Residential Two-Stage Gas Furnaces: Do They Save Energy?

Alex Lekov, Victor Franco, and James Lutz
Lawrence Berkeley National Laboratory

ABSTRACT

Residential two-stage gas furnaces account for almost a quarter of the total number of models listed in the March 2005 GAMA directory of equipment certified for sale in the United States. Two-stage furnaces are expanding their presence in the market mostly because they meet consumer expectations for improved comfort.

Currently, the U.S. Department of Energy (DOE) test procedure serves as the method for reporting furnace total fuel and electricity consumption under laboratory conditions. In 2006, American Society of Heating, Refrigeration and Air-Conditioning Engineers (ASHRAE) proposed an update to its test procedure which corrects some of the discrepancies found in the DOE test procedure and provides an improved methodology for calculating the energy consumption of two-stage furnaces.

The objectives of this paper are to explore the differences in the methods for calculating two-stage residential gas furnace energy consumption in the DOE test procedure and in the 2006 ASHRAE test procedure and to compare test results to research results from field tests. Overall, the DOE test procedure shows a reduction in the total site energy consumption of about 3% for two-stage compared to single-stage furnaces at the same efficiency level. In contrast, the 2006 ASHRAE test procedure shows almost no difference in the total site energy consumption. The 2006 ASHRAE test procedure appears to provide a better methodology for calculating the energy consumption of two-stage furnaces. The results indicate that, although two-stage technology by itself does not save site energy, the combination of two-stage furnaces with BPM motors provides electricity savings, which are confirmed by field studies.

Introduction

A residential gas furnace can be designed with single-stage controls or modulating controls. There are two different types of modulating controls which can be applied to furnaces, two-stage or step-modulation controls. In this paper, we examine only modulation with two-stage controls, which accounts for the large majority of the modulating furnaces. A two-stage furnace requires all or some of the following components: a two-stage gas valve, two-stage controls, a multiple speed blower motor, and two-speed inducer motor. A two-stage control is any control that uses a two-stage adjustment of the furnace input rate in response to changes in the heating load. Based on thermostat demand, the two-stage control cycles the burners between a reduced heat input rate and off or between the maximum heat input rate and off.

Two-stage furnaces use two types of blower motor designs: permanent split capacitor (PSC) and brushless permanent magnet (BPM)[1]. PSC motors are reasonably efficient when operating at high speed, however, when these motors are operated at low speed, their efficiencies

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

drop significantly. Overall, BPM motors are more suitable in two-stage designs because they offer much higher efficiencies at lower speeds than PSC motors. Almost all BPM motors are used in two-stage furnaces (DOE 2004; Habart 2005; Kendall 2004).

Two-stage gas furnaces account for almost a quarter of the total number of models in the March 2005 GAMA directory of certified equipment for sale in the United States (GAMA 2005). Although an exact estimate of the market share of two-stage furnace is not known, they are expanding their presence in the market place mostly because they meet consumer expectations for improved comfort (Carrier 2004; Lennox 2005). Furnaces that operate at substantially reduced output over longer periods of time can provide more uniform space temperatures, quieter operation, greater efficiency, and reduced emissions. In addition, financial incentives introduced to decrease the electricity consumption of furnaces, mainly by providing incentives for the use of BPM motors, have been shown to increase the market share of two-stage furnaces with BPM motors in Oregon, Wisconsin, and British Colombia (Habart 2005). The gas furnace tax incentives in Energy Policy Act of 2005 (EPAct 2005)[2] should have a similar effect.

Due to the increasing interest in two-stage furnaces, it becomes important to more accurately calculate the energy consumption in order to assess the potential energy savings of these furnaces compared to other furnace design options.

The current U.S. Department of Energy (DOE) test procedure (DOE 2006), which is based on American Society of Heating Refrigeration and Air-conditioning Engineers (ASHRAE) Standard 103-93 (ASHRAE 1993), has served as the method for reporting furnace total fuel and electricity consumption under laboratory conditions as well as Annual Fuel Utilization Efficiency (AFUE). The test results are then reported in a GAMA directory and are frequently used as a basis for comparing energy consumption between furnace models, calculating potential energy savings, and determining which furnace models should receive incentives.

In 2006, American Society of Heating Refrigeration and Air-conditioning Engineers (ASHRAE) proposed an update of its test procedure (ASHRAE 2006) to include modifications based on research conducted during the last several years (Stanley 2002). This new test procedure corrects some of the discrepancies found in the DOE test procedure and also provides a more accurate basis for the estimation of the energy consumption of two-stage furnaces.

This paper explores the differences in the methods for calculating two-stage residential gas furnace energy consumption in the DOE test procedure and in the 2006 ASHRAE test procedures and compares it to research results from field studies. The results from comparing the test procedures are significantly different and this paper attempts to summarize these results and point to the reasons for the differences.

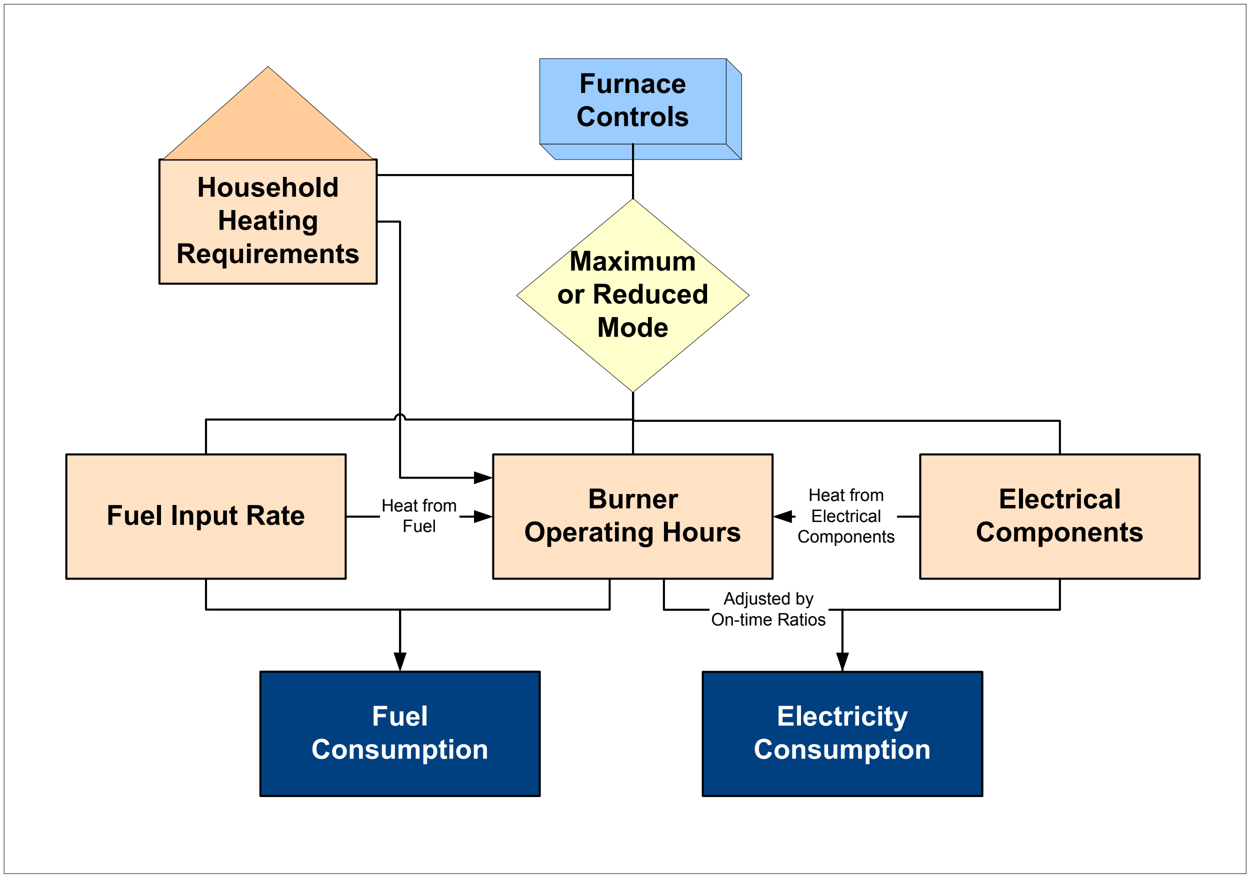
Methodology for Determining Two-Stage Furnace Energy Consumption

Figure 1 illustrates the basic parameters and methodology used in the DOE and 2006 ASHRAE test procedure to calculate fuel and electricity consumption of gas furnaces. The average annual fuel consumption of furnaces (E_F) and the annual auxiliary electrical energy (E_{AE}) are frequently used as furnace performance metrics.

---

[2] Most furnace models that meet current requirements for tax credits under EPAct 2005 are two-stage furnaces. EPAct 2005 provides tax incentives for consumers that either purchase furnace having an AFUE of 95% or greater or a furnace with an efficient blower motor that consumes less than or equal to 2% of the total site energy consumption of the furnace.

Figure 1. Fuel Consumption Calculation for Gas Furnaces in the DOE and 2006 ASHRAE Test Procedures



To satisfy the households heating requirements, the furnace operates at only the maximum operating mode if it has single-stage controls or a combination of the maximum and reduced operating mode if it has two-stage controls. The test procedures determine the ratio of time the furnace is operating at the reduced or maximum operating mode in two-stage furnaces by calculating an operating mode factor that uses the average outdoor temperature at which the furnace starts operating (65ºF), the typical outdoor design temperature (5ºF), and is a function of the oversize factor and the ratio of the reduced input rate to the maximum input rate.

The furnace fuel consumption is a function of the burner operating hours and the fuel input rate. The burner operating hours are determined by calculating the household heating requirements and the heat provided by the furnace fuel and the furnace electrical components.

The household hearting requirements are a function of an oversize factor and the furnace output capacity and use the national average heating load hours corrected for the operating conditions. The household heating requirements are satisfied by the furnace fuel and by heat generated by some of the furnace electrical components. Furthermore, the operating length of electrical components can differ from the operating length of the burner. For example, the furnace blower usually operates 10-30% longer than the burner to scavenge residual heat from the heat exchanger. This difference is calculated using on-time ratios for the individual electrical components.

Similarly, electricity consumption is a function of the burner operating hours adjusted by on-time ratios and the electricity use of the furnace electrical components. The burner operating hours are adjusted by on-time ratios to account for the differences in the operating length between the electrical components and the burner.

Neither test procedure accounts for standby power, which may amount to about 10% of the electricity used by furnaces (Pigg 2003). Furthermore, neither test procedure accounts for the electricity consumption by the blower for its air-conditioning operation during the cooling season. In fact, the furnace blower serves also as an air handler for the air conditioner and any efficiency improvement affecting the blower will also provide electricity savings during the cooling season.

Using the calculation methods described in these two test procedures, this paper calculates the fuel and electricity consumption for 12 design configurations that are divided into four efficiency levels and both single stage and two-stage control strategies. Furnaces with two-stage controls were evaluated with both PSC and BPM motors. The 80% and 81% AFUE efficiency levels represent non-condensing furnaces. The 90% and 95% AFUE efficiency level represent condensing furnaces.

The assumptions used in this paper to compare the test procedures are listed in Table 2.

Table 2. Assumptions Used to Compare the Energy Consumption Methods Between the Two Test Procedures

Parameters	Assumptions
Maximum fuel input rate	75 kBtu/hr
Reduced fuel input rate	68% of the maximum fuel input rate (based on manufacturer product literature and GAMA's March 2005 directory)
AFUE	AFUE at both the maximum and reduced operating mode is the same for each test procedure (DOE 2004; Habart 2005)
Heating Requirements	Heating Requirements are set constant regardless of AFUE level. (This is equivalent to assuming that furnaces having the same input capacities, but different efficiencies, serve a house with a constant design heating requirement.)
Electrical Components	Blower electricity and ignitor power are used to calculate the heat generated by the furnace electrical components, while the furnace blower, draft inducer, and the ignition device are used to calculate the electricity consumption for both test procedures.
PSC Motor Electricity	500 watts at the maximum operating mode (Jakob et al. 1994).
BPM Motor Electricity	398 watts at the maximum operating mode (DOE 2004).
Draft Inducer Electricity	76 watts at all operating modes (DOE 2004).
Ignition Device Electricity	400 watts at all operating modes (DOE 2004).

As shown in Table 2, we assume that a PSC motor would operate at 500 watts at the maximum operating mode (Jakob et al. 1994) and 80% of this at the reduced operating mode. We assume BPM motors to be 20.4% more efficient than PSC motors (DOE 2004) and therefore operate at 398 watts at the maximum operating mode and 50% of this at the reduced operating mode.

Note that the static pressure used in the test procedures to calculate the electricity consumption of furnace blowers is not consistent with field data, where the furnaces tend to operate at a higher static pressure (Chitwood 2005; Phillips 1998; Pigg 2003). Using a higher static pressure will in general increase electricity consumption by BPM motors, while maintaining air moving performance, and decrease the electricity consumption by PSC motors, while decreasing air moving performance (Walker et al. 2003).

Test Procedure Comparison

Table 3 summarizes the main differences between the DOE test procedure and the 2006 ASHRAE test procedures when calculating two-stage residential gas furnace energy consumption.

Table 3. Summary of Differences between Two Test Procedures for Calculating Energy Consumption by Two-Stage Natural Gas Furnaces

Parameter	2006 DOE Test Procedure	2006 ASHRAE Test Procedure
Fuel Consumption	Calculated at the maximum operating mode only.	Calculated at both the maximum and reduced operating mode.
Electricity Consumption	Calculated at the maximum and reduced operating mode.	Accounts for on-time ratios at the reduced operating mode.
Burner Operating Hours (BOH)	BOH at the reduced operating mode is a function of BOH at the maximum operating mode adjusted by a ratio of the reduced and maximum fuel input rates.	Maximum and reduced operating modes calculated separately.
Household Heating Requirements	Uses Design Heating Requirement (DHR), which is a step function of output capacity.	Replaces DHR with a linear function dependent on output capacity and fixed oversize factor.
Operating Mode Factor	Factor from reference table. A step function, since the oversize factor depends on DHR.	Factor calculated directly using a linear function of output capacity and fixed oversize factor.
Heat from Fuel	Only uses the fuel input rate and furnace AFUE at the maximum operating mode	Uses the fuel input rate and furnace AFUE at both the maximum and reduced operating mode
Heat from Electricity	Calculated at the maximum operating mode only.	Determined at the maximum and reduced operating mode.
On-time ratios	Uses fixed on-time ratios at the maximum operating mode. A correction factor is used in calculating BOH to compensate for longer use of electrical components.	Variable on-time ratios that are determined at the maximum and reduced operating mode. No additional correction factor is used.
Electrical Components Contribution	Blower electricity and ignitor power are used to calculate the heat generated by the furnace electrical components, while the furnace blower, draft inducer, and the ignition device are used to calculate the electricity consumption for both test procedures.	Ignition device heat and electricity contribution not calculated.

Since the 2006 ASHRAE test procedure takes into account burner operating hours and input capacities at both maximum and reduced operating modes, it better matches the field data that show that two-stage furnaces operate predominately at the reduced operating mode (DOE 2004; Habart 2005; Pigg 2003). The electricity consumption calculations in the 2006 ASHRAE test procedure provides a more accurate determination of the on-time ratios at the maximum and reduced operating mode than in the DOE test procedure. Therefore, the 2006 ASHRAE test procedure provides a more accurate basis for estimating both fuel and electricity consumption.

The calculation of the burner operating hours for two-stage furnaces differs between the test procedures. In the DOE test procedure, the burner operating hours at the reduced operating mode are a function of the burner operating hours at the maximum operating mode and a ratio of the maximum to reduced input fuel rate. In the 2006 ASHRAE test procedure, the burner operating hours are calculated independently for the maximum and reduced operating mode.

In the DOE test procedure, the heating requirements of the house used to calculate the burner operating hours are determined using the Design Heating Requirement (DHR) parameter. DHR is also used to apportion the annual heating load between the reduced and maximum operating mode for two-stage furnaces. DHR is a step function of furnace heating capacity and a small rise in the heating capacity impacts DHR value in a way that results in higher energy consumption for more efficient furnaces. This causes the DOE test procedure methodology to not always be suitable for comparing furnace energy use. The 2006 ASHRAE test procedure replaces DHR with a linear function that includes the heating capacity at the maximum and reduced operating mode and a constant oversize factor.

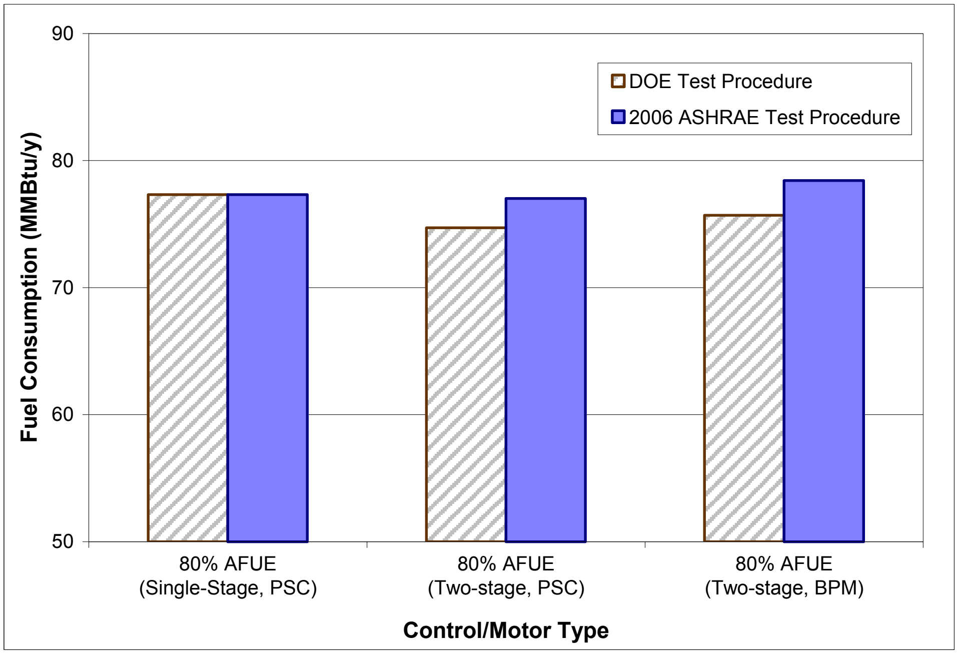
Burner Operating Hours are corrected both by the heat provided by the fuel and by the heat from electrical components. In the DOE test procedure, the heat from the electrical components and the cycling rates are calculated at the maximum operating mode only. In practice, two-stage furnaces operate most of the time in the reduced mode, which lengthens the furnace operation. To compensate for this, the DOE test procedure applies a factor that reflects the ratio of on-time for the two-stage furnace versus the single-stage furnace. This factor is not included in the 2006 ASHRAE test procedure, since electricity consumption and the on-time ratios are calculated separately for the maximum and reduced modes. This approach reduces the fraction of heat from the electricity components.

Energy Consumption Results

We report the results from a study that analysis the fuel and electricity consumption of different AFUE levels, controls, and motor types. This paper separately looks at the impact of the fuel and electricity consumption for a sample of furnace design configurations. It also looks at the total energy consumption for several efficiency levels.

As a sample, Figure 2 shows the fuel energy consumption results at 80% AFUE for the following configurations: single stage with PSC, two-stage with BPM, and two-stage with BPM. For single-stage controls both test procedures show the same fuel consumption. The DOE test procedure shows fuel savings of 3.4% for two-stage furnaces with PSC motors compared to single stage furnaces, while the 2006 ASHRAE test procedure shows only a 0.4% decrease in fuel consumption. The DOE test procedure shows fuel savings of 2.1% for two-stage furnaces with BPM motors compared to single stage furnaces, while the 2006 ASHRAE test procedure shows a 1.4% increase in fuel consumption. The 2006 ASHRAE test procedure shows a 3% higher fuel consumption for a two-stage furnace with a BMP motor as compared to the DOE test procedure due to a more accurate calculation approach, which decreases the heat contribution from the electrical components. Furthermore, both test procedures show a 1-2% higher fuel consumption for two-stage furnaces with BPM motors than for those with PSC motors, since BPM motors are more efficient than PSC motors and therefore generate less heat, which would otherwise contribute to satisfying the heating requirements.

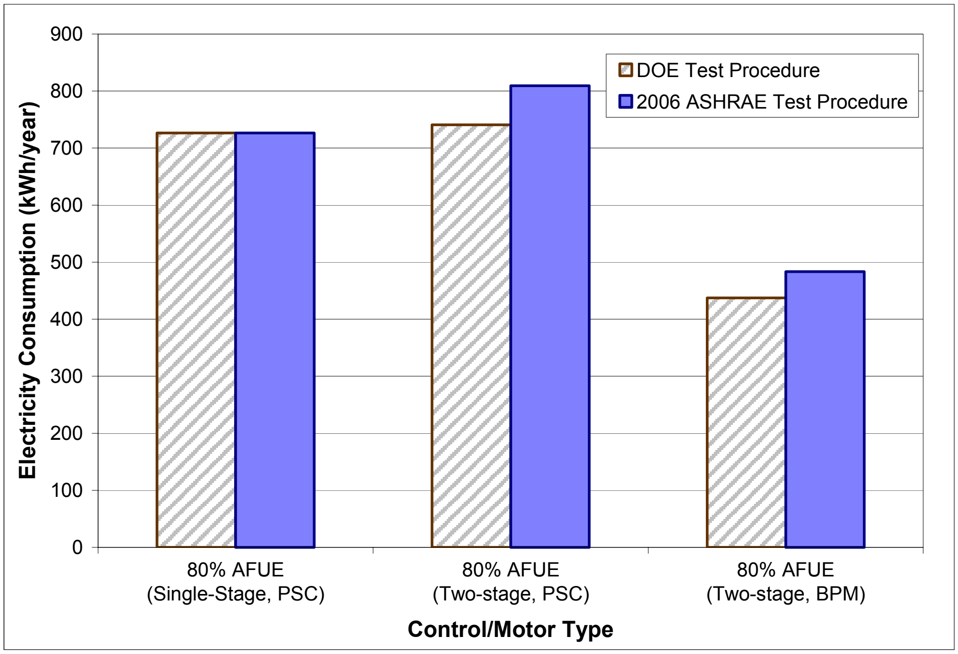
Figure 2. Fuel Consumption Comparison



A field study in Canada showed an increase in fuel consumption for furnaces with BPM motors (Gusdorf 2002), which is in line with the increased fuel consumption calculated based on the 2006 ASHRAE test procedure.

Figure 3 shows the electricity consumption results. For single-stage controls the two test procedures show no differences in the electricity consumption. The DOE test procedure shows an electricity consumption increase of 2.0% for two-stage furnaces with PSC motors compared to single stage furnaces, while the 2006 ASHRAE test procedure shows a 11.4% increase in electricity consumption. The DOE test procedure shows electricity savings of 39.8% for two-stage furnaces with BPM motor compared to single stage furnaces, while the 2006 ASHRAE test procedure shows only a 33.5% decrease in electricity consumption. The 9-10% increase in the 2006 ASHRAE test procedure electricity consumption for two-stage furnaces with the same motor as compared to the DOE test procedure is mainly due to an increase in the period of blower operation compared to the burner operation at the reduced operating mode. Furthermore, both test procedures show a 40-41% electricity consumption decrease for two-stage furnaces with BPM motors compared to those with PSC motors. Even though two-stage furnaces with BPM motors have more operating hours than two-stage furnaces with PSC motors, BPM motors are much more efficient than PSC motors at the reduced operating mode.

Figure 3. Electricity Consumption Comparison

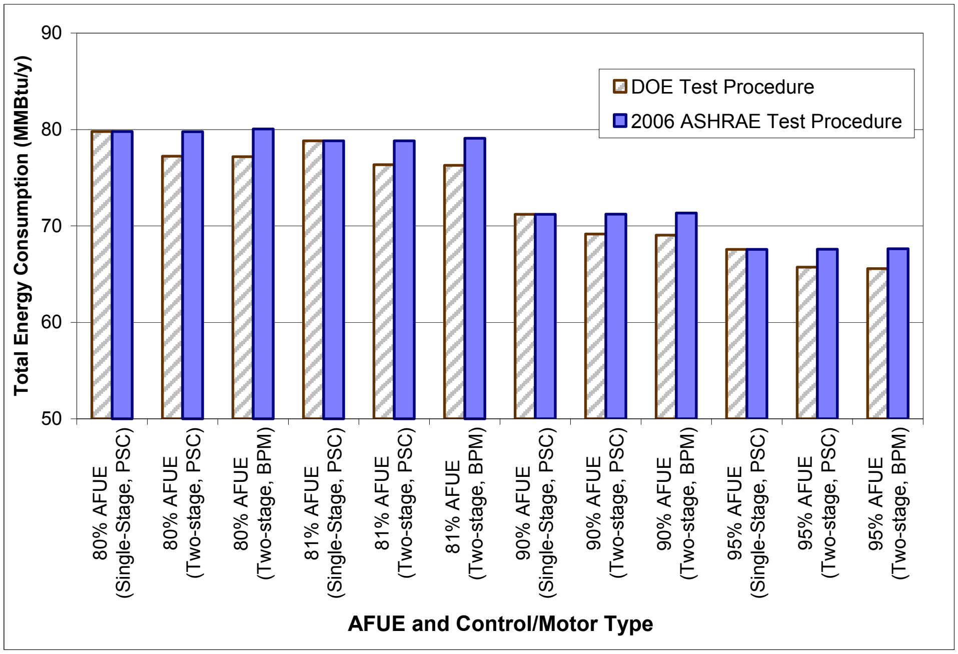


A field study in Wisconsin showed a 40% decrease in electricity consumption for furnaces with BPM motors (Pigg 2003) compared to furnaces using PSC motors. This is in line with the results based on the DOE and 2006 ASHRAE test procedures.

Figure 4 shows the combined fuel and electricity consumption using the calculation methods described in the DOE test procedure and the 2006 ASHRAE test procedure for several furnace efficiency levels (80%, 81%, 90%, and 95% AFUE), that represent non-condensing and condensing furnaces. For two-stage designs, the DOE test procedure consistently shows a reduction in energy consumption by about 3% compared to single-stage furnaces at the same AFUE level. In contrast, the 2006 AHRAE test procedure shows almost no difference in the total energy consumption at the same efficiency level. The reason is that although two-stage furnaces operate longer at the reduced mode, this is offset by lower fuel input rate at this mode.

In the 2006 ASHRAE test procedure the results for single-stage as well as for two-stage furnaces show that a one percent change in AFUE results in about the same percent reduction in the total energy consumption. In contrast, the DOE test procedure for two-stage furnaces shows about a 4% decrease in total energy consumption for a 1% percent AFUE change. The 2006 ASHRAE test procedure offers a more accurate method for calculating the energy consumption of two-stage furnaces.

Figure 4. Total Energy Consumption at Various AFUE Levels



Note that although the energy consumption of two-stage furnaces is about the same as that of single-stage furnaces, the consumer using a two-stage design with a BPM motors will still benefit financially, because they would reduce use of the more expensive electricity (Sachs and Smith 2004).

Conclusions

This paper presents furnace energy consumption calculations based on the current DOE test procedure and the 2006 ASHRAE test procedure. It also includes a summary of the methodology used in both test procedures to determine the energy consumption of two-stage furnaces. A detailed comparison of the differences between the two procedures is also presented.

The DOE test procedure shows fuel savings of 3.4% for two-stage furnaces relative to single-stage furnaces at the same AFUE, while the 2006 ASHRAE test procedure shows only a 0.4% decrease in fuel consumption. The electricity consumption of two-stage furnaces as opposed to single-stage furnaces increases by 11% in the 2006 ASHRAE test procedure as opposed to a 2% increase in the DOE test procedure. Overall, the DOE test procedure shows a reduction in the total energy consumption of about 3% for two-stage furnaces at the same efficiency level. In contrast, the 2006 ASHRAE test procedure shows almost no difference in the total energy consumption. The 2006 ASHRAE test procedure results seem to be confirmed by field studies. This study also provides a comparison of the energy consumption among different efficiency levels. The results show that a change of AFUE produces an equivalent reduction in the total energy consumption in the 2006 ASHRAE test procedure calculations.

This paper shows that the main improvements in the 2006 ASHRAE test procedure are: (a) the approach used to calculate the heat generated by the furnace's electrical components (b) the approach for calculating on-time ratios for the furnace's electrical components, (c) properly accounting for maximum and reduced operating modes, and (d) the approach used to determine the design heating requirement.

Based on the 2006 ASHRAE test procedure, which appears to provide a more accurate method for calculating the energy consumption of two-stage furnaces, the results indicate that two-stage technology by itself does not save energy. However, the combination of two-stage furnaces with BPM motors provides electricity savings and overall financial benefits to the consumers.

References

[ASHRAE] American Society of Heating Refrigerating and Air-Conditioning Engineers. 1993. "Method of Testing for Annual Fuel Utilization Efficiency of Residential Central Furnaces and Boilers." *ANSI/ASHRAE* 103/1993. Atlanta, Ga.: American Society of Heating Refrigerating and Air-Conditioning Engineers.

———. 2006. "Public Review of Method of Testing for Annual Fuel Utilization Efficiency of Residential Central Furnaces and Boilers." *BSR/ASHRAE Standard* 103-1993R. Atlanta, Ga.: American Society of Heating Refrigerating and Air-Conditioning Engineers.

[Carrier] Carrier Corporation. 2004. *Infinity 80 Gas Furnace Consumer Brochure*. February 18. http://xpedio.carrier.com/idc/groups/public/documents/marketing/858-436-021804.pdf Farmington, Conn.: Carrier Corporation.

Chitwood, Rick. 2005. Personal Communication. Raw Data of Airflow Tests Conducted in California Houses for CEC 2008 Residential Standards Research, CN500-04-006, September. Mt. Shasta, Calif.: Chitwood Energy Management.

[DOE] U.S. Department of Energy. 2004. Energy Conservation Program for Consumer Products: Energy Conservation Standards for Residential Furnaces and Boilers; Proposed Rule Furnace and Boiler Advanced Notice of Proposed Rule (ANOPR). July 29. http://www.eere.energy.gov/buildings/appliance_standards/residential/furnaces_boilers.html Washington, D.C.: U.S. Department of Energy.

———. 2006. 10 Code of Federal Regulations, Part 430-Subpart B Appendix N—Uniform Test Method for Measuring the Energy Consumption of Furnaces and Boilers. January 1. Washington, D.C.: U.S. Department of Energy.

[GAMA] Gas Appliance Manufacturers Association. 2005. *Consumers' Directory of Certified Efficiency Ratings for Heating and Water Heating Equipment*. March. Arlington, Va.: Gas Appliance Manufacturers Association.

Gusdorf, J., M.C. Swinton, E. Entchev, C. Simpson, and B. Castellan. 2002. "The impact of ECM furnace motors on natural gas use and overall energy use during the heating season of CCHT research facility." Gas Technology Institute's First Natural Gas Technologies Conference and Exhibition, Orlando, Fla., September 29-October 2. http://irc.nrc-cnrc.gc.ca/fulltext/nrcc38443/nrcc38443.pdf Ottawa, Canada: Canadian Centre for Housing Technology (CCHT).

Habart, Jack. 2005. Natural Gas Furnace Market Assessment. August. http://www.energytrust.org/Pages/about/library/reports/0508_GasFurnaceMarketAssessment.pdf Portland, Ore.: Energy Trust of Oregon.

Jakob, F. E., J. J. Crisafulli, J. R. Menkedick, R. D. Fischer, D. B. Philips, R. L. Osbone, J.C. Cross, G. R. Whitacre, J. G. Murray, W. J. Sheppard, D. W. DeWirth, and W. H. Thrasher. 1994. *Assessment of Technology for Improving the Efficiency of Residential Gas Furnaces and Boilers*, Volume I and II – Appendices, GRI-94/0175. September. Chicago, Ill.: Gas Research Institute, AGA Laboratories.

Kendall, Mark A. 2004. "Energy-Saving Opportunities in Residential Air-Handler Efficiency." *ASHRAE Transactions*, V. 110, Pt.1. Atlanta, Ga.: American Society of Heating, Refrigerating and Air-Conditioning Engineers.

[Lennox] Lennox Industries, Inc. 2005. G60V *Gas Furnace Product Brochure*. May. http://www.lennox.com/pdfs/brochures/LennoxG60VGasFurnace.pdf Richardson, Tex.: Lennox Industries, Inc.

Phillips, Bert G. 1998. "Impact of Blower Performance on Residential Forced-Air Heating System Performance." *ASHRAE Transactions*, V. 104, Pt.1. Atlanta, Ga.: American Society of Heating, Refrigerating and Air-Conditioning Engineers.

Pigg, Scott. 2003. "Electricity Use by New Furnaces: A Wisconsin Study." Madison, Wis.: Energy Center of Wisconsin.

Sachs, H. M., and S. Smith. 2004. "How Much Energy Could Residential Furnace Air Handlers Save?" *ASHRAE Transactions*, V. 110, Pt.1. Atlanta, Ga.: American Society of Heating, Refrigerating and Air-Conditioning Engineers.

Stanely, Liu. 2002. Proposed Revisions of Part of the Test Procedure for Furnaces and Boilers in *ASHRAE Standard* 103-1993. September. Gaithersburg, Md.: U.S. Department of Commerce, National Institute of Standards and Technology, Building Environment Division, Building and Fire Research Laboratory.

Walker, Ian, M.D. Mingee, and D.E. Brenner. 2003. "Improving Air Handler Efficiency in Residential HVAC Applications," LBNL 53606, August. Berkeley, Calif.: Lawrence Berkeley National Laboratory.