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Laboratory Evaluation of Residential Furnace Blower Performance

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Environmental Energy Technologies Division

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Abstract

A testing program was undertaken at Lawrence Berkeley National Laboratory and an electric utility (Pacific Gas and Electric Co.) to compare the performance of furnace blowers. This laboratory testing program was undertaken to support potential changes to California Building Standards regarding in-field furnace blower energy use. This technical support includes identifying suitable performance metrics and target performance levels for use in standards. Five different combinations of blowers and residential furnaces were tested for air moving performance. Three different types of blower and motor combinations were tested in two different furnace cabinets. The blowers were standard forward–curved impellors and a prototype impeller with reverse-inclined blades. The motors were two 6-pole permanent split capacitor (PSC) single-phase induction motors, a brushless permanent magnet (BPM) motor and a prototype BPM designed for use with a prototype reverse-inclined impellor. The laboratory testing operated each blower and furnace combination over a range of air flows and pressure differences to determine air flow performance, power consumption and efficiency. Additional tests varied the clearance between the blower housing and the furnace cabinet, and the routing of air flow into the blower cabinet.

Introduction

The blowers in residential furnaces typically move the heated air through a duct system that distributes heat and then returns it to the furnace. Usually the blowers are double inlet models with the inlets to the centrifugal blower at both sides. The motor mounts inside the inlet cone on one side. If a house has central air-conditioning, the same blower is usually used to move the cooled air throughout the house.

Although furnaces, air conditioners and heat pumps have become significantly more efficient over the last couple of decades, residential forced air system blowers have not experienced similar improvement. The most common blowers have been shown by in-field testing to have efficiencies of only 10% to 15% (Phillips 1998 & 1995 Gusdorf et al. 2002). These low efficiencies indicate that there is significant room for improvement of both electric motor and the aerodynamic performance of furnace blowers.

An important consideration in analyzing forced air system blowers is that essentially all of the wasted electricity is manifested as heat. This extra heat reduces air conditioning cooling and dehumidification performance and effectively acts as fuel switching for fossil fuelled furnaces. For electric furnaces, this heat substitutes directly for the electric resistance heating elements. For heat pumps, this heat substitutes for vapor compression-based high COP heating and effectively reduces the COP of the heat pump.

A typical furnace uses about 500W. for a 1000 hours of furnace operation this is 500kWh. At a typical California electricity price of 17cents/kWh this would cost a homeowner $85/year.

In this study, the aim is to characterize the performance of residential furnace blowers to determine typical energy consumption, how performance differs between standard laboratory rating conditions and real life applications, what attributes of blowers contribute significantly to their performance, and to use this information to evaluate proposed performance testing in the state of California. The basis for this is to laboratory test several furnace blowers over a wide range of conditions and combine these laboratory test results with the results of other studies.

Proposed Blower Performance Specifications for California Building Code

The proposed prescriptive standard for the 2008 California Building Energy Standards is: "Furnace fans in new homes shall simultaneously demonstrate a watt draw less than 400 W/1000 cfm (2.5 cfm/W) and a cooling flow greater than 350 cfm/ton of nominal cooling capacity with a wet coil.". These requirements would be evaluated by field testing of installed systems. For testing with a dry coil there will need to be some derating applied to the field test data. It is possible that there will be a similar rating specification for houses with no cooling, but in terms of cfm/kBtuh.

The 2.5 cfm/W performance level is critical because (as the test results show) the majority of furnace blowers (which use PSC motors) operate very close to this specification, such that relatively small changes in performance (for example due to duct flow resistance, cabinet restriction, return ducting geometry) can be critical for meeting the specification.

Residential Blower Characteristics

PSC motors with forward inclined blade blower wheels

This is by far (>90% of the residential market) the dominant air handler used today. The single-phase permanent split capacitor (PSC) motor are six-pole induction motors with a synchronous rotation speed of 1200 rpm. Multiple taps are used to operate at several fixed speeds over a range of air flow rates, with highest air flows about 1.5 times the lowest air flows. The speed is set by using different taps that result in different slip, or lag from synchronous speed, of the rotor. Different speeds are necessary to match the different airflow requirements for heating and cooling operation and allow a single blower to have a wider range of applications than if it operated at a single speed. Speed is controlled by changing jumpers on the control board located on the fan housing and/or spade-lug connectors on the motor. The relatively constant rotational speed at each tap means that the air flow is highly variable with static pressure. As shown in Figure 1, the blower wheel has many narrow chord forward curved bent sheet metal blades, with large gaps between the wheel and housing. The housing has one opening on each side with the direct drive motor located in one of these openings (Figure 2), and a rectangular discharge. This side entry means that the air flow pattern inside the air handler cabinet is fairly convoluted as air typically enters the bottom of the cabinet, flows around the housing then changes direction 90° to enter the blower wheel. Also, unlike older belt-drive blowers, the mounting of the electric motor in the inlet restricts the flow on that side of the fan.

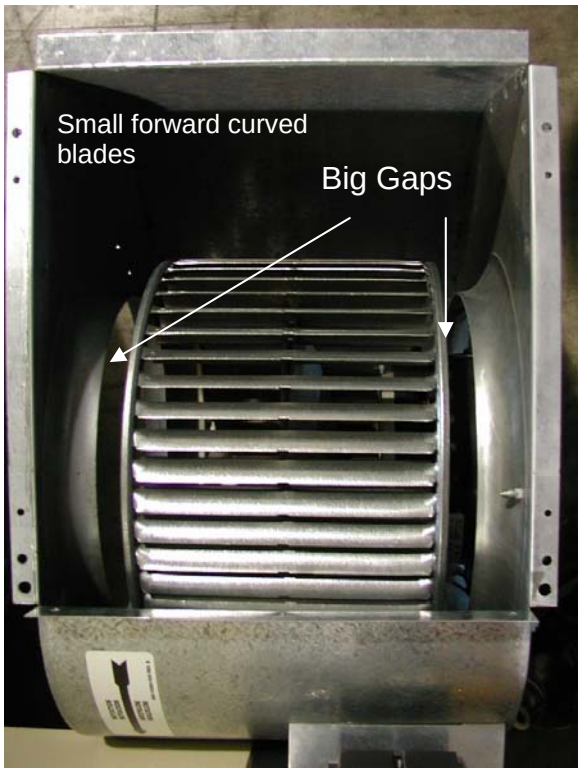


Figure 1. Blower viewed from the air exit.

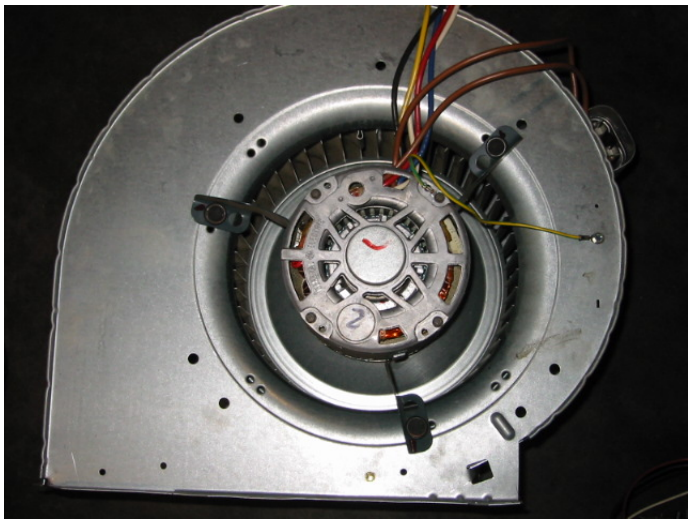


Figure 2. Fan housing inlet with direct drive PSC motor

BPM motors and forward inclined blade blower wheels

The second motor type tested was a brushless permanent magnet (BPM) motor. These motors electronically control the rotating stator field by shifting the field to different coils in the windings. The rotor consists of permanent magnets directly mounted on the shaft of the motor. By varying the voltage and frequency of the electrical current to the stator coils, the

motor can be made to rotate over a wide range of speeds and torques. By programming controls based on the performance of the blower, the blower and motor combination can provide a constant air flow across a wide range of static pressures. Because the magnetic field of the rotor is provided by permanent magnets, this type of motor is more efficient than a PSC induction motor, where the field in the rotor is induced by the current caused by the rotating magnetic field of the stator coils. A key characteristic related to their wide speed range is their ability to operate at much lower air flow rates, making them more suitable for continuous fan operation for mixing and/or distribution of ventilation air. The ability to operate at much lower air flows (usually about 2.5 times less than the maximum air flow) results in considerably less power being used at low fan speeds. The blower wheel and housing are the same as those used with PSC motors.

Prototype Blower

In 2000, the U.S. Department of Energy funded development of a prototype blower with backward inclined impellor blades (shown in Figure 3). To achieve the same airflows the impellor rotates faster than impellors with forward curved blades. Because of the narrower inner diameter and the higher rotational speed of the impellor (up to 2000 rpm compared to a maximum of 1200 rpm for the forward inclined blower, a new generation BPM was developed for this blower. Because of the higher rotational speeds to achieve the required air flow, this impellor could not be used with a PSC motor. A report by Weigman et al. (2003) discusses the development of the prototype air handler in detail.

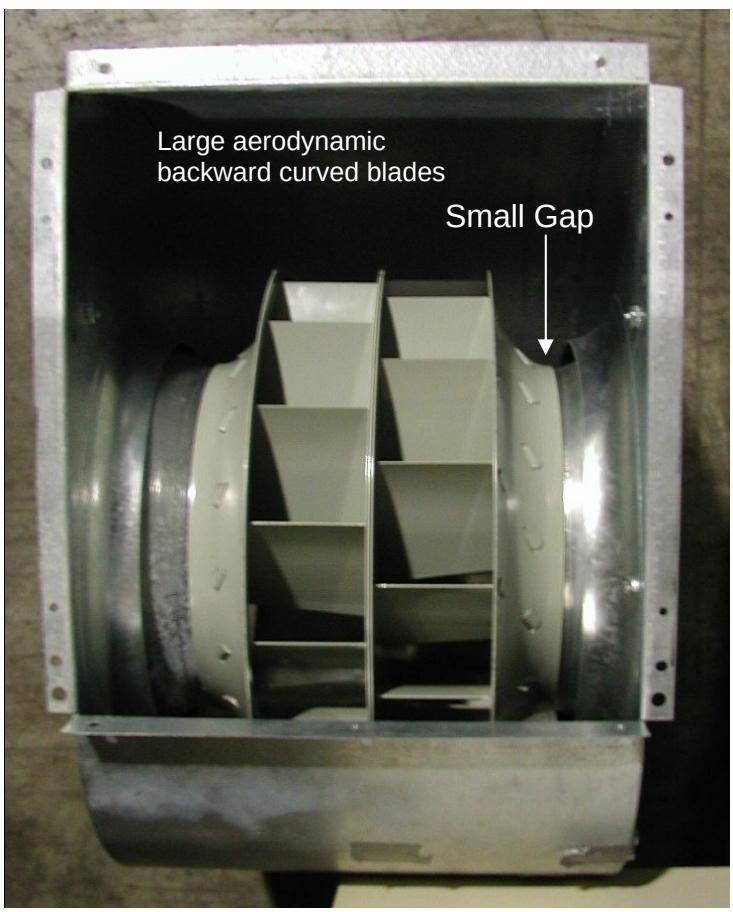


Figure 3. Prototype blower showing different blade design and fan to housing clearances compared to the standard blower in Figure 1.

Comparing blower performance

The blowers were compared by examining their air flow and power consumption characteristics over a wide range of operating pressures. Criteria for evaluation included:

- How air flow rates change with system air flow resistance
- Performance changes with changes in operating speed
- Comparing air flow and power consumption at typical operating conditions
- Comparing blower efficiency (output air power divided by electricity input)
- Comparing cfm/W ratings (the performance metric most likely to be used by rating schemes)

Efficiency Calculations

The efficiency is defined as the air power divided by the electric power consumption of the electric motor and includes both electric and aerodynamic effects. The air power is defined as the volumetric air flow through the blower multiplied by the pressure difference across the blower.

$$\eta = \frac{Q\Delta P}{W}$$

Where η is the efficiency, Q the air flow (m^3/s), ΔP the pressure difference (Pa) and W is the electric power (Watts).

The pressure difference is the difference in total pressure (static plus velocity) between the blower inlet and exit. In practice, static pressure is often used because the velocity pressures are low. To determine the efficiency of the blower the pressure difference needs to be measured at the inlet to the blower wheel and at the blower exit. These locations are difficult to access and the complexity of the flow field at these locations adds considerable difficulty and uncertainty to these measurements. In field applications, "external static" pressure is used. That is the pressure difference between the return plenum/blower cabinet and the supply plenum. This pressure difference includes pressure drops in the cabinet itself and across the furnace heat exchanger. For systems including cooling coils, this external static pressure will also include pressure drop across the coil. In this study, the LBNL tests measured static pressures in the blower cabinet and supply plenum as well as total pressure at the fan exit (before the furnace heat exchanger). For the figures and analysis, the external static (plenum-to-plenum) pressure difference was used as this is the pressure difference that will be used in field tests and the applicability of the test results will be discussed in terms of application to possible future field testing requirements in building codes.

Interpreting cfm/W ratings

When interpreting cfm/W results it is important to realize that there is a limit on cfm/W ratings for 100% efficient operation:

- For static pressure in inches of water the limit is 8.5 cfm/W per inch of water, so at half an inch of water the limit is 17 cfm/W. At lower pressures the limit increases and at higher pressures it decreases.
- For static pressure in Pa the limit is 2120 cfm/W per Pascal. At 125 Pa the limit is 17 cfm/W. This dependence of the cfm/W limit on pressure is illustrated graphically in Figure 4. Clearly, there are large potential benefits for low static pressure systems.

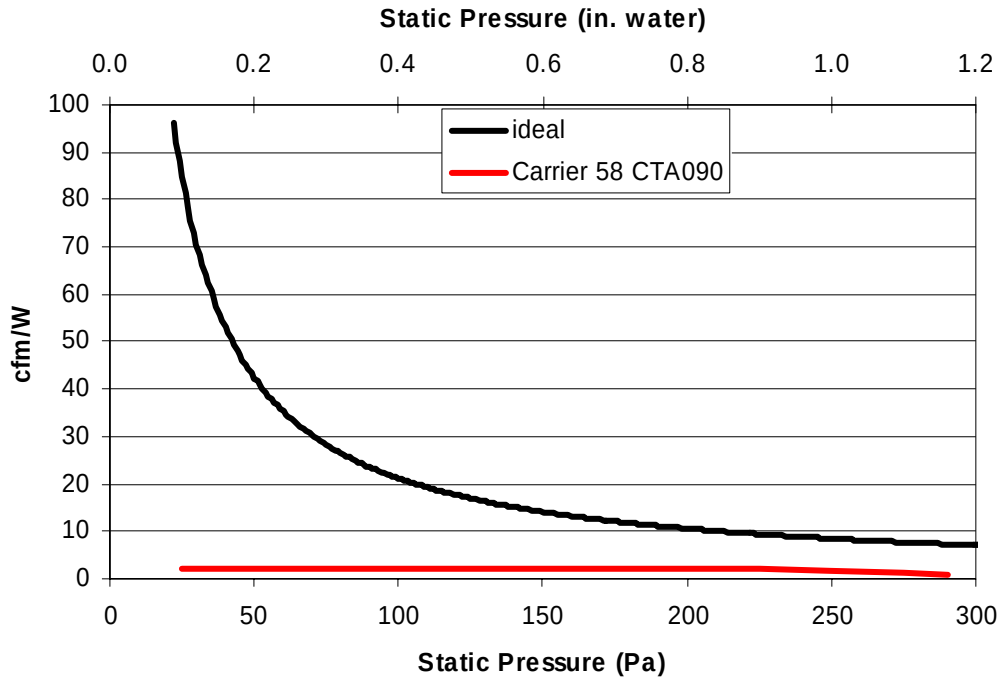


Figure 4. Maximum theoretical cfm/W for different static pressures compared to a typical residential unit

Furnace Blowers Tested

Table 1 summarizes key characteristics of the furnaces and blowers tested in this study. A total of five combinations of furnaces and blowers were evaluated. Furnace #2 and #3 are essentially the same furnace, just with different blowers.

Table 1. Blower and Furnace Characteristics

Furnace	Blower & Blower motor	Controls
Furnace # 1 80 kBtu/h 2.5 – 3 Ton AC	Forward curved blades (10x7 Blower) with PSC motor (1/3 hp)	Speed taps on motor
	Prototype backward inclined with prototype BPM motor	Software on laptop
Furnace # 2 88 kBtuh 3.5 ton AC	Forward curved blades (10x8 Blower Size) with PSC motor (1/3 hp)	Speed taps on motor
Furnace # 3 2-stage, 88 kBtuh 1.5- 4 Ton AC	Forward curved blades (10x8 Blower) with BPM motor (½ hp)	Circuit board in furnace
	Prototype backward inclined with prototype BPM motor	Software on laptop

The current study combines measurements made by an electric utility using a standard AMCA 210 (Laboratory Method of Testing Fans for Aerodynamic Rating Performance) type air handler test and LBNL laboratory tests.

The furnaces were tested in a horizontal configuration. The burners did not operate during the test and no gas was hooked up. No cooling coils or filters were installed. In real field installations the cooling coils and filters will act as additional flow resistance leading to increased pressures across the blowers.

Previous Field and Laboratory Studies

Field studies by many researchers (see Field Testing Bibliography) have shown that existing fans in residential air handlers typically consume about 500W, supply about 2 cfm/W and have efficiencies on the order of 10% to 15%. In particular, California homes showed a higher than average consumption of about 570W (Proctor and Parker 2000 and Wilcox 2004) and use 510W/1000 cfm or about 2 cfm/W. The results of the California Energy Commission field survey currently nearing completion (Chitwood 2005 – personal communication) that focuses on new construction in California show similar results, with an average of about 700W per system and 2 cfm/W.

A Canada Mortgage and Housing Corporation (CMHC 1993) study showed that typical furnace fan efficiencies are on the order of 15%, but poor cabinet and duct design can reduce this to about 7%. The spread from best to worst systems was on the order of ten to one indicating that it is possible to have much better performance using existing technologies. Another Canadian study by Phillips (1998 & 1995) performed field tests on 71 houses and found air handler efficiencies in the range of 10-15%.

More recently, the Energy Center of Wisconsin (Pigg (2003) and Pigg and Talerico (2004)) tested 31 houses with new (less than three years old) furnaces during the heating season. Almost all the BPM furnaces used more electricity in these real installations than their DOE test procedure ratings suggest: with a median of 82% above rated values. This was attributed to the static pressures in these field installations being much higher than those used in rating procedures. Test procedure external static pressures are typically 0.20 or 0.23 inches of water (50 or 57.5 Pa) depending on the capacity (DOE Furnace Test procedure[1] and ARI (2003)). The measured field data showed a range of 0.24 to 1.9 inches of water (60 to 475 Pa) with an average of 0.5 inches of water (125 Pa) at the high fire rate.

Natural Resources Canada (Gusdorf et al. (2002 and 2003)) have tested two side-by-side calibrated test houses to evaluate the change in energy for using a BPM rather than a PSC motor for continuous fan operation as required in many Canadian houses. Laboratory tests of the air handlers used in the study showed PSC efficiencies in the range of 10 to 15% with

[1] Code of Federal Regulations, Title 10, Part 430, Subpart B, Appendix N, Uniform Test Method for Measuring the Energy Consumption of Furnaces and Boilers.

BPM efficiencies of 17 to 18% over the range of flows used for heating and cooling. The biggest differences were for continuous operation where the BPM was six times more efficient than the PSC by being able to operate at about half the flow rate of the PSC during continuous operation. The results of this study showed that for a continuously operating fan in the heating season there was a 74% reduction in electricity use for using a BPM (26% of the whole-house electricity use). There is a corresponding increase in natural gas usage in the heating season of 14% to account for the reduction in waste heat from the electric motor. For cooling the savings were 48% of fan energy and 21% of all air conditioner use.

Preliminary laboratory studies have been performed by LBNL (Walker et al. 2004) on furnace #1. In addition, LBNL obtained a second prototype and used an outside contractor to perform standardized testing on Furnace #3 (Biermayer et al. 2003). In the LBNL study the blowers were tested over a range of air flows and static pressures: 500 to 1000 cfm and 0.4 to 1.2 in. water (100 to 300 Pa). The test results showed that the prototype fan was about twice as efficient as a standard fan (23% compared to 12%). Another prototype was tested by Brookhaven National Laboratory (Andrews et al. 2003) and showed similar results.

LBNL Laboratory testing

All the tests were conducted using the Energy Performance of Buildings Group full-scale duct system and test chamber (Figure 5). The test chamber is a 32' long, 8' wide, 8' tall box (9.2 m x 2.4 m x 2.4 m) over a 4' (1.2 m) "crawl-space". The chamber is constructed using standard wood framing materials (two-by-fours and plywood), with all joints taped and sealed to reduce air leakage (chamber background leakage is about 60 cfm25 [30 L/s at 25 Pa]). The furnaces were placed on a stand outside the chamber and connected with insulated flexible ducting to the test chamber, as illustrated in Figure 6.

Figure 5. Exterior view of test chamber.

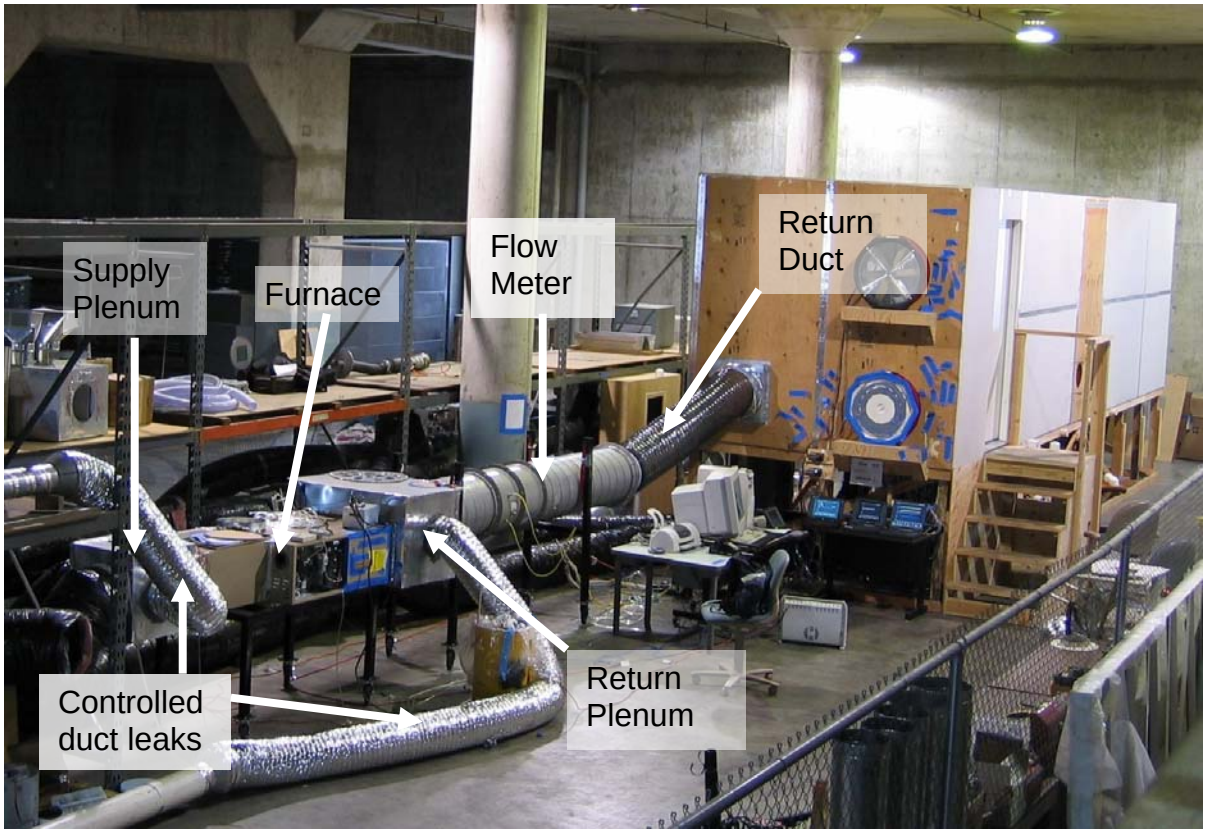


Figure 6. Air Handler Test Apparatus. Controlled duct leaks were used in duct leakage tests and were sealed for the air handler tests. Supply ducts are out of view on the floor behind the furnace and plenums.

The duct system is comprised of the following components (in order of air flow from the chamber): return register, return flexible duct, large flow nozzle, return plenum, fan box, furnace, supply plenum, two main ducts, and ten supply registers. The supply ducts contain dampers that are used to modulate the air flow and pressures in the system. These two main ducts branch into ten individual ducts, each connected to a supply register. The supply ducts are made of flexible insulated duct and are mounted on hangers in the crawlspace.

Total system airflow was measured using a high precision flow nozzle (±0.5% of measured flow) located in the return duct upstream of the return plenum (as illustrated in Figure 6). Fan inlet and exit pressures were measured upstream and downstream of the fan using electronic pressure sensors (±1.5% accuracy). The locations for these pressure measurements were carefully chosen after experimenting with several pressure probe placements in order to avoid unstable or extreme results caused by non-uniform flows. Downstream pressure measurements were taken between the fan outlet and the furnace heat exchanger (see Figure 7) and in the supply plenum. The fan outlet pressures were measured using a total pressure probe. The supply plenum pressures were determined by averaging together four static pressure probes in four corners of the plenum. The results given later use the supply plenum pressures. A photo-optical sensor was used to measure fan rotational speed as shown in Figure 8. Fan electrical power use was measured with a true power meter (±1%), which also

gives details of power factor and an harmonic analysis. All the data were recorded using five second time averages after waiting for readings to stabilize (about one minute).

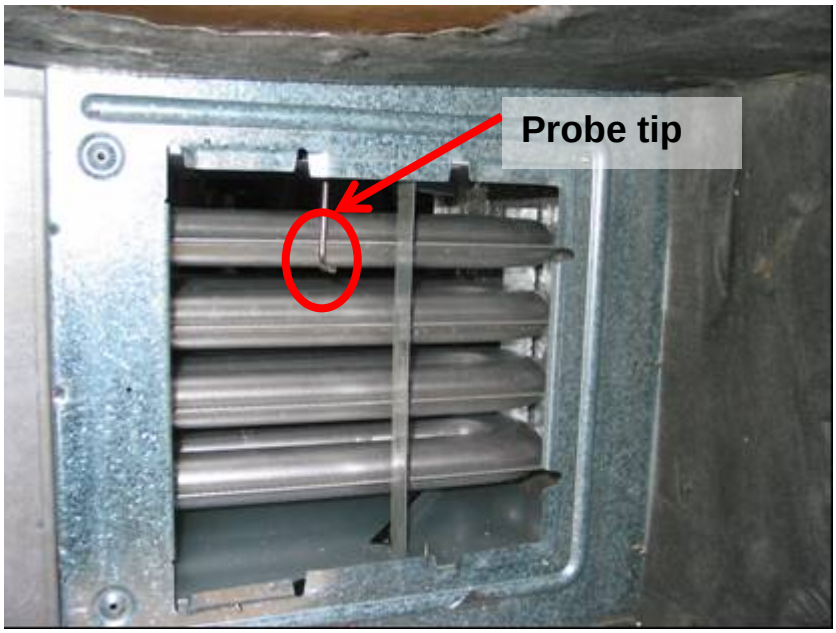


Figure 7. Entry to Furnace #1 heat exchanger showing pressure probe location.

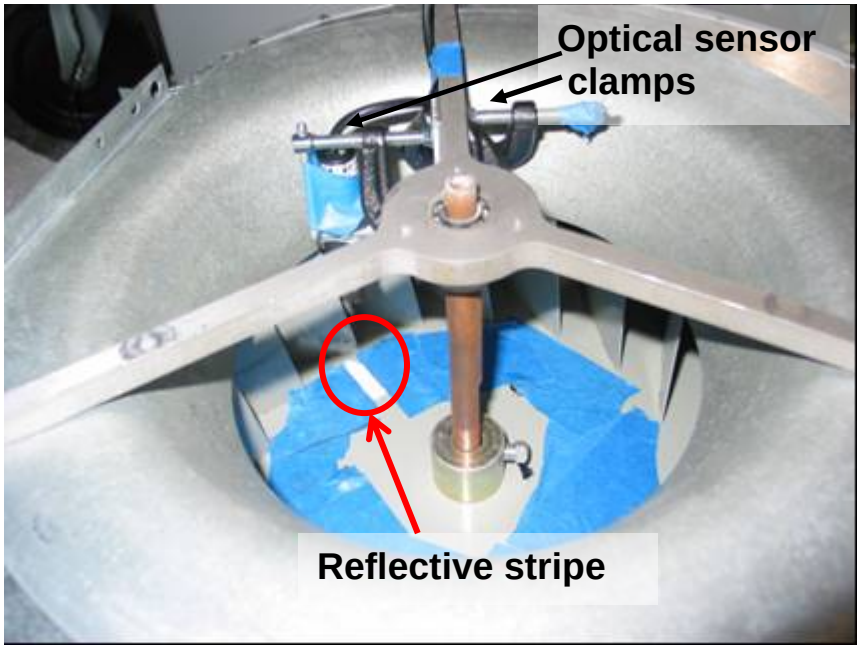


Figure 8. Rotational Speed Sensor Installation showing reflective stripe to generate pulse and photo sensor mounting

Blower noise levels were measured at the return grille as an indicator of occupant exposure and also outside the blower cabinet. In both cases the sound pressure level meter was pointed directly at the sound source. For the return grille measurements, the meter was placed one meter from the grille face pointed at the center of the grille. For the cabinet measurements the meter was located one meter from the blower cabinet access panel and centered on the access panel. All the results were A-weighted to represent human response. For each blower speed setting, the background noise level was recorded with the blower off.

Air inlet size and location

The standard or baseline performance was determined with the air entering each furnace through the bottom of the furnace. Return duct design and furnace placement often mean that air enters through the sides of the cabinet or through multiple locations. In the laboratory testing, air was ducted from the return plenum to the side entry via flexible duct as shown in Figure 9. To investigate the effects of different air entries, the following tests were performed:

For Furnace #1, with the both the prototype and PSC motor the air entered through:

- Furnace bottom (Normal operation)
- One 14 inch diameter duct on the motor side of the cabinet
- One 14 inch diameter duct opposite the motor
- Both 14 inch ducts – one on each side
- Two 10 inch diameter ducts (one each side) plus the open bottom

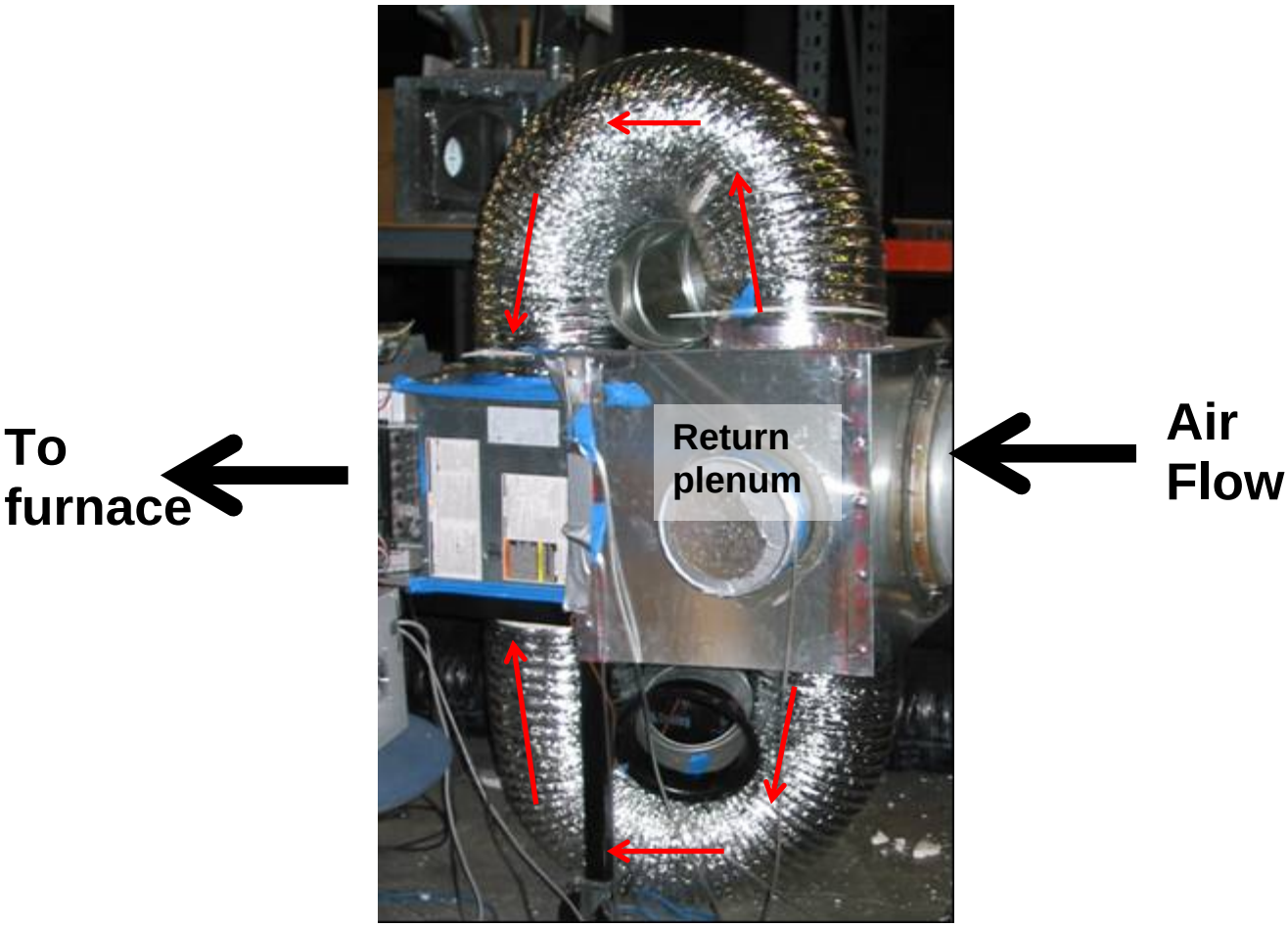


Figure 9. Furnace #3 with two 14 inch diameter side entry ducts. The furnace is mounted horizontally so the side entry is from the top and bottom in this photograph.

Figure 10. Fabricated Motor Side entry for Furnace #1

For furnace #3 BPM motor (at both 400 cfm/ton and 350 cfm/ton) air entered through:

- Furnace bottom (Normal operation)
- One 14 inch diameter duct on the motor side of the cabinet
- One 14 inch diameter duct opposite the motor
- Both 14 inch ducts – one on each side

For furnace #3 with prototype motor and blower air entered through:

- Furnace bottom (Normal operation)
- One 14 inch diameter duct on the motor side of the cabinet
- One 14 inch diameter duct opposite the motor
- Both 14 inch ducts – one on each side
- Both 14 inch ducts plus the open bottom

For furnace #2 (PSC motor) all the tests were performed in the normal configuration.

The side entry openings were fabricated by cutting holes of the appropriate diameter and inserting mounting flanges as illustrated in Figure 10. For the side entry only conditions the normal bottom opening was blocked from the inside.

Restrictive Cabinets

The effect of cabinet restrictions was evaluated by inserting rigid materials (either wall board or rigid insulation foam) against the walls of the cabinets that face the blower openings. Several thicknesses of materials were used. All the tests had the air entering the bottom of the cabinet (the normal configuration). The three furnace cabinets had the following clearances before any blocking:

- Furnace #1: two inches top and bottom (the furnaces were tested on their sides so the blower entries are at the top and bottom as viewed from the side)
- Furnace #2: three inches top and bottom
- Furnace #3: three inches top (motor side) and two inches bottom

The following blocking geometries were evaluated:

- 0.5 inch
- 1 inch
- 1.5 inch (for Furnace #2 only)
- For Furnace #3 the non-blocked clearance was asymmetric, with 3 inches on one side and 2 inches on the other. For this furnace we examined having different blocking on the two sides, with 1 inch an 1.5 inch blocking. This left gaps of of 2 inches and 0.5 inches respectively.

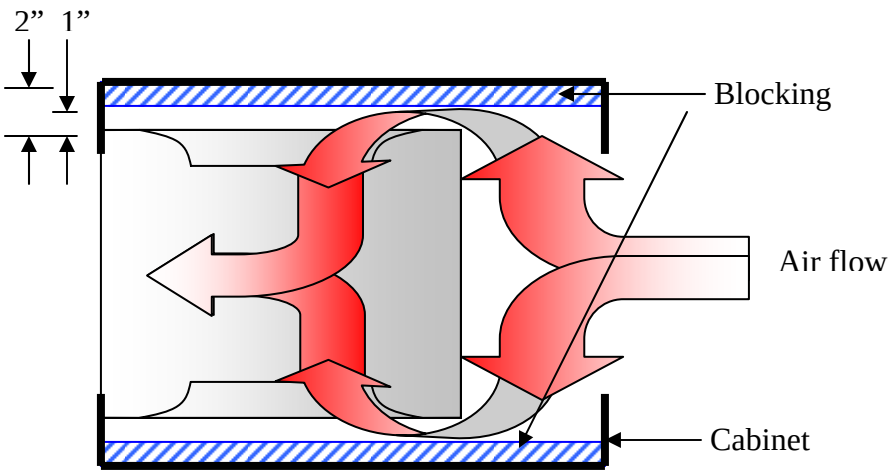


Figure 11. Illustration of blocking added to restrict fan inlet clearance.

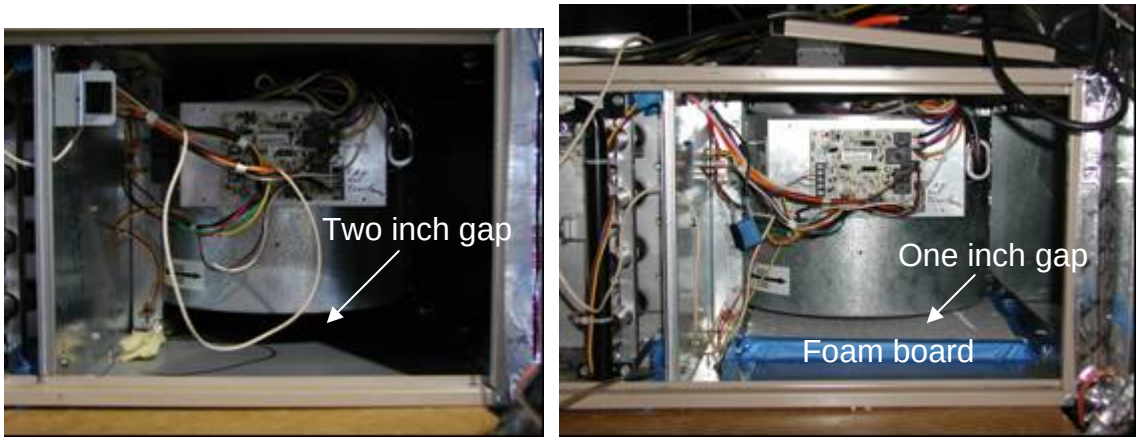


Figure 12. Standard fan in cabinet with no restriction (left) and with added foam board restriction (right).

Electric Utility Tests

The tests performed at the electric utility used an apparatus similar to those illustrated in AMCA 210 (1999). The furnaces were mounted horizontally, with the bottom of the furnaces open to the room (Figure 13). Air exiting the furnace traveled through a duct system to an array of flow nozzles (Figure 14) that were used to measure the air flow rate. An auxiliary fan at the exit of the apparatus was used to control the air flows and system pressures. The use of this auxiliary fan allowed these tests to achieve lower pressure differences than the LBNL tests whose minimum air flow was set by the resistance of the duct system. Static pressure differences were measured relative to the room from which the furnace drew air. The static pressure was measured downstream of the furnace exit using a tubing ring connecting four duct taps. Thus, the utility test results are comparable to the LBNL test results using the plenum pressures (rather than the pressures measured between the fan outlet before the furnace heat exchanger). Other information, such as air temperatures, barometric pressure, motor power consumption and rotational speed were recorded together with the air flows and pressures.

The same five furnace/blower combinations as used in the LBNL study were tested. All the tests were with air entering through the bottom of the furnace with no attached return plenum. There were no tests with additional blocking and no sound measurements were made.

Figure 13. Furnace mounted in electric utility test apparatus

Figure 14. Flow nozzles in electric utility test apparatus

LBNL Laboratory Results

For furnace #1 the test results in Figure 15 show that the prototype with its BPM is better at maintaining air flow as pressure differences increase. The PSC motor data show a distinct pressure performance limit of about 300 Pa (1.2 in. water), whereas that prototype can operate at up to 500 Pa. The prototype shows a gradual decrease in flow with increased pressure difference due to being operated in a constant torque mode. Usually BPM blowers operate to maintain a constant flow (see Figure 16 for furnaces 2 and 3). This maintenance of air flow at higher pressures is reflected in the power consumption data that shows a gradual increase with pressure for the prototype, but a reduction with increasing pressure for the PSC. The power consumption results for the prototype with the BPM shows how low flow operation can be done with very low power consumption (less than 100W) compared to the PSC. Because high cfm/W ratings and low power consumption can be obtained for a BPM motor by operating at low air flows (and correspondingly low system pressures) any performance specification should include a minimum air flow rate. This is because air conditioner (and to a much lesser extent furnace) performance decreases as air flow is lowered. In addition, flow reductions for PSC blowers at high operating pressures could result in lower air conditioner performance that needs to be avoided. The peak efficiency for the PSC occurs at about 250 Pa (1 in. water) for all the speed settings. For the prototype, the pressure corresponding to peak efficiency increases at higher speeds/torque settings, and is generally about double the PSC efficiency.

In terms of cfm/W, the PSC shows little pressure related variation and is close to 2 cfm/W for all fan speeds until about 200 Pa (0.8 in. water). Above this pressure the cfm/W declines rapidly. For the prototype, the cfm/W rating is close to 10 at low speeds and pressures, and declines to about 2 cfm/W (same as the low pressure difference PSC values) as the pressure increases to 300 Pa. If we consider a typical duct system operating at 200 Pa (0.8 in. water) static pressure and 365 cfm/ton or 1095 cfm for a three ton system we can estimate the performance of these two air handlers at this operating point. The PSC uses about 610 W at 1.9 cfm/W or 525 W/1000 cfm. This result is close to those found in field surveys for PSC motors. The prototype uses about 370W at 2.8 cfm/W or 357 W/1000cfm. In heating mode we can determine the new operating point by assuming the same duct system, but having the PSC operate at med-high speed. This results in a new air flow rate of about 950 cfm at a static pressure of 170 Pa (0.7 in. water). At this point the PSC uses 450 W at 2.15 cfm/W or 465W/1000cfm and the prototype uses 275 W at 3.4 cfm/W or 290 W/1000cfm.

The results for furnace #2 in Figure 17 show that the two cfm/ton settings for the BPM result in very similar results, with the 400 cfm/ton setting providing higher air flow. For furnaces 2 and 3 the PSC results are similar to furnace #1, with cfm/W ratings between 2 and 2.5 up to 200 Pa (0.8 in. water) then declining as pressures increase. There is a large (30%) reduction in air flow at typical operating pressure differences of 200 Pa (0.8 in. water). The BPM results show almost constant flow up to about 300 Pa (1.2 in. water) at higher speeds. At 200 Pa (0.8 in. water) the BPM operates at about 3 cfm/W, increasing at lower pressures to about 7 cfm/W at typical rating conditions (about 50 Pa (0.2 in. water)). At pressures greater than 300 Pa (1.2 in. water) the BPM drops below 2 cfm/W.

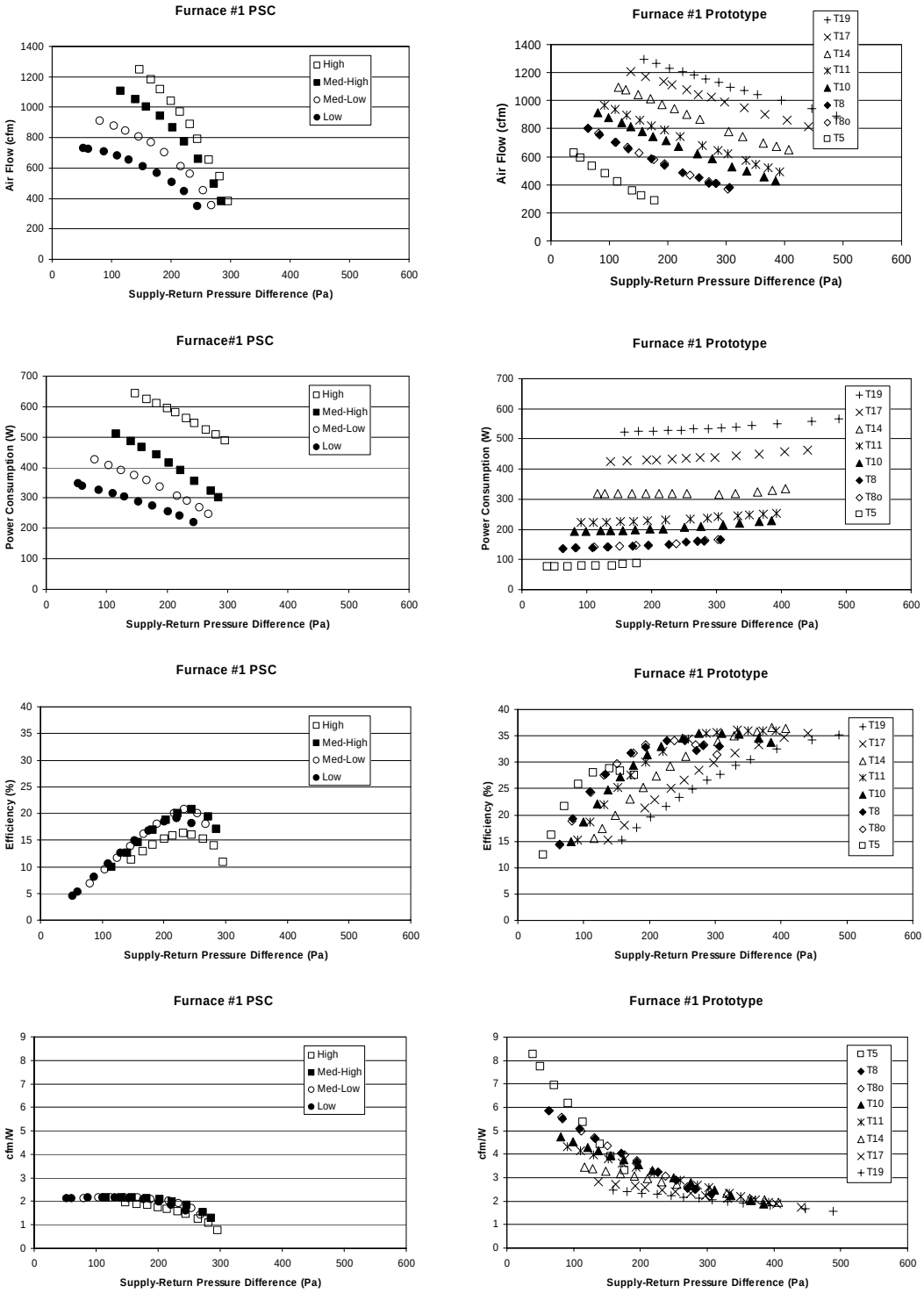


Figure 15. Furnace #1 test results. T numbers are torque settings (5 low to 19 high).

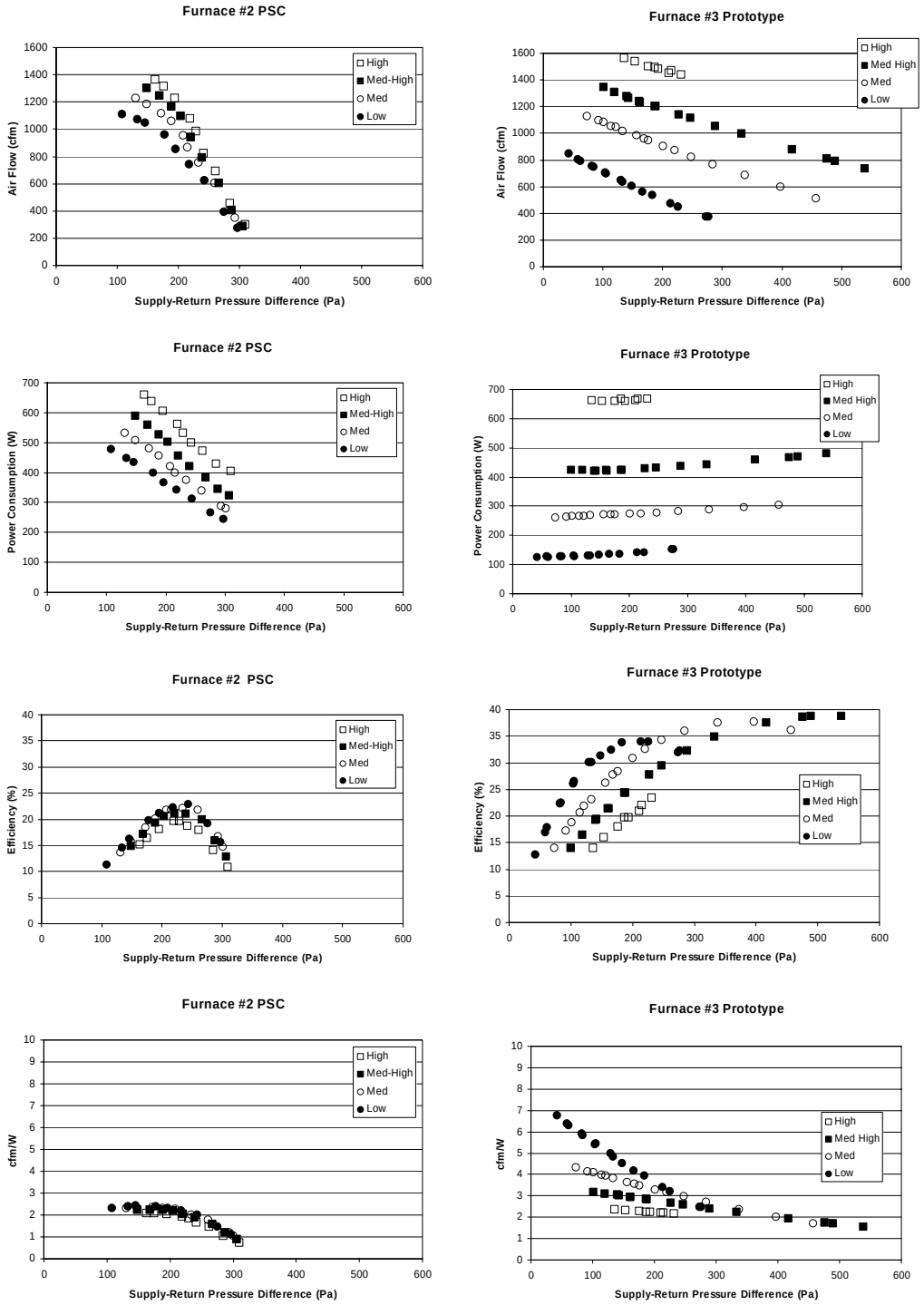


Figure 16. Furnace #2 and #3 test results.

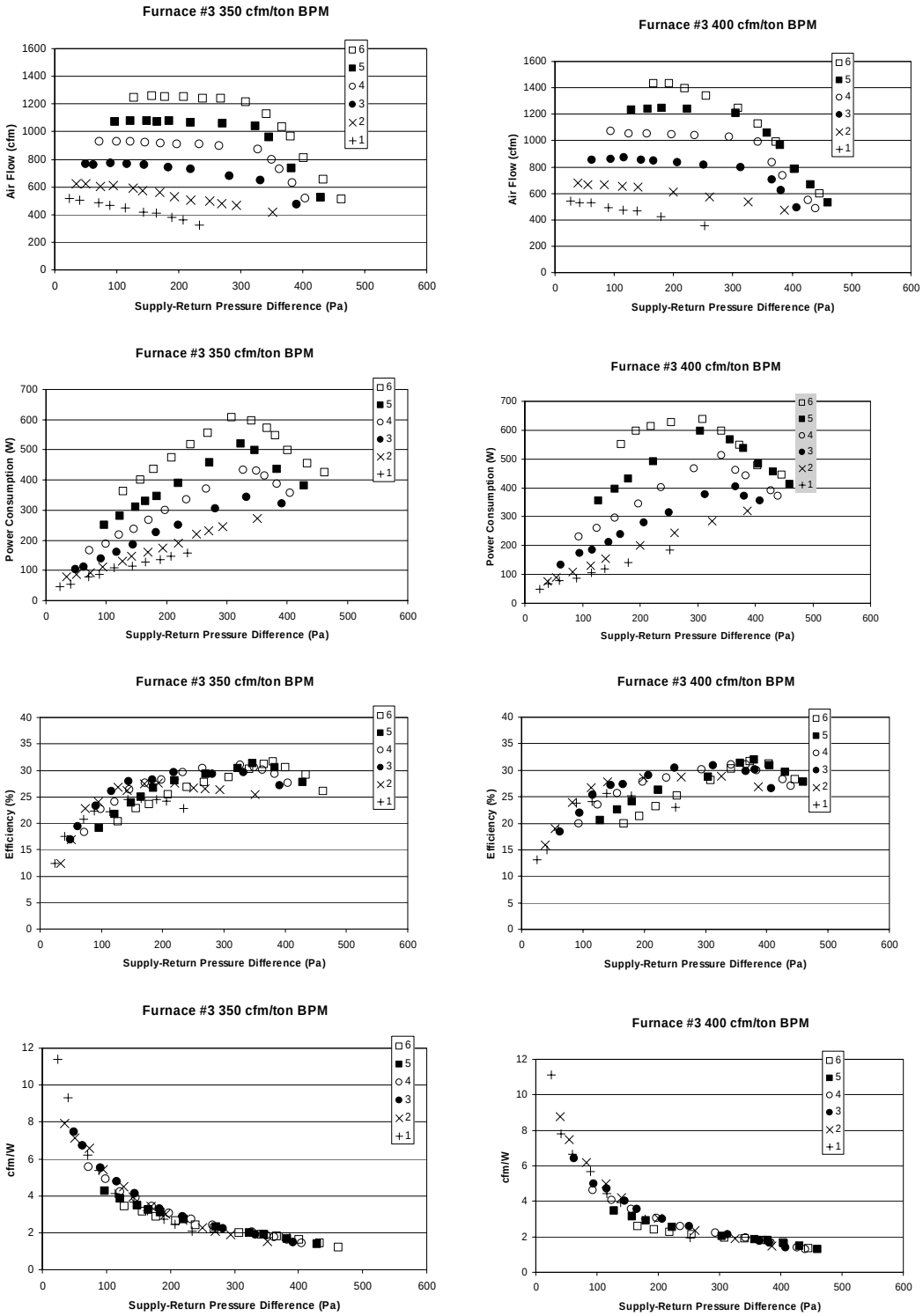


Figure 17. Furnace #3 test results at two different cfm/ton ratings. T numbers are torque settings (5 high to 1 low).

Air Inlet Size and Location Effects

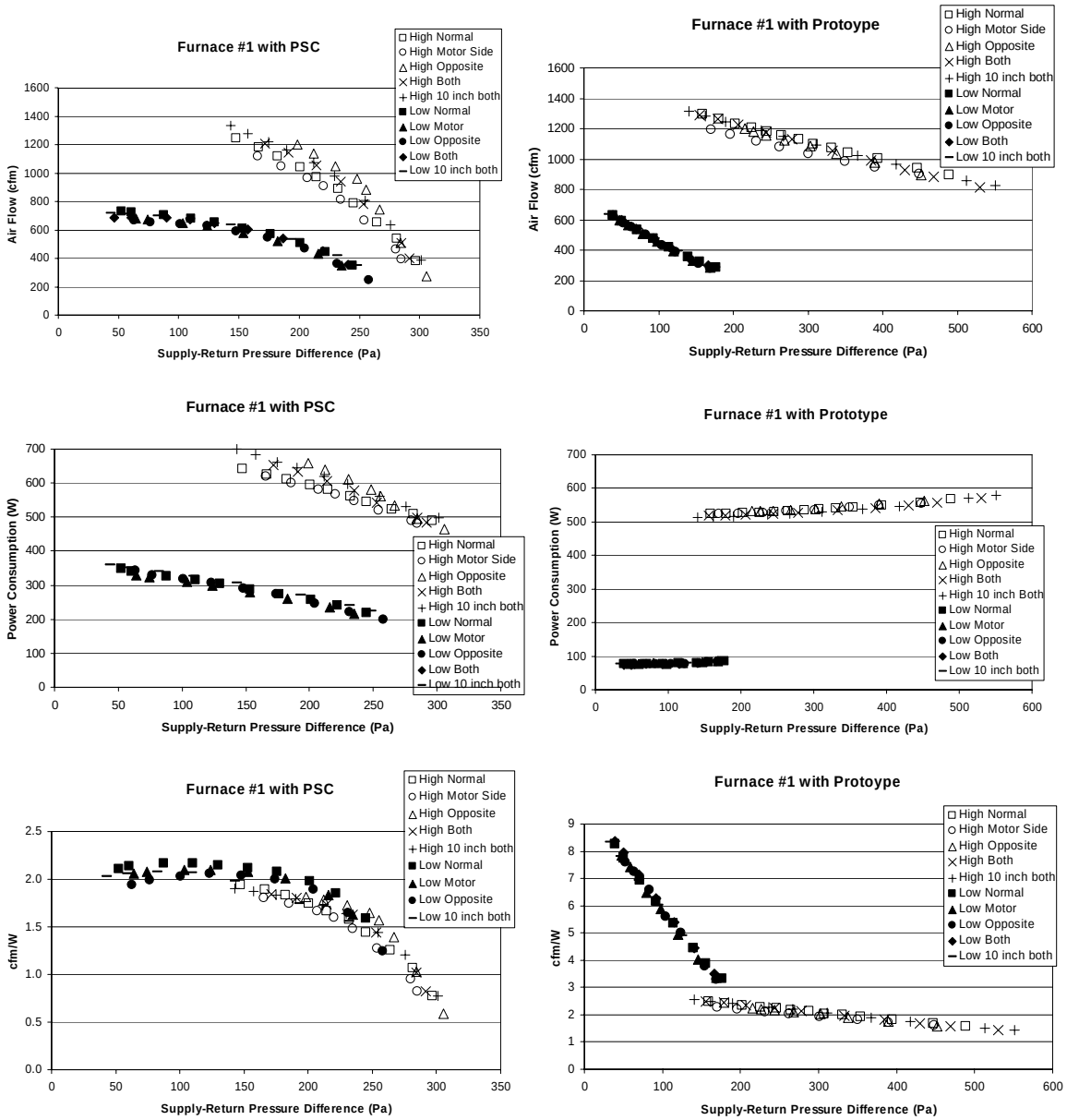


Figure 18. Effect of air inlet location for Furnace #1 with both PSC and prototype motors.

For Furnace #1, the results illustrated in Figure 18 show that the standard bottom entry gives the best performance, with the exception of the prototype with the open bottom and dual side entries. The air flow and cfm/W changes are on the order of 5 to 10 % for the different openings. The biggest effect on air flows is a reduction of about 10% for an opening on the motor side of the blower only. This is probably because the motor presents a significant blockage to air flow from this side. The results in Figure 18 are for the two extremes of operation – highest and lowest speeds. The results for intermediate speeds fall between these

two with no extreme anomalies. The effects are greatest at higher speeds. Figure 19 shows the high speed results only on an expanded scale to better illustrate the differences.

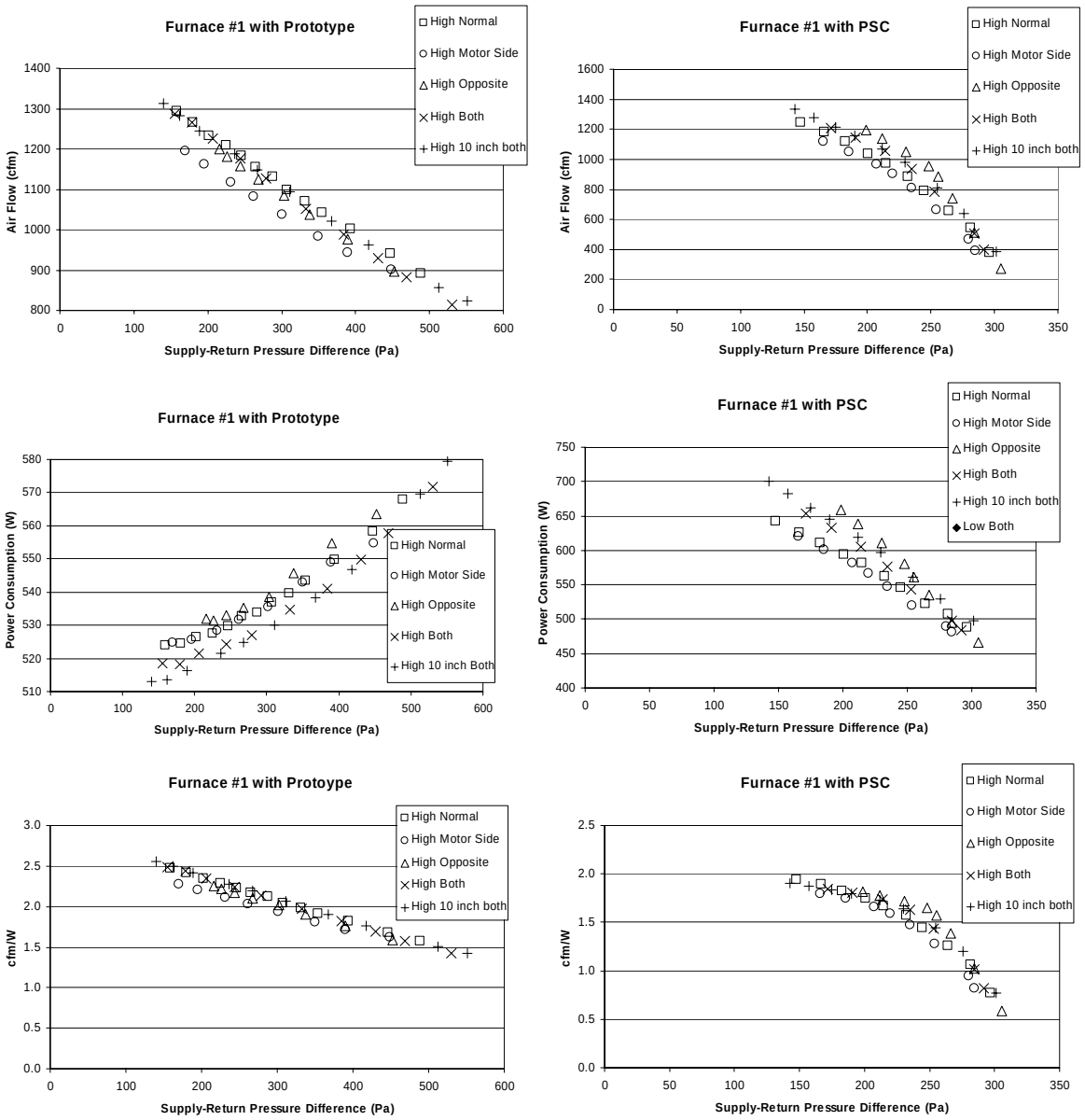


Figure 19. Effect of air inlet location for Furnace #1 with both PSC and prototype motors on high speed.

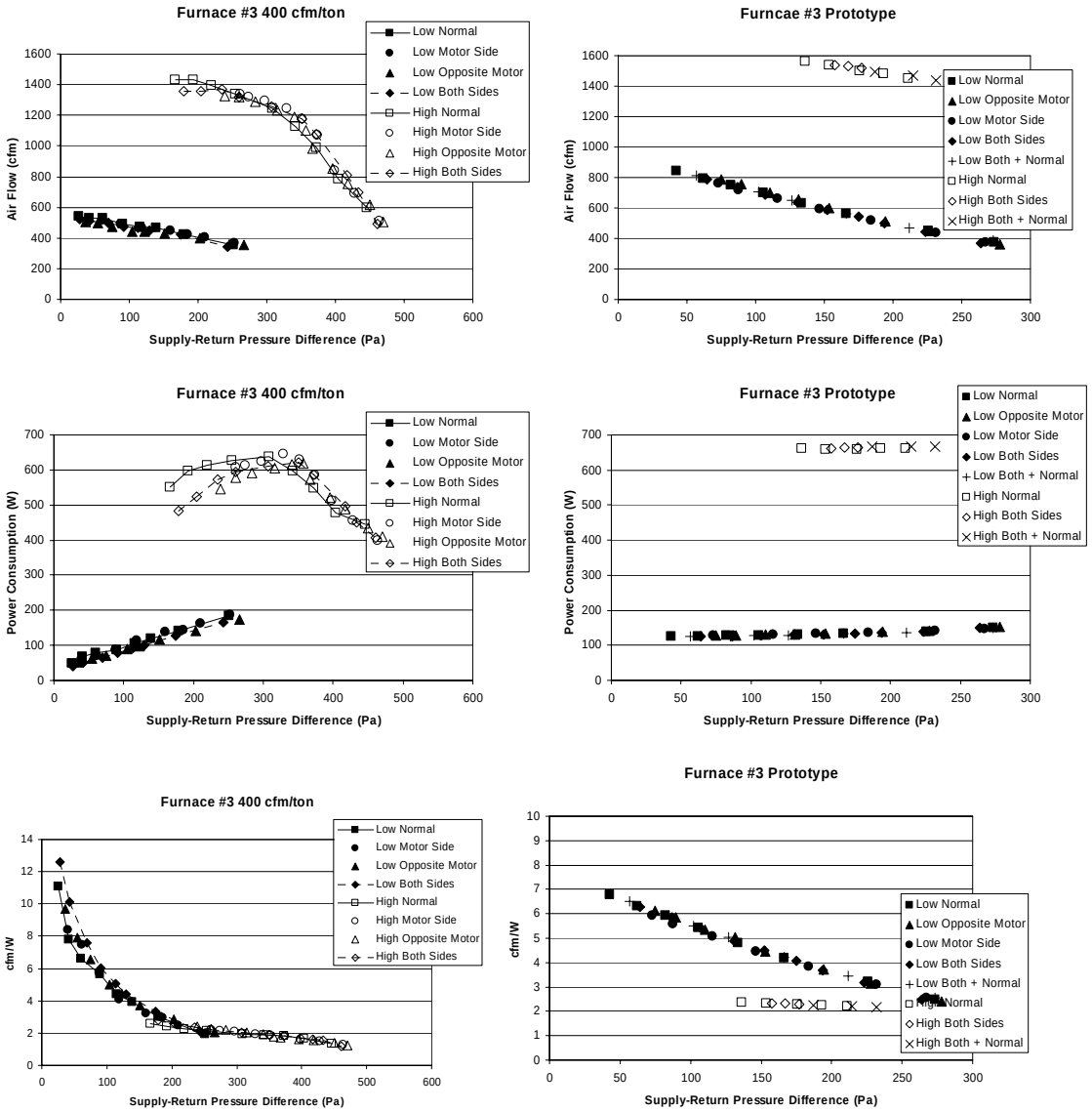


Figure 20. Effect of air inlet location for Furnace #3

The results in Figures 20-22 are for the two extremes of operation – highest and lowest speeds. The results for intermediate speeds fall between these two with no extreme anomalies. For Furnace #3, the change from bottom entry to other geometries reduced the air flow and cfm/W ratings. The biggest change was for the most restrictive entry: motor side only, where the cfm/W rating dropped by 24% for the 400 cfm/ton BPM motor. The effects were less severe for the prototype motor. Critically, the cfm/W rating for the 400 cfm/ton tests dropped below 2.5 cfm/W for some of the cases implying that an installation that was acceptable using bottom entry may not be if side entry is used. For the PSC results in Figure 21, the fractional changes in air flow are greater than the cfm/W ratings because the PSC uses proportionally less power as air flows decrease. This means that inlet location is more important for making a furnace blower meet air flow requirements rather meeting a cfm/W requirement.

Cabinet Restriction

For furnace #1, Figure 22 shows how decreasing clearance from 2 in. (50 mm) to 1 in. (25 mm) reduces air flow by about 7% for the prototype and about 15% for the PSC, with the PSC showing greater sensitivity at higher speed settings. The corresponding changes in cfm/W of about 0.25 for both PSC and prototype at typical operating conditions would be critical for a system attempting to meet a performance specification of 2 cfm/W. In Figure 23 the BPM shows less sensitivity to restriction, possibly due its control systems. Table 1 summarizes the results of the cabinet restriction testing.

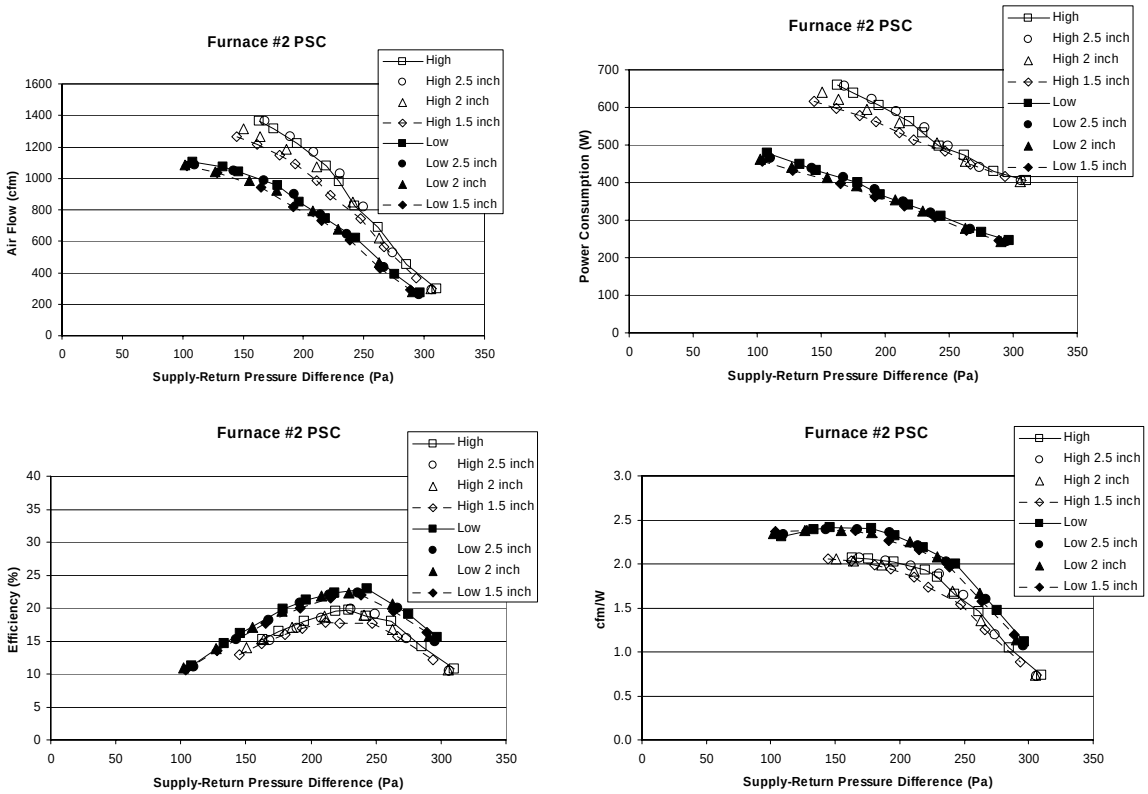


Figure 21. Furnace #2 sensitivity to cabinet restriction for high and low speeds with no restriction (about 3 inches clearance), 2.5 inch, 2 inch and 1.5 inch clearance between cabinet walls and fan housing.

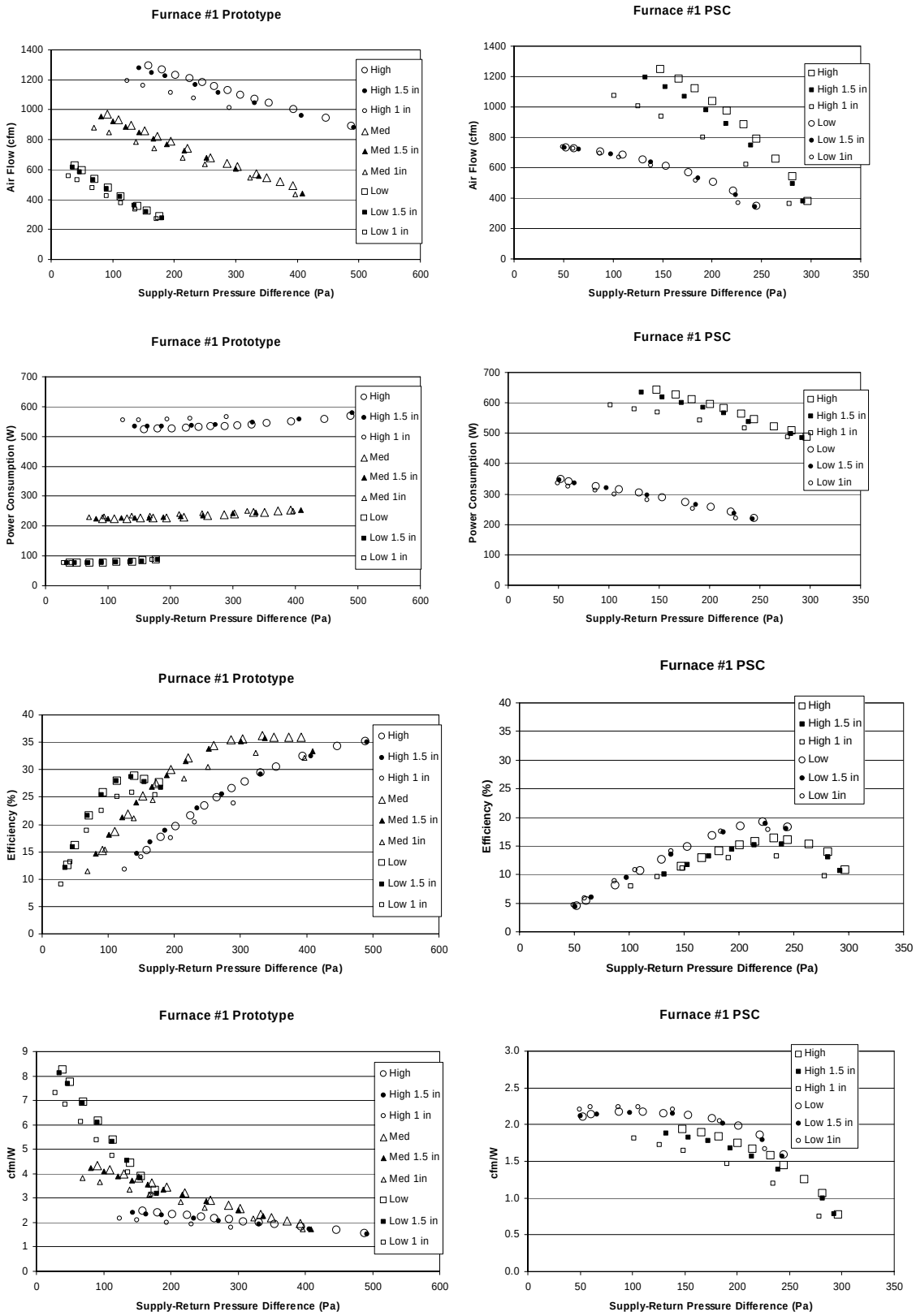


Figure 22. Furnace #1 sensitivity to cabinet restriction for high and low speeds with no restriction, 1.5 inch, and 1 inch clearance between cabinet walls and the fan housing.

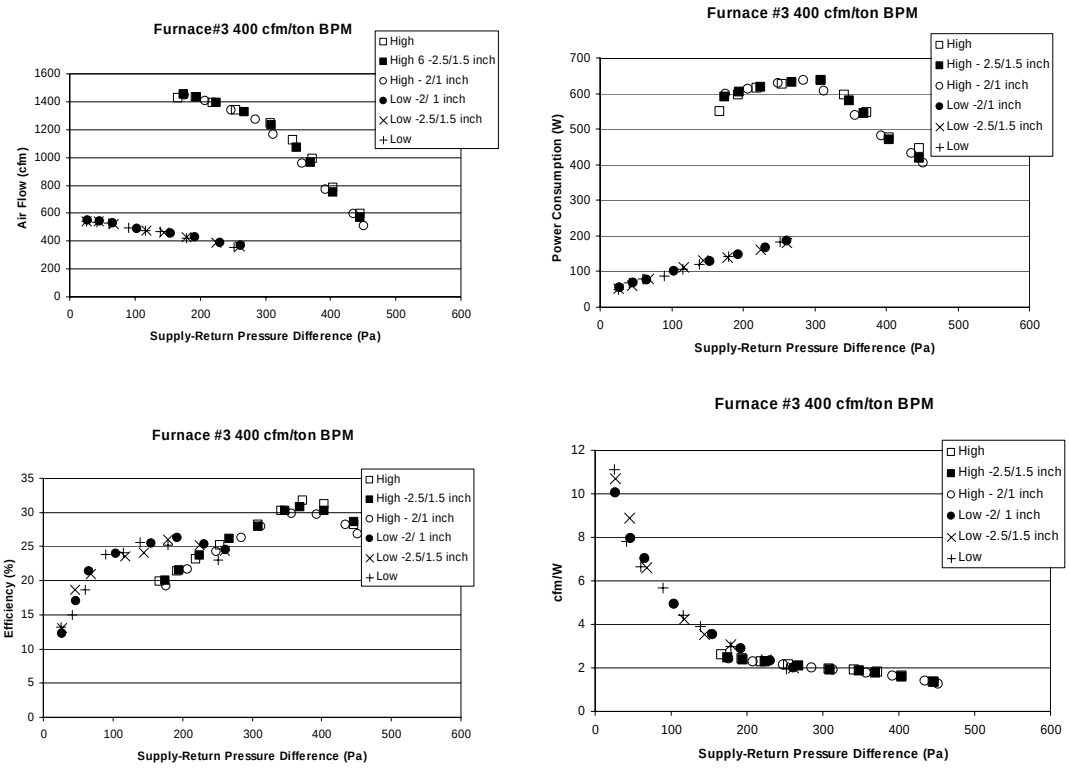


Figure 23. Furnace #3 sensitivity to cabinet restriction for high and low speeds with no restriction, 2.5/1.5 inch, 2/1 inch clearance between upper and lower cabinet walls respectively and the fan housing.

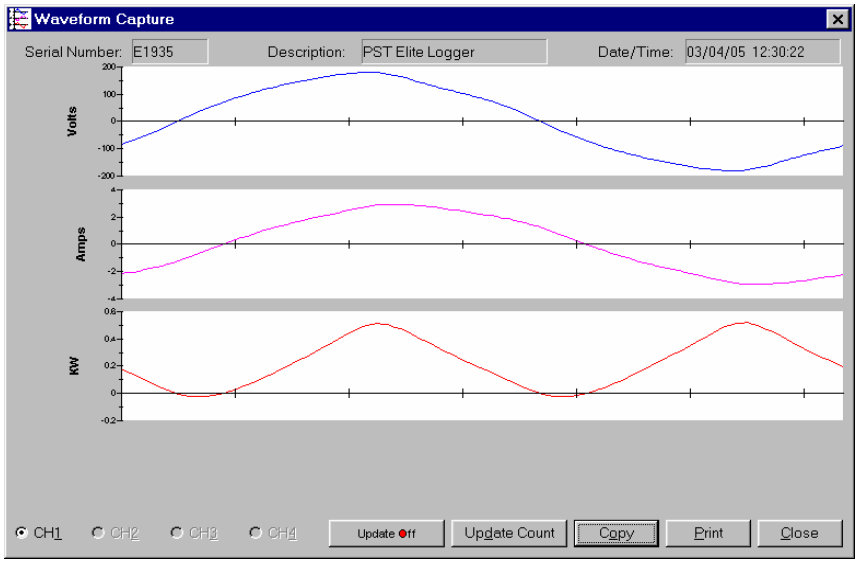
Table 1. Effects of cabinet restriction on furnace blower performance									
		Flow (cfm)	Flow (cfm)	Flow Change	Flow Change	cfm/W	cfm/W	Change cfm/W	Change cfm/W
Furnace	Speed	No Blockage	Max. Blockage	cfm	%	No Blockage	Max. Blockage		%
#2 PSC	High	1362	1268	-94	-7	2.1	2.1	0	0
	Low	1106	1078	-28	-3	2.3	2.4	0.1	4
#1 PSC	High	1246	1075	-171	-14	2.1	2.2	0.1	5
	Low	732	738	6	1	1.9	1.8	-0.1	-5
#1 Prototype	High	1294	1192	-102	-8	2.5	2.1	-0.4	-16
	Low	626	557	-69	-11	8.2	7.5	-0.7	-9
#3 BPM	High	1429	1444	15	1	2.6	2.4	-0.2	-8
	Low	542	548	6	1	11.1	10	-1.1	-10
#3 Prototype	High	1561	1516	-45	-3	2.4	2.3	-0.1	-4
	Low	805	774	-31	-4	6.4	6.2	-0.2	-3
Average					-4.6			-0.3	-4.6

Power factor

Table 2 summarizes the results of the power factor measurements. Power factors were recorded for all flow and pressure difference operating points and Table 2 gives typical values. In general the Power Factor is greater than 0.85 for the PSC motors and ranges from 0.5 to 0.6 for the BPMs. For the two prototypes, the power factor did not change more than a few percent over the tested pressure and flow range. This is probably due to operating in a constant torque mode. The BPM results are more complex and showed a gradual increase in power factor to a peak at about 250 to 350 Pa pressure difference then decreasing after this point. The PSC motors had power factors that typically decreased by about 5% to 10% as pressure difference increased. The biggest changes were for Furnace #2 with the PSC motor, where the power factor dropped from 0.94 at high flow and low pressure (1300 cfm and 160 Pa) to 0.78 at 299 cfm and 310 Pa. Figures 24-28 show how the BPMs generate large odd order harmonics due to the current being highly non-sinusoidal. For the PSC motor in Furnace #1, the PF ranged from 0.68 to 0.92 depending on the motor operating point and the pressure across the fan. Two different pressure differences were used to investigate the effect of fan loading on electric motor performance and therefore power factor. Figure 24 shows an example of the power, voltage and current waveforms where the power factor is high (0.92). Figure 25 shows the results of an harmonic analysis that show that for this high power factor almost all the energy is in the first harmonic.

Table 2. Results of power factor measurements from LBNL testing	
Furnace #1 Prototype BPM	
Speed Setting[2]	Power Factor
Low	0.53
Medium	0.55
Medium High	0.59
High	0.63
Furnace #1 PSC motor	
Speed Setting	Power Factor
Low speed low plenum pressure	0.86
Low speed high plenum pressure	0.92
High speed low plenum pressure	0.83
High speed high plenum pressure	0.68
Furnace #3 Prototype BPM	
Speed Setting	Power Factor
Low	0.56
Medium	0.62
Furnace #3 Standard BPM	
Speed Setting	Power Factor
Low	0.53
Medium	0.56
High	0.62
Furnace #2 PSC motor	
Speed setting	Power Factor
High	0.95
Low	0.92

[2] For the prototype the control was more of a torque than speed setting



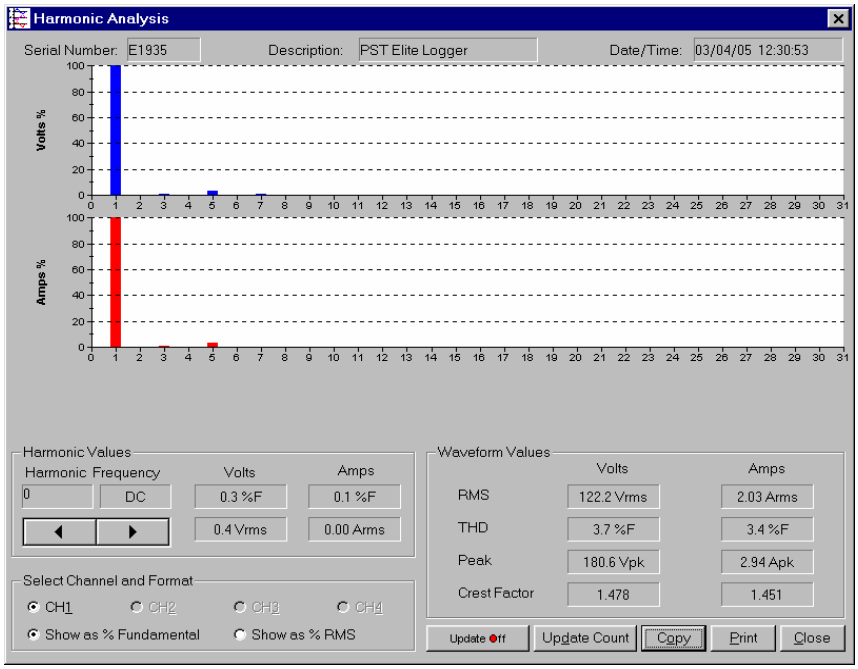


Figure 24. Wave form and Harmonic analysis for Furnace #1 PSC motor, low speed, high plenum pressures.

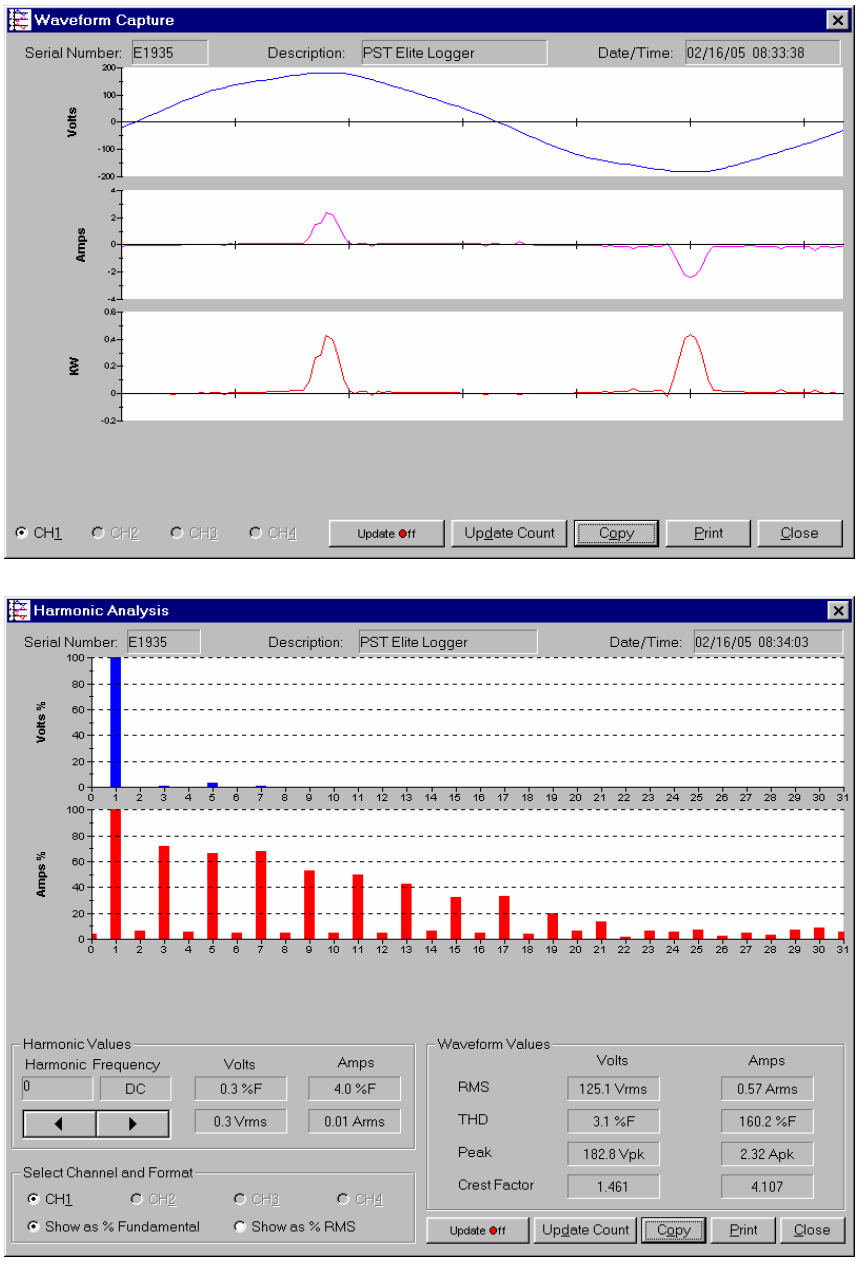
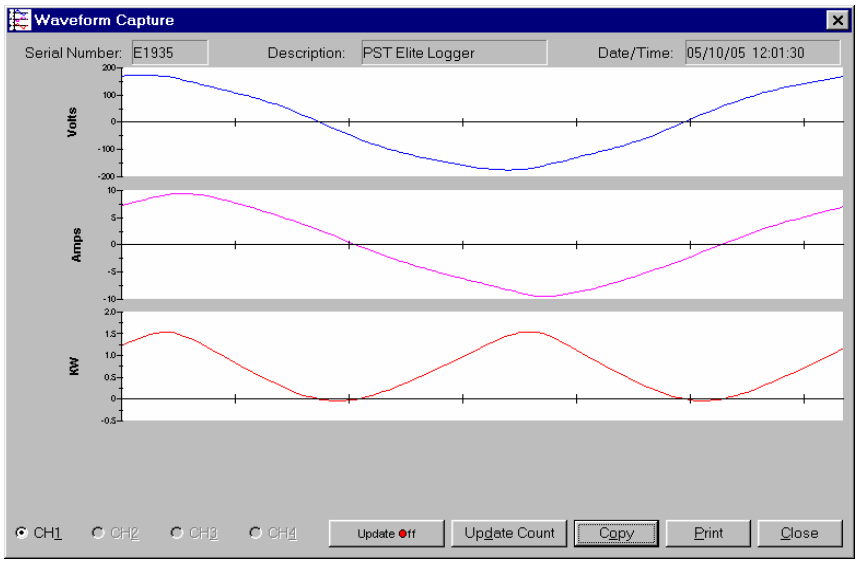


Figure 25. Wave form and harmonic analysis for Furnace #1 PSC Prototype BPM motor, torque setting 2.



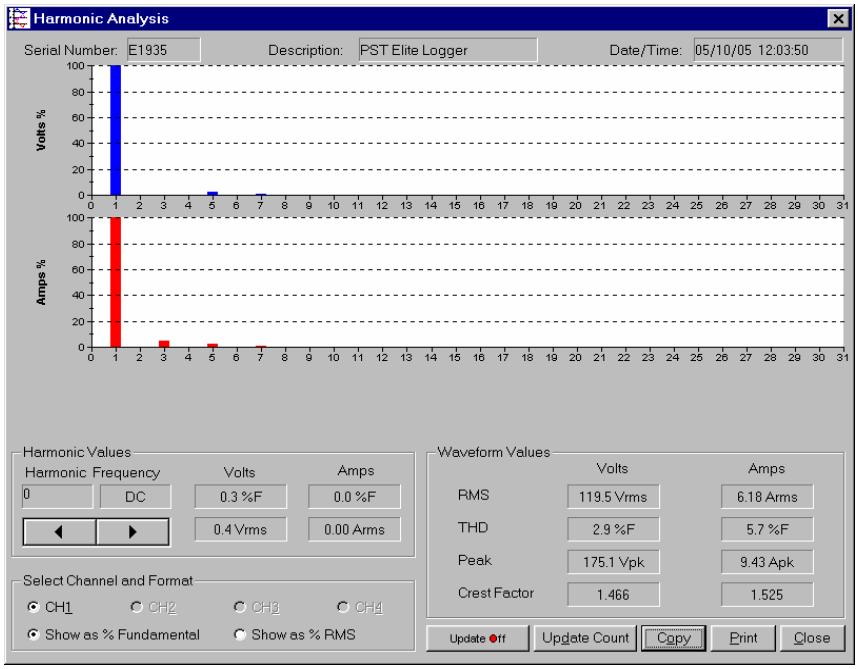


Figure 26. Wave form and harmonic analysis for Furnace #3 PSC motor, high speed setting.

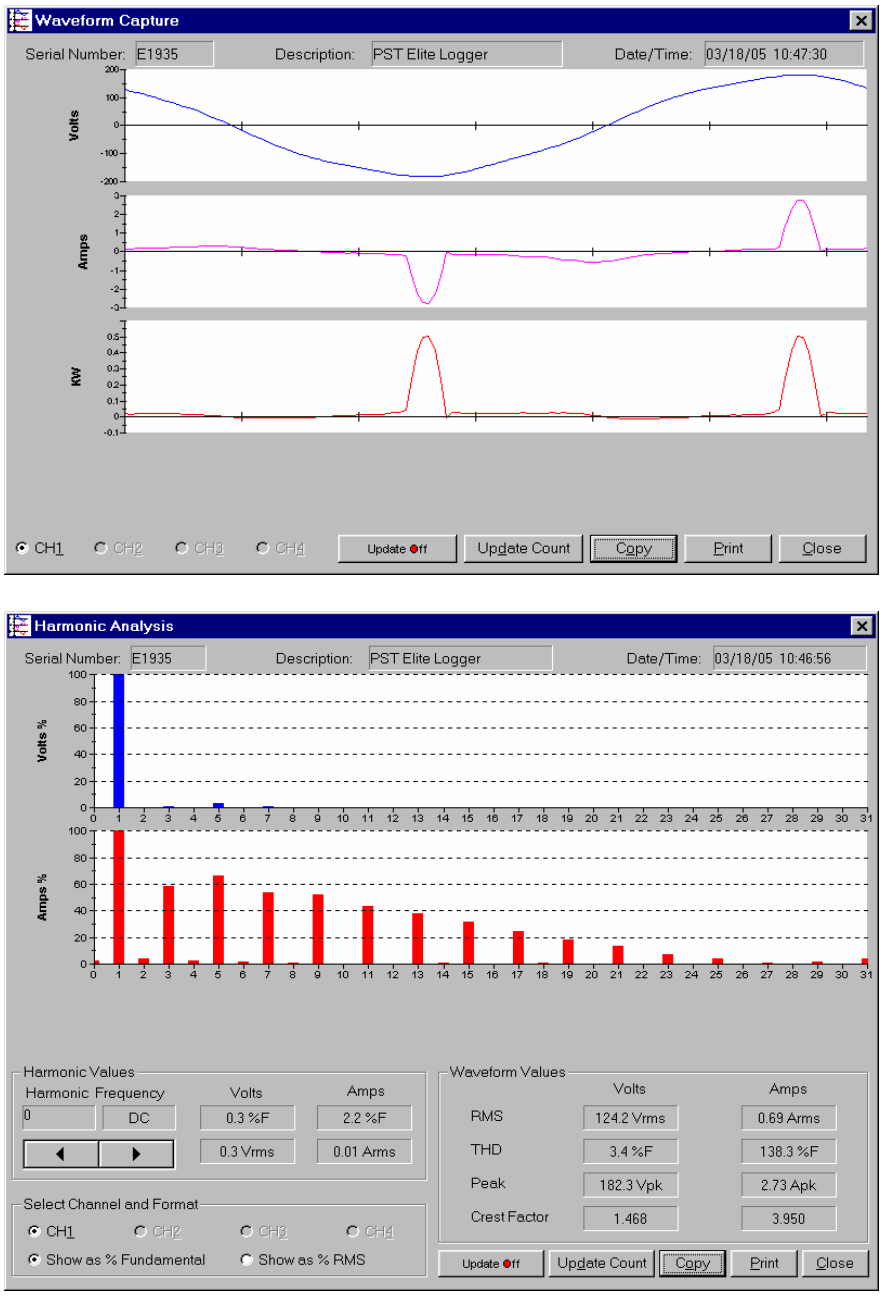


Figure 27. Wave form and harmonic analysis for Furnace #2 BPM motor, lowest speed setting.

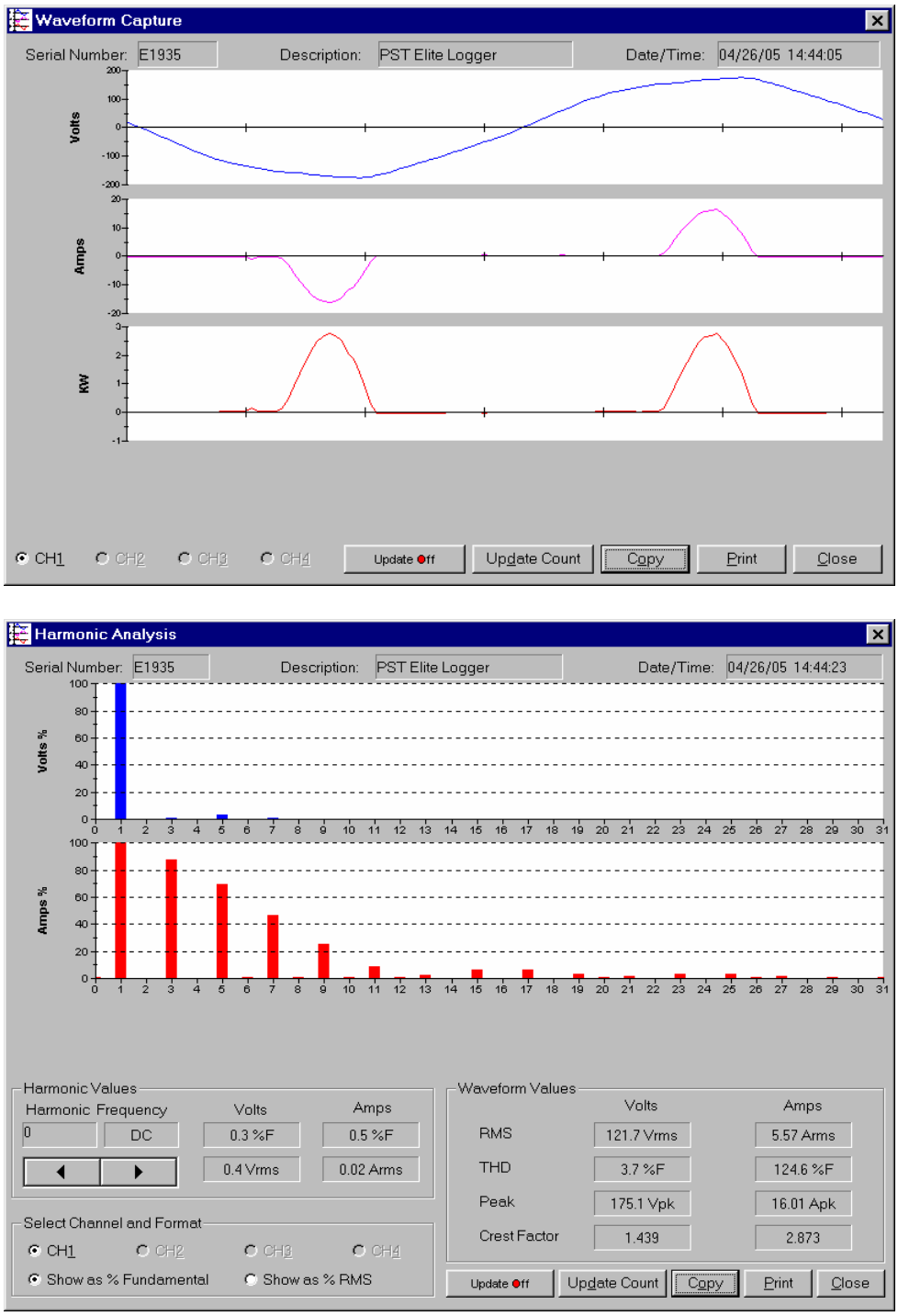


Figure 28. Wave form and harmonic analysis for Furnace #2 prototype BPM motor, torque setting 11.

Fan Noise

The noise levels were measured at the return grille as an indicator of occupant exposure and also outside the blower cabinet. The results for the return grille measurements (that are most relevant for occupant exposure) are shown in Figures 29 and 30. For each blower speed setting, the background noise level was recorded with the blower off. The background noise was close to 36 dB (within one dB), except for the medium-high PSC measurements, where the background noise was 42 dB. This difference in background noise was due to other activities in the test building. Note that this difference in background noise does not account for the higher readings with the PSC motor at this speed.

For the grille measurements shown in the figures, generally there is more noise at higher speeds, except for the PSC motor where noise was greatest at the medium-high setting. For the PSC the noise level peaked at about 250 Pa (one inch) of pressure difference. There is less of general trend with pressure for the prototype. The higher flow rate measurements are about 57 dB for both blowers. The lower air flows achievable with the prototype led to lower sound pressure levels at the lowest flow rate compared to the PSC lowest flow rate.

The measurements at the cabinet showed much greater differences. For the PSC motor, the cabinet measurements were typically slightly lower than at the grille by about 0.5 dB. Conversely, the prototype was significantly louder (by almost 6 dB) at the cabinet than at the grille. This result indicates that the return ducting possibly had more effect on the prototype noise than on the PSC noise.

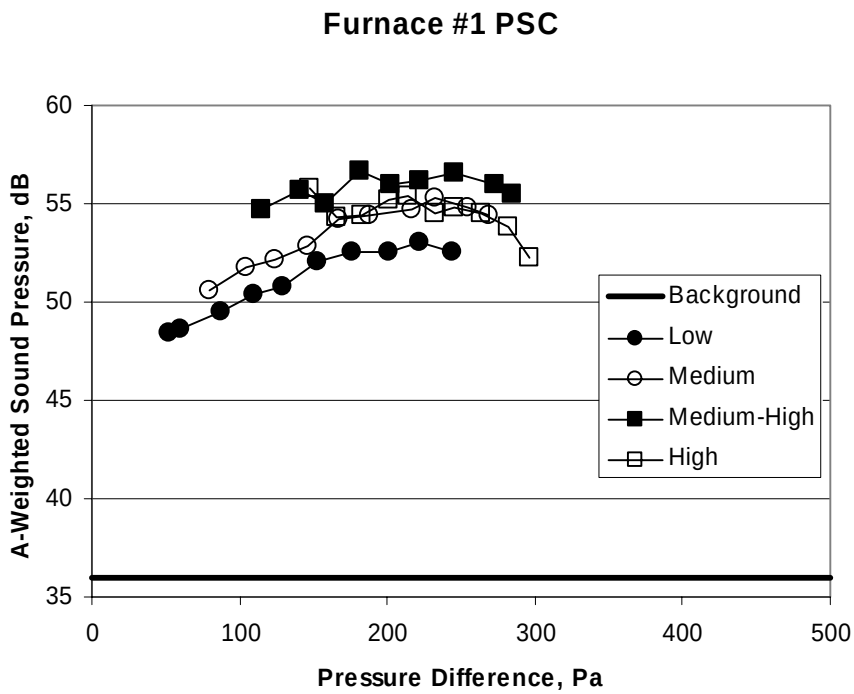


Figure 29. Results of sound measurements for Furnace #1 with the PSC motor.

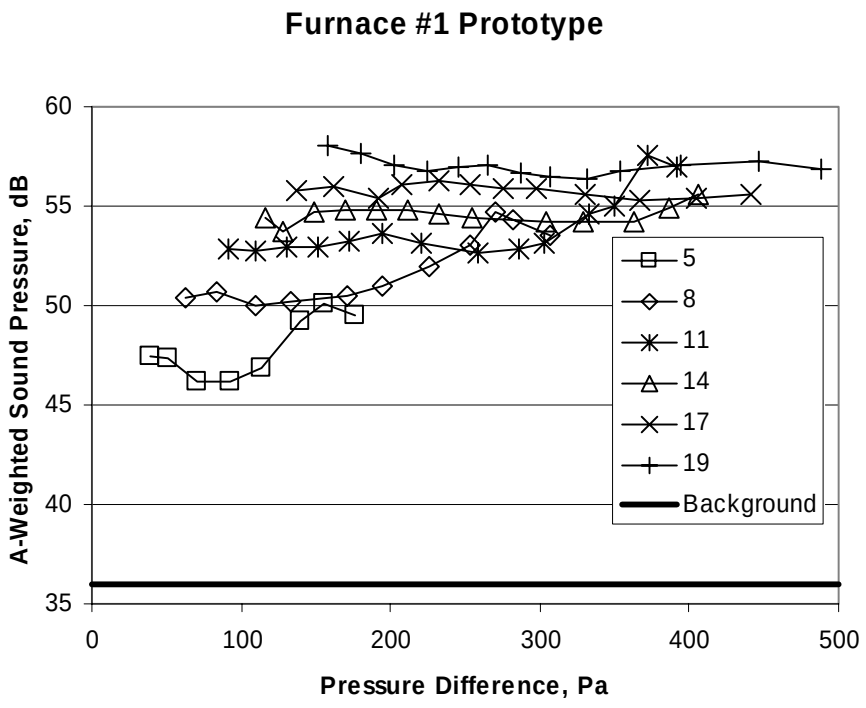


Figure 30. Results of sound measurements for Furnace #1 with the prototype motor.

Electric Utility test Results

The tests in the electric utility test facility summarized in Figures 31-34 showed the same key characteristics for the different fan/motor combinations as for the LBNL testing:

- BPM motors are better at maintaining airflow as static pressures increase. This means that they are more tolerant to high resistance duct installations in the sense that they are better able to maintain the air flow across heating and cooling heat exchangers so that they operate efficiently. The flip side of maintaining airflow into increasing pressure differences is the corresponding increase in power use. Therefore there is a balance between maintaining heat exchanger effectiveness and the extra fan power requirements. Because high cfm/W ratings can be obtained for a BPM motor by operating at low air flows (and correspondingly low system pressures) any performance specification should include a minimum air flow rate. This is because air conditioner (and to a much lesser extent furnace) performance decreases as air flow is lowered.
- Peak overall (motor and aerodynamic) efficiencies are about 40% for the prototypes, about 30% for current production BPMs and about 25% for PSC motors. For the PSC motors, these peak efficiencies occur at static pressures of about 0.8 in. water (200 Pa). This is a fortunate coincidence as field data show that 0.8 in. water is the typical pressure difference seen by a residential air handler in California duct systems. At lower operating pressures of 0.5 in. water (125 Pa), the efficiencies drop to 12% to 15%. At typical rating points (about 0.2 in. water (100 Pa)) the efficiencies are even lower at 5% or less. For the current equipment BPM, the efficiency peak is spread out from about 0.5 in water (125 Pa) to greater than 1.0 in. water (250 Pa), with higher efficiencies at lower operating settings. At typical operating pressures there is a broad range from 15% to 30% efficiency depending on the operating setting. This shows that it is important for installers to choose the correct operating settings when installing these air handlers and that different settings may be appropriate depending on the specific installation. The prototype showed similar efficiency value as the current equipment BPM at normal operating conditions.
- In terms of cfm/W, the PSC air handlers are fairly constant at about 2 to 2.5 cfm/W for all speeds, with slightly lower cfm/W rating for lower speeds. The performance falls off sharply above about 1.0 inch of water static pressure (250 Pa). The BPM devices have significantly higher cfm/W ratings as pressures are reduced, approaching values greater than 15 cfm/W for low pressures, but at pressures above 0.8 in. water their cfm/W performance is similar to a PSC.
- The Furnace #3 results for 350cfm/ton and 400 cfm/ton tests show essentially the same results, just with lower operating points for the 350 cfm/ton case.

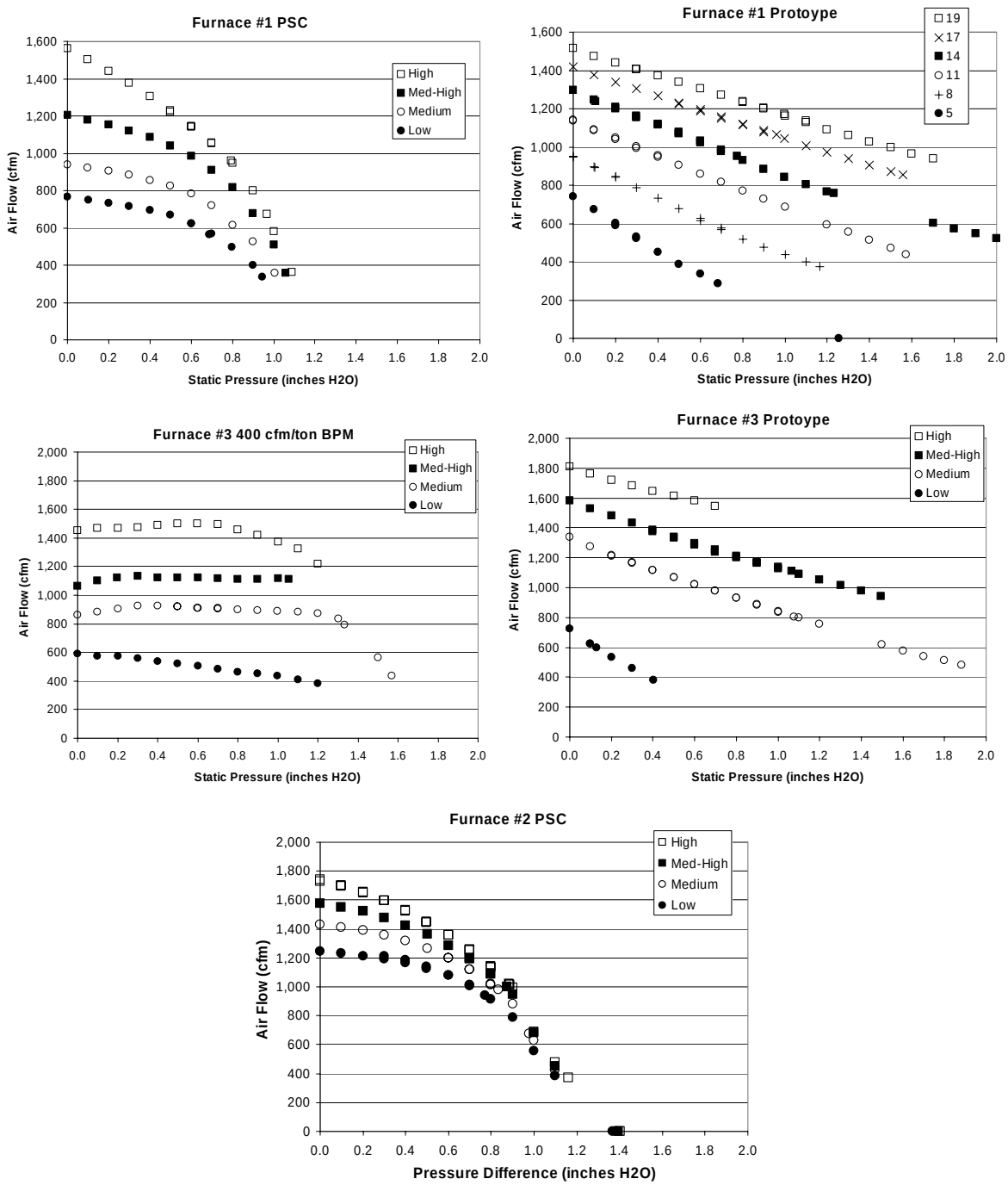


Figure 31. Furnace blower air flow

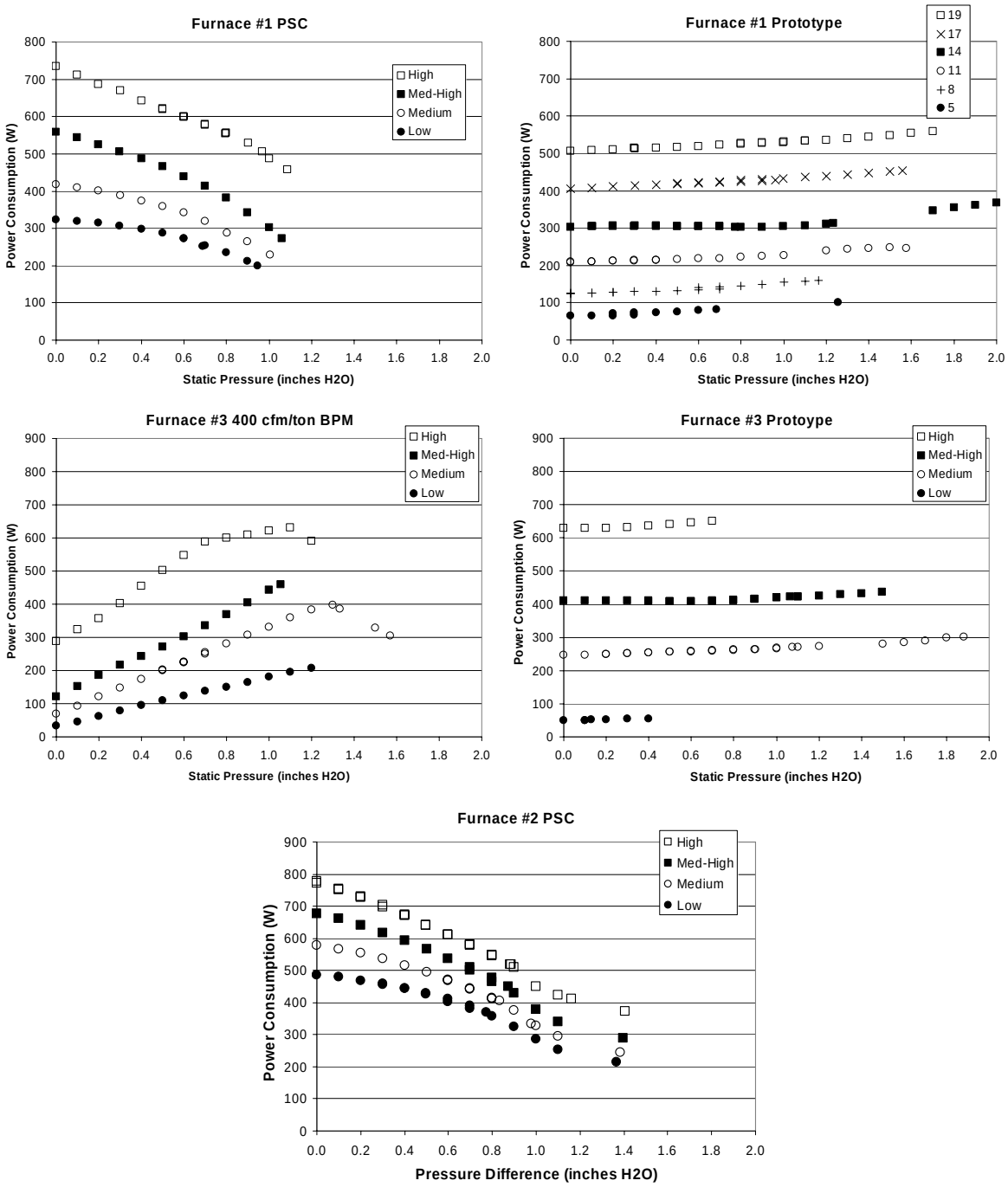


Figure 32. Furnace blower power consumption

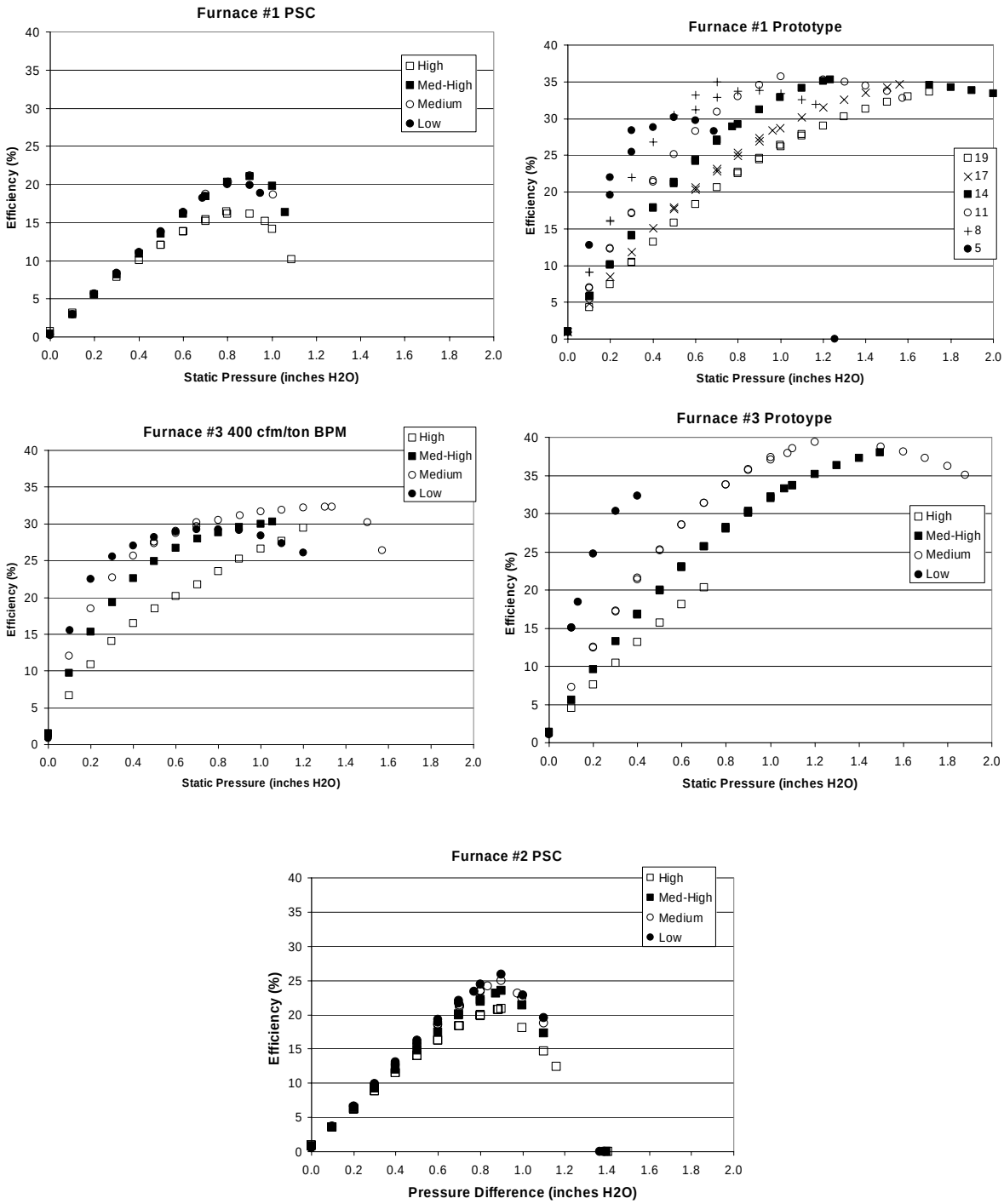


Figure 33. Furnace Blower efficiency

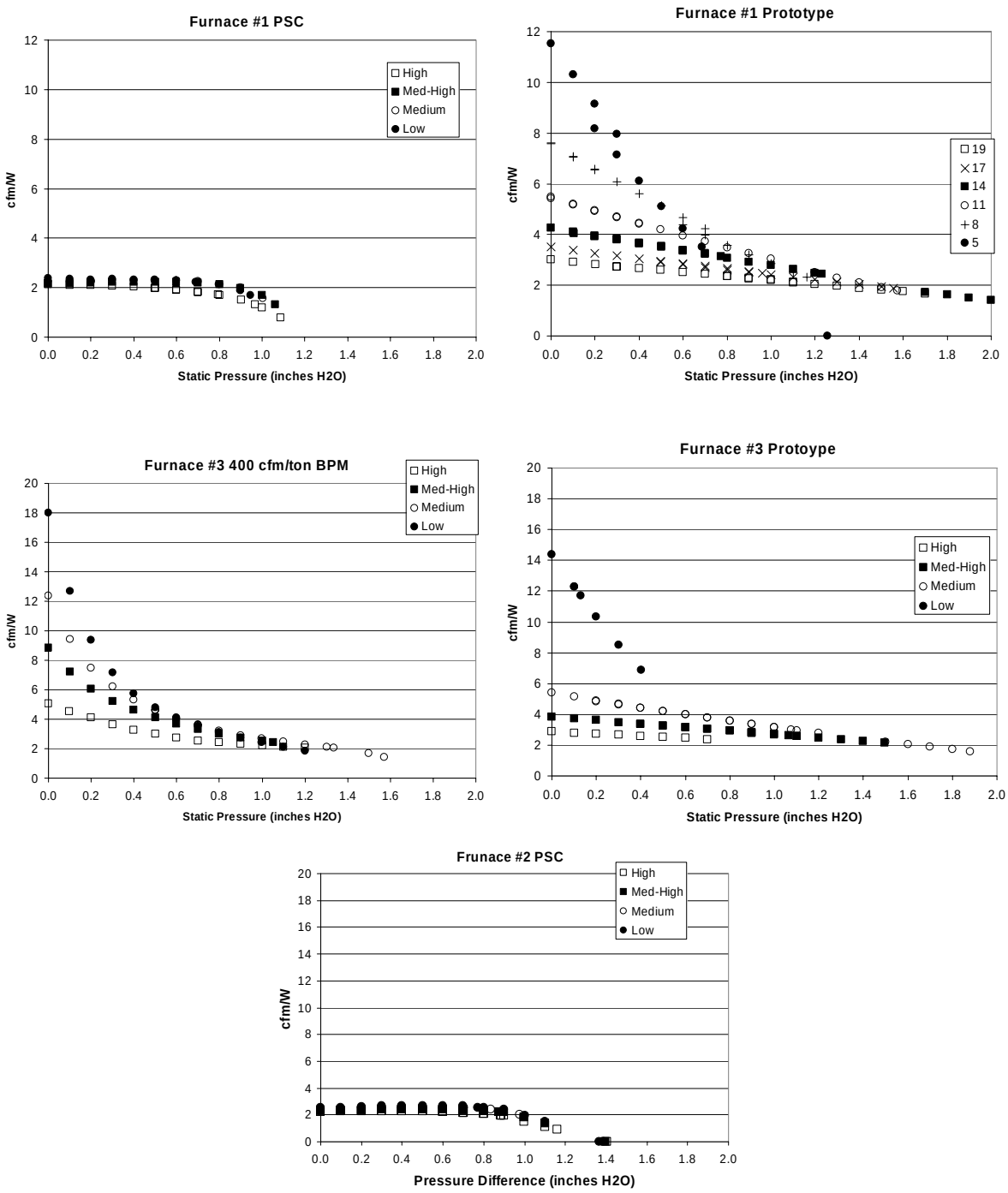


Figure 34. Furnace blower cfm/W ratings

Comparing Laboratory test data to Manufacturer's Published Data

Figure 35 compares the measured test results for Furnace #1 to data taken from the manufacturer's specifications for this furnace. At high speed the manufacturer's rating overpredicts the air flow by about 100 cfm. For other speeds it tends to underpredict by about 100 cfm, the exception being at medium-high speed where there is little difference above 0.5 in. water pressure difference.

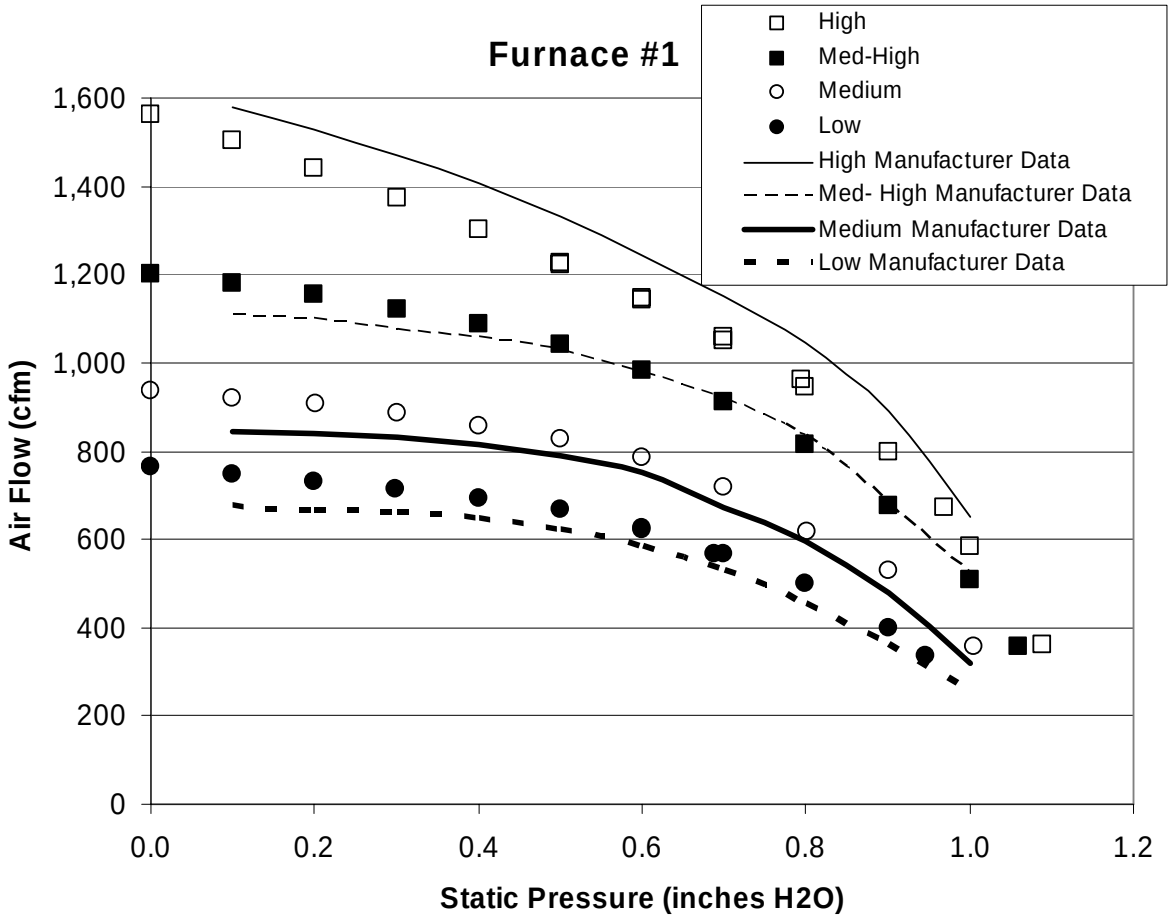


Figure 35. Comparing Laboratory Test Data to Manufacturer's Published Data

Comparing PSC and BPM performance

The PSC and BPM performance can be more directly compared by looking at specific operating conditions. Field tests show that high speed operation results in about 365cfm/ton at 0.8 in. water. For furnace #1, at 2.5 tons we will take as the cooling operating point a flow of about 950 cfm at 0.8 in. water (200 Pa). At this operating point the PSC consumes 554 at 1.7 cfm/W. The closest BPM prototype operating point provides 930 cfm at 303 W and 3.1 cfm/W. For heating, we will assume that the medium-high PSC setting is used resulting in about 910 cfm at 0.7 in. water (175 Pa) consuming 415W at about 2.2. cfm/W. The closest prototype speed for heating gives a flow of about 850 cfm at 0.6 in. water (150 Pa) consuming 215W at about 4 cfm/W. These comparisons are illustrated in Figures 36 and 37.

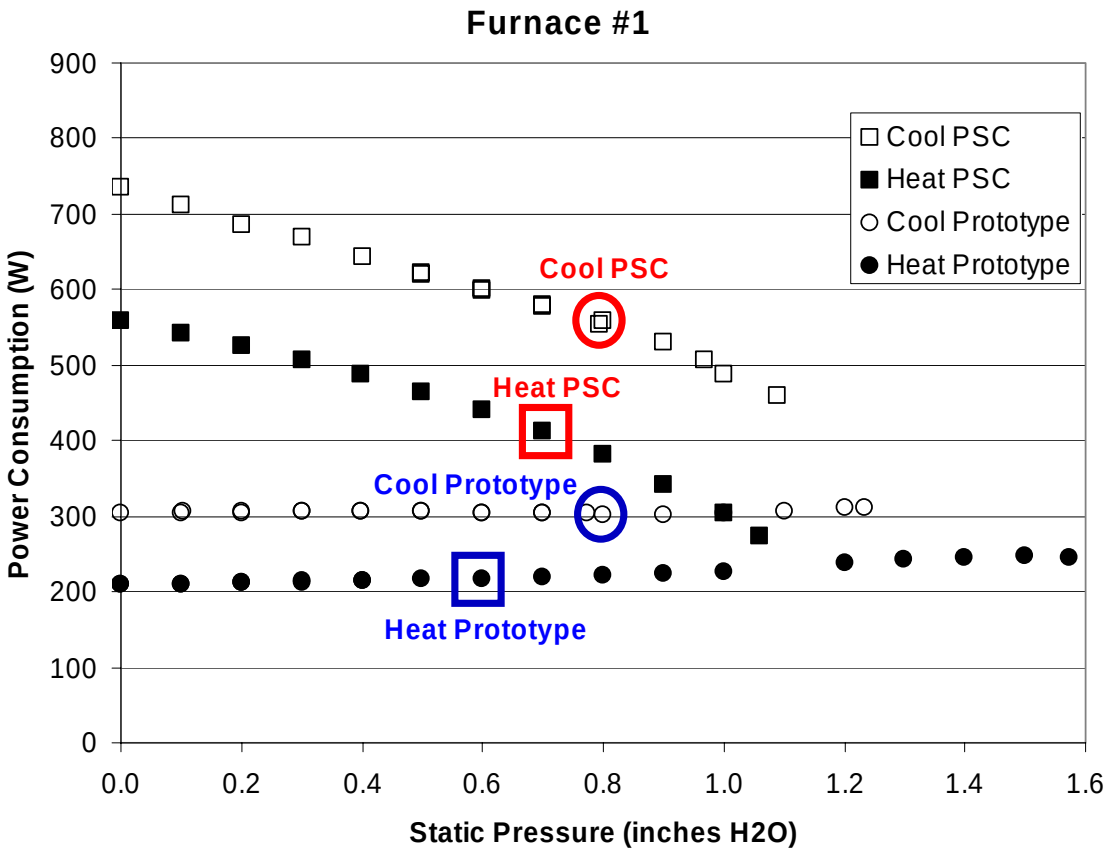


Figure 36. Furnace #1 comparison of power consumption in typical heating and cooling modes.

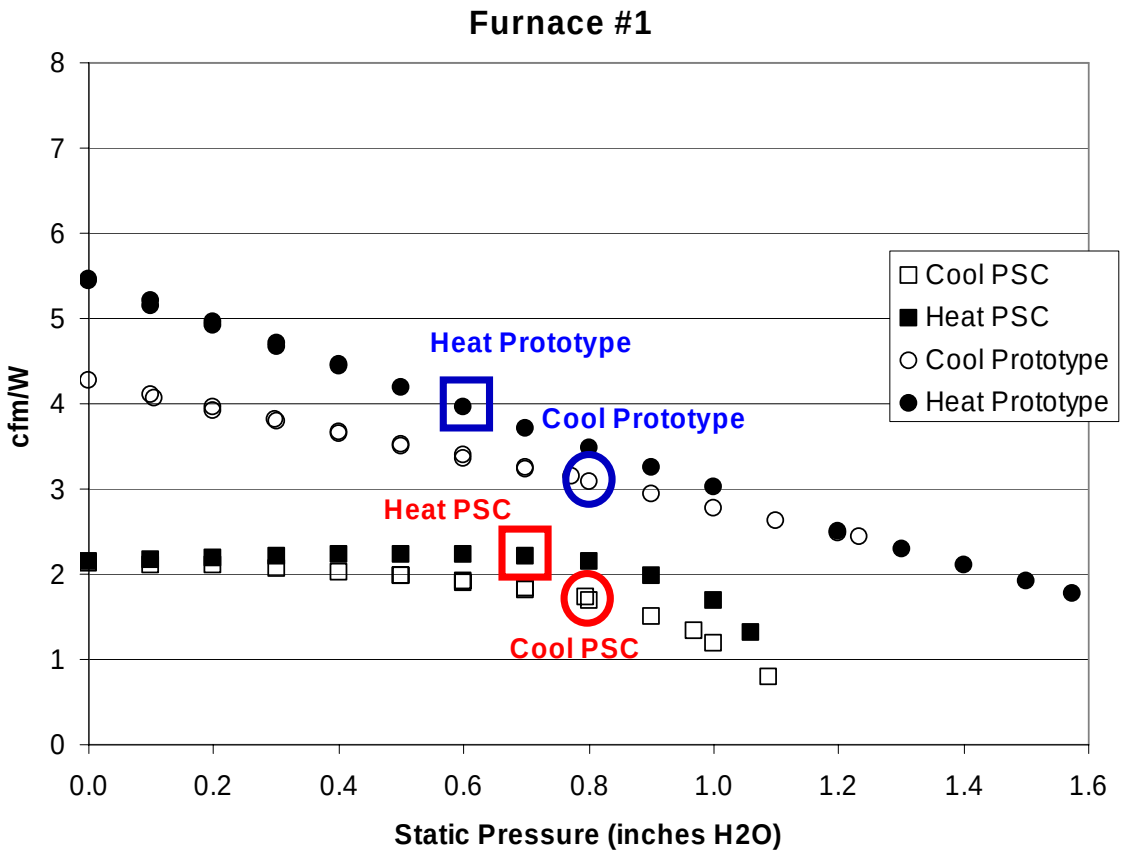


Figure 37. Comparison of cfm/W ratings for typical operating settings for Furnace #1.

In repeating this analysis for the other furnaces the PSC and BPM (i.e., combining Furnace #2 and Furnace #3 test results) rather than the prototype were used because these are devices that are currently available unlike the prototype. Figure 38 shows the air flows that at a typical operating point of 0.8 in. water, the PSC cannot provide the required 400 cfm/ton (1600 cfm for this 4 ton unit) and it has an airflow of 1140 cfm. By contrast, the BPM does much better at maintaining the correct flow and provides 1460 cfm. Figure 39 shows that in this pressure difference regime, the BPM increases its power consumption to maintain the flow, but the PSC decreases its power consumption as it is unable to maintain the air flow. At 0.8 in. water pressure difference the BPM consumes 50 more W than the PSC. However, if we use a different BPM speed to match the PSC airflow at this pressure (the "Matched BPM" results) then the BPM uses 180W less than the PSC. The corresponding cfm/W ratings are 2.1 cfm/W for the PSC, 2.4 cfm/W for the BPM and 3.1 cfm/W for the matched BPM. For heating the matched BPM and heat PSC data are compared. At the lower setting, the system pressure drops to 0.7 in. water and the air flow drops to 1117 cfm. At this operating point the BPM uses 340 W compared to 440 W for the PSC. The cfm/W ratings reflect this and are 2.5 cfm/W for the PSC and 3.5 cfm/W for the BPM.

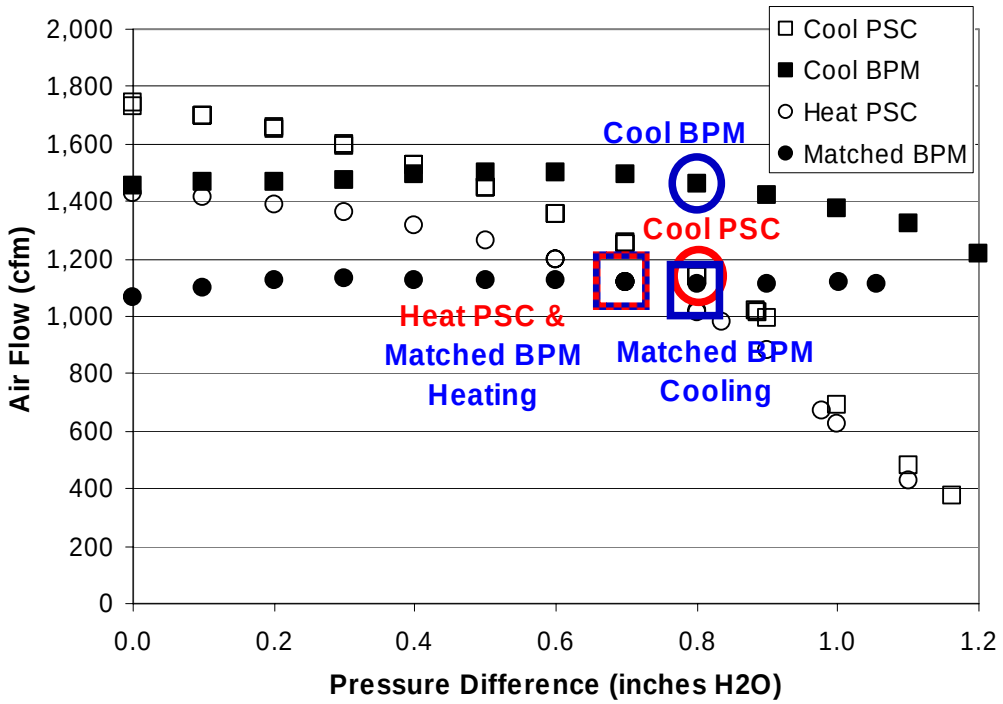


Figure 38. Comparing air flows for a PSC and BPM motor.

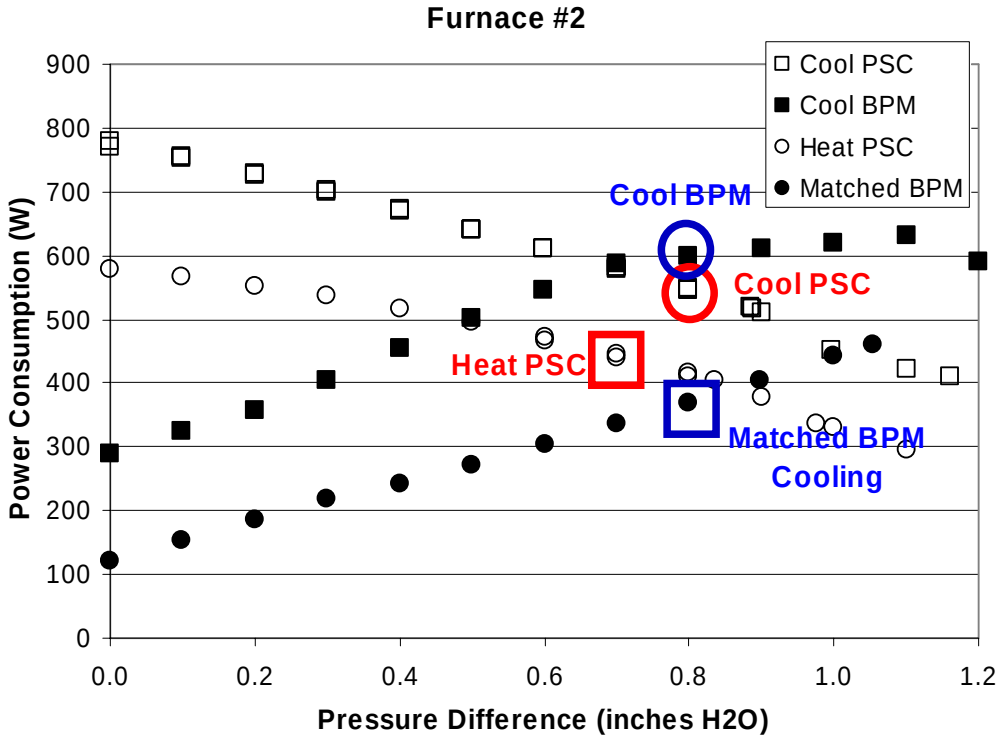


Figure 39. Comparing power consumption at typical operating points for a PSC and BPM motor.

Summary

Analysis of these detailed laboratory investigations has shown that:

- BPM and PSC blowers have distinctly different performance characteristics that must be accounted for when proposing performance specifications.
  - BPM blowers have better performance in terms of maintaining air flow at typical system pressures and reduced power consumption compared to PSC blowers. However, the advantage for BPM blowers is marginal at high pressures above about 0.8 in. water (200 Pa).
  - As system pressures increase, the PSC blower power consumption decreases as it is unable to maintain air flow.
  - PSC blowers have cfm/W ratings that are very close to proposed performance specifications, while the generally higher cfm/W ratings for BPM blowers will make it easier for them to meet these specifications.
- A performance specification should include both an air flow specification and a cfm/W specification.
- Because the performance of blowers at operating conditions is close to probable performance specification limits, although the fractional performance changes are about 15% for PSC blowers, the effects of restrictive cabinets and return air inlet locations could be significant.
- For occupants there are no noise issues related to the use of high speed backward inclined blower wheels.

These laboratory tests have examined only a small sample of furnaces, however, these general conclusions can be broadly applied based on input from furnace manufacturers and the test results from other unpublished studies (e.g., Proctor 2005 – personal communication). Specific furnace/blower combinations will have different air flow characteristics, cfm/W ratings and pressure difference sensitivity, but the general trends and observations will still apply.

Acknowledgements

The following individuals contributed to this document from unpublished sources: Bruce Wilcox, Rick Chitwood and John Proctor. Darryl Dickerhoff performed the laboratory testing at LBNL and provided review comments together with Peter Biermayer of LBNL. Robert Davis performed the laboratory testing at PG&E.

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