Laboratory and Field Tests of an Efficient Fan Controller® in Cooling and Heating Mode on Residential HVAC Systems

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Abstract

Laboratory and field tests of a residential heating, ventilating, air conditioning (HVAC) Efficient Fan Controller® (EFC®) were performed at a third-party ISO-certified test laboratory used by manufacturers and USDOE to test HVAC equipment for compliance with minimum Federal efficiency standards. The patented EFC® technology saves cooling or heating energy by extending fan operation after the thermostat call for cooling or heating has ended based on the duration of the thermostat call for cooling or heating. The variable cooling fan-off delay is based on the air conditioning compressor operating time which determines how much water vapor is condensed on the evaporator to provide evaporative cooling after the thermostat call for cooling has ended. The variable heating fan-off delay is based on the heating system operating time which determines how much heat is stored in the heat exchanger to provide additional heating after the thermostat call for heating has ended. For gas furnaces, the EFC® energizes the thermostat G terminal after a brief delay to increase fan speed and airflow to satisfy the thermostat sooner and save energy. Cooling energy savings vary from 3.9 to 38.3% with average savings of 15.2 ± 0.8% based on 46 laboratory tests and normalized cooling savings of 19.9% based on 22 field tests. Gas furnace heating energy savings vary from 4 to 21% with average savings of 15.9 ± 0.7% based on 24 laboratory tests and savings of 13.5% based on 10 field tests. Heat pump heating energy savings vary from 2 to 29% with average savings of 12.5 ± 1% based on 48 laboratory tests. Hydronic heating energy savings vary from 4 to 31% with average savings of 16.3 ± 1.7% based on 20 laboratory tests. The EFC® potential annual energy savings are 0.11 quadrillion Btu (quads) or 0.12 exajoules (EJ) in California or 4.65% of the total estimated annual energy use in California of 2.4 quads or 2.53 EJ.

Introduction

Residential and commercial heating, ventilating, and air conditioning (HVAC) consumption in the United States accounts for 30% of average summer peak-day electricity loads, 13% of total electricity use, and 44% of total natural gas use [1]. A 2002 study published by the Hewlett Foundation indicates that improving HVAC cooling and heating efficiency represents one of the largest economically achievable opportunities for energy efficiency and peak demand savings [2]. This paper provides lab and field test results of a patented Efficient Fan Controller® (EFC®) installed on residential split-systems and packaged HVAC systems with direct-expansion (DX) R22 refrigerant-based cooling and gas furnace, heat pump, or forced-air hydronic hot water heating [7].[1] The EFC® saves cooling or heating energy by extending fan operation after the thermostat call for cooling or heating has ended based on the duration of the thermostat call for cooling or heating. The variable cooling fan-off delay time is based on the air conditioning compressor operating time which determines how much water vapor is condensed on the evaporator to provide evaporative cooling after the thermostat call for cooling has ended. The variable heating fan-off delay is based on the heating system operating time which determines how much heat is stored in the heat exchanger to provide additional heating after the thermostat call for heating has ended. For gas furnaces, the EFC® energizes the thermostat G terminal after a brief delay to increase fan speed and airflow to satisfy the thermostat sooner and save energy. Laboratory tests were performed on four HVAC systems: 1) 3-ton (10.55 kW) split-system DX cooling and gas furnace, 2) 3-ton (10.55 kW) packaged DX cooling and gas furnace, 3) 1.5-ton (5.28 kW) spilt-system heat pump with DX heating and cooling, 4) 1.5-ton (5.28 kW) split-system DX cooling with forced-air hydronic hot water heating.[2] The equipment was set up in two chambers to simulate

[1] US Patent 8763920, US Patent 9328933, US Patent 9500386. US Patent 9671125, US Trademark Efficient Fan Controller® Reg. No. 5,163,211 (First Use 03-01-2012), EFC® Reg. No. 5,198,335 (First Use 03-01-2012)

[2] One ton of cooling is defined as the heat energy removed from one short ton of water (2,000 pounds or 907.1847 kg) to produce one ton of ice at 32F (0 C) in 24 hours. The energy required for the phase change of liquid water at 32F (0C) into solid ice at 32F is referred to as the heat of fusion which is 144 Btu/lb multiplied by 2,000 lbs of water or 288,000 Btu of energy over

indoor and outdoor conditions per AHRI 210/240 [3]. Test conditions differ from those used to rate cooling and heating systems to match typical installations in California.[3] Field tests were performed on a 3.5-ton (12.31 kW) split-system DX cooling and 120,000 Btu per hour (35.17 kW) gas furnace serving a single-family residence located in Reno, Nevada. Lab and field tests are provided for both cooling and heating.

Test Equipment Laboratory Setup

Tests were performed at Intertek®, an AHRI-certified laboratory, located in the United States. The laboratory is used by manufacturers to certify air conditioners and heat pumps for AHRI equipment efficiency testing for the U.S. Department of Energy (DOE) compliance and enforcement program to meet energy conservation standards required by the Energy Policy and Conservation Act of 1975 (as amended) [8]. The test facility consists of climate-controlled indoor and outdoor chambers where ducts, evaporator, condenser, furnace or hydronic heating equipment and forced air units are located. The HVAC systems and standard test equipment were assembled and installed in the test chambers by laboratory technicians. The AHRI 210/240 cooling verification tests were performed according to ANSI/AHRI 2008 Standard for Performance Rating of Unitary Air-Conditioning and Air-Source Heat Pump Equipment Standard 210/240 and ANSI/ASHRAE Standard 37-2009 [2, 4]. Thermal Efficiency verification tests were performed according to ANSI Z21.47-5th Edition 2006/CSA 2.3-5th Edition 2006 [9]. The psychrometric room meets ASHRAE 41.2-1987 standard specifications [5]. Calibration for all equipment at the laboratory test this facility is conducted in accordance with ISO 17025 requirements by an ILAC accredited calibration provider. Gas furnace heating equipment performance and AFUE tests were performed per ANSI Z21.47 specifications.

The rated DX cooling capacity of the 3-ton split-system HVAC unit is 33,800 Btu per hour (Btuh or 9.67 kW) and the rated heating capacity is 54,000 Btuh (15.83 kW). The 3-ton split-system default cooling time delay is either 0 seconds or 90 seconds after the air conditioning compressor turns off, and the default heating time delay is 120 seconds after the furnace turns off. The rated cooling capacity of the 3-ton packaged HVAC unit is 35,800 Btuh (9.82 kW) and the rated heating capacity is 55,200 Btuh (16.18 kW). The 3-ton packaged unit default cooling time delay is either 0 seconds or 60 seconds after the air conditioning compressor turns off, and the heating time delay is 120 seconds after the furnace turns off. The EFC® fan-off time delay varies depending on system type, mode of operation, and length of time the cool source or heat source operate.

The 1.5-ton split-system Heat Pump (HP) rated total cooling capacity is 17,600 Btuh (Btuh) and the sensible cooling capacity is 13,900 Btuh (4.07 kW) at 95°F outdoor air temperature and 525 cfm evaporator airflow with 80°F indoor DB and 67°F indoor WB temperatures. The rated total cooling capacity is 17,000 Btuh (4.98 kW) and sensible cooling capacity is 13,600 Btuh (3.99 kW) at 95°F outdoor air temperature and 75°F indoor drybulb and 62F indoor wetbulb temperatures. The rated heating capacity is 18,000 Btuh (5.28 kW) at 47°F outdoor air temperatures. The heat pump rated cooling efficiency is 14-SEER and the heating coefficient of performance (COP) is 3.76 at 47°F outdoor air temperature. The heat pump cooling or heating fan-off time delays are fixed during setup at either 0 seconds or 65 seconds after the cool or heat source turns off.

The 1.5-ton hydronic (HYD) split-system rated total cooling capacity is 17,500 Btuh (5.13 kW) at 95°F OAT and 80°F indoor DB and 67°F indoor WB temperature, The hydronic system rated cooling efficiency is 13 SEER with the model MHH-19-410 condensing coil and 95°F OAT and 550 cfm

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a 24 hour period requires 12,000 Btu/hour to make one ton of ice in one day. The British thermal unit (Btu) is heat required to raise the temperature of one pound (0.454 kg) of water one degree Fahrenheit (°F or 0.556 C). The Btu is equivalent to 1055.06 joules or 251.997 calories.

[3] Cooling tests were performed at 95°F (35 C) drybulb (DB) outdoor and 75°F (23.9 C) DB and 62°F (16.7 C) wetbulb (WB) indoor temperatures. Gas heating tests were performed at 47°F (8.3 C) DB outdoor and 72°F (22.2 C) DB and 53°F (11.7 C) WB indoor temperatures. Heat pump tests were performed at 17°F (-8.3 C), 35°F (1.7 C), 47°F (8.3 C), and 62°F (16.7 C) outdoor temperatures and 70°F (21.1 C) DB and 55F (12.8 C) WB indoor temperatures. Hydronic heating tests were performed at 47°F (8.3 C) outdoor temperatures with 130F (54.4 C) and 140F (60 C) hot water temperature and 70°F (21.1 C) DB and 55F (12.8 C) WB indoor temperatures. The ARI 210/240 EER_A and EER_B indoor air dry-bulb temperature is 80°F (44.2C) and the wet-bulb is 67°F (37.2C). The EER_A outdoor air dry-bulb is 95°F (52.8C). The EER_B outdoor air dry-bulb is 82°F (45.6C). The SEER outdoor air dry-bulb is 82°F, indoor air dry-bulb is 80°F (44.2C), and indoor air wet-bulb is 57°F (31.7C).

evaporator airflow with 80F indoor drybulb and 67°F indoor wetbulb temperatures. The rated heating capacity is 18,000 Btuh (5.28 kW) with 550 cfm (235.98 liters per second, lps) airflow at 70°F entering air drybulb temperature and 3 gallons per minute (gpm or 0.189 lps) at 140F hot water supply temperature. The rated hot water heating efficiency is 78%. The hydronic heating coil is designed to receive 1 to 3 gpm of 120 to 180°F hot water circulated by a 1/25th hp (30W) pump where the water is heated by a storage water heater. The hydronic unit default cooling or heating time delay is fixed during setup at either 0 seconds or 60 seconds after the cool or heat source turns off.

The DX cooling tests were performed under non-steady state field conditions to measure sensible cooling capacity and efficiency with no time delay or fixed time delay of 60 seconds for the packaged unit or 90 seconds for the split-system after the air conditioning compressor turned off. Non-steady state cooling tests were performed with the EFC® product providing a variable time delay on the evaporator fan depending on length of time the compressor operated. The gas furnace heating tests were performed under non-steady state field conditions to measure the sensible heating capacity and efficiency with fixed time delay of 120 seconds after the gas furnace turned off. Non-steady state heating tests were performed with the EFC® product providing increased fan speed from low-to-high or medium-to-high speed after 4 minutes of furnace operation and variable time delay on the fan after the furnace turns off depending on length of time the furnace operated. The heat pump and hydronic tests were performed under non-steady state field conditions to measure sensible cooling or heating capacity and efficiency with no time delay or fixed time delay of 65 seconds for the split-system heat pump or 60 seconds for the split-system hydronic system after the cool or heat source turned off. Non-steady state cooling and heating tests were performed with the EFC® product providing a variable time delay on the fan depending on length of time the cool or heat source operated.

Cooling Test Data and Energy Savings Analysis

The laboratory performed 22 split- and packaged system cooling tests and 24 heat pump cooling tests with and without the EFC®. The tests were performed at 75F return air DB and 62F return air WB temperatures and 95F DB outdoor air temperature. The laboratory tests measured the additional sensible cooling capacity provided by the EFC® using an extended fan-off time delay which varies as a function of the cooling equipment operational time compared to the baseline system with no time delay or a fixed fan-off time delay. The laboratory tests measured sensible cooling capacity output (Btu or Joules) with and without the EFC® for compressor operational times varying from 5 to 50 minutes. The laboratory tests also measured total sensible cooling capacity for 60 minutes at the same conditions. The ratio of sensible cooling capacity for each test divided by the total sensible cooling capacity for 60 minute tests is defined as the cooling Part Load Ratio (PLR) as shown in **Equation 1**. The cooling PLR is used to normalize the cooling savings for each test or test scenario.[4]

Equation 1 $$PLR_C = \frac{Q_{C_o}}{Q_{C_r}}$$

Where, PLR_C = cooling part load ratio of delivered sensible cooling capacity for each test divided by the total sensible cooling capacity of the equipment (dimensionless),
Q_{C_o} = delivered sensible cooling capacity measured for each test (Btu or Joules), and
Q_{C_r} = total sensible capacity measured at same conditions for 60 minutes (Btu or Joules).

Laboratory test data of the cooling energy savings and the average cooling energy savings per test scenario are plotted in **Figure 1**. Cooling energy savings are calculated using the power function regression **Equation 2** based on the cooling part load ratio (PLR).[5]

Equation 2 $$\Delta\eta_C = \left(0.0390\ (PLR_C)^{-0.8870}\right)100$$

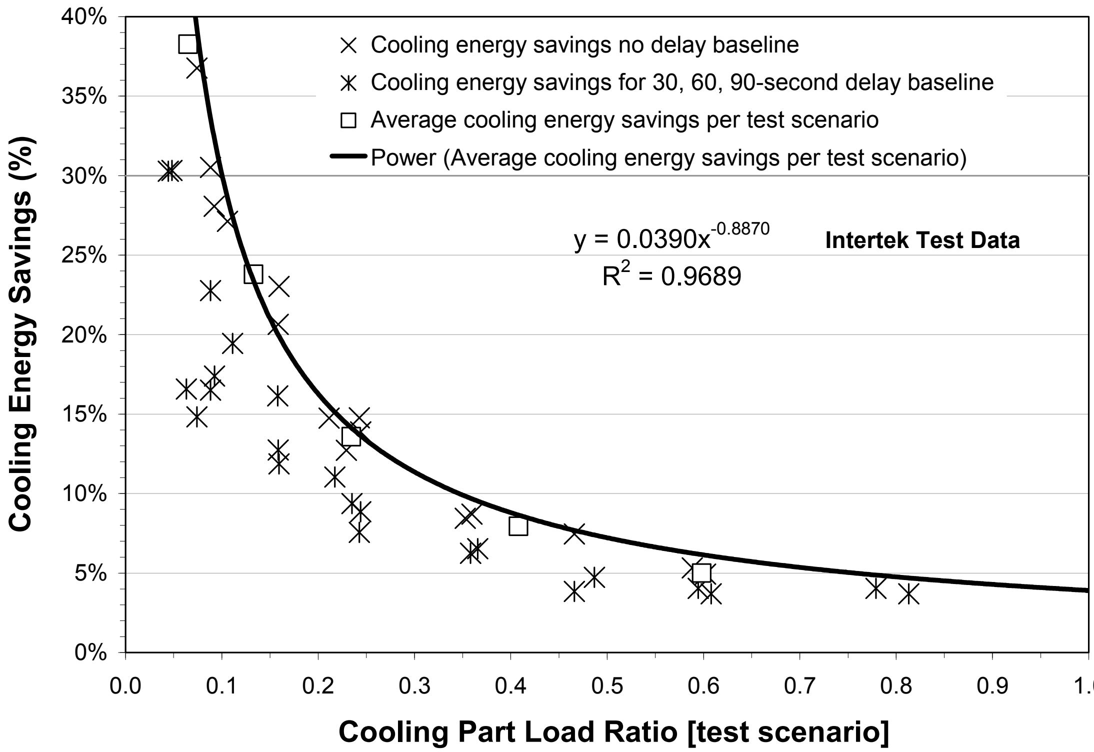
[4] Scenarios are defined as weighted average test results for test performed at approximately the same PLR where the baseline is either zero or a fixed fan-off time delay for the same class of DX or heat pump equipment independent of total capacity.

[5] The power function regression equation is $f(x)= a \cdot x^n$, where “a” is the coefficient or initial value of the function (y-intercept at x=1), “x” is the independent variable (PLR), “n” is the exponent, and “f(x)” is the dependent variable (output of the function).

Where, $\Delta\eta_c$ = EFC® cooling savings compared to baseline based on lab tests (%).

Figure 1 shows the EFC® cooling energy savings varying from 3.9 to 38.3% compared to baseline fan-off delays of zero, 30, 60, 65, and 90-seconds and PLR values ranging from 0.044 to 0.813 based on 46 laboratory tests. Approximately 90% of air conditioners in California have a pre-existing fan-off time delay of zero based on field data from 61,545 units [7].

Figure 1: Cooling Energy Savings versus Part Load Ratio for EFC®



The eQuest building energy software (version 3.65) and the Database for Energy Efficiency Resources (DEER) eQuest residential single-family, multi-family, and mobile home building prototypes were used to evaluate the baseline HVAC energy use and peak demand for each building prototype and 16 California climate zones [11]. Based on the eQuest simulations, the average annual cooling PLR values range from 0.12 to 0.28 and the weighted average cooling PLR is 0.22 [7]. The average annual EFC® cooling energy savings are 15.2 ± 0.8% based on **Equation 2** and housing stock weights for each climate zone from US Census data [10].

Laboratory and field tests demonstrate that the EFC® improves thermal comfort by overshooting the thermostat setpoint and providing longer off-cycle times to reduce compressor on-cycle times. The EFC® can also prevent evaporator coil icing by continuing to operate the fan to evaporate cold-water condensate from the coil at the end of each cooling cycle. This prevents ice formation when the evaporator coil temperature is below freezing which can be caused by low airflow, dirty air filters, low refrigerant charge, low thermostat cooling setpoint, and refrigerant restrictions. Coil icing can reduce evaporator airflow by 17 to 37% and reduce sensible efficiency by 4% to 12% [12].

Field test results for a 3.5-ton (12.31 kW) air conditioning split-system with 21% duct leakage and the same system with the EFC® are shown in **Figure 2**, **Figure 3**, and **Table 1**. **Figure 3** shows normalized cooling kWh savings of 19.9% based on EFC® usage of 20.7 kWh compared to normalized usage of 25.88 kWh for the base system (see **Table 1** row v). The base AC compressor operated for 306.5 minutes to satisfy the thermostat over the 429.5 minute test period, and the EFC® AC compressor operated for 264.2 minutes or 14% less than the base over the same test period. The EFC® provides 24.2% more compressor off time than the base AC system (165.3 versus 133 minutes). The difference is due to 52 minutes of EFC® fan-only evaporative cooling.

Figure 2: Field Measurements of Sensible EER* for the Base Air Conditioning System

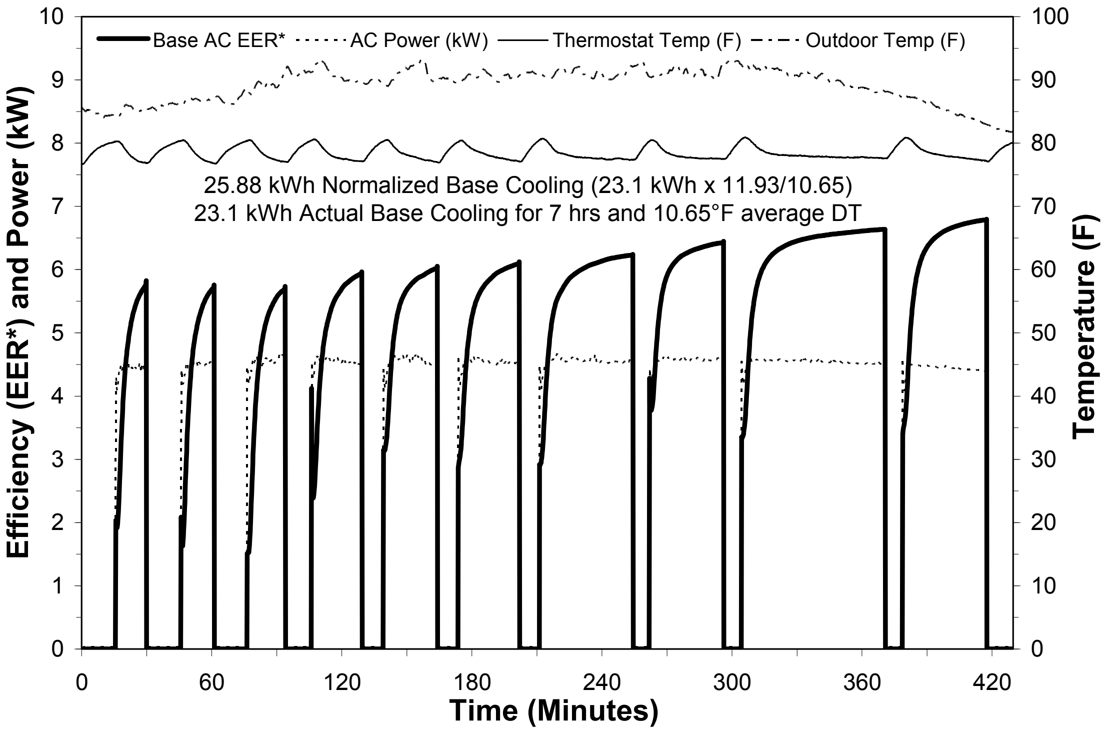
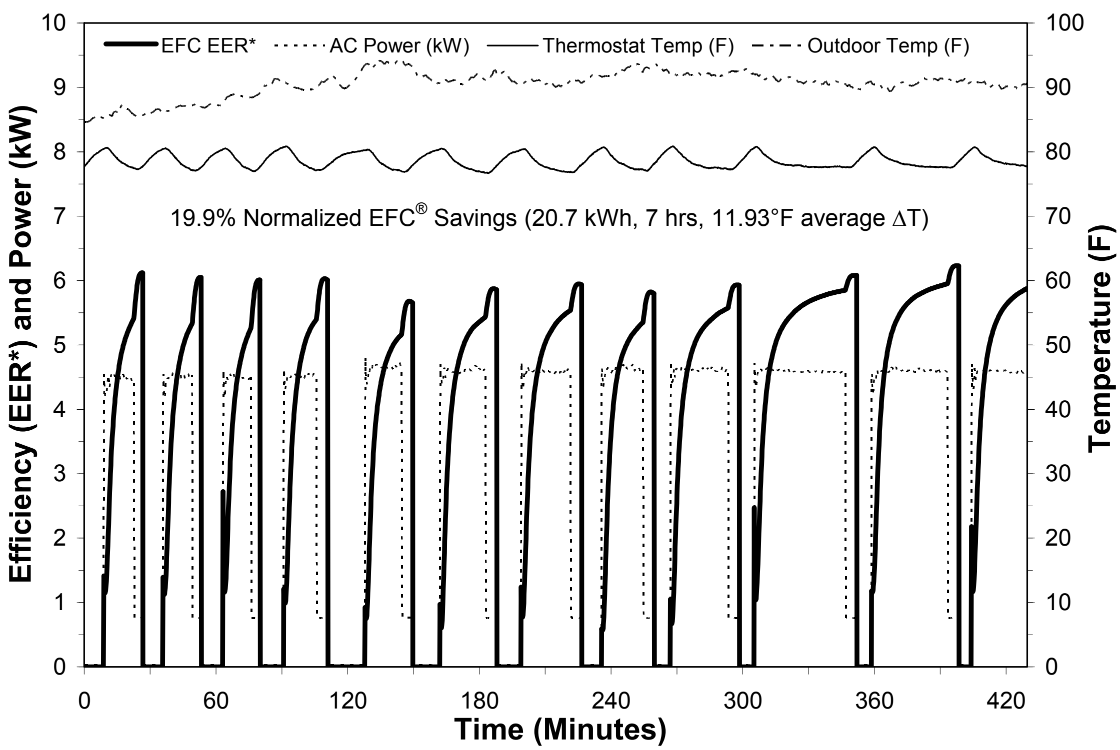


Figure 3: Field Measurements of Sensible EER* for the Air Conditioning System with the EFC®



The base AC operated with average outdoor air minus indoor air temperature difference (ΔT) of 10.65 +/- 0.1°F (Table 1, row m), outdoor temperature of 89.09 +/-0.09°F, and indoor air temperature of 78.44 +/-0.03°F. The EFC® operated with average ΔT of 11.93 +/- 0.08°F (p), outdoor air temperature of 90.51 +/-0.07°F and indoor air temperature of 78.58 +/-0.04°F. The EFC® used 20.68 kWh or 10.2% (s) less electricity than the base AC system which used 23.10 kWh. The EFC® average Part

Load Ratio (PLR) is 0.32 and the EFC® cooling savings are 10.5% (u) based on Equation 6. The normalized EFC® cooling savings (v) are 19.9% based on normalized base AC energy of 25.88 kWh (d) equal to base AC energy of 23.1 kWh times 11.93 ΔT for EFC® (p) divided by 10.65 ΔT for base AC system (row m). Predicted savings (based on the PLR) do not include the increased off cycle time.

Table 1: Field Tests of the Base Air Conditioner with and without the EFC®

Description	**Row**	**Total**
Base AC Compressor On Time (minutes)	a	306.5
EFC® Compressor On Time (minutes)	b	264.2
Base AC Energy (kWh)	c	23.10
Normalized Base AC Cooling Energy based on ΔT (kWh)	d=c × [p/m]	25.88
EFC® AC Energy (kWh) includes 0.645 kWh for EFC® fan operation	e	20.73
Base AC Compressor Off Time (minutes)	f	133.0
EFC® Compressor Off Time (minutes) EFC® fan-only evaporative cooling is 52 minutes	g	165.3
Base AC Mechanical Sensible Cooling (Btu) [compressor plus fan]	h	145,102
EFC® Mechanical Sensible Cooling (Btu) [compressor plus fan]	i	112,491
EFC® Fan Only Sensible Cooling Energy (Btu)	j	11,129
Base AC Outdoor Air Temperature (°F)	k	89.09
Base AC Indoor Air Temperature (°F)	l	78.44
Base AC Average Outdoor minus Indoor Air Temperature (ΔT) (°F)	m	10.65
EFC® Average Outdoor Air Temperature (°F)	n	90.51
EFC® Average Indoor Air Temperature (°F)	o	78.58
EFC® AC Average Outdoor minus Indoor Air Temperature (ΔT) (°F)	p	11.93
Base AC Average Return RH (%)	q	33.46
EFC® Average Return RH (%)	r	33.87
EFC® Cooling Savings Non-normalized (%)	**s=1-[e/c]**	**10.2%**
EFC® Average PLR	t	0.32
EFC® Cooling Savings based on PLR and Eq. 1 $\Delta\eta_c = 0.0390(PLR_c)^{-0.8870}$ (%)	**u**	**10.5%**
EFC® Cooling Savings Normalized based on ΔT Base divided by ΔT EFC® (%)	**v=1-[e/d]**	**19.9%**

Figure 4 compares cooling energy savings based on laboratory and field tests. The relationship between energy savings and PLR with 21% duct leakage is provided in the power function regression **Equation 3**.

Equation 3 $$\Delta\eta_{c_d} = 0.0343\, PLR_S^{-0.8393}$$

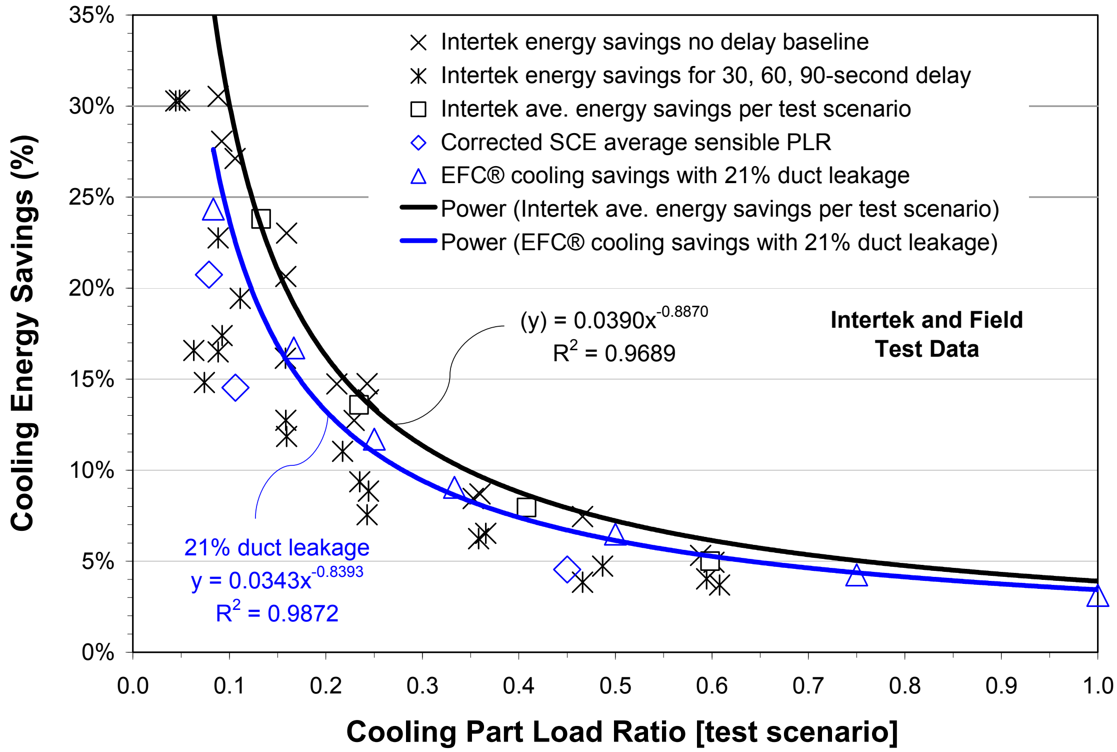
Where, $\Delta\eta_{c_d}$ = EFC® cooling savings with 21% duct leakage based on field tests.

Table 2 compares the difference between laboratory and field test cooling energy savings versus PLR. The field tests are within 1.3 +/- 0.4% of laboratory test results for PLR values from 0.17 to 1.0. Field tests are within 11% of laboratory tests for PLR of 0.08. These tests indicate duct leakage has a larger impact on cooling energy savings for short cycle PLR values. Otherwise, the field and lab tests provide comparable energy savings. Duct leakage has significantly less impact on cooling savings for compressor operating times of 10 minutes or greater (PLR ≥ 0.17).

Table 2: Field Test Results of Base and EFC® Sensible EER* with 21% Duct Leakage

Description	**1**	**2**	**3**	**4**	**5**	**6**	**7**
Compressor On Time (minutes)	5	10	15	20	30	45	60
Part Load Ratio (PLR)	0.08	0.17	0.25	0.33	0.50	0.75	1.00
Eq. 6 Laboratory test cooling energy savings [k]	35.3%	19.1%	13.3%	10.3%	7.2%	5.0%	3.9%
Field test cooling energy savings with duct leakage [l]	24.4%	16.7%	11.7%	9.1%	6.5%	4.2%	3.1%
Difference lab minus field test energy savings [m=k-l]	-11.0%	-2.4%	-1.6%	-1.3%	-0.7%	-0.8%	-0.8%

Figure 4: Cooling Energy Savings versus Part Load Ratio for EFC®



Gas Furnace Heating Test Data and Energy Savings Analysis

The laboratory performed 48 split- and packaged gas furnace heating tests (24 baseline tests and 24 measure tests). The tests were performed at 72°F (22.2 C) return air DB and 53°F (11.7 C) return air WB temperatures and 47°F (8.3 C) DB outdoor air temperature. The laboratory tests measured the additional heating capacity provided by the EFC® using an extended fan-off time delay which varies as a function of the heat-source operational time compared to the baseline system with no time delay or a fixed fan-off time delay. The laboratory tests measured heating capacity output (Btu or Joules) with and without the EFC® for furnace operational times varying from 5 to 30 minutes. The laboratory tests also measured total heating capacity for 60 minutes at the same conditions. The ratio of heating capacity for each test divided by the total heating capacity for 60 minute tests is defined as the heating Part Load Ratio (PLR) as shown in **Equation 4**. The heating PLR is used to normalize the gas furnace heating energy savings each test and each test scenario.[6]

Equation 4 $$PLR_h = \frac{Q_{h_o}}{Q_{h_r}}$$

Where, PLR_h = heating part load ratio of delivered heating capacity for each test divided by the total heating capacity of the equipment (dimensionless),
Q_{h_o} = delivered heating capacity measured for each test (Btu or Joules), and
Q_{h_r} = total heating capacity measured at same conditions for 60 minutes (Btu or Joules).

[6] Scenarios are defined as weighted average test results for tests performed at approximately the same PLR where the baseline is the fixed fan-off time delay for the same class of gas furnace heating equipment independent of total capacity.

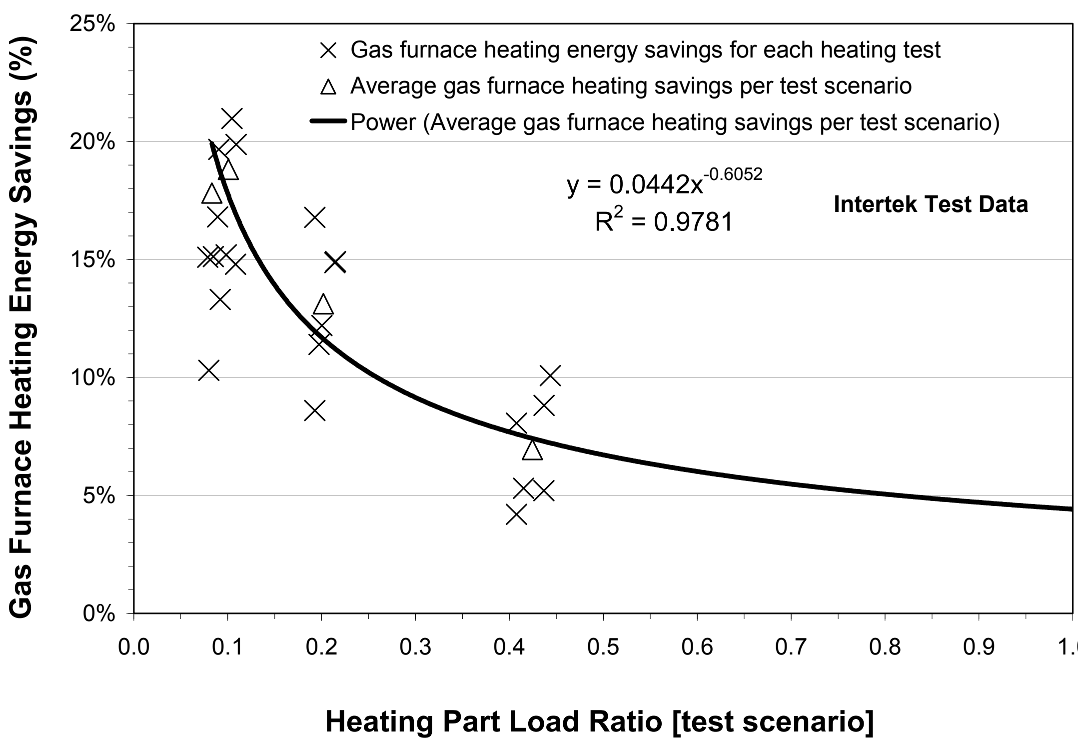
Laboratory test data of the heating energy savings and the average heating energy savings per test scenario are plotted in **Figure 5**. Gas furnace heating energy savings are calculated using regression **Equation 5** based on the PLR.

Equation 5 $$\Delta\eta_h = \left(0.0442\ (PLR_h)^{-0.6052}\right)100$$

Where, $\Delta\eta_h$ = EFC® gas furnace heating savings compared to baseline based on lab tests (%).

Figure 5 shows the EFC® heating energy savings varying from 4.2 to 21% with medium-speed or high-speed fan operation compared to baseline fan-off delays of 45 and 120 seconds with low-speed or medium-speed fan operation and PLR values ranging from 0.075 to 0.444 based on 24 laboratory tests. Based on the eQuest simulations, the average annual heating PLR values range from 0.11 to 0.2 and the weighted average heating PLR 0.14 [7]. The average annual EFC® heating savings are 15.9 ± 0.7% based **Equation 5** and housing stock weights for each climate zone from US Census data [10].

Figure 5: Gas Furnace Heating Energy Savings versus Part Load Ratio for EFC®



Field test results of a 120,000 Btu per hour (35.17 kW) gas furnace heating system with 21% duct leakage and the same system with the EFC® are provided in **Table 3** and **Figure 6.** Test results provide furnace on time (minutes), energy use (Btu), sensible heating capacity (Btu), heating efficiency (%), efficiency improvement, and heating energy savings for the base unit without the EFC® installed and the same unit with the EFC® installed. Tests were performed with air sampling sensors located upstream and downstream of the forced air unit located in an unconditioned crawl space with ducts located in an unconditioned attic where the attic temperature is colder than the conditioned space.

Table 3: Field Tests of Base and EFC® Furnace Efficiency with 21% Duct Leakage

Description	**8/9**	**10/11**	**12/13**	**14/15**	**16/17**
Base Furnace On Time (minutes)	6	10	15	20	30
120-Second Delay Furnace Energy Input (Btu) [a]	10,574	18,382	28,142	37,903	57,423
120-Second Delay Heating Capacity (Btu) [b]	6,260	12,140	19,388	26,675	41,063
120-Second Time Delay Heating Efficiency [c=b/a]	59.2%	66.0%	68.9%	70.4%	71.5%
EFC® Furnace Energy Input (Btu) [d]	10,086	17,569	26,190	36,601	51,404
EFC® Delivered Heating Capacity (Btu) [e]	7,214	13,610	20,271	28,130	39,412
EFC® Heating Efficiency [f=e/d]	71.5%	77.5%	77.4%	76.9%	76.7%
EFC® Heating Efficiency Improvement [g=f/c-1]	20.8%	17.3%	12.3%	9.2%	7.2%
EFC® Extra Fan Energy (kWh)	0.022	0.024	0.033	0.014	0.012
120-Second Delay Furnace Input to Match EFC® [h=e/c]	12,186	20,608	29,424	39,970	55,114
EFC® Energy Savings (Btu) [i=h-d or i=(e-b)/c+a-d]	2,100	3,039	3,234	3,369	3,710
Part Load Ratio (PLR)	0.08	0.15	0.24	0.32	0.08
EFC® Heating Energy Savings [j=(1-c/f) or j=i/h]	**17.2%**	**14.7%**	**11.0%**	**8.4%**	**6.7%**

Figure 6 shows time series data for the heating efficiency, rated efficiency, and outdoor air temperature (°F).

Figure 6: Field Measured Gas Furnace Efficiency versus PLR with 21% Duct Leakage

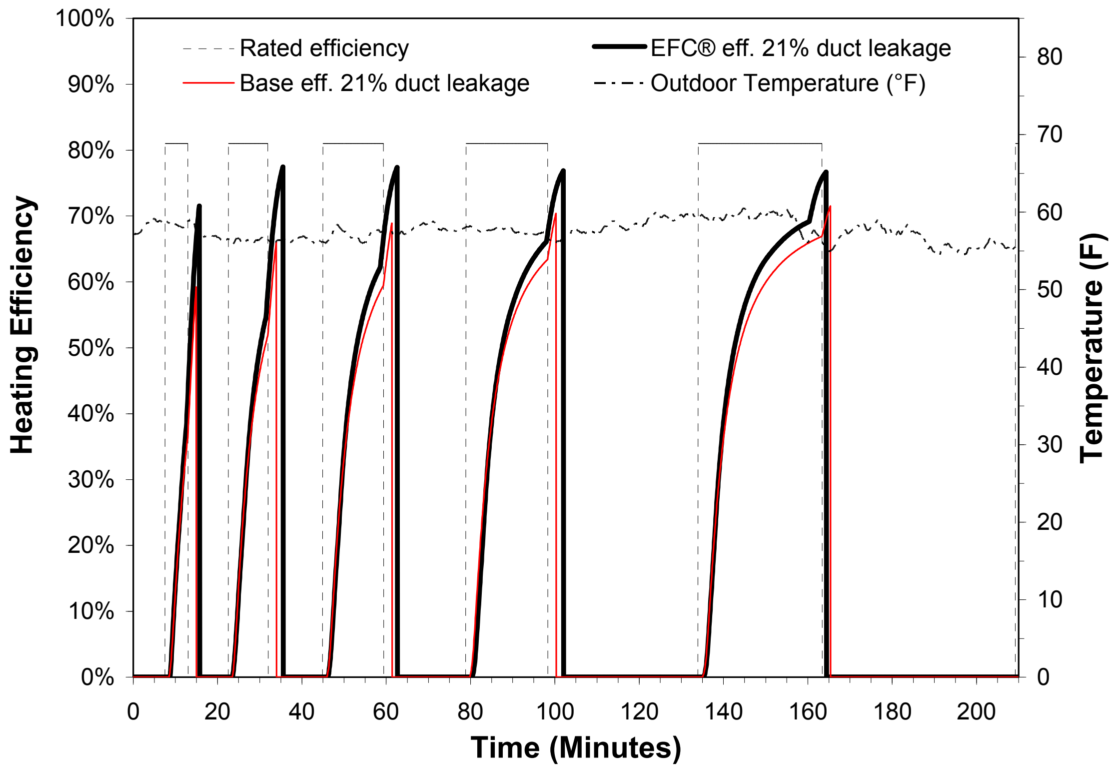


Figure 7 compares heating energy savings based on laboratory and field tests indicating similar results. Gas furnace heating energy savings based on field measurements with 21% duct leakage are calculated using regression **Equation 6** based on the PLR.

Equation 6 $$\Delta\eta_{h_d} = \left(0.0485\ (PLR_h)^{-0.5224}\right)100$$

Where, $\Delta\eta_{h_d}$ = EFC® gas furnace heating savings with 21% duct leakage based on field tests (%).

The average EFC® gas furnace heating savings are 14.5% based on 0.14 PLR and **Equation 6**.

Table 4 compares the difference between laboratory and field test heating energy savings versus PLR. The field tests are within 0.7 +/- 1.4% of laboratory test results for PLR values from 0.08 to 0.49. These tests indicate duct leakage has a larger impact on heating energy savings for short cycle PLR values. Otherwise, field and lab tests provide comparable energy savings. Duct leakage had less impact on heating savings for furnace operating times of 10 minutes or greater (PLR ≥ 0.15).

Figure 7: Gas Furnace Heating Energy Savings versus Part Load Ratio for EFC®

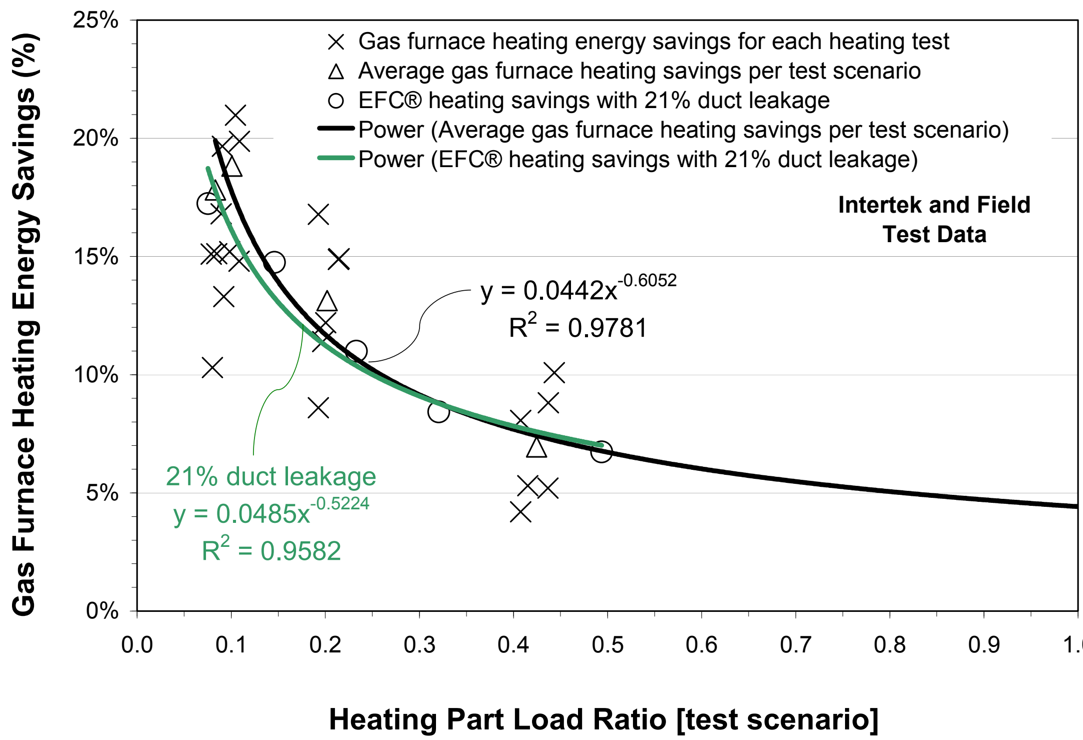


Table 4: Field Test Results of Base and EFC® Heating Efficiency with 21% Duct Leakage

Description	1	2	3	4	5
Furnace Operating Time (minutes)	5	10	15	20	30
Part Load Ratio (PLR)	0.08	0.15	0.23	0.32	0.49
Eq. 17 Laboratory test heating energy savings [k]	21.2%	14.2%	10.7%	8.8%	6.8%
Field test heating energy savings with duct leakage [l]	17.2%	14.7%	11.0%	8.4%	6.7%
Difference lab minus field test energy savings [m=k-l]	3.9%	-0.6%	-0.3%	0.4%	0.0%

Heat Pump Heating Test Data and Energy Savings Analysis

The laboratory performed 48 split-system heat pump heating tests (24 baseline tests and 24 measure tests). The tests were performed at 17°F (-8.3 C), 35°F (1.7 C), 47°F (8.3 C), and 62°F (16.7 C) outdoor temperatures and 70°F (21.1 C) DB and 55°F (12.8 C) WB indoor temperatures. The laboratory tests measured the additional heating capacity provided by the EFC® using an extended fan-off time delay which varies as a function of the heat-source operational time compared to the baseline system with no time delay or a fixed fan-off time delay. The laboratory tests also measured total heat pump heating capacity for 60 minutes at the same conditions.[7] The ratio of heating capacity for each test divided by the total heating capacity for 60 minute tests at the same test conditions is defined as the Part Load Ratio (PLR) as shown in **Equation 6**. The PLR is used to normalize the heat

[7] Heat pump input Btu values are based on measured kWh times 3412 Btu/h.

pump heating energy savings each test and each test scenario. The heating PLR is used to normalize the heat pump heating energy savings each test and each test scenario.

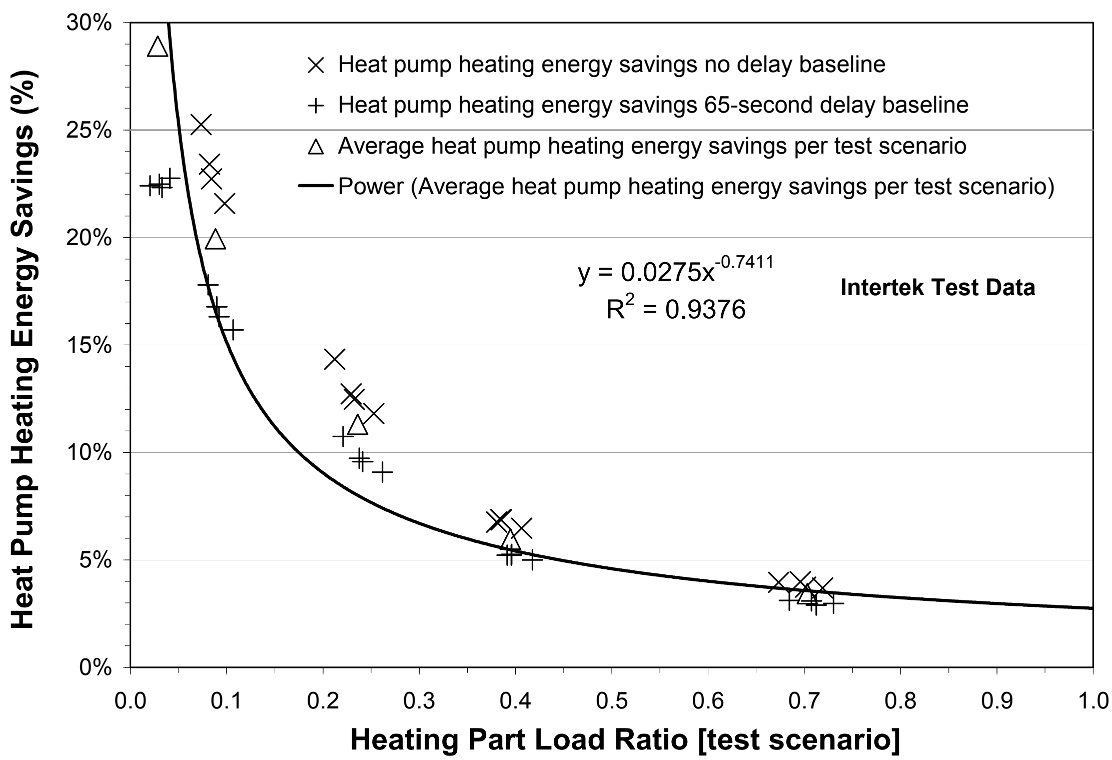
Laboratory test data of the heating energy savings and the average heat pump heating energy savings per test scenario are plotted in **Figure 8**. Heat pump heating energy savings are calculated using regression **Equation 7** based on the PLR.

Equation 7 $$\Delta\eta_h = \left(0.0275\left(PLR_h\right)^{-0.7411}\right)100$$

Where, $\Delta\eta_h$ = EFC® heat pump heating savings compared to baseline based on lab tests (%).

Figure 8 shows the EFC® heat pump heating energy savings varying from 2 to 28.9% compared to baseline fan-off delays of zero or 65 seconds and PLR values ranging from 0.02 to 0.72 based on 48 laboratory tests. Based on the eQuest simulations, the average annual heating PLR values range from 0.09 to 0.27 and the weighted average heating PLR 0.13 [7]. The average annual EFC® heat pump heating energy savings are 12.5 ± 1% based on **Equation 7** and housing stock weights for each climate zone from US Census data.

Figure 8: Heat Pump Heating Energy Savings versus Part Load Ratio for EFC®



Hydronic Heating Test Data and Energy Savings Analysis

The laboratory performed 20 split-system hydronic hot water heating tests. The tests were performed at 47°F (8.3 C) outdoor temperatures with 130°F (54.4 C) and 140°F (60 C) hot water temperature and 70°F (21.1 C) DB and 55F (12.8 C) WB indoor temperatures. The laboratory tests measured the additional heating capacity provided by the EFC® using an extended fan-off time delay which varies as a function of the hydronic heating operating time compared to the baseline system with no time delay or a fixed 60-second time delay. The laboratory tests also measured total hydronic heating capacity for 60 minutes at the same conditions. The ratio of heating capacity for each test divided by the total heating capacity for 60 minute tests at the same test conditions is defined as the Part Load

Ratio (PLR) as shown in **Equation 7**. The PLR is used to normalize the hydronic heating energy savings each test and each test scenario. The heating PLR is used to normalize the hydronic heating energy savings each test and each test scenario.

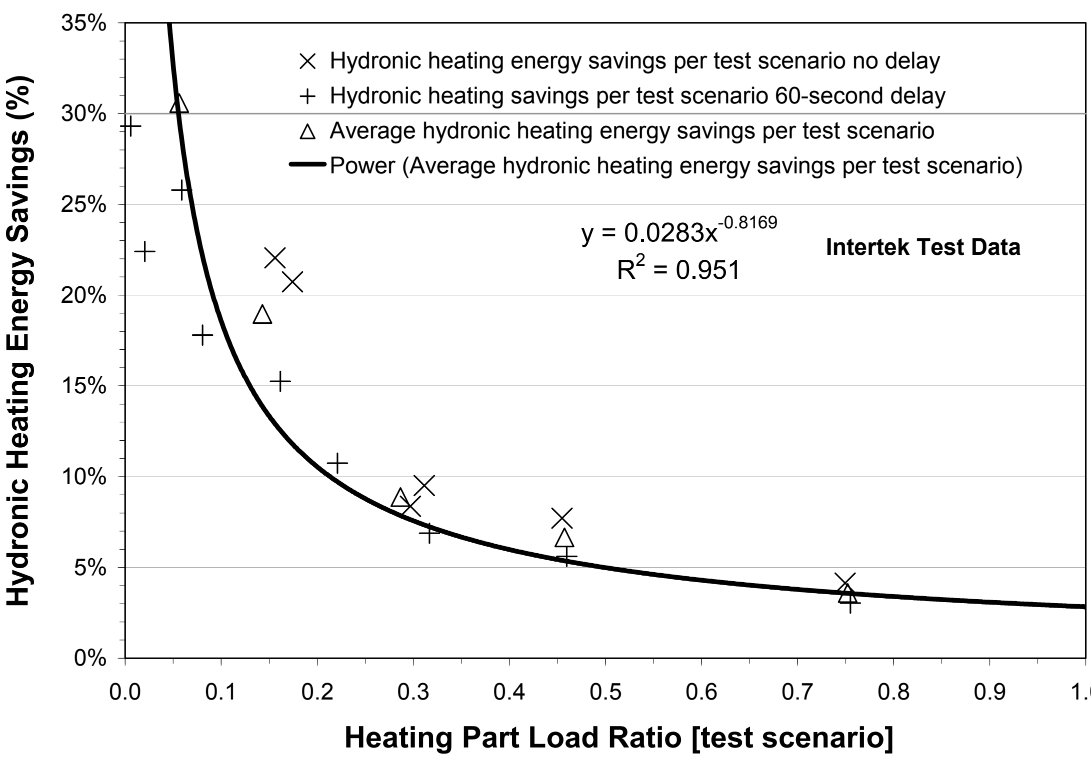
Twelve laboratory tests were performed with the water heater set at 130°F (54.4 C) and eight tests were performed with the water heater set at 140°F (60 C). Laboratory test data of the heating energy savings and the average hydronic heating energy savings per test scenario are plotted in **Figure 9**. Hydronic heating energy savings are calculated using regression **Equation 8** based on the PLR.

Equation 8 $\Delta\eta_h = \left(0.0283(PLR_h)^{-0.6169}\right)100$

Where, $\Delta\eta_h$ = EFC® hydronic heating savings compared to baseline based on lab tests (%).

Figure 9 shows the EFC® hydronic heating savings varying from 4.1 to 30.6% compared to baseline fan-off delays of zero or 60 seconds and PLR values ranging from 0.056 to 0.075 based on 20 lab tests. Based on the eQuest simulations, the average annual heating PLR values range from 0.09 to 0.20 and the weighted average heating PLR 0.12 [7]. The average annual EFC® heating energy savings are 16.3 ± 1.7% based on **Equation 8** and housing stock weights for each climate zone from US Census data [10].

Figure 9: Hydronic Heating Energy Savings versus Part Load Ratio for EFC®



Discussion

The EFC® lengthens “off-cycle” times for subsequent cooling cycles by 3 to 36% by overshooting the cooling thermostat setpoint by 0.5 to 1.6F (0.3 to 0.9 C). The EFC® heating tests lengthen “off-cycle” times for subsequent heating cycles by 2 to 30% by overshooting the heating thermostat setpoint by 0.3 to 2.2F (0.2 to 1.2 C). Participant survey responses from occupants who had the EFC® installed in their cooling and heating system for 5 years indicate increased thermal comfort due to the EFC® overshooting the thermostat setpoint [7]. These tests results indicate that mild climates with frequent on-off cycles can realize greater savings than hot climates with longer cycles. Laboratory and field tests also demonstrate that the EFC® can prevent evaporator coil icing by continuing to operate the fan and evaporate cold-water condensate from the coil at the end of each cooling cycle which prevents ice formation when the evaporator coil temperature is below freezing. This helps maintain thermal comfort, efficiency and equipment life per the ACCA Standard 4 and Standard 5 HVAC Quality installation and maintenance standards [6].

The EFC® cooling energy savings vary from 3.9 to 38.3% with average savings of 15.2 ± 0.8% based on 46 laboratory tests. Field measurements of an air conditioning system with 21% duct leakage and the same system with the EFC® found normalized cooling energy savings of 19.9% based on 22 field tests. Gas furnace heating energy savings vary from 4 to 21% with average savings of 15.9 ± 0.7% based on 24 laboratory tests. Field measurements of a gas furnace heating system with 21% duct leakage and the same system with the EFC® found average normalized heating savings of 13.5% based on 10 field tests. Heat pump heating energy savings vary from 2 to 29% with average savings of 12.5 ± 1% based on 48 laboratory tests. Hydronic heating energy savings vary from 4 to 31% with average savings of 16.3 ± 1.7% based on 20 laboratory tests. According to the US EIA, California uses approximately 0.74 quadrillion Btu (quads) or 0.79 exajoules (EJ) per year for space cooling and heating [1]. Assuming the EFC® can save 15% on cooling and heating, the estimated potential annual energy savings are 0.11 quadrillion Btu (quads) or 0.12 exajoules (EJ) in California or 4.65% of US EIA total estimated annual energy use in California of 2.4 quads or 2.53 EJ.

Conclusions

Laboratory and field tests of the EFC® provide evidence to support the cooling and heating energy efficiency savings claims. Cooling tests demonstrate improved thermal comfort by overshooting the thermostat setpoint and providing longer “off-cycle” times from variable fan-off time delays based on cooling or heating operational time. Test results indicate that mild climates with frequent on-off cycles can realize greater savings than hot climates, but HVAC systems operating in either type of climate can realize increased efficiency and 10 to 20% energy savings. The laboratory and field tests also demonstrate that the EFC® can prevent evaporator coil icing by continuing to operate the fan and evaporate cold-water condensate from the coil at the end of each cooling cycle which prevents ice formation when the evaporator coil temperature is below freezing.

Cooling energy savings vary from 3.9 to 38.3% with average savings of 15.2 ± 0.8% based on 46 laboratory tests and normalized cooling savings of 19.9% based on 22 field tests. Gas furnace heating energy savings vary from 4 to 21% with average savings of 15.9 ± 0.7% based on 24 laboratory tests and savings of 13.5% based on 10 field tests. Heat pump heating energy savings vary from 2 to 29% with average savings of 12.5 ± 1% based on 48 laboratory tests. Hydronic heating energy savings vary from 4 to 31% with average savings of 16.3 ± 1.7% based on 20 laboratory tests. California uses approximately 0.74 quadrillion Btu (quads) or 0.79 exajoules (EJ) per year for space cooling and heating. Assuming the EFC® can save 15% on cooling and heating, the estimated potential annual energy savings are 0.11 quadrillion Btu (quads) or 0.12 exajoules (EJ) or 4.65% of the total estimated annual energy use in California of 2.4 quads or 2.53 EJ.

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