Issues Associated with Variable Speed Fans in Space Conditioning Systems

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Introduction

Over the last 30 years, energy conservation efforts have resulted in higher and higher efficiency requirements for residential and light commercial heating and cooling equipment. The efficiency of air handler blower motors and other electrical components, however, have not been regulated. As heating and cooling efficiency increases, the electrical consumption becomes an increasingly large fraction of the total energy consumption of the system. With higher heating and cooling efficiency, the ability to obtain further energy savings is decreased, and one must look elsewhere to obtain additional energy savings.

Standard residential and light commercial air handlers use centrifiugal fans with forward curved blades, driven by axially mounted, permanent split-capaticance (PSC) electric motors. These fan and blower combinations are inexpensive, reliable, and have good flow tolerance for static pressure changes. These units are generally sold with 3 or 4 speed settings, selected separately for heating, cooling and fan-only operation by the field installer by setting jumpers on a control board. However, PSC motor driven fans can vary their speed over only a small speed range, on the order of 70% to 100%. Speed control is accomplished by applying voltage to different sets of motor windings, introducing slip. This slows the motor down, but at a significant efficiency penalty (Biermayer, et al, 2004). Unfortunately, PSC motors have electrical efficiencies on the order of 60% at full speed, and less than 40% at low speed (Sachs and Smith, 2003). When the blower is included, efficiency drops to 10% to 15% (Walker and Lutz, 2005).

Appliance manufacturers have been selling systems with variable speed blowers as a premium product, often as part of high AFUE furnaces or high HSPF heat pumps. These systems use blower wheels which are similar to conventional PSC driven systems, but they are powered by electrically commutated motors (ECMs). ECM is a trademark of GE, which manufactures most of this type of motor sold. They are also known as BPM (brushless permanent magnet), and other terms. These motors operate on DC current which is provided by the motor's control board. The controls on these motors are configured such that the installer sets the desired airflows. The system will then vary the torque and power provided to the motor so as to maintain the desired airflow. ECM motors have a very wide speed range, down to 25% of full flow or less. These motors also have electrical efficiencies of about 75% at high speed, and they remain above 70% across the entire speed range. However, they are relatively expensive.

The difference in full speed electrical efficiency alone – 75% vs. 60% – is enough to gain the attention of energy efficiency advocates. However, ECM systems offer additional opportunities for energy savings. Fan power consumption is proportional to the cube of the airflow. Systems with ECM fan motors have the ability to dramatically reduce airflow at certain operating conditions. One example often cited in the literature

(Phillips, 1998; Sachs and Smith, 2005; Pigg and Talerico, 2004; Gusdorf, et al, 2003) is when the system is operated in air circulation mode. In this mode, the ECM system is able to supply an airflow that is 25% to 35% of the airflow that a PSC system can supply. This results in energy savings of more than 95%. If it is assumed that this mode of operation is utilized for any significant fraction of the year, annual energy savings are very large. These savings are largely due to simple physics – power is proportional to the cube of the airflow, so even small reductions in airflow offer significant energy savings.

The energy savings available by using ECM motors has lead to calls for minimum efficiency requirements for residential and light commercial air handling fans (Sachs and Smith, 2003). The Energy Policy Act of 2005 authorizes DOE to set minimum efficiency standards on furnace fans, either by incorporating them into the existing rulemaking on furnace efficiency or as a separate rulemaking. There is currently no deadline for DOE to complete this. When DOE does begin their rulemaking process, they will need to have data on which they can base their rules. This will require an accurate and equitable method of testing airflow and electricity consumption, and they will need to be able to show that implementing a rule setting minimum efficiency levels for the motor or the fan/motor combination will be economically justified on a national basis. In order to do this, the economic impact of high efficiency motors will need to be evaluated in a number of areas, and the differences in impacts for various climates will also need to be evaluated. Some of these areas of impact include:

- Electrical efficiency
  - Full load
  - Part load

- Fan Efficiency
  - Full load
  - Part load
  - Cabinet effects

- System effects
  - Furnace HX
  - Cooling coil and condenser
  - Heat pump in heating
    - w/ strip heat
    - w/o strip heat
  - Electric resistance coil

- Duct interactions
  - Leakage
  - Conduction
  - Room to room air balance

- Space effects
  - Stratification
    - High wall/ceiling supply registers

    - Floor/low wall supply registers
    - Ceiling returns
    - Floor/low wall returns
  - Stagnation
  - Dehumidification
  - Air Cleaning

- Occupant interactions
  - Temperature setpoint modifications
  - Continuous air handler operation

This report examines how the use of variable speed motors in furnaces and heat pumps, in both heating and cooling modes, might affect system operation in each of these areas. We review existing data in these areas, summarize any conclusions that might be drawn, and identify technical areas where additional technical data is needed.

In the Results section of the report, a discussion of each of the major impact areas listed above is provided, including a theoretical discussion for each, exploring how the use of a variable speed fan and ECM motor can be expected to impact system performance. This is followed by a description of related research, with an analysis of the significance of the research results.

As the static pressure imposed on a blower driven by a PSC motor increases, the airflow decreases, following along a pressure-flow line on a fan curve. Because the power consumed by a fan is proportional to the cube of the airflow, power consumption also decreases with increasing static pressure when PSC motors are used. ECM motors, on the other hand, are controlled so as to maintain constant airflow, regardless of static pressure changes. As a result, as the static pressure increases (e.g., as filters become loaded with dirt), the power consumption of the motor increases to maintain the airflow. This can be advantageous, particularly in cooling applications, where having the desired airflow over the cooling coil can provide better cooling efficiency. Solely from the viewpoint of fan electricity consumption, however, this is a negative aspect of ECM motors.

The availability of ECMs, which have substantially higher electrical efficiency than standard PSC motors, have led to calls for regulating the efficiency of air handler blower motors and even furnace induced draft blower motors and air conditioner condenser fan motors.

Variable speed or multi-speed air distribution fans are gaining popularity with regulators and the public, largely because of their increased electrical efficiency. Variable speed fans are also commonly sold as part of a high efficiency furnace or heat-pump, which become more popular as energy prices rise.

Claims are made for increased heating and cooling efficiency and increased comfort with variable speed fans. Claims for increased efficiency, however, may be overstated due to the details of the SEER and AFUE test procedures, and system effects which limit the efficiency gains. Comfort improvements may also be overstated, depending on the configuration of the air distribution system and location of ductwork.

Approach

This project is primarily a literature review, with evaluation of specific primary sources and analyses they provide. The project examined primary research relating to the operation of variable speed fans and ECM motors. We also interviewed researchers who had performed research in an attempt to gain additional insight into their experiences with variable speed system that might extend beyond their published results. This was particularly true in cases where the performance of variable speed equipment was not the primary focus of the research. We also contacted equipment manufacturers to obtain product literature.

Results

In the introduction, six aspects of HVAC system operation were identified which might be impacted by the use of a variable speed circulating fan with an ECM motor. Each of these aspects will be discussed below. Under each topic, we will discuss the theoretical impacts, and any related research results. In addition, we will also discuss test procedure issues which will need to be addressed prior to a rulemaking.

Test Procedure Issues

Currently, furnaces are tested using a DOE test procedure, which is based on ASHRAE Standard 103, which determines the AFUE rating. An output of this test is the Annual Auxiiliary Electrical Energy Consumption, E_{AE}. EAE is based on the electrical consumption at heating conditions when the system provides a specified temperature rise with a specified external static pressure. The test does not include a direct measurement of airflow, only an indirect one based on the fuel input and steady state efficiency of the furnace.

Manufacturers also report on the maximum airflow that the furnace can provide against a static pressure of 0.5” w.g. This value is reported in product literature to ensure the unit can provide the airflow required for a selected air conditioner size. This value, however, is not reported to DOE, and the procedures used by the manufacturers to develop it are not entirely clear. It is assumed that ANSI/AMCA 210/ASHRAE 51-1999, *Laboratory Method of Testing for Aerodynamic Performance Rating*, is used, although there are variations in test procedure that can be used while complying with the standard.

In order for DOE to set efficiency limits on air handling efficiency, specification of a test procedure will be required. For furnaces, a maximum E_{AE} value could be specified. This has the advantage of utilizing an existing DOE test procedure. It has the disadvantage of being specific to furnaces – it would not be applicable to heat pumps or dedicated air handlers, and would be problematic for application to combination water heating/space heating systems. It also may be a problem for this approach in that different units will have different airflows, and differences in E_{AE} would not be representative of true efficiency differences.

Development of a test procedure based on ANSI/AMCA 210/ASHRAE 51, or something similar, would seem to be a better and more universal approach. This test involves measuring airflow at various speed settings against a range of external static pressures, developing a fan curve, or series of fan curves, for the fan. Measurement of electricity consumption at each point provides the efficiency of the fan across its range of airflow and pressure.

Biermayer, et al (2004), tested furnaces with PSC and ECM motors using the ANSI/ AMCA 210/ASHRAE 51 procedure. They identified some issues that would need to be addressed before testing of ECM systems could be mandated.

One issue is that simply specifiying that testing be performed in accordance with the standard appears to be insufficient. This conclusion was reached because the results they obtained for the tested systems had results that were significantly different from the results reported by the manufacturers. For the PSC system, they found airflow up to 40% greater than the manufacturer's data at low static pressures. For the ECM system, arflow was up to 10% lower. The researchers believe that the differences were due to differences in test setup or procedure.

Another issue was that when testing the ECM system, the controls of the system work to maintain airflow by adjusting blower speed in response to static pressure changes. When the ECM furnace and a prototype ECM blower were tested, data could not be collected at pressures below 0.5" w.g. This appears to be an artifact of the test procedure, and will need to be resolved before testing of ECM systems can be mandated.

Another minor issue was also discussed by Biermayer. GE reports that ECM motors operate with power factors of 0.6 or less. This is not an issue in terms of energy consumption, but it does affect sizing of power distribution equipment (since they must be sized for actual current which will be larger, with lower coincident voltage, when systems have low power factor). In their testing, measurements of voltage and current were taken along with power consumption. These measurements had problems which resulted in calculation of power factors greater than one, which is impossible. It was determined that due to the nature of the ECM control system, multiple harmonics are established within the power lines. This requires the use of true RMS measuring transducers to provide accurate readings of voltage and current. The authors speculate that this is the cause of the erroneous readings.

Another issue that has been raised by other researchers (Proctor and Parker, 2001) is the static pressure against which residential and light commercial air handlers should be rated. Currently, the DOE test procedure uses a pressure of 0.2" w.g. when determining E_{AE}, although when manufacturers provide airflow ratings 0.5" w.g, as mentioned above.

Proctor and Parker reviewed data from nine different field tests of installed systems in Arizona, Nevada, California, Florida, New Jersey and Canada. They found high electricity consumption by the air handlers, approaching 1000 watts. The average external static pressures for the nine studies ranged from 0.38" w.g. to 0.55" w.g. The authors contend that by provided E_{AE} values based on substantially lower static pressures, expectations for energy consumption are being set artificially low. They also contend that the reported efficiency of cooling and heating is also being inflated, since the increased static pressure seen in the field reduces system airflow, resulting in a reduction in efficiency, and the additional fan heat reduces cooling system effectiveness. Based on these and other similar results, it seems clear that air handler performance rating should be done at approximately 0.5" w.g.

Based on the fan data for the PSC furnace provided by Biermayer and fan data from Lennox for an ECM furnace, changing the external static pressure has a signifcant impact on the relative efficiency of PSC versus ECM motors. Figure 1 from Biermayer shows that cfm/W for a PSC system is nearly constant as the pressure is decreased from 0.5" w.g. to 0.1" w.g. Unfortunately, they were unable to test the ECM system at pressures below 0.5" w.g., so the ECM 2.3 line does not continue to 0.1" w.g. However, the trend at pressures above 0.5" w.g. shows decreasing efficiency with increasing pressure. (The ECM 4.0 line is for a prototype system, which uses backward curve fan blades, and is not relevant for this discussion, as it is not in production.)

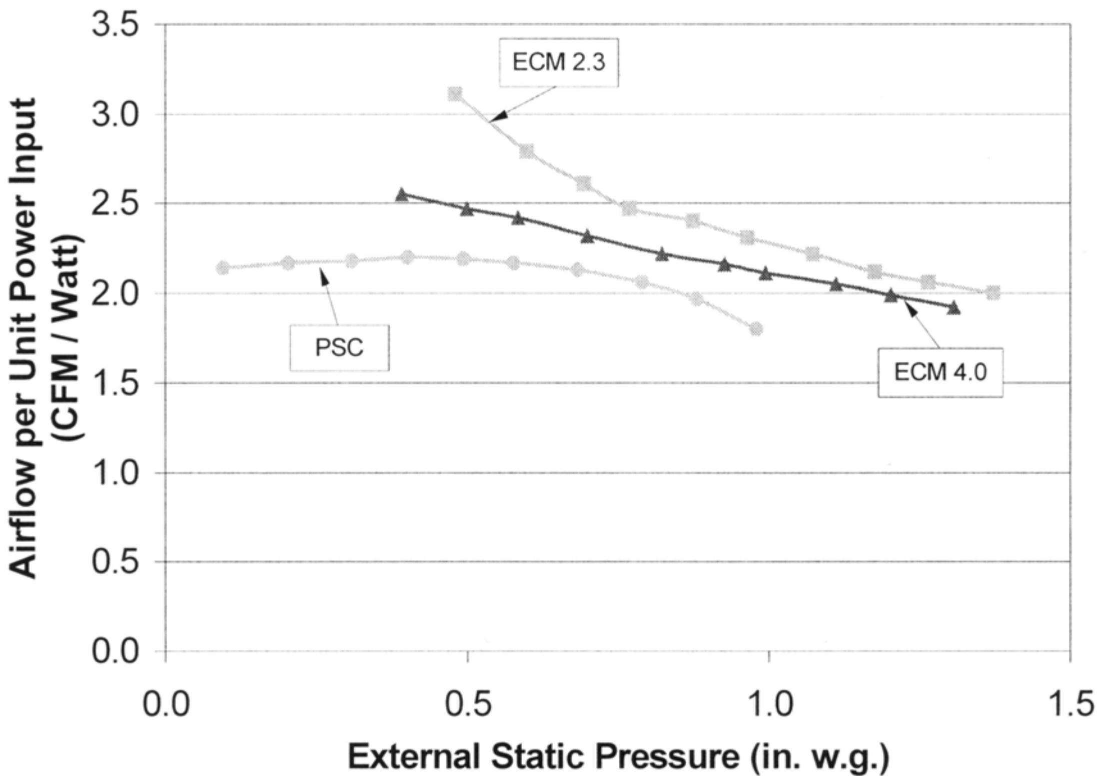

Figure 1 Aerodynamic Efficiency of PSC and ECM Systems. *Results from Biermayer, et al, 2004, shows little effect of increasing external static pressure on the efficiency of the PSC system up to 0.7" w.g. but with the ECM 2.3 (a production system) he efficiency is dropping as pressure is increased. (The ECM 4.0 system is a prototype.)*

Table 1 shows calculations of cfm/W for PSC and ECM systems. The PSC data are from Biermayer and the ECM data are from Lennox (2005). The efficiency advantage of the ECM system relative to the PSC system, while still significant, is much smaller at the higher static pressure. Selection of the rating conditions will obviously be significant in the relative ratings of PSC and ECM systems.

Table 1 Airflow, Power Consumption and Efficiency of Production PSC and ECM Systems.

	Ext. Static – 0.1" w.g.			Ext. Static – 0.5" w.g.		
	Cfm	**Watts**	**Cfm/W**	**cfm**	**Watts**	**Cfm/W**
Carrier PSC*	1666	777	**2.14**	1483	676	**2.19**
Lennox ECM**	1635	285	**5.74**	1635	430	**3.80**

* 58CTA090---10114, high speed, corrected to standard conditions (Biermayer, et al, 2004)

** G60UHV-60C-090, bottom return air, speed switch 2, 2nd stage cooling, "Adjust" normal (Lennox 2005)

Electrical Efficiency

The nominal electrical efficiency of ECM motors is significantly higher than that of PSC motors used in standard furnaces. This increased efficiency has numerous system effects which contribute to the attaction of these motors for energy conservation advocates. In addition to the improved efficiency at air handler rating conditions, ECM motors offer good turndown characteristics as well. PSC motors have very limited capabilities for variable speed operation. Typically, these systems can operate at only 4 speeds or so, over a small range, and power consumption is only slightly reduced at lower speed. ECM motors, on the other hand, can operate over a wide range of speeds. Operation at lower speeds has negligible effects on electrical efficiency, and because fan power is proportional to the cube of airflow, low speed operation offers dramatic reductions in electrical power.

Gusdorf, et al, (2002) performed testing of typical, otherwise identical, furnaces with PSC and ECM motors in side-by-side research houses. Some of their data are shown in Table 1. They found that at heating airflow of 591 and 658 cfm for the ECM and PSC usints respectively, electrical consumption was 246 W for the ECM vs. 423 W for the PSC, a reduction of 42%.

At low speed, the ECM motor allowed airflow to be reduced to 218 cfm (37%) while the PSC could only reduce flow to 486 cfm (74%). At these airflows, the power consumptions were 22 W and 316 W, respectively. This is a savings of 93%. When the ECM was constrained to operate at approximately the same low speed airflow as the PSC (463 cfm), the power consumption of the ECM was 146 W, 54% less than the PSC.

The current author used the data above to adjust the power consumption of the ECM cases in heating and equal circulation mode for the differences in airflow. Extreme care should be taken with any of these adjustments. Airflow measurement is difficult to do with high precision, and the differences in measured airflow are close to the uncertainty in the original measurements. These results are shown in Table 1 as the "Adjusted" cases. These adjustments assumed that cfm/W would remain unchanged over the range of the airflow adjustments, which is not a particularly sound assumption. It is a conservative assumption, though, since cfm/W decreases as airflow increases for an ECM motor. In any case, with these adjustments the heating mode electricity savings decrease to 35%, and the equal flow curculation mode savings become 52%. If the adjustment results in understated ECM power consumption, then the savings may actually be somewhat less.

Table 1 Comparison of ECM and PSC Air Handler Power Consumption

	Airflow (cfm)			Power (W)			Cfm/W	
Mode	**ECM**	**PSC**	**ECM/PSC**	**ECM**	**PSC**	**ECM/PSC**	**ECM**	**PSC**
Heating	1,252	1,394	90%	246	423	58%	5.09	3.30
Equal Circ.	981	1,030	95%	146	316	46%	6.72	3.26
Circulation	462	1,030	45%	22	316	7%	20.99	3.26
Heating (Adj.)	1,394	1,394	100%	274	423	65%	5.09	3.30
Eq. Circ. (Adj.)	1,030	1,030	100%	153	316	48%	6.72	3.26

Note: The *Heating*, *Equal Circ.* And *Circulation* cases are from Gusdorf, et al, 2002. The *Heating (Adj.)* and *Eq. Circ. (Adj.)* cases are the responsibility of this author, not Mr. Gusdorf or his associates.

In the heating season, the fan and motor are located in the heating air stream, and the energy consumed by the motor serves to heat the house. When a PSC motor is replaced by a more efficient ECM motor, additional heating fuel must be consumed by the furnace to compensate for the reduced electrical consumption. Using the data from Table 1 above, in the heating case, the additional gas consumption will depend on the furnace efficiency. A reduction electrical input from 423W to 246W, translates into an additional 604 Btuh of output. For an 80% AFUE furnace, this requires an additional 755 Btuh of input gas. For a 90% furnace, the additional gas consumption is 671 Btuh. To provide this additional gas consumption, the furnace must operate for a longer time, meaning that the fan must also operate longer. For the furnaces used to generate the data in Table 1, for each burner cycle, the fans run for about 120 seconds longer than the burner fires (delay by 30 seconds after firing starts, and 140 or 150 seconds after burner shutoff). Assuming an 80,000 Btuh input, 80% AFUE furnace, and depending on the burner cycle time and on-time fraction, there is an increase in gas consumption of 1% to 2.8%. Table 2 shows calculations of the increased gas consumption.

Table 2 Additional Gas Consumption Due to Decreased Fan Heat ECM vs. PSC Fan Motors, Fans in "Auto" Mode, 80% AFUE

Cycles per hour	3			6		
	Fan on-time (min.)	Add'l gas (Btuh)	Gas use % incr.	Fan on-time (min.)	Add'l gas (Btuh)	Gas use % incr.
Burner % on time (w/PSC)						
10%	12	151	1.9%	18	226	2.8%
20%	18	226	1.4%	24	302	1.9%
30%	24	302	1.3%	30	377	1.6%
40%	30	377	1.2%	36	453	1.4%
50%	36	453	1.1%	42	528	1.3%
60%	42	528	1.1%	48	604	1.3%
70%	48	604	1.1%	54	679	1.2%
80%	54	679	1.1%	60	755	1.2%
90%	60	755	1.0%	60	755	1.0%
100%	60	755	0.9%	60	755	0.9%

As the number of cycles increases, the amount of time the fans are running increases because of the overrun time for each burner cycle. Also, as the burner on time decreases (heating load gets smaller), the percentage increase in gas consumption begins to rise dramatically. This is because at some point of decreasing load it reaches a point where the fan heat of the PSC is sufficient to meet the entire load, but gas must still be used by the ECM system.

The data in Table 2 represent the increased gas consumption for a single hour. For an entire heating season, the furnaces typically average about 30% on-time, so the increased gas consumption might be expected to be 1.2% to 1.6%, when the comparison is between systems being operated with the fans in the "Auto" mode.

Often, however, when furnaces with ECM motors are installed, they are operated with the fan running continuously (Pigg and Talerico, 2004). In this case, there is some give back of electrical savings, when compared to a PSC system running in the auto mode. This is due to the added run time of the ECM motor, which is occurring when the PSC motor would be off. However, as seen in Table 1, an ECM motor operating at its lowest speed consumes little electricity, about 22 Watts. Table 3 shows the effect on additional gas consumption that would result.

Table 3 Additional Gas Consumption Due to Decreased Fan Heat ECM in "On" Mode vs. PSC in "Auto" Mode, 80% AFUE

	Cycles per hour	3			6		
		Fan on-time (min.)	Add'l gas (Btuh)	Gas use % incr.	Fan on-time (min.)	Add'l gas (Btuh)	Gas use % incr.
Burner % on time (w/PSC)	10%	48	76	0.9%	42	161	2.0%
	20%	42	161	1.0%	36	246	1.5%
	30%	36	246	1.0%	30	331	1.4%
	40%	30	331	1.0%	24	415	1.3%
	50%	24	415	1.0%	18	500	1.3%
	60%	18	500	1.0%	12	585	1.2%
	70%	12	585	1.0%	6	670	1.2%
	80%	6	670	1.0%	0	755	1.2%
	90%	0	755	1.0%	0	755	1.0%
	100%	0	755	0.9%	0	755	0.9%

For a furnace operating at 3 cycles per hour, the increase in gas consumption is no more than 1% at any load, decreasing slightly at full load and at very low loads. At 6 cycles per hour, the increased gas consumption is slightly higher, as much as 2% at low loads. At low loads, the added fan run time is long enough to reduce the extra gas consumption by about 1% compared to when the ECM system runs in "Auto" mode. At high loads, the fans are running nearly all the time in "Auto" mode, and there is no difference between "On" and "Auto." However, if we assume that the burner on time will average about 30%, for those people who operate their ECM furnaces continuously, the added gas consumption will be slightly less than those who operate in "Auto."

The third case that should be investigated is a comparison of operating both the PSC and ECM equipped systems continuously in the "On" mode. This is the case that is often cited when large electrical savings are shown. In this case the electrical consumption differences between the two systems are quite substantial, 22 Watts vs. 316 Watts when the burner is off. Table 4 shows the resulting increases in gas consumption.

Table 4 Additional Gas Consumption Due to Decreased Fan Heat ECM vs. PSC Motors, "On" Mode, 80% AFUE

	Cycles per hour	3			6		
		Fan on-time (min.)	Add'l gas (Btuh)	Gas use % incr.	Fan on-time (min.)	Add'l gas (Btuh)	Gas use % incr.
Burner % on time (w/PSC)	10%	48	1154	14.4%	42	1104	13.8%
	20%	42	1104	6.9%	36	1054	6.6%
	30%	36	1054	4.4%	30	1004	4.2%
	40%	30	1004	3.1%	24	955	3.0%
	50%	24	955	2.4%	18	905	2.3%
	60%	18	905	1.9%	12	855	1.8%
	70%	12	855	1.5%	6	805	1.4%
	80%	6	805	1.3%	0	755	1.2%
	90%	0	755	1.0%	0	755	1.0%
	100%	0	755	0.9%	0	755	0.9%

Again, as the heating load gets large, there is no difference between "On" and "Auto" modes. At lower heating loads, however, the increased gas consumption becomes quite significant. At 30% load, the increase is about 4.3%. At lower loads, the increase is even greater, in percentage terms, around 14% at 10% load.

However, for an 80,000 Btuh input, 80% AFUE furnace, the additional run time is just under 1%. This assumes the furnace fan is operating in the "auto" mode, and that fan run times are the same as the burner operating time, which is not strictly true.

If the furnace fan is operating continuously, the situation changes. The amount of extra burner operation will depend on the on-time fraction of the burner and the airflow of the two fans in continuous mode. Assuming that the fans operate as described in Table 2 on the "Heating" and "Circulation" lines (burner on or off, respectively) and that the average burner on-time is

While the electricity savings shown in Table 1 are dramatic, they do not tell the whole story. Furnaces sold with ECM motors are almost always marketed as multi-speed systems, with multiple firing rate burner systems. These units then operate at low speed much of the time. Because power consumption falls with the cube of the airflow, low speed operation results in dramatic electrical savings over single speed operation. For example, Pigg and Talerico (2004) report 50% savings for Wisconsin houses in heating operation, from 800 kWh with PSC systems to 400 kWh with ECM systems. These results were normalized to the gas consumption, so these values are for annual gas use of 800 therms. If, as is reported elsewhere, the use of ECM motors results in an increase in gas consumption, then the actual savings may be slightly less than 50%.

Sachs and Smith, 2003, in a report for ACEEE, estimate annual electricity savings of 500 kWh/yr in the heating season on average across the U.S. They also estimate annual savings of 225 kWh/yr in cooling, which is a combination of air handler and compressor savings. They also estimated savings for three heating dominated climates, as shown in Table 2. Their analysis is a modeling study based on the E_{ae} value included in furnace energy ratings. E_{ae} is the average annual auxiliary electrical consumption of a gas furnace. They estimated that the furnace fan uses 90% of the E_{ae}, with the rest being used by the draft inducer and controls. They also used heating load hours and cooling load hours from ARI's "Appendix A: Uniform Test Method for Measuring the Energy Consumption of Central Air-Conditioners." Gusdorf, et al, 2004

Table 2 Regional Estimates of Savings from Better Furnace Fans and Motors.

		U.S. Avg.	New England	Wisconsin	Pacific NW, Mountains
Rate Tariffs	Elec. ($/kWh)	0.08	0.11	0.08	0.06
	Gas ($/Therm)	0.80	0.96	0.70	0.90
Electricity Saved (kWh)	Heating	500	548	617	685
	A/C	200	131	125	125
Total Savings	KWh/yr	700	679	742	810
	$/yr	$57	$75	$56	$49
Extra Gas Needed	Therms	19	23	23	22
	$	$15	$22	$9	$20
Net Savings	$	$42	$53	$47	$29

Table from Sachs and Smith, 2004

Phillips (1998) estimated that annual furnace run times for heating average 1200 hours for furnaces installed since 1990 across Canada. Savings of 180 to 250 kWh/yr for automatic furnace operation, 2,600 kWh/year for continuous. Contends that additional electricity savings could be achieved by increasing the furnace temperature rise to 40°C (72°F), thereby reducing the airflow required to meet the heating load. Electrical savings arise due to the cubic relationship between airflow and fan power.

Walker (2005) cites ARI 210/240 (2003) that combined heating and cooling operating hours per year are 3000. This leaves 5760 hours of ventilation only or off time.

Heating efficiency drops at low airflow due to increased discharge and flue gas temperature. Estimated 2% to 4% decrease for a 10°C (18°F) rise in supply air temperature. *RLH: for a supply temperature of 130F, this is a rise of about 60F. 18F gets to 148F, a 13.8% increase in delta T, which means a 13.8% decrease in airflow.*

Fan Efficiency

In addition to the electrical efficiency benefits of ECM motors, researchers have also looked at changes to the design of the fan itself in search of improved efficiency. Typical furnace fans use forward curved fan blades. These fans are typically constructed from sheet metal, with fairly large tolerances between the fan and the fan housing (Walker, 2005). These fan systems are low cost and easy to assemble. They also have desirable static pressure characteristics, in that they give a fairly constant flow over a wide static pressure range. The efficiency of these fans, however, is quite low. Walker (2004) tested a typical furnace with forward curved fan blades and PSC motor, and compared it to a prototype system with backward curved blades and ECM motor. He found that the conventional fan had efficiency of 12% to 14% (wire to air). The prototype had efficiences of 21% to 25%. For the protoype system he calculated the motor and fan-only efficiencies. The motor efficiency was approximately 75% except at very low speeds when it increased to nearly 90%. The aerodynamic efficiency, though, varied widely from 12% to 45%, depending on flow and fan speed. The aerodynamic efficiency of the conventional fan is not provided.

Phillips (1998) shows that air handler efficiency for recent furnaces ranges from 10% to 30%, with an average of 19%. He proposes that changes to fan wheel design could double the efficiency of the air handler, and would be more cost-effective than alternative motor technologies, although no details are provided.

Walker (2005) has also suggested that design improvements to the air handler cabinet can improve the airflow and save significant fan energy.

Sachs and Smith (2004) discuss the low efficiency of residential air handlers, and propose that performance requirements be placed on them. However, they contend that a metric such as one which compares electricity use to furnace capacity will not be successful when applied to cooling climates, since cooling airflow requirements will be much higher than for heating. They prefer an efficiency parameter such as W/1000 cfm at defined external static pressures. Such a metric allows manufacturers to improve airhandling efficiency not only through motor improvements but through aerodynamice improvements such as improved fan wheels and better cabinet design.

System Effects

Cooling Efficiency

Proctor and Parker (2001) examined a nine residential field studies covering 245 homes in Canada, California, Nevada, Arizona, Florida and New Jersey. They found that installed systems had static pressures of 0.38” w.g. to 0.55” w.g. This is in contrast to the value assumed in current DOE test procedures of 0.1” w.g. or 0.2” w.g. (depending on the cooling capacity). They also found that average cooling airflow ranged from 311 cfm/ton to 387 cfm/ton (average values from the 7 studies with air conditioning). This compares to target airflow rates of 400 cfm/ton.

They then examined the energy impact of correcting the low airflow. If the correction were to be made by moodifying the ductwork, such that the pressure drop was decreased, then system EER improved by 2.4% to 4.5% for every 10% increase in airflow. However, if the airflow was increased by increasing blower power, then in the range of airflows cited above, the overall system EER decreased by as much as 5% for each 10% increase in airflow. This is a combination of increased efficiency for the compressor counteracted by increased energy consumption by the blower, and increased load from the motor heat.

The analysis performed by Proctor and Parker was based on systems with conventional PSC motors. The system behavior for ECM systems is different than with PSC motors. With a PSC motor, increased static pressure results in reduced airflow, and reduced power consumption because of the reduced airflow. With an ECM motor, increased static pressure results in the motor increasing speed to maintain the desired airflow. The system automatically creates the situation described above which decreased system EER using PSC motors. However, since the ECM motors use much less power than PSC motors (see Table 1 above), even at higher static pressures, it is likely that the effect will be a net positive. However, since the typical static pressures are so much higher than the rating conditions, the benefit will be much less than would otherwise be anticipated.

Cycling Losses

Systems with variable capacity, in heating, cooling or both, will usually operate at reduced capacity over longer operating cycles. This will have the beneficial effect of reducing the number of operating cycles, and thereby reducing the cycling losses. In heating, these losses will primarily be

Variable speed fans offer extended operating cycles, reducing cycling losses. For furnaces, these losses are typically minor, primarily operation of the inducer and blower while no fuel is being consumed. For heat pumps, the effect may be somewhat greater, due to the time delay between when the compressor begins operating and when the indoor, condenser coil has warmed to the point when it can provide heat to the conditioned air stream. These losses will still be relatively small. When a heat pump is operating with electric resistance backup heat, there are virtually no cycling losses.

In cooling, however, cycling losses can have a significant negative effect, particularly on latent cooling. At the end of a compressor cycle, the coil will be wet from moisture condensed from the conditioning airstream, and the coil will be cold. Typically, the blower will continue to operate after the compressor is shut off, allowing the coil to continue removing heat from the conditioned air stream. In the process, however, some portion of the condensate on the coil will be re-evaporated back into the space, providing negative latent cooling – humidification. At the beginning of the compressor cycle, there will be some time lag before the evaporator coil will be cooled below the space dewpoint, and latent cooling begins. There is a further time delay before the condensate willhave built up to where significant amounts drain away. If the cooling cycles are too short, typically when sensible loads are low, latent cooling will have barely begun before the compressor shuts off, resulting in very little latent cooling taking place. By operating the cooling coil for a longer time, at a lower airflow, these cycling losses of latent capacity are reduced.

When latent capacity is reduced due to short cycling of the system, comfort in the space will be compromised. A typical response of the occupant will be to lower the thermostat setpoint. This has the effect of artifically increasing the sensible load, but at the same time increasing the relative humidity (for a given indoor dewpoint), possibly resulting in cool, clammy conditions. In any case, the reduced thermostat setpoint will result in increased energy consumption. Improving the latent cooling by reducing the cycling losses, may result in occupants being comfortable at higher space temperatures, reducing load on the system and energy consumption.

Note, however, that the reduction in cycling losses is not due to the use of and ECM fan motor, but to the use of variable capacity heating and cooling equipment in conjunction with the ECM fan motor. These benefits can not be credited to ECM motors without accounting for the additional first costs of the additional variable speed equipment.

Duct Interactions

Systems with ECM an motors are sold as variable speed systems. Marketing for these systems describe the comfort improvments provided by operating at reduced airflow. The reduced airflow results in extended operating times, which is advertised to provide more uniform conditions throughout the house, improving comfort. When operated in continuous fan mode, better indoor air quality is advertised because more air is circulated through the filtration system, increasing the amount of contaminants removed.

Newer homes in many parts of the country, particularly in the western and southern states, are built with the duct system in the unconditioned attic. Duct systems built in this way commonly have leaks allowing conditioned air to escape to the outdoors. If the leaks are on the return side of the system, unconditioned air from the attic is drawn into the system increasing the conditioning load on the system. Even if the duct system does not leak, the often extreme conditions in the attic result in increased conduction losses through the duct material. Multiple studies have been performed on the magnitude of the duct losses (Andrews 2003), and they have generally found that 25% to 40% of the input heating or cooling is lost from ducts in undonditioned spaces.

Using a variable speed air handler with such a duct configuration will increase the amount of energy lost from the ducts. Duct conduction losses will be proportional to operating time and supply air temperature, and may be slightly dependent on supply air velocity. Supply temperature may not change significantly compared to single speed operation, so extending the operating time will increase conduction losses making them a much larger proportion of the input energy. Duct leakage losses are also likely to increase as a percentage of input energy, although the reduction in duct pressure will mitigate against this effect.

Andrews (2003) performed a study, including theoretical analysis and laboratory experiments, of the effect of low speed heating operation on duct losses. He found that when a furnace operated at 50% capacity and airflow, that delivery effectiveness (DE) dropped by an amount which varied depending on the amount of insulation used on the ductwork and the indoor-attic temperature difference. For uninsulated ducts, with the system operating at full capacity, the DE varied from 0.8 to 0.55 as the temperature difference increased from 0°F to 60°F. When operating at half-speed, the DE deecreased by another 15 to 20 percentage points, to 0.65 to 0.25 over the same temperature difference range. With insulated ducts, the decrease in DE was reduced. With R-4 ducts, DE decreased about 10 percentage points, from about 0.89 - 0.84 to 0.83 - 0.73 when operating at half-speed. When R-8 insulation was used, the reduction was again about 10 percentage points of DE, from 0.92 - 0.88 to 0.87 – 0.77.

These are significant decreases in delivery effectiveness, which may well result in energy consumption increases that outweigh any electrical savings. One of Andrews' assumptions, however, should be revisited. Based on a review of literature on two speed furnaces with ECM motors and two stage burners, these units typically operate with the first stage firing at 2/3 of the full firing rate, rather than 50% as assumed by Andrews. Changing this assumption in heating mode would presumably reduce the drop in DE values. On the other hand, some fraction of systems with ECM motors will be operated continuously, with a flow rate that is substantially lower when there are no calls for heating or cooling. This 100% operating time will further decrease DE beyond the 10 percentage points estimated by Andrews, although the extent of this decrease is uncertain.

To put these changes in delivery effectiveness in context, a 10 percentage point drop in DE means that 10% of all energy input into the duct system in the form of heating or cooling will be lost to the outdoors. This is equivalent to a 10% drop in AFUE <u>and</u> a 10% drop in SEER. In other words, from an energy standpoint, for houses with ducts in unconditioned space, specification of a 92% AFUE, two-stage furnace with a 13 SEER, two-stage air conditioner, would be equivalent to a system with a single speed 82.8% AFUE and 11.7 SEER.

Space Effects

Air Mixing

Traditionally, in heating climates, supply registers were located in the floor or the baseboard, located near outside walls, often under windows. This allowed the warm supply air to circulate through the room through convection and for the rising warm air to counter drafts caused by cool exterior surfaces. In cooling climates, supply registers are located high on the wall or in the ceiling. This prevents obstruction of the register by furniture or drapes, and allows conventive circulation during cooling. Newer houses in any climate also use high registers because better insulation levels and better windows means that the inside surface of exterior walls do not get very cold, so drafts are not a problem. The air velocity of the supply stream is used to mix the air and avoid space discomfort from excessive stratification. Because convective forces are used to mix conditioned air with room air, the performance of the register is not important, allowing the use of cheap stamped registers.

The installation of variable speed air handlers presents potential problems for HVAC systems designed for single speed operation or using low quality registers, i.e., nearly all conventional houses. Particularly when operating in the non-dominant season (heating in a cooling climate, or vice-versa) operation with low air velocities may result in inadequate mixing in the space. Supply air may stratify and move along the floor or ceiling toward the return grill, causing large temperature differences between the floor and ceiling. The resultant occupant discomfort may induce the occupants to change the thermostat setpoints to improve comfort.

Holton (2002) and Rittlemann (2005) conducted testing of room air mixing with reduced supply volumes. Using standard residential registers, they found that comfort conditions were reduced due to poor mixing of supply and room air. High performance commercial diffusers were found to perform well, but were felt to be cost prohibitive. They believe that high registers are appropriate for modern, high-performance houses, even in heating dominated climates.

While variable speed operation is not necessarily associated with the use of ECM motors, all systems with ECM motors currently on the market offer variable speed operation. Particularly for retrofit applications with floor registers in warmer climates, low speed operation may have a negative impact on comfort. One solution to this problem would be to limit such systems' to full speed, or close to sull speed operation. However, this may reduce a significant portion of the energy savings available, in that energy savings are proportional to the cube of the airflow. Even small reductions in airflow can provide significant energy savings with ECM motors.

The significance and characteristics of this aspect of variable speed system operation are not well quantified. This problem may not be significant at all – veriable speed systems are marketed as improving comfort – but further research may be warranted to identify the characteristics of potentially problematic applications, and to quantify any effects.

Humidity Control

As new residential construction has become better insulated, more airtight, and windows have become better, thermal loads have decreased, particularly sensible loads. Latent loads, however, have not decreased as much, since the primary latent loads are due to occupants, their activities, and ventilation or infiltration air. The use of an air handler with an ECM motor will exacerbate this situation, because the energy consumed by the fan motor appears in the airstream as an additional sensible load. The reduced energy consumption by an ECM motor reduces this load.

In recent years, furnace airflow has increased about 25% (Proctor and Parker, 2001), primarily as a means of increasing furnace efficiency. Increasing airflow can also serve to improve cooling efficiency, allowing the evaporator temperature to rise, reducing the compression energy required. However, standard guidance for selection of cooling airflow has not changed, 400 cfm/ton is the standard recommendation. A primary reason that cooling airflow is not increased to improve efficiency is that such an increase reduces latent cooling capacity. Any increase in the evaporator temperature, and hence the supply air temperature, increases the dewpoint of the supply air.

Some system installers in arid climates, where dehumidification is of little concern, intentionally set the system airflow higher just to obtain the efficiency improvements (Chitwood, 2002). In most of the country, however, dehumidification is a primary concern during cooling. Even with the standard 400 cfm/ton airflow, many systems struggle to maintain adequate space humidity levels. Variable speed ECM blower motors offer an approach to improving this situation. If a humidistat were to be used, the blower speed could be adjusted in cooling to modify the sensible heat ratio of the coil. When the space humidity is above setpoint, the blower could be slowed to decrease the evaporator temperature and supply air dewpoint, increasing the humidity removal. When the space humidity is at or below setpoint, the airflow can be increased to improve efficiency. This variation in airflow would need to be restricted to a fairly small range, particularly on the downward end of the range, both to minimize efficiency decreases and to minimize the risk of icing on the evaporator coil. The author is not aware of such a control option being offered at present, but such a system will offer significant comfort benefits, but the efficiency impacts will depend on the relative amounts of operation at increased or decreased airflow, and the relative efficiency impacts on the condensing unit.

Air Cleaning

Variable speed furnaces and air handlers are marketed as providing improved indoor air quality when they are operated continuously at low airflow. This mode of operation provides air circulation through the system's air filter at all times. The increased total airflow provides more air changes through the filter and should result in lower concentrations of those contaminants that the filter removes. Operation of the system in continuous fan mode, as discussed earlier, results in increased energy consumption compared to the ECM system in "auto" mode, and offsets the energy saved compared to a PSC system in "auto" mode. The air cleaning benefits available to purchasers of ECM systems have value to some of them, but there will be little or no energy savings from from that subgroup.

Occupant Interactions

Variable speed air handlers with ECM fan motors offer substantial energy savings for continuous fan operation compared to units with conventional PSC motors. These savings are due to the electrical efficiency of the motor and to the much lower airflow that can be provided (ECM equipped systems can operate at much lower airflow than PSC systems). However, systems with ECM motors are sold with the ability to have economical continuous air circulation as a benefit, leading to the use of "fan-on" mode with these systems much more than with conventional systems. Pigg and Talerico (2004), based on interviews with consumers, estimated that 18% of consumers switched from auto mode to continuous fan operation. They believe that this change in behavior is largely due to advice from builders or contractors and the ECM system's economy in this mode. The use of continuous fan operation causes an increase in electrical energy consumption which mitigates against the savings that ECM systems provide. In fact, the authors believe, based on field study data, that comparison of an ECM system operating with continuous fan operation will result in a slight *increase* in electricity consumption compared to a PSC system in "auto" mode. Essentially, for 18% of the system installations, switching to an ECM system results in electricity increases, not savings.

Summary and Conclusions

The use of ECM motors compared to conventional PSC motors provides an immediate increase in electrical efficiency. This increased efficiency reduces electricity consumption by the fan, and reduces the associated heat gain, reducing cooling load. In heating, however, there is an increase in gas consumption to offset the reduced heat provided by the motor.

Annotated Bibliography

Abney, Jenny, Dan Int-Hout, Gordon Jones. 2000. ECM Motors in Series Flow Fan Powered Terminals and Unit Ventilators. White paper from www.krueger-hvac.com/lit/pdf/whiteecm.pdf, accessed 9/2/2005.

Test and analysis of ECM motors in commercial series fan box applications showed significant electrical energy savings.

Andrews, John W., Ph.D., P.E. 2003. *Effect of Airflow and Heat Input Rates on Duct Efficiency.* ASHRAE Transactions, Vol. 109, Part 2. American Society of Heating, Refrigerating and Air Conditioning Engineers. Summer 2003.

Investigated the effect of variable speed furnace operation in heating mode on losses from ducts in unconditioned space. Showed through two different calculations and one experimental analysis that operation at 50% load (both airflow and firing rate) that the conductive heat losses increase dramatically, resulting in delivery effectiveness decreases of 10 to 15 percentage points. Recommends against replacing single speed furnaces with modulating furnaces in buildings with ducts located in unconditioned space.

Biermayer, Peter J., James Lutz, and Alex Lekov. 2004. *Measurement of Airfloow in Residential Furnaces.* Ernest Orlando Lawrence Berkeley National Laboratory. May 2004.

Tested furnaces and furnace blower assemblies, both ECM and PSC. Found that there were problems with the procedures of ANSI/AMCA 210/ASHRAE 51 test procedures as used for variable speed ECM systems. Found that ECM systems with standard control software could not be tested below 0.5" wg because the fan speed would drop to zero, or even reverse. Recommended a series of steps aimed at improving test methods for determining fan efficiency.

Chitwood, Rick. 2002. Personal conversation regarding contractor practices in California new construction. Stated that he sets up air handlers with airflow of 450 cfm/ton to improve efficiency, since humidity control is not an issue in central California. January 29, 2002. Folsom, California.

Edwards, Craig, Martin Adelaar, Ken Cooper. 1999. Residential Sector Climate Change Foundation Paper. Paper for the Buildings Table of the Canadian Climate Change

Secretariat. www.sheltair.com/library/Residential%20Foundation%20Paper.pdf, accessed 9/2/2005.

General discussion of ways to reduced greenhouse gas emissions from the residential sector of the Canadian economy. Includes brief mention of ECM motors, citing increased electrical efficiency relative to PSC motors.

Gusdorf, John, Skip Hayden, Evgueniy Enchev, Mike Swinton, Craig Simpson and Bill Castellan. 2003. *Final Report on the Effects of ECM Furnace Motors on Electricity and Gas Use: Results from the CCHT Research Facility and Projections.* NRCC-38500. Canadian Centre for Housing Technology, CANMET Energy Technology Centre, Ottawa, Ontario, Canada.

Testing of identical furnace air conditioner systems in side by side research houses, with and without the PSC fan motor in one furnace replaced with an ECM motor of the same nominal power. Results showed reductions in electricity consumption in heating and cooling, with increases in heating gas consumption. Energy effects were much less than predicted in an ACEEE study.

	ACEEE	CCHT/CMHC	Ratios
Electrical Savings w/ A/C (kWh/yr)	617	324	1.9 / 0.525
Electrical Savings w/o A/C (kWh/yr)	742	372	2.0 / 0.501
Gas Increase (m^3)	65	26	2.5 / 0.400

The ACEEE report cites a GE report that, on average, "estimates 2.38 times the savings for ECM motors that ACEEE does," and assumes "that GE did not include estimates of the values of gas required to make up for reduced electricity waste by the motor."

Much of the savings shown by CCHT/CMHC are due to electrical savings during low speed, continuous circulation mode operation of the air handler. The ECM motor could operate at a much lower airflow, and most of the savings cited were due to the electrical savings during continuous ventilation operation. The savings in the table above are for conventional operation with the fan running only during calls for heating or cooling. Gusdorf, et al, concluded that "for houses without continuous circulation, the benefits of ECMs are not very significant." The analysis included only Canadian locations, so the impact in cooling dominated climates is not included.

Kendall, Mark A. 2004. *Energy-Saving Opportunities in Residential Air-Handler Efficiency.* ASHRAE Transactions, Vol. 110, Part 1. American Society of Heating, Refrigerating and Air Conditioning Engineers. Winter 2004.

Describes efficiency differences between PSC and BDC (ECM) motors. Argues that existing efficiency metrics adequately incentivize the use of high efficiency motors. States that motor efficiency is included in existing SEER ratings, andd therefore for a given SEER level there are no savings from switching from PSC to

ECM motor. Significant savings are accrued only if the fan is operated continuously.

Massachusetts. 2005. *An Act Establishing a Minimum Energy Efficiency Standard for Certain Products.* Commonwealth of Massachusetts, House Bill No. 4299.

Sets minimum efficiency standards for a number of products, including residential furnaces and boilers. Gas and propane furnaces must have an AFUE rating of at least 90%, oil furnaces must be 83%, hot water boilers 84%, and steam boilers 82%. Furnaces must have an electricity ratio (ER) of 2% or less, except oil furnaces shall be 2.3% or less, where: $ER = (3.412*E_{AE})/(1000*E_F + 3.412*E_{AE})$

Pigg, Scott and Tom Talerico. 2004. *Electricity Savings from Variable-Speed Furnaces in Cold Climates.* Energy Center of Wisconsin.

Reports on the results of two studies – a field study of 31 new furnaces and a survey of homeowners on how they operate their furnaces to compare behavior with and without ECMs. Found higher static pressure than used in Federal rating standards, and that increased use of continuous fan operation reduces the actual electrical savings. They provided energy savings for houses with and without continuous fan use, based on 800 therms of gas consumption in heating and a 2.5 ton a/c unit operating 400 hours per year in cooling. Savings are 400 kWh heating, and 70 kWh in cooling, -30 kWh in standby power and 25 kWh in reduced compressor power, 465 kWh total for non-continuous fan operation. For continuous fan operation, the savings were 400 kWh heating, 70 in cooling, 2,960 in fan operation, and 25 in reduced cooling for a total of 3,455 kWh. An increase in gas consumption was not calculated.

Phillips, Bert G. 1998. *Impact of Blower Performance on Residential Forced-Air Heating System Performance.* ASHRAE Transactions, Vol.104, Part 1. American Society of Heating, Refrigerating and Air Conditioning Engineers. Winter 1998.

Discusses a survey of residential heating appliances across Canada. Showed that while motor efficiency of newer furnaces increased, these units also had higher airflow per unit heat input and higher external statuc pressure,resulting in increased fan energy consumption. States that increasing AFUE ratings have included trading off of reduced fuel input for increased electrical input. Concludes that changes to furnace design could reduce blower energy requirements, particularly the use of airfoil blower wheels, the external static pressure used in the AFUE test should be increased, and that electricity consumption should be incorporated into furnace performance ratings.

Proctor, J. and D. Parker. 2001. *Hidden Power Drains: Trends in Residential Heating and Cooling Fan Watt Power Demand.* FSEC-PF361-01. Florida Solar Energy Center, Cocoa, Florida.

Rice, C. K. and S. K. Fischer. 1984. *A Comparative Analysis of Single and Continuously Variable-Capacity Heat Pump Concepts*. Proceedings of the DOE/ORNL Heat Pump Conference: Research and Development on Heat Pumps for Space Conditioning Applications. U. S. Department of Energy, Office of Building Energy Research and Development. Washington DC. December 1984.

Modeling study of the performance of design optimized heat pumps. Not very useful for furnace application.

Rittleman, W. 2005. Telephone conversation regarding testing of residential diffusers at a test house in Pittsburgh. Stated that testing showed that low speed heating had lower comfort with high registers. Mixing was better with a lower supply air temperature.

Sachs, Harvey M., and Sandy Smith. 2003. *Saving Energy with Efficient Residential Furnace Air Handlers: A Status Report and Program Recommendations.* Report to the American Council for an Energy-Efficient Economy. April 2003.

Analysis of furnace air handler efficiency, including review of current technologies and market barriers. Looks at energy savings of higher efficiency fan motors, assuming decreased costs after significant market penetration. Analysis based on heating climates and includes increased fuel consumption to offset reduced electrical energy into the airstream. Includes savings during cooling. Did not assume any change in airflow or impact on fuel efficiency. Did not address cooling dominated climates, stating that "appropriate efficiency metrics are not yet available." Recommends adding performance based approach to electrical efficiency based on how efficiently the air handler performs it's task rather than a prescriptive requirement for particular motor class or other parameters.

Sachs, Harvey M., and Sandy Smith. 2004. *How Much Energy Could Residential Furnace Air Handlers Save?.* <u>ASHRAE Transactions</u>, Vol.110, Part 1. American Society of Heating, Refrigerating and Air Conditioning Engineers. Winter 2004.

Analysis of the electrical savings that might be achieved with higher eficiency motors, improved aerodynamics, improved fans or other measures.

Walker, I. S. 2004. *Improving Air Handler Efficiency in Houses.* LBNL 54760. Ernest Orlando Lawrence Berkeley National Laboratory. May 2004

Walker, I. S. 2005. *State-of-the-Art in Residential and Small Commercial Air Handler Performance.* LBNL 57330. Ernest Orlando Lawrence Berkeley National Laboratory. March 2005.

Walker, I. S., and J. D. Lutz. 2005. *Laboratory Evaluation of Residential Furnace Blower Performance.* LBNL 58752. Ernest Orlando Lawrence Berkeley National Laboratory. September 2005.