Dirty Air Conditioners: Energy Implications of Coil Fouling

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ABSTRACT

Residential air conditioning is responsible for a substantial amount of peak electrical demand and energy consumption throughout most of the United States. Coil fouling, the deposition of indoor dusts and other particulate matter on evaporator heat exchangers, increases system pressure drop and, correspondingly, decreases system air flow and air conditioner performance. In this paper, we apply experimental and simulation results describing particle deposition on evaporator coils as well as research about indoor particle and dust concentrations to determine coil fouling rates. The results suggest that typical coils foul enough to double evaporator pressure drop in about 7.5 years, much sooner than the expected 15 - 30 year life time for an evaporator coil. The most important parameters in determining coil fouling times are the efficiency of the filter and indoor particle concentrations, although filter bypass and duct and coil design are important as well. The reduced air flows that result from coil fouling cause typical efficiency and capacity degradations of less than 5 %, however they can be much greater for marginal systems or extreme conditions. These energy issues, as well as possible indoor air quality issues resulting from fouling by biological aerosols, suggest that regular coil cleaning to ameliorate low flow and the elimination of filter bypass should be an important part of residential air conditioning commissioning and maintenance practices.

Introduction

Residential air conditioning is responsible for a substantial amount of energy consumption and peak demand in the United States. Fouling of indoor fin and tube heat exchangers, particularly air conditioner evaporators, causes a reduction in flow. Furthermore, air conditioner performance suffers from reduced airflow (for example, Parker *et al.*, 1997; Proctor, 1998).

Despite its potential importance, there has been relatively little research on residential evaporator coil fouling. There have been several anecdotal reports of HVAC heat exchanger fouling (e.g. RSC, 1987; Neal, 1992). In the engineering literature, Krafthefter and Bonne (1986) report that a typical residential heat pump condenser coil will foul sufficiently to cause a 20 % reduction in performance over a 4 to 7 year period. Although very useful in raising the importance of heat exchanger fouling, there is some reason to believe that the work of Krafthefter and Bonne (1986) might be an overestimate of the impacts of fouling because their analysis used indoor particle concentrations which are considerably larger than suggested by more recent literature, and they only consider removal by a high efficiency filter and deposition on the heat exchanger. Krafthefter *et al.* (1987) extend this work with further experiments and simulations to examine the role of high efficiency air cleaners in reducing heat exchanger fouling. For typical residential heat pump and air conditioning systems, they predict a 10 – 25 % average energy cost savings over the 15 year life of the heat exchanger with a properly installed air cleaner.

The purpose of our study is to systematically predict the fouling rates of typical residential evaporator coils and to predict the consequent energy and performance impacts. A parametric analysis is used to determine the relative importance of filtration, duct system design, and indoor concentrations on fouling times.

Analysis Overview

The prediction of the fouling times and energy consequences of coil fouling is based on a model of heat exchanger fouling that we developed specifically for residential heat exchangers. The fouling level is then translated into an effective flow resistance, pressure drop, and flow reduction. The reduction in flow leads to estimates of air conditioning efficiency and performance changes based on the laboratory and field tests of other researchers.

The overall analysis strategy is to start with indoor air particle and dust concentrations and calculate what fraction of particles are removed by deposition in the return duct and by filtration. The fraction that is not removed by filtration is then available to deposit on the heat exchanger. The fraction that deposits on the heat exchanger causes an additional pressure drop that can then be related to a corresponding drop in airflow. The reduced flow leads to energy use increases and peak power effects. Each of these calculations and corresponding assumptions are derived and explained below.

The first important quantity is the mass concentration distribution function of material that deposits on the coil, m_c (mg/µm·m^3). This is calculated, as a function of particle diameter, as:

$$m_c = P_d\left(1-\eta_f+\eta_f b_f\right)\eta_c\left(1-b_c\right)m_{in} \tag{1}$$

Where P_d is the penetration through the return duct system (dimensionless), η_f is the filter efficiency (dimensionless), b_f is the filter bypass (dimensionless), b_c is the coil bypass (dimensionless), η_c is the coil deposition fraction (dimensionless), and m_{in} is the indoor particle size mass distribution function (mg/µm·m^3). All of these quantities are functions of d_p, the particle diameter, and the integration of Equation (1) over all relevant particle diameters (d_p = 0.1 - 100 µm) gives the total mass concentration that deposits on the coil, M_c (mg/m^3):

$$M_c = \int_{d_p} P_d\left(1-\eta_f+\eta_f b_f\right)\left(1-b_c\right)\eta_c m_{in}\,\mathrm{d}d_p \tag{2}$$

All of the terms in Equations (1) and (2), are varied to determine their importance and to evaluate the results for different cases. The following describes each parameter and the assumptions that went into determining the values of each parameter.

P_d, the fraction of particles that are not removed by deposition in the duct work, is calculated from the work of Sippola and Nazaroff (2002) on particle penetration through commercial ducts. Their findings suggest that, at typical residential return duct velocities, deposition of particles is caused by particle deposition in bends and gravitational settling. Three cases, based on field observations and design guidelines in ACCA (1995) were considered: simple, typical, and complex duct systems. An important limitation of the analysis considered here is that return duct leakage is not considered. In theory, a leak in a return duct could suck particles into the duct that could in turn deposit on the heat exchanger. This effect is not included in this analysis because there is insufficient information in the literature about particle concentrations in air surrounding the return duct (typically in attics, crawslpaces, garages or basements) as well as limited information about how these particles penetrate typical duct leaks. Although the magnitude of this effect is not known, it would tend to decrease the fouling time because of the availability of additional particles to deposit on the heat exchanger.

η_f, the efficiency of the filter is calculated from filter efficiencies described in ASHRAE Standard 52.2 (1999). Standard 52.2 is a method of test that produces a Minimum Efficiency Reporting Value (MERV) rating which is a measure of the efficiency of the filter at removing particles of various sizes. For this analysis three cases are considered: a low efficiency, but very common, MERV-2 coarse hair furnace filter, a MERV-6 mid-efficiency filter (the minimum being considered by ASHRAE Standard 62.2P, the proposed residential ventilation standard for new homes), and a very high efficiency MERV-12 filter. Increased filter efficiency as filter loading occurs are not included in this analysis, but would tend to increase fouling times. Equations (1) and (2) are valid for return grill filters as well as air handler cabinet filters because deposition in the filter and the duct are independent, and because there is assumed to be no return duct leakage.

b_f is the amount of air that bypasses a filter because of poor installation or maintenance. There has been very little formal study of this phenomenon. Three cases are considered based on documented anecdotal studies of filter bypass in several residences. The first corresponds to the situation of a filter in a loose fitting slot (10% bypass) and the second corresponds to filter with a large gap around it or that is only fixed on one edge which is estimated to have 25% air bypass. Although very uncommon, the no bypass case (requiring deliberate sealing or gasketing) is considered as well because one inexpensive option that might reduce coil fouling is to eliminate bypass. Bypass is assumed to be constant for all particle sizes and the second order effect of bypass increasing as filter loading occurs is not considered. The inclusion of this effect would tend to decrease fouling times.

η_c is calculated from a verified model of particle deposition on HVAC heat exchangers (Siegel and Nazaroff, 2002). Three fin pitches, corresponding to the range of values typically found in residential HVAC heat exchangers, are considered: 2.3, 4.7, and 7.1 fin/cm (6 , 12, and 18 fins/inch or FPI). The work of Siegel and Nazaroff (2002) was extended to account for the "A-coil" geometry typical of residential central air conditioning systems. This geometry also allows some air to bypass the coil, b_c. This bypass factor has a linear effect on Equation (2) and was fixed at 10 %, based on the geometry of a typical residential air handler cabinet. A modification to account for increased deposition because of wet coils (based on experimental deposition on cooled and condensing coils) was also included.

m_{in}, the indoor particle size distribution, is based on the work of Riley *et al.* (2002) who modeled indoor particle concentrations based on outdoor particle levels. Several modifications were made to the Riley *et al.* to make it appropriate for our purposes. Riley *et al.* considered a continuously operating air handler (occasionally done in newer houses for ventilation), we added another air handler operation that cycled on for 10 minutes every hour. Also, Riley *et al.* considered particles up to 10 µm in diameter and no indoor sources. We considered this a very clean case. We also modeled a more typical "dirty" case where we extend the particle size range to larger particles and included indoor sources by assuming that that there are four people conducting normal activity in the house for eight hours a day and use particle resuspension fractions from Thatcher and Layton (1995). We also assume the presence of dust fibers because microscopy of fouled coils revealed that they are common fouling agents. There is very limited information on residential dust fiber concentrations – we used concentrations measured in 13 daycare centers from Schneider (1986). The particles and fibers in all four cases were assumed to have a density of 1 g/cm^3 (62.4 lb/ft^3) if they are smaller than 2.5 µm and 2.5 g/cm^3 (156 lb/ft^3) for larger particles (Riley *et al.*, 2002).

A summary of the parameters considered and their sources appear in Table 1. A base case of the most common values of each parameter was selected based on the author's engineering judgment of the most common values for each parameter. The base case system consists of a complex duct system, a MERV-2 filter, 10% filter bypass, a 4.7 fin/cm (12 FPI) coil, and a particle concentration resulting from a house with typical infiltration and no indoor particle sources.

Table 1: Parameters varied in the simulation of mass concentration

Parameter	Reference	Number of Parameter Values	Case Description (Base Case is in boldface)
P_d, Duct Penetration	Sippola & Nazaroff (2002)	2	Simple, ***Typical***, Complex
η_f, Filter Efficiency	ASHRAE (1999)	3	***MERV 2,*** MERV6, MERV 12
b_f, Filter Bypass	Anecdotal evidence and scaling analysis	3	0%, ***10%***, 25%
η_c, Coil Deposition Fraction	Siegel & Nazaroff (2002)	3	High fin pitch, ***Typical,*** Low fin pitch
M_{in}, Indoor Particle Distribution Function	Riley *et al.* (2002), Schneider (1986), Thatcher & Layton (1995)	2 2 2	Clean, ***Dirty*** Rural and ***Urban*** Outdoor Conc. ***Cycling*** and Cont. Operation

Once the mass concentration deposited on the coil for each case is determined, the fouling time, τ_{foul}, which is defined as the time, typically expressed in years, that it takes the coil to foul until its pressure drop doubles is calculated as:

$$\tau_{foul} = \frac{M_{foul}}{Q\,M_c\,DC} \tag{3}$$

Where M_{foul} is the experimentally determined deposited mass that cause the pressure drop of the coil to double (see Experimental Methods, below), Q is the air flow rate through the system (fixed at 2700 m^3/hr (1400 CFM) for a typical 3.5 ton (12.3 kW) air conditioner), and DC is the duty cycle of the air handler fan. The duty cycle is not an independent parameter because it relates to the m_{in} values described above. The m_{in} cases with continuous fan operation have a duty cycle of unity, and the typical ventilation cases have a duty cycle of 1/6.

A possible point of confusion in Equation (3) is that M_{foul} assumes a constant flow rate. In our analysis, the pressure drop of the coil at the original flow is doubled, but the pressure drop of the fouled coil will less than double because the flow decreases as a result of the additional pressure drop. This affect is implicitly included in our analysis because the pressure drop and flow through the coil are calculated as part of an iterative solution between the system and the fan curve, described below.

It is important to put the fouling time in the context of the lifetime of the coil. Typical residential coils have an approximate lifetime of about 15 years. However, coils frequently remain in service even when the outdoor unit or the compressor is replaced, and they often stay in service for 30 years. From this perspective, a fouling time of approximately 15 years or more is a reasonable target for when remedial action (such as coil cleaning or improved design or filtration to limit fouling) should be considered. For the examples discussed in this paper, we assumed that a coil was fouled if its pressure drop were double that of a clean coil based on our controlled laboratory experiments that showed significant coil fouling for a doubling of pressure drop.

Once the fouling time has been calculated, the remaining question is: what is the effect of a doubling of coil pressure drop on air conditioner capacity, efficiency and power consumption? This question is not straightforward because the flow through an air conditioner coil is determined by the intersection point between the fan curve and the system curve (ACCA, 1995). This is shown in Figure 1. The fan curve is determined by the fan and its installation, the system curve is determined by the flow resistance of all of the components in the system including the return duct, filter, coil and supply duct. So, increasing the pressure drop (and therefore the flow resistance of the coil) will have a different effect on the system curve depending on the on the flow resistance of the rest of the system. Furthermore, residential fan curves have different slopes at different points, which means that doubling the coil pressure drop of a system operating at one point in the curve will have a different effect than a doubling the coil pressure drop at another point on the curve.

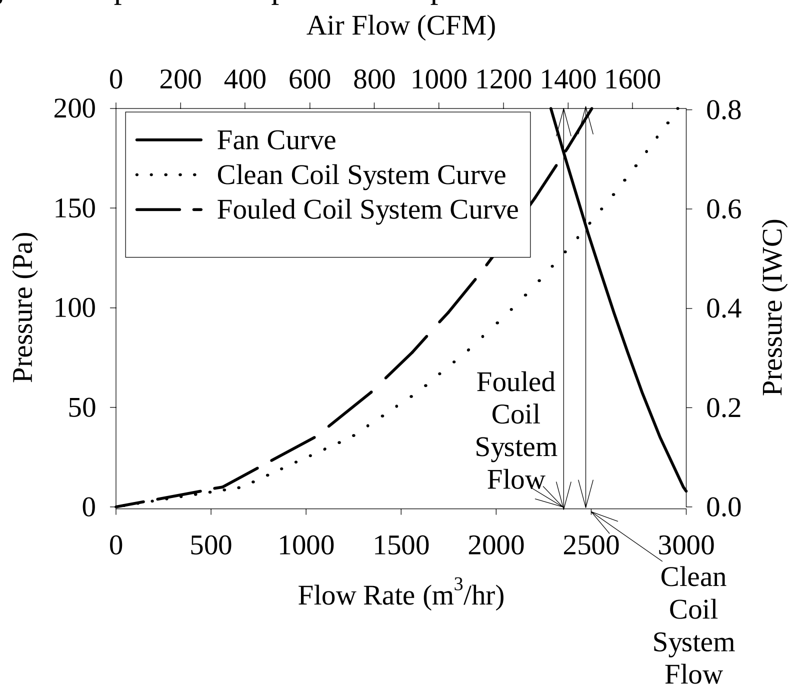

Figure 1: Fan curve and system curves for clean and fouled coil.

To estimate the flow resistances of typical systems we used supply and return duct static pressures (based on measurements taken from over 250 houses measured by LBNL and other researchers) and the pressure to flow relationship for a typical 3.5 ton air conditioner coil from manufacturers literature and ACCA (1995) to determine the average impact on flow of a doubling of coil pressure drop in a residential system. Although the pressure drop at constant flow doubles, the consequent reduced flow causes a less than doubling of the pressure drop at the new flow.

We considered three fan curves: a manufacturers fan curve from ACCA (1995), a fan curve from a laboratory test system (Parker *et al.*, 1997), and a fan curve we measured in a house in Fresno, California. The conventional wisdom is that fan curves have an inverted parabolic shape (ACCA, 1995; ASHRAE, 2000). However, all of the fan curves described above had a linear shape over a large range of flows (the lowest flow being about half of the highest flow).

Once this effect on flow was determined, we used the experimental work of Parker *et al.* (1997) and Palani *et al.* (1992) to determine the effect of reduced flow on air conditioner performance. Another potential energy impact is the role of coil fouling in changing fan power draw, an often neglected aspect of residential air conditioner use (Proctor and Parker, 2000). Any change in fan energy use will cause the air conditioner to have to remove more or less heat from the air stream. HVAC fan power, W, is given by:

$$W = \frac{Q\,\Delta P}{\eta_{fan}\,\eta_{motor}} \tag{4}$$

Where Q is flow through the fan, ΔP is the total external pressure drop of the system, η_{fan} is the fan efficiency, and η_{motor} is the fan motor efficiency. Typical values for the product of fan and motor efficiency were determined to be 19% by Phillips (1995) and 19-23% in Parker *et al.* (1997). We used 20% in our analysis.

Laboratory Tests of Coil Fouling

One of the unknown variables in Equation (3) is the relationship between mass of deposited dust, M_{foul}, and pressure drop. To establish this relationship, we adapted the apparatus from earlier experiments (Siegel and Nazaroff, 2002) to determine the amount of pressure drop that results from deposited material.

Experimental Methods

The apparatus used for these tests is depicted in Figure 2. A fan was used to move air through a 0.15 m (6 inch) square duct. 25 g (0.055 lb) batches of standard test dust (AFTL Laboaratories SAE Coarse) were introduced to the duct upstream of a 0.15 m square test coil. The dust was introduced with a flour sifter to promote uniform mixing of the dust in the duct. The dust was sampled on filters 0.3 m (12 inch) upstream and downstream of the duct and, the filters were weighed, and mass techniques were used to determine the mass concentrations of dust in the air in the duct.

The dust air concentrations were corrected for non-isokinetic sampling using the methods of Vincent *et al.* (1985). Corrections for non-uniform mixing, and for measured deposition on the floor of the test duct were also included in the analysis. The static pressure drop across the coil was monitored continuously with a digital manometer (Energy Conservatory Model DG-3). The experiment was stopped when the pressure drop across the coil had roughly doubled. The fan was relatively insensitive to changes in the coil pressure drop and produced a constant flow over the course of the experiment.

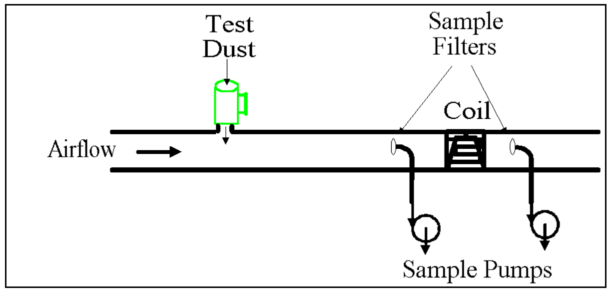

Figure 2: Apparatus used to determine deposited mass to pressure drop relationship

Experimental Results

Figure 3 shows that the pressure drop of the test coil relative to its clean pressure drop increases as mass is deposited. The horizontal error bars are an estimate of the uncertainty from a propagation of error analysis. The mass balance for the experiment was closed to within 3 %, indicating that almost all of the test dust was accounted for in the analysis. The relative pressure drop increased geometrically with deposited mass (with an R^2 value of 0.97 for a polynomial fit of order 2).

At the tested bulk velocity of 2 m/s (400 ft/min), a reasonable value based on guidelines in ACCA Manual D (ACCA, 1995), the mass deposited to make the coil pressure drop double was 140 ± 10 grams. The flow through the system was constant as the pressure drop doubled. Averaged over the face area of the coil gives a deposition of about 6 kg for every m^2 of face area. This value was used to get M_{foul} in Equation (3) above.

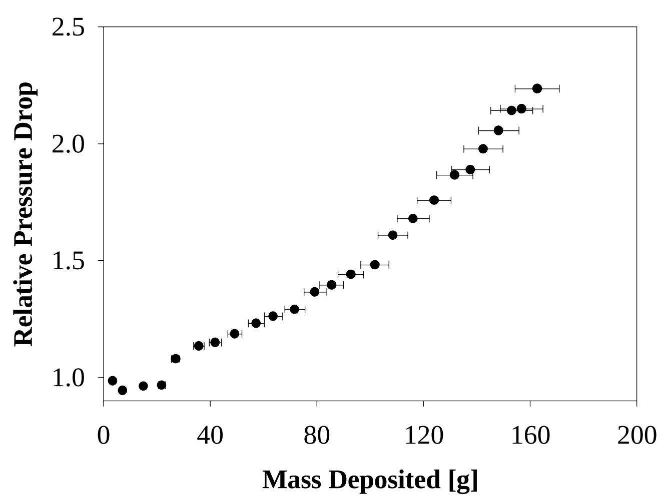

Figure 3: Experimental results at 2 m/s (400 ft/min)

Analysis Results

The fouling times, defined as the time it takes for the pressure drop of the coil to double at constant flow, spanned a large range. The average fouling time for all conditions was 33.6 years, but this value was skewed by several very high fouling times (500 + years). The median fouling time was 7.1 years. The fouling time for the base case (MERV-2 filter, urban outdoor concentration, cycling air conditioner, dirty indoor environment, typical coil (4.7 fins/cm or 12 FPI), 10% filter bypass, typical duct penetration) was 7.6 years. The average change in the fouling time ratio (to the base case) resulting from changing each parameter is shown in Table 2. A fouling time ratio greater than one means that coil takes longer to foul than base case. A fouling time ratio of less than 1 means that the coil fouls faster than the base case. The data in Table 2 also appear graphically in Figure 4, with the exception of duct system variation because this did not affect fouling time. The error bars do not represent an uncertainty, but represent one geometric standard deviation above and below the geometric mean.

Table 2: Fouling time ratios.

			Fouling Time Ratio		
Variable	**Base Case**	**Going to**	**Median**	**GM**	**GSD**
Filter Efficiency	MERV 2	MERV 6	1.39	1.39	1.08
		MERV 12	10.04	6.89	2.79
Indoor Concentration	Urban	Rural	0.43	0.45	1.23
	Cycling	CA	0.31	0.30	1.09
	Dirty	Clean	1.85	1.70	1.45
Coil Efficiency	4.7 fin/cm	2.4 fin/cm	1.82	1.90	1.11
		7.1 fin/cm	0.71	0.70	1.05
Filter Bypass	10%	None	1.81	1.12	2.26
		25%	0.73	0.86	1.38
Duct Penetration	Typical	Simple	0.99	0.99	1.01
		Complex	1.02	1.02	1.01

Table 3 shows the pressure drop and flow of a clean and fouled coil that has deposited enough mass to double the pressure drop at constant flow. Although the pressure drop at constant flow doubles (as measured in the experimental data), the consequent reduced flow in a system where flow rate is not controlled causes a less than doubling of the pressure drop at the new flow. This effect is included in our analysis. Although the resulting flows and pressure drops are substantially different for the different fan curves, the fractional flow reductions were similar (5.4 – 6.5%) for all the fan curves. It should be pointed out that much greater impacts are possible for systems with already reduced flow or on a steeper point on the fan curve.

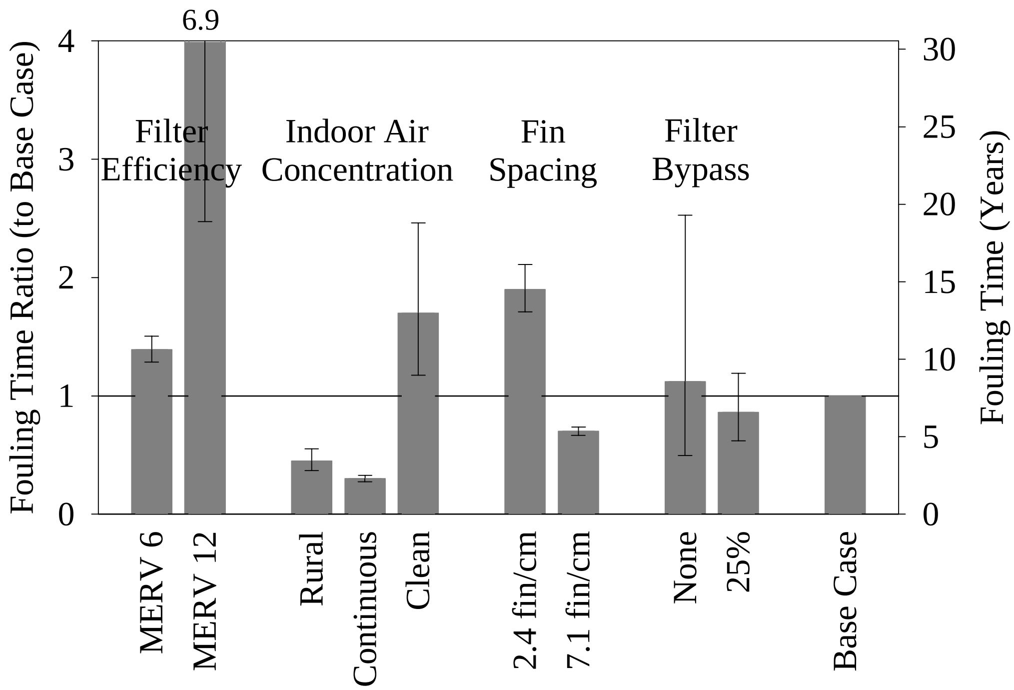

Figure 4: Fouling time ratios (relative to Base Case). Error bars indicate one geometric standard deviation from the mean by varying the all other parameters in the simulation.

Table 3: Flow reduction and pressure drop for different fan curves.

Fan Curve Source	Heat Exchanger Pressure Drop (Pa)		Flow Reduction
	Clean	Fouled	
ACCA (1995)	54.0	83.4	5.4 %
Parker *et al.* (1997)	36.1	49.9	5.8 %
Measured	32.8	41.8	6.5 %

For a properly tuned air conditioner, a 5 - 10 % drop in flow causes a 2 - 4 % drop in Energy Efficiency Ratio (EER), capacity, and power draw (Parker *et al.*, 1997; Palani *et al.*, 1992). However, for a more marginal system (i.e. a system with insufficient air flow across the coil), these effects can be 10 – 20 % or even greater. Also the effect of low refrigerant charge can have an interaction with low air flow, further degrading system performance (Proctor, 1997).

In a system with a fouled coil that we are considering, the flow drops by 5 – 7 %, but the pressure increases by 6 – 16 %, so the power draw of the fan increases by 1-10 %, depending on the fan curve being used. This contradicts standard fan laws which suggest that the predicted decrease in fan power is 15 – 18 %. Using the Parker *et al.* (1997) measured data, the decrease would be 3.8 - 4.6%. Using Equation (4), the magnitude of fan power draw increases due to coil fouling is in the range of 5 - 60 W, with an additional penalty of added heat having to be removed from the air stream during cooling operation.

Discussion

The fouling time of the base case was 7.6 years. This is slightly longer than the 4-7 years found by Krafthefter *et al.* (1987). The primary reason for the difference is because Krafthefter *et al.* (1987) used a higher indoor particle concentrations.

From the results in Table 2 and Figure 4 the importance of varying each parameter becomes clear. Filter Efficiency, particularly going to a MERV-12 filter from the base MERV-2 filter, has a large impact on fouling times, causing the fouling time to increase, on average, by seven times over the base case. There is substantial variation in this value because of the interaction between filter bypass and filter efficiency. For very high efficiency filters, filter bypass makes a big difference in whether particles are available to deposit on the heat exchanger. Increasing the amount of particles in indoor air also has a big impact on fouling times. Going from a typical urban to typical rural location increases fouling time by about a factor of two. This increase is caused by the high concentrations of coarse mode (< 2 μm) particles in rural outdoor environments. Running the air conditioner continuously has an even larger effect on fouling time (decreasing it to 30% of the cycling case), largely because the coil is continually exposed to particle laden air (i.e. the duty cycle is unity). Eliminating resuspension of indoor particles and dust fibers increases the fouling ratio by a factor of two. Changing the filter bypass causes a 10 - 15% change in fouling time on average, however, there is a strong interactive effect with filter type. The added efficiency of a MERV 12 filter can be largely compromised by filter bypass

Another important result of this study is that, over the 0.01 – 100 μm particle diameter range considered, the particles that are most responsible for fouling are those between 1 – 10 μm. Although much larger particles and fibers cause more of a pressure drop when they deposit, and deposit with high efficiency, they are more likely to be filtered or deposit in return ductwork. Also, large particles exist in indoor air at much lower concentrations than smaller particles. A related result is that even submicron particles, which are relatively unlikely to deposit on the coil, contribute non-trivially to fouling because they exist in indoor air at very high concentrations and are relatively unlikely to be filtered or deposit in duct work. Fibers are responsible for 20 % of fouling, on average. This significant contribution suggests that more research on indoor residential fiber concentrations would be useful for evaluating their impact on fouling.

We have used the doubling of the clean coil pressure drop at the original flow as a measure of a fouled coil. For this level of pressure drop, in a typical residential system, the pressure drop at the fouled flow is increased about 40%, the air flow is reduced by 5 - 10%, and the efficiency and capacity of the air conditioner decrease by 2 – 4%. This is a relatively modest decrease in performance; however, the results above assume that the system already had correct airflow. Several researchers (Parker, Sherwin *et al.*, 1997; Proctor, 1997; Proctor, 1998) have found that low air flow is common in many residential air conditioning systems and hence performance impacts can be much greater because the change in air conditioner capacities are more sensitive to flow changes at lower air flows.

Coil cleaning is not a routine part of maintenance in residential systems, and it is unclear whether coil cleaning always removes deposited material, rather than just pushing it deeper into the coil. If a deposited material isn't removed from a coil, the pressure drop continues to increase at a geometric rate (see Figure 3). After twice as long as the fouling times reported in this paper, the coil pressure drop, at constant flow, will have increased by a factor of four. This can lead to much more serious air flow (reductions of 10 - 20%) and performance degradations (5 - 15 %).

This paper has focused on fouling rates and the energy consequences of coil fouling. The indoor air quality effects that can result from biological growth on coils can also be significant. Siegel and Walker (2001) suggest that common bioaerosols, including fungal spores and bacteria, can deposit and thrive on typical evaporator coil surfaces. This problem further reinforces the need for frequent coil inspection and verified cleaning that reduces the pressure drop to the manufacturers specified value.

Conclusions

In this paper, we have applied experimental and simulation results describing particle deposition on evaporator coils as well as research about indoor particle and dust concentrations to determine the energy impacts of coil fouling. The results suggest that typical coils foul enough to double evaporator pressure drop (at constant flow) in about 7.5 years. This is considerably shorter than typical evaporator coil lifetimes of 15-30 years. The most important parameters in determining coil fouling times are the efficiency of the filter and indoor particle concentrations, with filter bypass and fin spacing as secondary effects. Efforts to improve the prediction of fouling time would greatly benefit from more detailed information about large particle (>10 µm) and fiber concentrations in indoor air.

The reduced air flows that result from coil fouling cause flow reductions of 5 –7 % and typical efficiency and capacity degradations of less then 5%. However these impacts can be much greater for marginal systems or extreme conditions. The importance of residential air conditioning energy use means that these degradations have a significant impact on peak electricity demand. These energy consequences, combined with the potential indoor air quality problems associated with biological fouling, suggest that it would be useful to conduct additional research on residential coil fouling. In the meantime, residential commissioning procedures should include measurement of air flow, coil inspection for low flow situations, and verified cleaning to eliminate potential energy and indoor air quality effects.

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