Better Unitary Equipment Air-Handlers for Efficiency and Humidity Control

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ABSTRACT[1]

Regulatory requirements drive unitary equipment design. For residential equipment, SEER reflects performance at moderate temperatures, and is largely independent of high temperature efficiency and high latent heat removal capability. The test procedure gives too little credit for advanced air handlers that reduce air conditioning load and facilitate adaptive humidity control through automatic fan speed adjustment. DC permanent magnet variable speed motors have much lower market share than less efficient permanent split capacitor designs: changing saves 15% - 25% at high fan speed, and at least 50% at lower speeds (high latent cooling). Humidistats allow dynamic humidity control by reducing air flow, cooling the evaporator. Following market transformation to increase market share, federal equipment stanards should be augmented to include specific air handler air flow efficiency levels, such as 0.2 watts/cfm at size-dependent static pressures. We estimate that customer payback will be less than three years in a mature market.

INTRODUCTION

Background

Air conditioners[2] vary in performance characteristics. Some are more efficient overall than others (use less electricity to provide comfort conditioning), some excel at high temperature efficiency, and others are designed for optimum performance in particularly humid climates, with higher than usual latent heat capacity.[3] The energy crises of the early and late 1970s greatly increased interest in two parallel questions: how to characterize performance, and what (if any) standards should be set to cull the least efficient units from the market place. Following the implementation of standards by California and their serious consideration by New York and other states, manufacturers sought federal standards rather than diverse state-by-state regulation. The National Appliance Energy Conservation Act of 1987 (NAECA, Pub. L. 100–12) led to national standards that gave manufacturers the uniformity in performance rating methods they sought, and the increase in average efficiency sought by environmental advocates and others. The rating method developed is a weighted index of cooling system performance called SEER, or Seasonal Energy Efficiency Ratio. SEER attempts to include cycling losses (lower performance as the unit turns on and cools its evaporator). SEER also attempts to look at performance over a range of outside temperatures, to approximate seasonal performance. This contrasts the EER (Energy Efficiency Ratio) approach used for commercial equipment in the US, and the COP used by ISO standards in Europe. These measure steady-state operating efficiency at specified conditions,

As constructed, SEER approximates performance in moderate temperature zones. On average, it is reasonably good in a wide band extending west from Washington, DC.[4] Unfortunately, the US climate varies enormously from East to West and South to North. In general, the Southwest and parts of California are very concerned with efficiency at high ambient temperatures (EER_{95}), because they have much higher frequency of very high temperatures than the "average" climate in SEER.[5] Low performance at high temperatures adds to electric utility peak demand problems. If the minimum SEER rises from the preseent 10 to 13 (or 12), ACEEE has testified that peak demand will be reduced by 18% (12%). If the present median EER_{95} = 9.3 for SEER 10 equipment[6] were changed to EER_{95} = 11.7, there

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[2] In this paper, the term "air conditioner" is to be taken generically to include residential air conditioners and heat pumps. By extension, it usually (unless otherwise noted) includes light commercial split and unitary packaged equipment.

[3] Perversely, good humidity removal ability is usually characterized as a low *sensible heat ratio* (SHR).

[4] Of course, this is only coincidentally the headquarters of the Department of Energy, which establishes the regulations.

[5] S. Kavanaugh (personal communication, 2001) has pointed out that Table 6.1.2 of the *Uniform Test Method for Measutring the Energy Consumption of Central Air-Conditioners* shows that 66% of the "bin hours" used to calculate SEER are at ambient temperature of 79°F or less, and only 2% are above 95°F. That is, the test is dominated by hours when most air conditioners are expected to be turned off!

[6] Testimony of Marshall Hunt, PGE, cited in ACEEE NOPR testimony dated December 1, 2000.

would be additional peak savings of about 3%.[7] In a band from eastern Texas into New Jersey, SEER has this shortcoming and one other: it does not reflect the need for high ability to remove humidity. Indeed, as discussed below, some designs that improve rated efficiency actually decrease latent heat removal capability.

Goal of the paper

The goal of this paper is to show that better air handlers can help meet the latent heat removal requirements for satisfactory use of equipment to be used in hot and humid climates. Because regulatory requirements so strongly influence unitary equipment design (and marketing), we need to understand how SEER fails to support use of advanced air handlers that would help meet the equipment needs in these climates. We conclude that no single parameter is adequate to meet the range of requirements in different regions. The least bad solution is likely to involve performance requirements at moderate temperature and at high temperature, and an air handling efficiency requirement. It is possible that prescriptive measures can be substituted for performance requirements for some parameters. This would limit design options (bad) but simplify compliance testing (good). The air handler issue is the focus of this paper. We show that better air handlers are available, save energy cost-effectively, and facilitate design of equipment that meets hot and humid climates requirements better than the bulk of present market offerings. In particular, better air handlers are the best route to adaptive humidity control, by varying the air flow across the evaporator coil to decrease coil temperature and increase condensation of water vapor.

We show that electronically commutated DC permanent magnet motors (variously referred to as ECPMs, ECMs, and ICMs), which are frequently specified with premium equipment, save energy and can allow better humidity control. Holding other factors constant, motor substitution saves about 30% of fan energy at high speed (maximum sensible cooling), and at least 60% at lower speeds (high latent cooling, heating, air circulation). ACEEE proposes that federal requirements for equipment efficiency be augmented to include specific air handler air flow efficiency levels, such as 0.2 watts/cfm at static pressures characteristic of real field installations. Manufacturers could comply with any combination of motor technologies, fan redesigns, and air handler aerodynamic improvements. We estimate that customer payback will be less than three years in a mature market. Society will benefit from at least 0.2 kW of undiversified capacity avoided at each end use location, at low cost. For the present decade, utility incentives and other voluntary programs can help increase market share, drive down costs, and provide the savings and humidity control for customers.

On Motor Types

Residential air handlers for furnaces, air conditioners, and heat pumps typically use ½ or ¾ horsepower motors. Shaded pole motors, the least efficient fractional horsepower motor type, are apparently no longer used in this application. Instead, an estimated 90+% of all units are shipped with multi-tap permanent split capacitor (PSC) alternating current induction motors. Typically these will have connections to select any of four alternative speeds. The installer attempts to match one (high) speed to the air flow required for cooling, and a lower speed for heating.[8] This is field-set, because variations in ductwork static pressure require tuning the system to the location. Although the air-conditioning and heating fan speeds may differ, both are fixed speeds that do not vary during the operating cycle.

In contrast, an estimated 5% - 10% of "high-end" units are shipped with electronically-commutated, permanent magnet motors (ECMs). These are inherently variable speed, and much more efficient at all speeds than PSCs. Table 1 shows the relative efficiency of PSC and ECM half-horsepower motors

[7] ACEEE Testimony, October 17, 2001, US DOE Docket Number: EE–RM—98—440

[8] Because the temperature at the evaporator exit is only about 20°F lower than the desired room temperature, while most heating systems will provide air with at least a 30°F differential, cooling requires more mass flow, and thus higher fan speed to move more air.

Table 1. Motor Efficiency for multi-speed (PSC) and variable speed (ECM) motors.

Technology (1/2 HP example):	Multi-speed (PSC)		Variable speed (ECM)	
	low	high	low	high
High Speed Efficiency	55%	67%	74%	78%
Low Speed Efficiency	34%	39%	>70%	>70%

This table gives characteristic (low and high) estimates for each technology at both high and low speed. Based on discussions with motor manufacturer. Efficiencies given are "wire-to-shaft," and do not include fan losses.

used in smaller to middle-sized air handlers. ECMs have higher efficiency than PSCs both at high and low speed.[9] At high speed for air conditioning, the ECM is 15% - 25% more efficient. At the lower fan speeds used in heating and ventilation, the efficiency difference is about a factor of two.

EFFICIENCY REGULATIONS AND IMPACTS FOR HUMIDITY CONTROL

Indications From Air-Conditioner/Heat Pump "SEER"

As noted above, federal regulations under NAECA as amended require minimum energy efficiency for all air conditioners and heat pumps sold in the US. The DOE is currently involved in regulatory and legal proceedings that will lead to an increase in the standard from SEER 10 to SEER 12 or SEER 13 in 2006, but no change in the test procedure is under active consideration[10]. These proceedings will not fix the defects in humidity control and high ambient temperature performance of the test procedure.[11] For present purposes, two other features of the test procedure are particularly noteworthy:

Static pressures.

Table 6 of ARI 210/240[12] specifies defaults as a function of unit size. Values range in 5 steps from 0.10 inches of water for units up to 28,000 Btuh to 0.30 inches of water for units between 106,000 and 134,000 Btuh. These external resistances to air flow are very low when compared with field research. Proctor and Parker (2000) combined prior studies that included 174 air-conditioned houses. For the 169 houses with full data sets[13], the average size was 3.5 tons, and the average static pressure was 0.48 inches.. ARI test conditions call for rating such systems with a static pressure of 0.15 or 0.2 inches water gauge,[14] so the ARI conditions used in the SEER test do not seem to reflect field reality. The effect is that air flows of equipment as installed are lower than the test predicts. This implies that the equipment will give slightly lower sensible heat ratios than projected by the tests – better humidity control but more energy used and less capacity to provide conditioned air to remote rooms.

Fan power.

The product manufacturer prescribes a specific air flow across the evaporator coil for each model, typically in the range of 350 - 400 cubic feet per minute (cfm). The test procedure has a default fan energy allowance of 365 watts per 1000 cfm of air moved (w/1000 cfm)[15]. Industry sources suggest that actual fan power with permanent split capacitor (PSC) motors is usually closer to 500 w/1000 cfm. Field tests reported by Proctor and Parker (2000) confirm that fan power required is above 500 w/1000 cfm for both existing and new houses.[16] The excess power reduces system efficiency in a way that is not reflected in the test. There is also collateral damage: If a manufacturer chooses to specify that a split system air conditioner be installed with a specific air handler which uses a better motor, the manufacturer can use the measured energy, which may be much less than 365 w/1000 cfm for ECM motors. However, relative to competitors' equipment, he is effectively credited only with the difference between 365 watts and the measured energy. Thus, there is less test credit for advanced motors than their actual

[9] In this, they differ from larger, integral horsepower induction motors with variable speed drives used for pumps and fans in commercial equipment. The overhead of a variable speed drive slightly reduces peak load efficiency.

[10] The relevant test procedure (or rating method) is Air-conditioning and Refrigeration Institute Standard 210/240-1994. Air-conditioning and Refrigeration Institute, Arlington, VA.

[11] California Energy Commission (CEC) will require a "thermal expansion valve" or equivalent and a minimum EER_{95} = 11.6 to deal with this problem. The requirements cannot go into effect unless the US DOE issues an "exemption from pre-emption." (Martin and Holland, 2001).

[12] ARI Standard 210/240-1994, Section 5. Air-conditioning and Refrigeration Institute, Arlington, VA.

[13] Table 1 in Proctor and Parker, 2000.

[14] ARI Standard 210/240-1994, Table 6, units 29,000 through 42,000 Btuh = 2.4 through 3.5 tons; units 43,000 – 70,000 Btuh are allowed 0.20 inches water.

[15] ARI Standard 210/240-1994, Section 5. Air-conditioning and Refrigeration Institute, Arlington, VA.

[16] Proctor and Parker, 2000, Table 2, find average fan power > 500 watts/1000 cfm for both existing and new houses, against the default value of 365 w/1000 cfm.

performance benefit. This is a disincentive for wider application of a more costly but more efficient technology.

Indications from furnace "AFUE."

The importance of the ECM for energy efficiency is not explicitly revealed in the air conditioner rating and test procedures. However, it can be estimated from gas furnace test data. Figure FAA depicts a typical condensing furnace, *sans* air conditioner evaporator coil, which sits above the combustion heat exchanger in an upflow unit like the sketch. The efficiency of the air handler (w/1000 cfm) is determined by static pressure (both internal to the furnace/air conditioner, and external in the ductwork), the aerodynamics of the fan and its enclosure, and the efficiency of the electric motor (typically ½ or ¾ hp). Although we focus here on motor efficiency, fan designs may improve, as well. In particular, sheet-metal centrifugal fans with many small, forward-curved blades are virtually universal today. They are mounted on the extended motor shaft, so the motor is inside the fan shroud. Higher precision polymer and reinforced polymer designs (perhaps with backward-curved blades) are being evaluated; these may offer both higher efficiency and less noise.

The efficiency measure for furnaces is a calculated seasonal efficiency measure called AFUE (Annual Fuel Utilization Efficiency). By design, this measure only measures gas consumption, and excludes the electricity used (primarily for the furnace/air conditioner fan, but including controls, induced combustion fans, etc). However, the manufacturers disclose, and GAMA[17] publishes, total electricity consumption for each model. A subset of the most efficient furnaces has been tabulated by size in Table 2.

Because we do not have sales-weighted data, we can only estimate the unit energy savings from advanced motors and air handlers, but it is certainly on the order of 500 kWh/yr or more.

[17] Gas Appliance Manufacturers Association, Arlington, VA. www.gamanet.org.

Table 2. Disclosed electricity consumption (kWh/yr) for high efficiency condensing furnaces[17]

Size, Btu/hr	Motor Type and kWh/yr electricity use		Saving, kWh/yr
	PSC	ECM	
26,000 - 42,000	459	97	363
43,000 - 59,000	678	123	555
60,000 - 76,000	711	167	544
77,000 - 93,000	806	266	540
94,000 - 110,000	1014	284	730
111,000 - 130,000	1314	255	1059

(Data from ACEEE, 2001, p. 24 – 27, Table titled Most Efficient Gas Furnaces.[18]

From the perspective of energy efficiency the 500 kWh/yr savings are very large. For example, it is slightly more than the *maximum* test cycle energy consumption of an 18 cubic foot, self-defrosting, top-freezer refrigerator for sale in the US in 2002. From another view, changing furnaces from PSC to ECM motors would save consumers 10% to 20% on their heating bills, since electricity is priced more dearly than gas. Because efficiency is regulated but comfort is not, the ability of ECM to both improve efficiency and help control humidity could help achieve greater market share for ECM systems.

RELEVANCE FOR HOT AND HUMID CLIMATES

Conventional furnaces and air conditioners work use closed loop (feedback) control governed by a single variable, temperature. In the air conditioning cycle, an increase in temperature at the thermostat in the living space turns on the air conditioner, which continues to run until the temperature falls to a set point. Conventional systems do not sense humidity or respond directly to changes in humidity. This and the fact that humidity control is not regulated reduce the incentives for good humidity control in units designed for national markets. Indeed, common strategies for improving SEER may *decrease* latent heat removal capabilities. Decreased humidity removal capability (higher sensible heat ratio) will be an outcome of designing with a larger evaporator relative to the fan output, or increasing the fan output for the same heat exchanger size (all other factors being held constant). In either case, the effect is to warm the evaporator. In a given operating cycle, it will then spend a higher fraction of the time at temperatures above the dew point, so there will be less condensation, less water removed from the air during that cycle. If the cycle controls also leave the fan on for a longer time after the compressor shuts off (to scavenge as much sensible heat as possible), this can also lead to re-evaporating moisture from the wet coil.

Now, consider adding a second closed-loop controller to the system operation, a "humidistat." This device "wants" to run the system whenever humidity levels rise, and turn it off when they fall into a comfort zone. As suggested above, the sensible heat ratio (the fraction of total work that is done in lowering temperature instead of condensing water vapor) can be adjusted by controlling the temperature of the evaporator while air is being forced across it. Clearly, this could be done by modulating the compressor output, but techniques for doing this are not common today.[18] ECMs and other true variable speed fan motors can dynamically control the sensible heat ratio, if the fan speed is controlled by a humidistat. Many different control sequences are possible, and can be elaborated with fuzzy logic, or "training" from the response of the whole house system (which may be coupled with an outdoor temperature indicator). For example, if relative humidity is high, the humidistat could "call" for air-conditioning with very low fan speed, to minimize sensible heat ratio and rapidly reduce humidity with minimum net air cooling. At slightly lower relative humidity levels, the controller would start the fan motor slowly, to operate in a condensing regime for the highest possible fraction of the cycle. The fan would taper down its speed fairly rapidly after the compressor shuts down, to minimize evaporation from the coil. Under low humidity conditions, the fan would keep operating after the compressor shut down as long as the downstream air was significantly cooler than the return air. These systems are marketed as premium products today.[19]

Thus, increasing the fraction of houses equipped variable speed motors offers the potential for improved humidity control. To the extent that consumers in hot and humid climates "overcool" today in an effort to remove humidity, better humidity control, with slightly warmer dry bulb (sensible) temperatures, may save energy beyond that associated with the more efficient motor. Of course, the more efficient motor has two effects on the electric bill. First, it draws about 15% to 25% fewer watts for fan power in the cooling cycle. For a three ton unit, the reduction might be from over 1000 watt to about 750.[20] Of course, the energy used by the motor is dissipated as heat, which requires additional compressor work. Counting both the direct and indirect (compressor) benefits, the demand reduction is in the range of 200 - 400 watts. Because air-conditioner use is strongly associated with utility demand peaks and capacity challenges, more efficient systems also have public policy implications for utility investments in new capacity, and for other methods of demand control.

DISCUSSION

The sections above make the case that residential air conditioning systems can control humidity with high energy efficiency, if variable speed ECM motors are used to vary the air flow rate across the evaporator coil. The ECM itself uses less energy to power the fan than a PSC motor at all motor speeds, contributing to efficiency. These motors have a small market share in premium products today, generally at SEER 13 and above. This section shows that ECMs are cost-effective for customers, that is, their use reduces life cycle costs[21]. We also attempt to quantify societal benefits from a complete changeover to ECMs, and the implications for the industry. The paper closes with suggestions for routes to facilitate market transformation for ECMs. Based on Table 2, assume that an average ECM will save more than 500 kWh/yr in heating mode. Table 3 adds estimated savings in cooling mode.

[18] "Premium" units with dual compressors (often of different sizes) have been available for many years. Products are available in 2002 that use a Bristol dual-capacity compressor, and Copeland has announced two different designs, one modulating and one dual-capacity.

[19] Motors from one manufacturer take advantage of the variable speed capability and controllability of the ECM with an additional feature: The installer sets the desired air flow (cfm), and the motor system automatically adjusts its power supply to achieve that flow.

[20] Estimated from manufacturer's brochure on product benefits

[21] We do not attempt to quantify either the amenity value of effective humidity control, or to estimate reduced losses due to poor humidity control, such as direct mold damage or health effects due to mold.

Table 3. Estimated Annual Savings with ECM in a climate with 800 equivalent full load cooling hours.

Power savings, excluding compressor, watts	250
Reduced compressor load, COP=3.3	76
Reduced unit power, watts	326
Hot climate full load equiv. Cooling hr	800
kWh avoided in cooling season	261
heating mode savings, kWh	500
Annual energy savings, kWh	761
Typical tariff, $/kWh	$ 0.10
Annual energy savings, $	$ 76

Costs for ECM-equipped systems today are difficult to estimate, since the motors are generally "bundled" with other features in premium systems. However, in manufacturer quantities, a high-efficiency 0.5 horsepower (hp) multi-tap inductive motor costs about $25 and its ECM counterpart about $105–115, a large premium (Kubo and others, 2001). If we double the OEM price of the motor for mark-ups to the consumer, the incremental cost today is in the range of $200. With annual savings of $76 (Table 3) based on a level tariff of $0.10/kWh, simple payback is about three years. If this were available as a stand-alone option when purchasing a new unit, many consumers would find it an attractive investment for its energy saving value alone.

With greater manufacturing volume and more competitors, Kubo and others (2001) estimate that the "mature" cost of ECM products would fall to $50–70 during this decade, but it may not disappear. ECM motors are more complicated and built to high precision. This represents a long-term (mature technology) incremental cost of $25–60, which would appear as a consumer price increase of $50–120. At this point, paybacks approach one year, which is rather compelling.

From the national policy perspective, full market transformation to ECM systems by 2008 would save about 6 quads cumulatively by 2020, about twice as much as any other program for additional standards examined by Kubo and others (2001). The same paper estimates that this market transformation would avoid about 27 GW in 2020, the equivalent about 75 new power plants. Thus, this issue has national policy ramifications.

From the perspective of equipment manufacturers, ECM motors are a key feature that differentiates "value-added" or premium products. Manufacturers believe that the features of these products must be protected, since they are more profitable than barely compliant "commodity" products at minimum SEER. Thus, they are unlikely to readily accept prescriptive requirements for ECMs as a component of efficiency standards such as SEER.

Interestingly, the electronic controls that are integral to ECMs also can help preserve value-added features, including explicit humidity control. Manufacturers of other products, such as cars and dishwashers, routinely use very similar construction, with many shared components, across a broad product line. More expensive models simply have more features "revealed" and available for use, or have minor differentiating features that add more perceived value than cost. The ability to rationalize production and significantly increase efficiency will allow some manufacturers to consider ECMs across the line, if costs fall enough.

For the next few years, there is no obvious opportunity for progress through the air conditioner standards, since the current round is not yet completed.[22] However, there are other routes to increase market penetration for advanced fan systems. DOE has opened a rulemaking for furnaces (including boilers). ACEEE has proposed that a level of 0.11 watt/cfm may be technically feasible and economically justified, using ECMs with current fans.[23] Since virtually all furnaces are equipped with air conditioners, at least for new houses, this would establish a market for more than 3 million units/year.[24]

In the meantime, ACEEE is encouraging the voluntary EnergyStar program to consider fan energy

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[22] DOE's "NOPR" proposing to roll back the SEER 13 rule of January, 2001 is being litigated. Foreseeable outcomes do not include modification of the rating method allowance for fan power.

[23] ACEEE comments on DOE Energy Conservation Standards for Residential Furnaces and Boilers, Docket Number: EE–RM/STD–01–350, letter dated August 16, 2001

[24] According to GAMA, 3.1 million gas-fired furnaces were shipped in 2000. http://www.gamanet.org/press/dec00totals.htm. *Appliance Magazine* (1/01) data suggest shipments of about 5.7 million furnaces + heat pumps (heating equipment), or 6.2 million heat pumps + air conditioners.

in its next air conditioner program revision, in 2004. ACEEE and others are also considering ways to include fan performance specifications in programs that give incentives for purchasing efficient equipment. This may include both utilities and state Public Benefit programs.

Finally, the mechanics of a standard to improve air handler efficiency and facilitate better humidity control must be considered. ACEEE favors a minimum performance standard for the air handling system, measured in watts/1000 cfm, since that is the parameter of interest. We believe that a standard <200 watts/1000 cfm, perhaps as low as 110 watts/1000 cfm, is technically feasible and economically justified – the key parameters for rulemakings. The advantage of a standard in the range of 200-w/1000 cfm would be that it might encourage introduction of other technologies that give most of the efficiency and controllability benefits of ECMs at lower cost. This, in turn, would encourage rapid price declines for ECMs. We note that the standard should measure efficiency at full power and some other level in the range of ½ load, and must do the rating at external static pressures that reflect field results. These steps can avoid gaming that would sacrifice efficiency gains.

To summarize, much more efficient fan motors are available for residential unitary air conditioners, heat pumps, and furnaces. These technologies inherently allow speed modulation, which will enable much better control of relative humidity through much more effective latent heat removal capabilities. These motors are cost-effective on an energy savings basis, and their prices are projected to fall significantly as market penetration increases from the present estimated 5% - 10%. In the near term, voluntary programs can significantly expand the market through incentives and better consumer information. In the longer term, the energy savings potential warrants adoption of a performance standard for air handlers.

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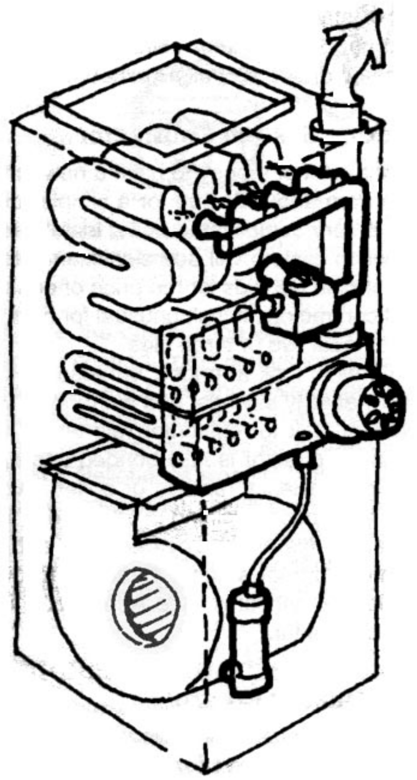

Figure 1. Schematic of Condensing Furnace, without air conditioner coil.