BPM Motors in Residential Gas Furnaces: What are the Savings?

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ABSTRACT

Residential gas furnaces contain blowers to distribute warm air. Currently, furnace blowers use either a Permanent Split Capacitor (PSC) or a Brushless Permanent Magnet (BPM) motor. Blowers account for the majority of furnace electricity consumption. Therefore, accurate determination of the blower electricity consumption is important for understanding electricity consumption of furnaces.

The electricity consumption of blower motors depends on the static pressure across the blower. This paper examines both types of blower motors in non-condensing non-weatherized gas furnaces at a range of static pressures. Fan performance data is based on manufacturer product literature and laboratory tests. We use field-measured static pressure in ducts to get typical system curves to calculate how furnaces would operate in the field. We contrast this with the electricity consumption of a furnace blower operating under the DOE test procedure and manufacturer rated conditions.

Furnace electricity use is also affected by operating modes that happen at the beginning and end of each furnace firing cycle. These operating modes are the pre-purge and post-purge by the draft inducer, the on-delay and off-delay of the blower, and the hot surface ignitor operation. To accurately calculate this effect, we use the number of firing cycles in a typical California house in the Central Valley of California. Cooling hours are not considered in the DOE test procedure. We also account for furnace blower use by the air conditioner and stand-by power.

Overall BPM motors outperform PSC motors, but the total electricity savings are significantly less than projected using the DOE test procedure conditions. The performance gains depend on the static pressure of the household ducts, which are typically much higher than in the test procedures.

Introduction

A residential furnace is an appliance that heats air and moves it through ductwork to the space being heated. It is equipped with a circulating blower to move air through the duct system. Currently, furnace blowers are designed using two types of motors: Permanent Split Capacitor (PSC) and Brushless Permanent Magnet (BPM)[1]. Blowers account for a majority of gas furnace electricity consumption. Accurate determination of blower electricity consumption is important to correctly evaluate the electricity consumption of gas furnaces. This paper considers how both types of blower motors in non-condensing non-weatherized gas furnaces perform at a range of static pressures.

Most furnace blower motors are PSC motors. PSC motors are reasonably efficient (above 70%) when operating at high speed. However, when these motors operate at low speed, their

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[1] BPM motors are also known as Electronically Commutated Motors (ECM) which is a registered trademark of General Electric.

efficiencies may drop down into the 20% range (DOE 2004). The blower in most gas furnaces is also used to circulate supply air when the air conditioner is operating. Since air conditioner evaporator coils need higher airflow than furnace heat exchangers, the blower motor operates at a lower speed, where it is less efficient, during furnace operation.

Technologies that use power electronics offer dramatic improvements in efficiency at low speeds. A rotating magnetic field is created in the armature by switching current in a coordinated manner among the six stator coils. In a BPM motor the rotor contains permanent magnets. The permanent magnets in the rotor are pulled around by the rotating magnet field of the starter. This creates a three-phase motor with essentially no losses in the rotor. The speed and torque of the motor can be varied by controlling the frequency and voltage applied to the armature coils. BPM motors can operate at efficiencies above 80% across a very wide range of speeds. Electronic controls on BPM motors allow furnace manufacturers to offer additional features such as reduced noise and better control of airflow which improve the consumer utility of furnaces.

Almost all BPM motors are used in two-stage furnaces (DOE 2004; Habart 2005). In these two-stage furnaces the burner operates at a reduced rate or a maximum rate. Overall, BPM motors are better for two-stage designs because they offer higher efficiencies at lower speeds, constant airflow at various static pressures, and quieter operation. BPM motors are associated with top-of-the-line furnaces, and are marketed to consumers as providing improved comfort and air quality (Carrier 2004a; Lennox 2005).

The electrically efficient motor increases fuel consumption, since it generates less heat, which otherwise would contribute to the space heating (Gusdorf et al. 2002).

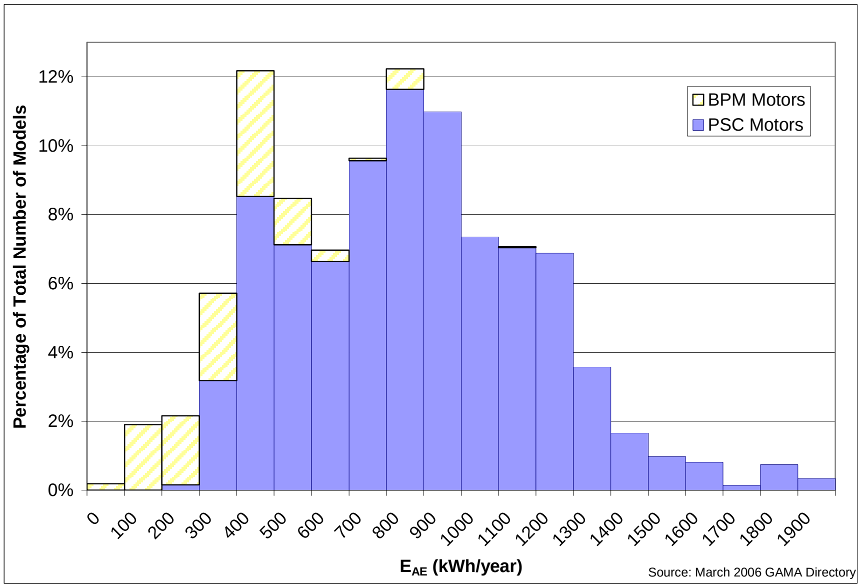
A field study in Wisconsin showed significant electricity savings for furnaces with BPM motors (Pigg 2003). The study showed an average 40% decrease in electricity consumption for furnaces using BPM motors compared to furnaces using PSC motors. The electricity savings rise to 70% when the furnace motor is used for year-round continuous fan operation

A study of Canadian households found that field static pressure varied from 0.3 to 1.10 in. w.g. (Phillips 1998). The study recommended that furnaces be measured at a more realistic 0.7 in. w.g., instead of 0.18 to 0.33 in. w.g. used in the DOE test procedure. This study also recommends furnace manufacturers increase blower wheel efficiencies and reduce airflow requirements to increase furnace blower efficiency. An estimate of 180 to 250 kWh/yr of electricity savings by using BPM motors is given.

Another study surveying seven residential furnace manufacturers concluded that furnaces with BPM motors would save 310 kWh/year for single-stage non-condensing furnaces, 410 kWh/yr for two-stage non-condensing furnaces, 190 kWh/yr for single-stage condensing furnaces, and 370 kWh/yr for two-stage condensing furnaces (Kendall 2004). Still another study, restricting its analysis to condensing furnaces, predicted that the U.S. average annual electricity savings for BPM furnaces would be 500 kWh/yr during the heating season and 200 kWh/yr during the cooling season (Sachs & Smith 2004).

The current U.S. Department of Energy (DOE) test procedure reports the Average Annual Auxiliary Electrical Energy Consumption (E_{AE}) (DOE 2006). E_{AE} is a measure of total electricity consumption of furnaces at test procedure conditions. It is reported in the Gas Appliance Manufacturers Association (GAMA) directory of equipment certified for sale in the United States. E_{AE} varies from 76 kWh/year to 1953 kWh/year (GAMA 2005). Figure 1 shows E_{AE} of non-condensing and condensing non-weatherized gas furnaces by motor type. The furnaces with the lowest E_{AE} ratings tend to use BPM motors. The motor type was determined from the March 2005 GAMA directory (GAMA 2005), manufacturer product literature, and by decoding model numbers (DOE 2004), E_{AE} does not account for electricity consumption by the furnace blower when it is used by the air conditioner or standby power.

Figure 1: Distribution of E_{AE} for Non-Weatherized Gas Furnaces



Source: March 2006 GAMA Directory

Many states have introduced incentives to decrease the electricity consumption of furnaces, by encouraging the use of BPM motors. These incentives have increased the market share of furnaces with BPM motors in Oregon, Wisconsin, and British Colombia (Habart 2005). The tax incentives for gas furnaces in the Energy Policy Act of 2005 (EPAct 2005) are expected to have a similar effect. The EPAct 2005 legislation provides tax incentives for consumers who purchase a gas furnace with an E_{AE} less than or equal to 2% of the total energy consumption of the furnace. Almost all furnaces which meet the EPACT 2005 tax incentive criteria have BPM motors. As of March 2006, 85% of furnace models with BPM motors meet the EPAct 2005 incentive criteria, while only about 1% of furnace models with PSC motors do (GAMA 2006).

Determining Electricity Consumption of Furnaces

The current DOE test procedure calculates E_{AE} at laboratory conditions, which are different than the conditions found in the field. This paper calculates the electricity consumption of furnaces with PSC and BPM motors under field conditions. In this study, we considered non-condensing non-weatherized gas furnace with the motor types and controls listed in Table 1.

Table 1: Furnace Characteristics

Fuel Efficiency Level	Input Capacity	AC	Controls	Motor Type
80% AFUE	88 kBtu/h	3.5 Tons	single-stage	PSC
				BPM
			two-stage	PSC
				BPM

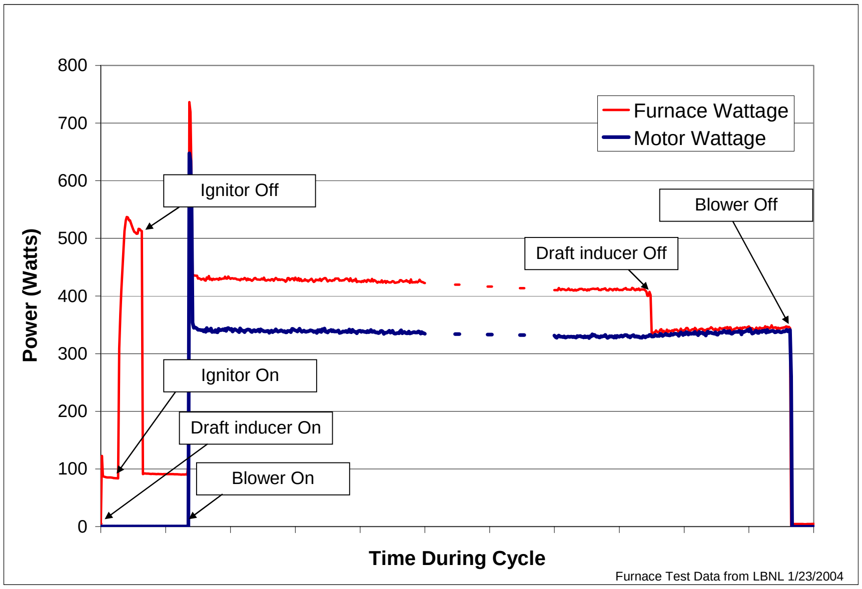
The DOE test procedure calculates furnace electricity consumption during the heating season only, using burner operating hours and the power rating and operating time of electrical components. We calculate the furnace electricity consumption during the heating season, the cooling season, and during standby.

In the DOE test procedure, the heating requirements are calculated using the Design Heating Requirement (DHR) and average conditions for the United States. We used a DOE-2 model to derive the hourly heating and cooling requirements for a prototypical house in California's Central Valley. The house heating load was 26.6 MMBtu/year and the house cooling load was 7.9 MMBtu/year. In this paper, we assume that the blower distributes airflow evenly throughout the household and all loads are adequately met.

The DOE test procedure calculates the furnace blower electricity consumption at a low static pressure, which is not consistent with field data. Furnaces overwhelmingly operate at higher static pressures (Walker et al. 2003). We compared furnace electricity use at the DOE test procedure conditions, the manufacturer rating conditions, and typical field conditions.

The furnace electrical components, the blower, the draft inducer and the hot surface ignitor, operate for a different amount of time than the burner operating cycle. The DOE test procedure accounts for these differences by using the on-time ratios between the electrical components and the burner. We calculated the number of furnace cycles by assuming the furnace fires up to five times per hour whenever heat is needed (DOE 2006). This allows a direct calculation of the electricity consumption by the draft inducer for pre-purge and post-purge, by the blower for the on-delay and off-delay, and by the hot surface ignitor. Typical furnace electricity consumption during a firing cycle is shown in Figure 2.

Figure 2: Electricity Consumption during a Furnace Firing Cycle



Furnace Test Data from LBNL 1/23/2004

The DOE test procedure estimates the burner operating hours by accounting for the heating requirements and the heat delivered by the burner and the electrical components. The heat generated by the electrical components reduces fuel consumption, everything else being equal.

The DOE test procedure does not account for the blower operation for the air-conditioner during the cooling season. We calculate the blower motor electricity consumption during the cooling season by taking into account the house cooling requirements, the air conditioner efficiency, the heat produced by the blower motor, the airflow at different static pressures, and the decrease in air-conditioning efficiency as outdoor temperature increases.

Cooling requirements were calculated using DOE-2. Since the annual house cooling load does not change when a furnace with a more efficient blower is installed, the cooling provided to the house by the air conditioning system must remain the same. A more efficient blower reduces the amount of heat from the blower motor that is added to the cooled air stream from the air conditioner. More cooling from the air-conditioner therefore reduces the cooling operating hours. To calculate the cooling operating hours, we used a 3.5 ton air conditioner and took into account the change in air conditioner efficiency as the temperature varied (Carrier 2006).

Finally, DOE's test procedure does not account for standby power, which may amount to about 10% of the electricity used by furnaces (Pigg 2003). For this study, we assume that a furnace using a PSC motor consumes 5 watts and a furnace using a BPM motor consumes 9 watts. The difference in standby power between furnaces with PSC motors and BPM motors is presumably because BPM motors require more complex controls.

Determining Furnace Blower Electricity Consumption at Various Operating Conditions

The operating conditions for the blower can be graphically displayed as the intersection of the system curve of the ducts in the house with the fan curve of the furnace. The system curve plots airflow through the ducts as a function of static pressure across the supply and return plenums. The fan curve plots airflow provided by the furnace blower as a function of static pressure. The intersection of these two curves is the airflow and static pressure at which the furnace will operate in those ducts. The electricity consumption of the motor can be calculated from this static pressure using the motor power curve (input power as a function of static pressure). Figure 3 shows an example of a system curve intersecting a furnace fan curve.

System Curves. In this study we look at three different system curves, based on the DOE test procedure, manufacturers furnace ratings, and conditions observed in the field.

The DOE test procedure conditions assume 0.23 in. w.g. static pressure at 1200 CFM airflow. Manufacturers rate their furnace blowers for cooling conditions assuming 0.5 in. w.g. static pressure at the rated air-conditioning airflow. To represent the field operating conditions, we used the average conditions for new houses with 3.5 ton air-conditioners from a study of California houses (Chitwood 2005). These conditions implied a 0.7 in. w.g. static pressure at 1200 CFM airflow. The airflows and static pressures listed in Table 2 were used to develop the three system curves shown in Figure 4.

Table 2: System Curves

	Static Pressure	**Airflow**
DOE test procedure	0.23 in. w.g.	1200 CFM
Manufacturer's rating	0.5 in. w.g.	1400 CFM
Field condition	0.7 in. w.g.	1200 CFM

Figure 3: System Curve and Airflow Fan Curve Intersection

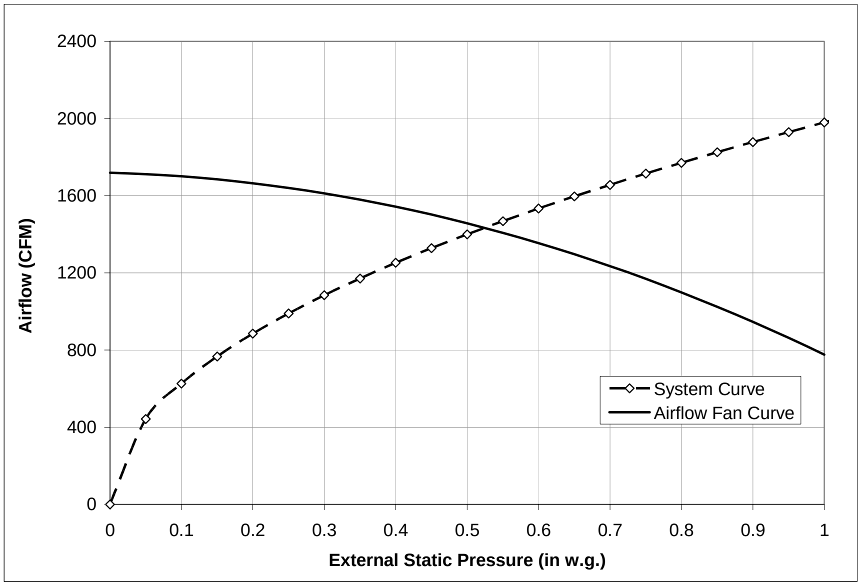
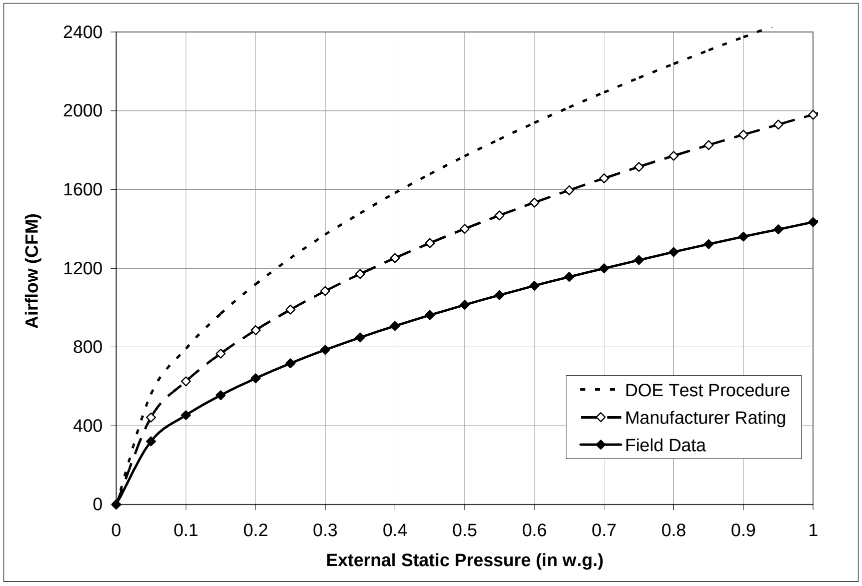


Figure 4: System Curves at the Three Operating Conditions



Fan Curves. Tables of airflow versus static pressure across the furnace are available from manufacturers in the product literature for each furnace. Power curves show blower motor input power as a function of static pressure across the furnace and are not always available in manufacturer's product literature. We used product literature tables and laboratory test results to generate fan and power curves (Carrier 2004b; Walker 2005).

Figure 5 shows the fan curves for a furnace with a PSC motor and Figure 6 shows the fan curves for a furnace with a BPM motor. The airflow with PSC motor fans tends to vary significantly with static pressure, while the airflow with BPM motor fans is relatively constant with static pressure.

Figure 5: PSC Motor Fan Airflow Curve

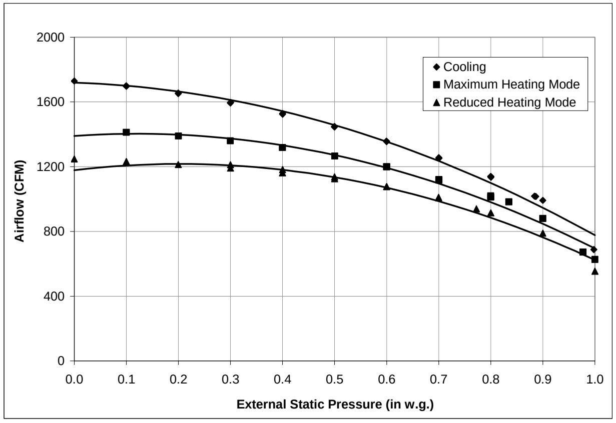


Figure 6: BPM Motor Fan Airflow Curve

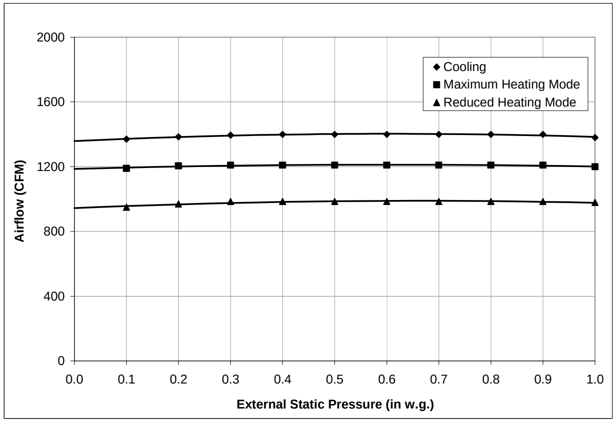


Figure 7 shows the fan power curves for a furnace with a PSC motor and Figure 8 shows the fan power used by a furnace with a BPM motor. The PSC motor power decreases with static pressure, while the BPM motor power increases with static pressure.

Figure 7: PSC Motor Fan Power Curve

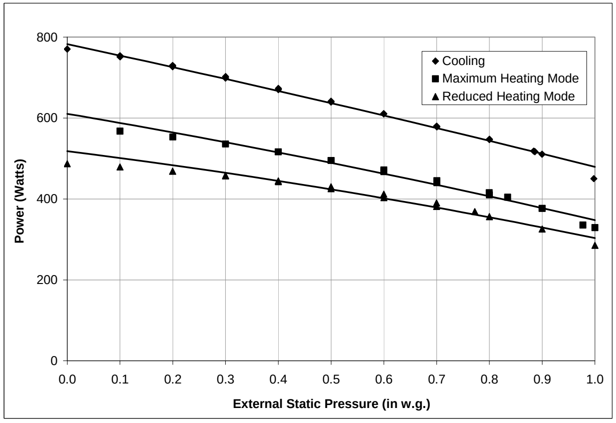
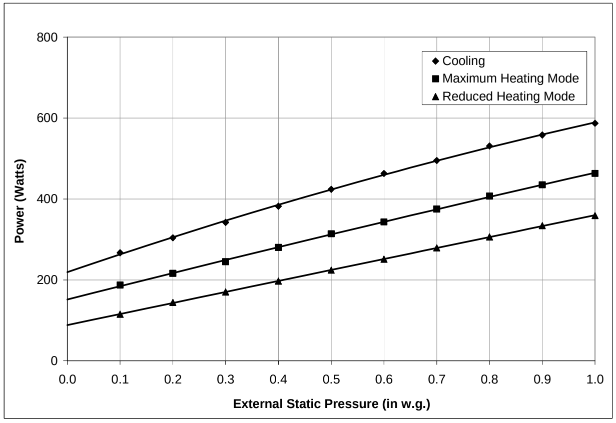


Figure 8: BPM Motor Fan Power Curve



Energy Consumption Results

Our analysis uses a single-stage PSC furnace (the most common configuration in today's furnace market) as a point of comparison for the other three furnaces; PSC (two-stage), BPM (single-stage), and BPM (two-stage). Figures 9 to 11 show the electricity consumption for four furnaces under three conditions; the DOE test procedure, the manufacturer rating, and field conditions. The results for the simulated Central Valley of California house are presented as bar charts that show the energy use by individual components (including standby power).

Figure 9 shows the electricity consumption results based on DOE test procedure operating conditions. When compared to a PSC single-stage furnace, BPM motors consume 37% less electricity for a single-stage furnace and 41% less for a two-stage furnace, while PSC motors consume 6% more when used in two-stage furnaces. The BPM two-stage furnace shows a 7% decrease in electricity consumption compared to the BPM single-stage furnace. The most significant difference in electricity consumption is between the blower motor electricity consumption by PSC and BPM furnaces. During the heating season, under these conditions, the PSC motor in the single-stage furnace consumes 2.3 times more electricity than the BPM motor in the single-stage furnace and 3.3 times more electricity than the BPM motor in the two-stage furnace. Both BPM furnaces use almost half the electricity of the PSC furnaces during summer operation. For BPM furnaces, standby power accounts for 20-25% of the electricity consumption.

Figure 9: Results Based on DOE Test Procedure Operating Conditions

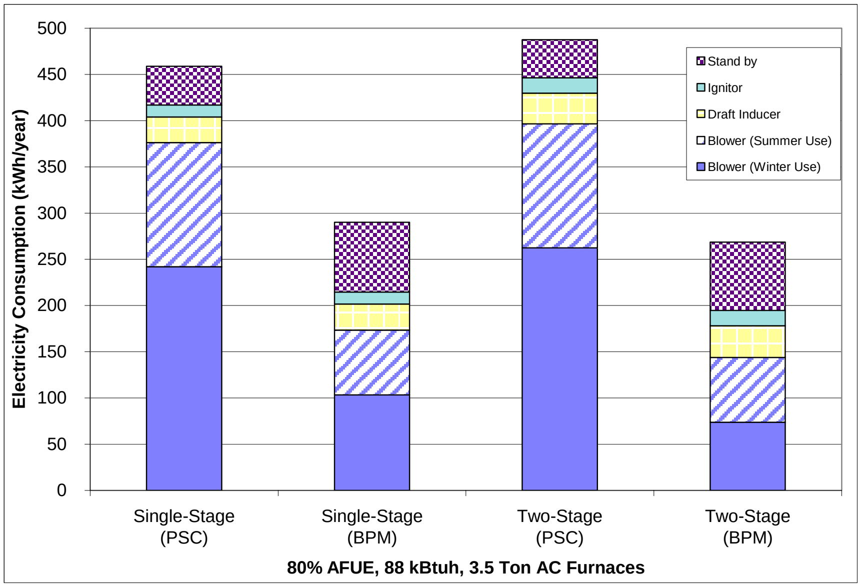


Figure 10 shows the electricity consumption results based on the rating conditions used by manufacturers. The results under these conditions follow a similar trend as under the DOE test procedure. When compared to PSC single stage furnace, furnaces with BPM motors consume 26% less electricity for a single-stage furnace and 32% less for a two-stage furnace, while PSC motors consume 7% more when used in two-stage furnaces. A two-stage furnace with a BPM motor shows a 9% decrease in electricity consumption as compared to a BPM single-stage furnace. The electricity consumption of a furnace with a BPM motor is higher under these conditions than under DOE test procedure conditions. The electricity consumption during the heating season shows that the PSC motor in the single-stage furnace consumes 1.8 times more electricity than the BPM motor in the single-stage furnace and 2.6 times more electricity than the BPM motor in the two-stage furnace. Both BPM furnaces use about two-thirds the electricity used by PSC furnaces during summer operation.

Figure 11 shows the electricity consumption results based on field operating conditions. The results are significantly different from results under the other two operating conditions. When compared to a PSC single stage furnace, BPM furnaces consume 1% less electricity for a single-stage furnace and 10% less for a two-stage furnace, while PSC motors consume 8% more when used in two-stage furnaces. A BPM two-stage furnace shows a 10% decrease in electricity consumption compared to a BPM single-stage furnace. The BPM electricity consumption is significantly higher under these conditions than under wither the DOE test procedure or the manufacturer rating conditions.

Figure 10: Results Based on Manufacturer Operating Conditions

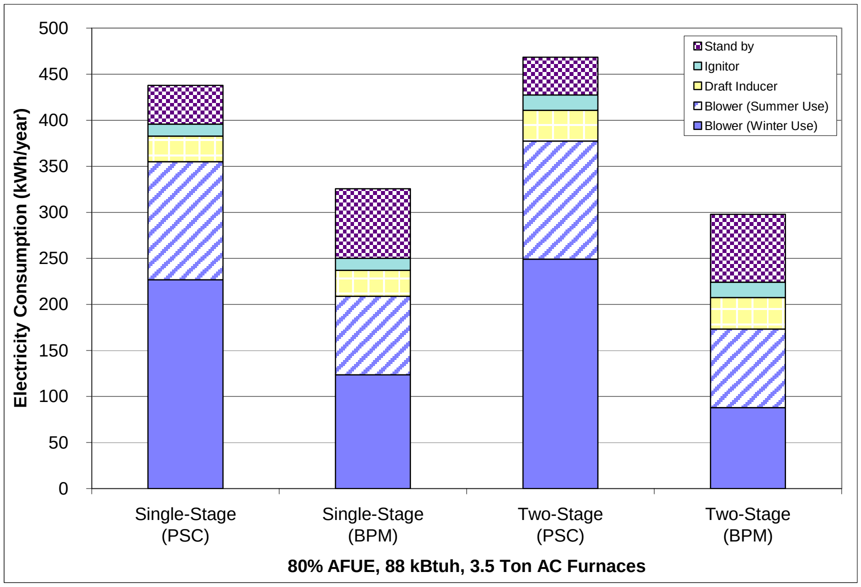


Figure 11: Results Based on Field Data Operating Conditions

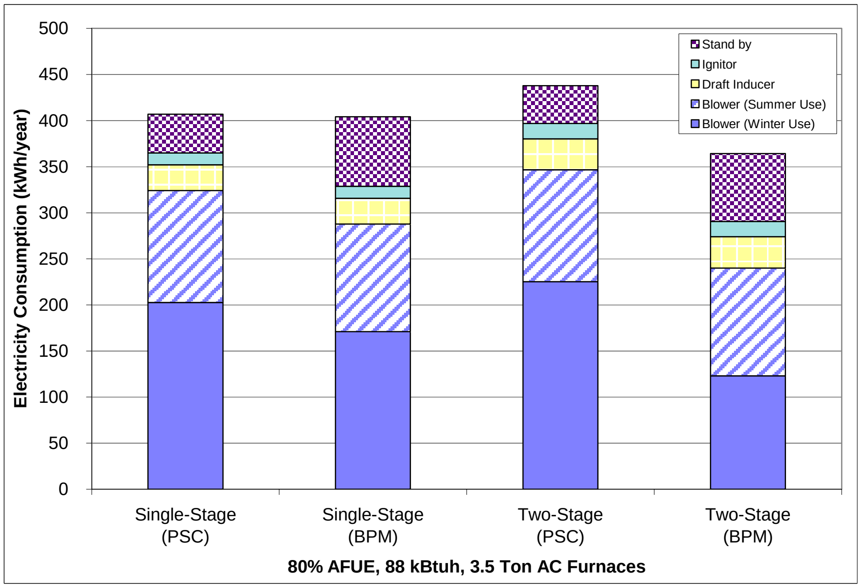
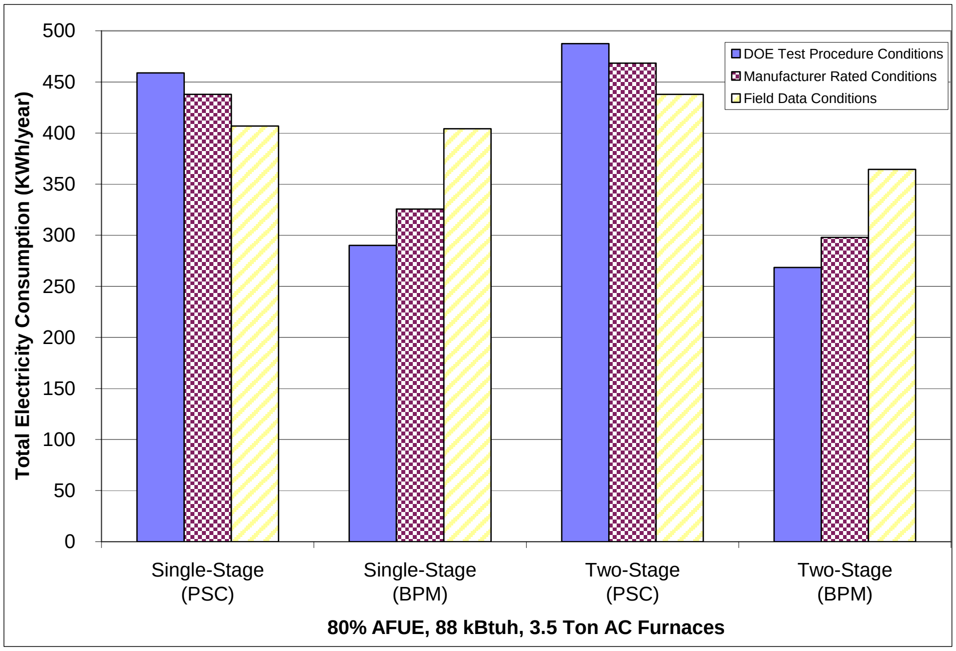


Figure 12 compares the total electricity consumption results for the three operating conditions and the four furnaces. When compared to the DOE test procedure results, PSC furnaces consume about 4% less electricity under the manufacturer rated conditions and about 10% less electricity under field conditions. When compared to the DOE test procedure results, BPM motors consume about 11% more electricity at manufacturer rated conditions and about 36% more electricity under field conditions. These results clearly show that PSC two-stage furnaces use more electricity than PSC single-stage furnaces. BPM furnaces show significant electricity savings compared to PSC furnaces under DOE test procedure and manufacturer rating conditions. However, under field conditions BPM single-stage furnaces show almost no savings relative to PSC single-stage furnaces. The electricity savings under field conditions for a two-stage furnace with a BPM motor compared to a single-stage furnace with a PSC motor are only about one quarter of the electricity savings at DOE test procedure conditions.

Figure 12: Total Electricity Consumption Results at all Operating Conditions



Discussion

In this study, we compared the electricity consumption, in a typical house in the Central Valley of California, of residential non-condensing, non-weatherized gas furnaces with single-stage and two-stage BPM motors to the same furnaces with PSC motors under three operating conditions: the DOE test procedure, the manufacturer rating, and field conditions.

The main reason electricity savings are smaller than estimated under DOE test procedure and manufacturers operating conditions, is that the furnaces in the field operate at higher static pressure. Since BPM motors maintain constant airflow they need to use more electricity as static pressure increases. To have significant savings, a furnace with a BPM motor needs to be installed in a house with low-pressure-loss distribution systems. These low-pressure distribution systems would have the additional benefit of improving air-conditioner efficiency. A low-pressure-loss distribution system would likely extend motor life, since the majority of furnaces with BPM motors are not intended to operate above 0.8 in. w.g.

Our results differ from those of earlier papers who drew their inferences from published data for E_{AE} (e.g., Sachs and Smith, 2004). This raises the possibility that the E_{AE} calculation is inaccurate for designs with BPM motors and higher standby power losses. Further analysis with other climates and with condensing furnaces are required to evaluate this hypothesis.

In this paper, we did not look at costs, but the reduced potential for energy savings are much less than expected, which may have implications for the incentives given for furnaces with BPM motors: This California based analysis suggests that savings may be climate-dependent and greater in regions with higher heating loads met at lower fan speeds

Finally, we assumed that there was sufficient airflow distribution throughout the household, but in the field this might not be true. Some remote areas of the household might be starved of airflow by using furnaces with a PSC motor. Furnaces with BPM motors may be able to maintain adequate airflow rates to meet the heating and cooling demands in exchange for under delivering on energy savings.

Conclusions

The results indicate furnaces with BPM motors outperform furnaces with PSC motors, but the gains depend greatly on the static pressure. For the climate conditions studied, our results show the field electricity consumption by furnaces with BPM motors is much higher than projected under DOE test procedure and manufacturer rating operating conditions. Although BPM furnaces show electricity savings compared to PSC furnaces, the savings are significantly smaller under field operating conditions. To show significant savings a BPM furnace needs to be installed in a house with low-pressure-loss duct systems.

In addition, standby power consumption in BPM furnaces is significantly higher than for PSC furnaces and accounts for about one-fifth to one-quarter of the total electricity consumption by BPM furnaces. This is not currently accounted for in the E_{AE} parameter in the DOE test procedure. Review of the E_{AE} procedure is warranted if further analysis in other (heating-dominated) climates confirms our results, because furnace electricity consumption is significant.

Overall, it appears the BPM motors used in furnaces offer electricity savings, but under the field conditions analyzed the savings are much smaller than estimated under DOE test procedure and manufacturer rated operating conditions.

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