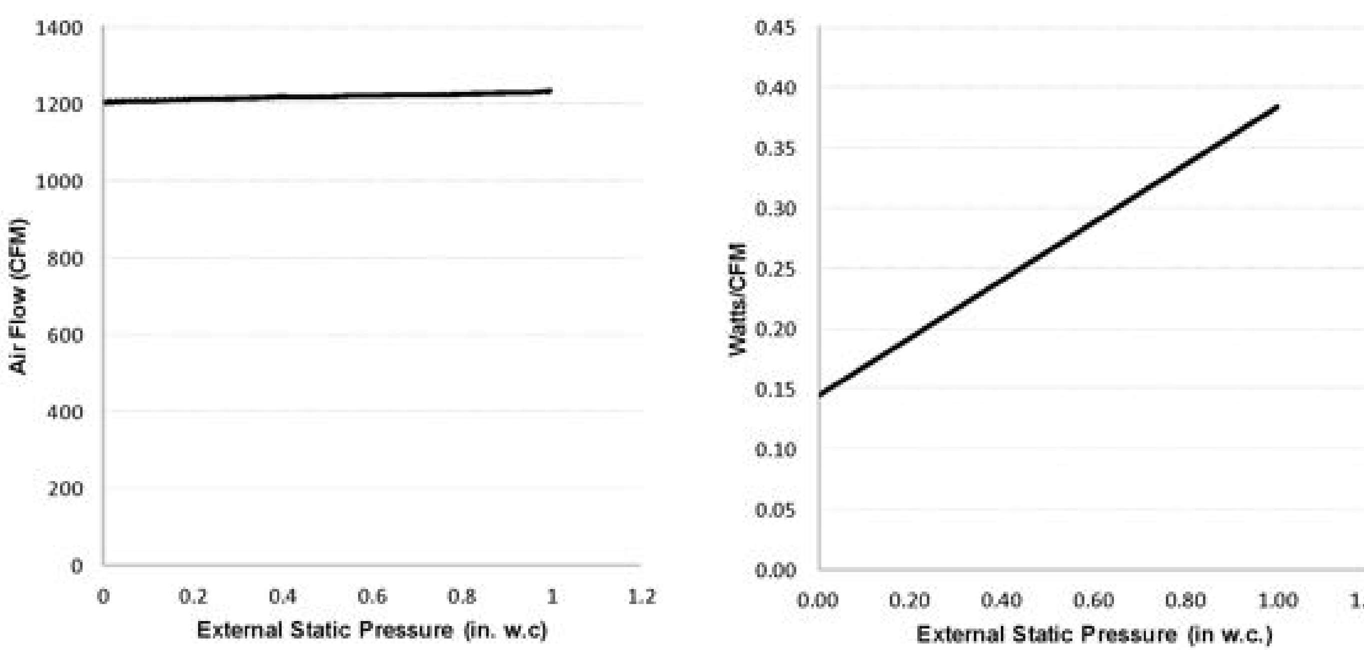

Figure 5. *Average fan airflow and fan efficiency curves for ECM blower*

under Fan:OnOff section of the IDF. Nominal cooling and heating capacities were adjusted under Coil:Cooling:DX:SingleSpeed and Coil:Heating:Gas sections respectively. Finally, timestep for each simulation case was changed to 6 under Timestep and Sizing:Parameters sections. Significant outputs obtained from EnergyPlus were annual energy consumption, annual HVAC energy, annual heating energy, and annual fan energy. These annual outputs were used to examine the impacts of pressure drops on total HVAC energy use.

Results

PSC Blowers

In this project, "HVAC energy" refers to the combination of fan, compressor and furnace energy use; "heating energy" refers to the furnace energy use; "fan energy" refers to the energy used by HVAC fan during either cooling or heating modes.

Figure 6 shows the difference of annual energy consumption vs. external static pressure; Figure 7 shows the difference of HVAC energy vs external static pressure; Figure 8 shows the difference of heating energy vs. external static pressure, and Figure 9 shows the difference of fan energy vs. external static pressure.

Figure 4 and Figure 8 share a similar trend line, where the cities that are located in colder climate consume more energy than those in hotter climates. For example, the difference of annual energy consumption in Aspen and Helena when pressure increases from 50 Pa to 350 Pa is about 3250 kWh and 2900 kWh respectively; Houston shows only 750 kWh difference in annual energy consumption. Aspen and Helena also consume more energy in heating due to the cold climate in the region. However, hotter climates are generally believed to consume HVAC energy faster than the colder and milder climates as shown in Figure 7. For instance, when pressure increases from 50 Pa to 350 Pa, Miami consumes around 820

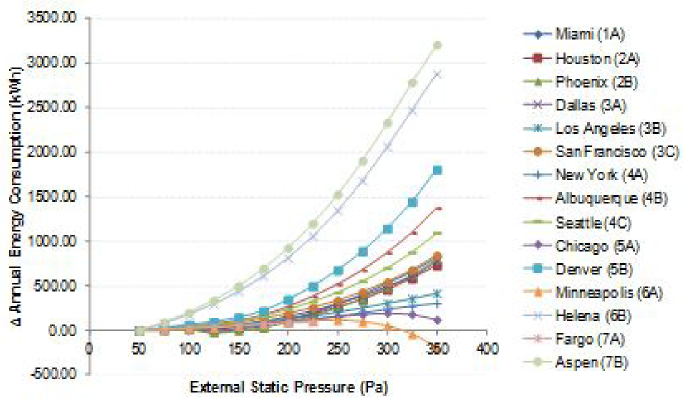

Figure 6. *Difference of annual energy consumption (kWh) vs external static pressure (Pa) for a PSC blower*

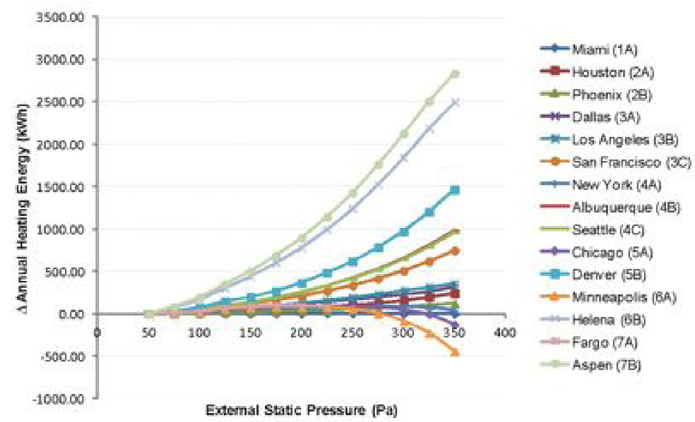

Figure 8. *Difference of annual heating energy (kWh) vs. external static pressure (Pa) for a PSC blower*

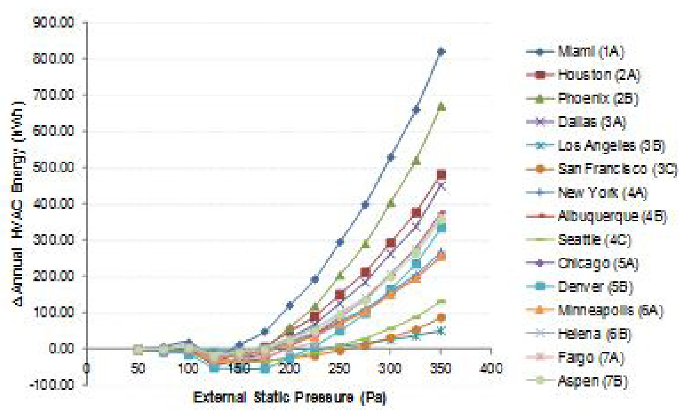

Figure 7. *Difference of annual HVAC energy (kWh) vs. external static pressure (Pa) for a PSC blower*

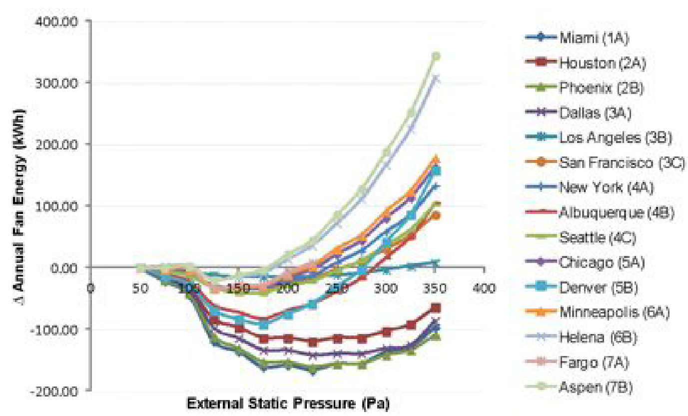

Figure 9. *Difference of annual fan energy (kWh) vs. external static pressure for a PSC blower*

kWh more energy in HVAC, this is likely due to the reject heat produced by the fan when the system is in cooling mode. Figure 9 shows that Miami, Houston, Phoenix, and Dallas actually save up fan energy within the pressures while places like Chicago, Denver, and Minneapolis consume around 150 kWh, 160 kWh, and 250 kWh more fan energy when the filter is extremely dirty.

ECM Blowers

Figure 10 shows the difference of annual energy consumption vs external static pressure; Figure 11 shows the difference of HVAC energy vs external static pressure; Figure 12 shows the difference of heating energy vs external static pressure, and Figure 13 shows the difference of fan energy vs. external static pressure.

HVAC system with ECM blowers installed shows very different results as the hotter climates such as Miami, Phoenix, and Dallas tend to increase their annual energy consumption by 750 kWh, 680 kWh and 380 kWh respectively. However, cities such as Aspen, Helena, San Francisco, and Seattle save some energy when the pressure increases. Besides, annual HVAC and fan energy consumption share similar trend line where places with hot climates such as Miami use up more energy, so this may likely be due to the heat produced by the fan which prevents the ECM blower from working efficiently. However, the increment is small if compared to those that install PSC blowers in their HVAC system. ECM blowers help to decrease the heating energy consumption in cold climates such as Aspen, Fargo, and Helena by 370 kWh, 360 kWh and 350 kWh respectively; while for hot climates, heating is not commonly used, and thus the line does not vary much along the pressures.

Discussion

A dirty filter, a fouled coil, or many other reasons can cause the increase of pressure drop in HVAC system. In this project, the assumption of dirty

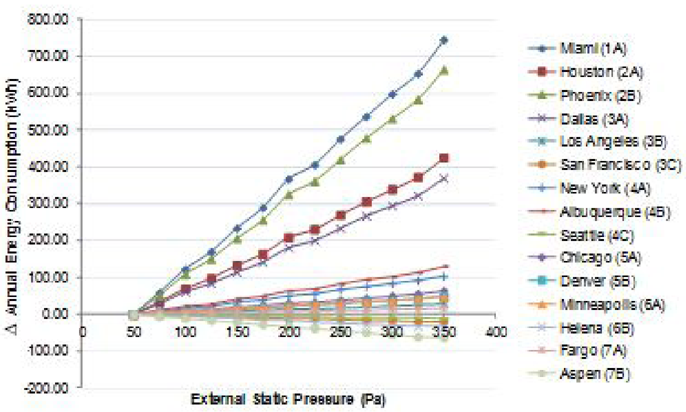

Figure 10. *Difference of annual energy consumption (kWh) vs. external static pressure for an ECM blower*

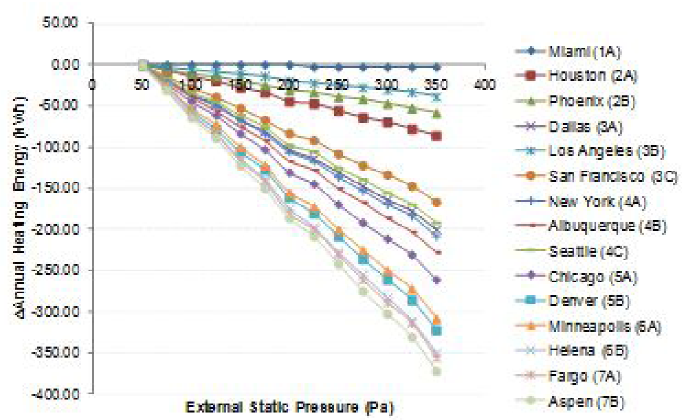

Figure 12. *Difference of annual heating energy (kWh) vs. external static pressure for an ECM blower*

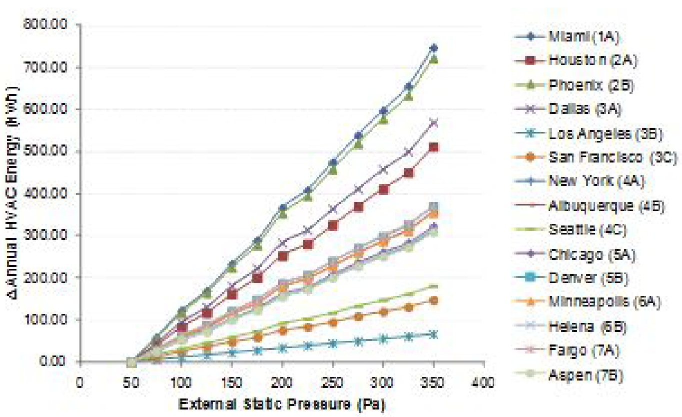

Figure 11. *Difference of annual HVAC energy (kWh) vs. external static pressure for an ECM blower*

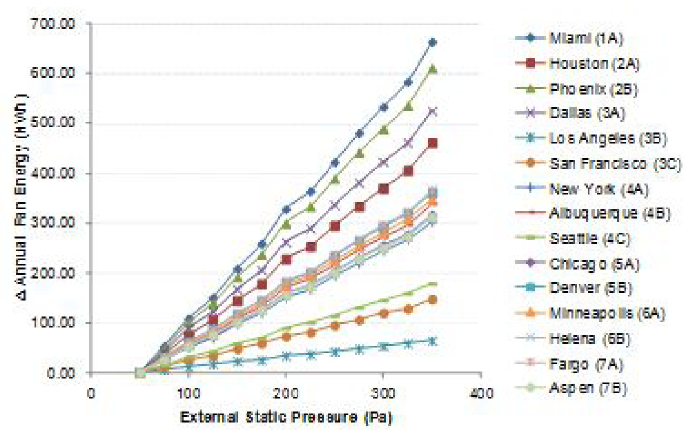

Figure 13. *Difference of annual fan energy (kWh) vs. external static pressure for an ECM blower*

filter was assumed and thus the increase of pressure drops. From Figure 6 to Figure 13, it is shown that ECM blowers generally save more energy when compared to PSC blowers in a long run. When external static pressure increases, ECM blowers tend to maintain the same airflow rate by increasing the power draw in order to provide the space sensible load requirements; however, the negative effect on energy consumption is considered smaller if compared to a PSC blower that needs to run longer in order to meet the sensible load requirements. Therefore, ECMs blowers are more energy efficient.

PSC blowers are considered in Figure 6, 7, 8, and 9. From Figure 7, some unsteady trends are noticed between the pressure of 50 Pa and 125 Pa, but it generally increases after 125 Pa, all the way up to 350 Pa. Cities that are observed to have larger increments in annual HVAC energy consumptions are Miami, Phoenix, Houston and Dallas, because in a hot and moist climate, the heat is rejected from the fan thus resulting in longer system runtime if compared to those cities that are in a milder and dry climates. In Figure 8, heating energy increases in cities that are located in cold climates such as Aspen and Helena while places like Miami, Houston, and Phoenix do not show any significant trend as the weather itself provides enough heat to the buildings. In Figure 9, the difference of annual energy consumption for fan typically decreases from 50 Pa to 175 Pa and increases back until 350 Pa for all cities. Although PSC blower usually runs longer in order to meet the space sensible load requirements, the power drawn is so much lesser than the extra time that it has to work when the pressure increases from 50 Pa to 175 Pa, which eventually results in energy-saving. However, when the pressure is more than 175 Pa, PSC draws more power to run longer in order to meet the space sensible load requirements. Besides that, the first and third graphs in Figure 4 show a downward trend in cities like Minneapolis, New York and Chicago but the reasons are unknown. Also, severe errors were detected while simulating the IDF for Fargo after 250 Pa, however, the reason still remains unknown.

ECM blowers are considered in Figure 10, 11, 12, and 13. As no significant change is observed in airflow rate for HVAC system that uses ECM blower, the change in HVAC energy, heating energy and fan energy is considerably small. Figure 11 and 12 share similar trend line for each location, therefore, this increase in energy can be likely due to the elevation in heat rejected into the airstream by the ECM blowers using more power as cities located in hotter climates are observed to have greater increment. The reduction shown in heating energy along the pressures for ECM blowers is greater in colder climates while places in hotter climates show almost no difference. It is likely because the house gains heat from the fan when it draws more power in order to maintain the same airflow rate when the pressure increases.

Conclusion

BEopt and EnergyPlus were used for whole building simulation in this project to investigate how fouled filter in HVAC system affects annual energy consumption. This project involved two types of fan blowers, fifteen cities, and various static pressures. The results showed that annual energy consumption increased for both PSC and ECM blowers installed in HVAC system when the filter was loaded (pressure increases) over time. However, HVAC system with ECM blower installed appeared to have lesser energy impacts if compared to PSC. For a PSC-fan HVAC system, annual HVAC and heating energy increased along with pressures because the fan ran longer in order to accommodate the space sensible load requirements. The fan energy consumption decreased from 50 Pa to 175 Pa and increased all the way up after 175 Pa. For an ECM-fan HVAC system, HVAC energy and fan energy consumption increased with a little increment each time along the pressure. On the contrary, heating energy use decreased over time which results in energy saving. These results proved that filter fouling could be an important cause for high household energy consumption.

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