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Performance Evaluation of Heat Pump Systems Based on a Load-based Testing Methodology

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ABSTRACT

This paper presents results of testing variable-speed heat pumps using a new load-based testing methodology that is described in Hjortland and Braun (2018), and Patil *et al*. (2018). The testing methodology involves emulating the response of a building's sensible and latent loads to equipment controls by dynamically adjusting the temperature and humidity setpoints of the psychrometric chamber reconditioning system using a simple building model. The advantage of this approach over existing testing approaches specified in rating standards is that it considers the interaction of the integrated controls with the equipment. As a result, it better captures the full range of part-load operation and the benefits of improved controls. This paper presents performance results for application of the automated load-based testing methodology to different variable-speed residential heat pump systems. In order to assess the benefits of load-based testing versus existing standards, tests were also conducted based on AHRI 210/240 and seasonal performance estimates are compared using data obtained with the two testing approaches.

1. INTRODUCTION

In recent years, it has become crucial to increase the efficiency of HVAC systems. To achieve higher efficiency, there has been widespread development of heat pumps that incorporate variable-speed compressors and fans combined with improvements in associated controls. Current equipment performance rating standards do not appropriately characterize the part-load performance of variable-speed systems and to some extent also fail to reward systems with better controls, largely because of the steady nature of the existing testing procedure. To address this issue, current rating standards need to be upgraded with alternative performance rating standards which account for advancement in technology. Recently, Cremaschi and Perez (2017) performed an experimental feasibility study of a load-based testing methodology for light commercial unitary HVAC system. They conducted load-based tests on a rooftop unit (RTU) under a constant sensible and latent load for test conditions. However, in their methodology it is difficult to emulate the dynamic load of a typical building that would be served by the test equipment in a different test facility.

Presently, research work is being carried out with Canada Standard Association (CSA) to develop a new test standard (a revision to CSA C656) based on a load-based testing methodology for residential heat pump and air conditioning systems. This methodology uses a dynamic load-based test approach in which the indoor room is subjected to a simulated load, and the equipment is allowed to respond accordingly as it tries to maintain the desired indoor conditions, while outdoor room conditions are held constant. This allows the actual behavior of the equipment and controls to be measured in a test facility in a manner that is representative of the actual field performance.

In this paper, performance results for two residential variable-speed heat pumps are presented which were tested based on the load-based test methodology. To assess the benefits of load-based testing compared with existing standards, tests were also conducted based on AHRI 210/240 and seasonal performance estimates are compared using test data obtained with the two different testing approaches when using the same weather data.

2. OVERVIEW OF LOAD-BASED TESTING METHODOLOGY

In the load-based testing methodology, the equipment responds to energy gains that are derived from a virtual building model and depend on ambient temperature and internal gains. The virtual building temperature and humidity response are calculated based on simple thermal and moisture load models along with measurements of the test unit capacity. This information is used to update temperature and humidity setpoints of the indoor psychrometric chamber re-conditioning system. The heat pump thermostat responds to the dynamic temperature variation to control the unit capacity in response to a deviation from its setpoint. For test conditions where the building load exceeds the equipment capacity, a full-load test is conducted. The methodology presented in this paper follows the draft CSA standard (2018), which is developed in Hjortland and Braun (2018). More details on the implemented CSA test methodology can be found in Patil *et al.* (2018). Virtual building load models are slightly different for the cooling and heating mode test procedures, which are discussed in the following subsections.

2.1 Cooling Mode Load Model

The sensible building load for cooling tests is defined as in Equation (1).

$$\mathrm{BL}(\mathrm{T_j}) = \frac{1}{1.5} \times \dot{\mathrm{Q}}_\mathrm{c}(95) \times \left[\frac{\mathrm{T_j} - \mathrm{T_{bal}}}{\mathrm{T_{OD}} - \mathrm{T_{bal}}}\right] \tag{1}$$

where $\dot{Q}_c(95)$ is the total cooling capacity at the standard AHRI 210/240 A2 test condition (steady state test at ODB = 95°F, IDB = 80°F, and IWB = 67°F), T_j is the outdoor room (ambient) temperature, and T_{OD} is the ambient design temperature (95°F for the humid cooling test and 102°F for the dry cooling test). $T_{bal,D}$ is the building design balance point temperature for cooling (67°F), and T_{bal} is the balance point temperature based on the current indoor room temperature (RAT(t)) which is updated according to

$$\mathrm{T_{bal}} = \mathrm{T_{bal,D}} + (\mathrm{RAT(t)} - \mathrm{T_{ID}}) \tag{2}$$

where T_{ID} is the indoor design temperature specified as the test unit thermostat setting (74°F for humid cooling test and 79°F for dry cooling test).

To simulate a dynamic virtual building, the indoor psychrometric room is controlled by its conditioning system based on the following updating equation, which is derived from a lumped capacitance assumption.

$$\mathrm{RAT(t + \Delta t)} = \mathrm{RAT(t)} + \frac{\Delta\mathrm{t}[\mathrm{BL} - \dot{\mathrm{Q}}_\mathrm{s}]}{\mathrm{C}} \tag{3}$$

where *RAT* is the setpoint provided to the psychrometric room system controller, *BL* is the sensible building cooling requirement at a particular test condition defined in Equation (1), $\dot{Q}_s$ is the net sensible cooling rate provided by the unit determined from air-side measurements, *C* is the simulated capacitance of the building, and Δt is the time interval for updating the psychrometric room controller setpoint.

Parallel to the sensible model above, a latent load model with a floating indoor room absolute humidity is used during the humid condition tests.

$$\mathrm{w(t + \Delta t)} = \mathrm{w(t)} + \frac{\Delta\mathrm{t}\left[\mathrm{BL}\left(\frac{1}{\mathrm{SHR_{building}}} - 1\right) - \dot{\mathrm{Q}}_\mathrm{l}\right]}{\mathrm{h_{fg}C_w}} \tag{4}$$

where w is a humidity ratio setpoint to be maintained by the reconditioning system controller, $\dot{Q}_l$ is the net latent cooling rate provided by the unit determined with air-side measurements, C_w is a simulated moisture capacitance associated with the mass of the indoor air, h_{fg} is the heat of vaporization of water, $SHR_{building}$ is the fixed building sensible heat ratio (0.8 for humid condition tests and 1.0 for dry condition tests**).** Table 1 shows the test conditions for cooling mode load-based tests. The specifications for determining the values of C, C_w and Δt are described in Patil *et al.* (2018).

Table 1: Cooling mode load-based test conditions

Test	**Humid Test Conditions**		**Dry Test Conditions**	
	ODB (°F)	Target IDB(°F)	ODB (°F)	Target IDB(°F)
A	N/A	74	113	79
B	104		104	
C	95		95	
D	86		86	
E	77		77	

2.2 Heating Mode Load Model

The sensible building load for heating tests is defined as in Equation (5).

$$BL(T_j) = 1.15 \times \dot{Q}_c(95) \times \left[\frac{T_{bal} - T_j}{T_{zl} - T_{ref}}\right] \tag{5}$$

where T_j is the outdoor room (ambient) temperature, T_{zl} is the design balance point temperature for heating (60°F), T_{ref} is an outdoor load reference temperature (5°F), and T_{bal} is the balance point temperature based on the current indoor temperature which is updated according to Equation (6).

$$T_{bal} = T_{zl} + (RAT(t) - T_{ID}) \tag{6}$$

where T_{ID} is the indoor design temperature specified as the test unit thermostat setting (70°F) and $RAT(t)$ is the most recent indoor dry-bulb temperature setpoint for the indoor room reconditioning system which is updated based on Equation (7).

$$RAT(t + \Delta t) = RAT(t) - \frac{\Delta t\left[BL(T_j) - \dot{Q}_s\right]}{C} \tag{7}$$

Table 2 shows the test conditions for heating mode load-based tests.

Table 2: Heating mode load-based test conditions

Test	Standard Outdoor Conditions		Marine Outdoor Conditions		Target IDB (°F)
	ODB (°F)	OWB (°F)	ODB (°F)	OWB (°F)	
A	-15	-15	N/A		70
B	-5	-6			
C	5	4			
D	17	15	17	16	
E	34	32	34	33	
F	47	41	47	45	
G	54	45	54	49	

3. EXPERIMENTAL SETUP AND PROCEDURE

3.1 Experimental Test Setup

The load-based testing was implemented using two adjoining psychrometric chambers. Figure 1 shows the schematic of the testing facility used at Herrick Laboratories. The schematic also shows the installation of a split system. Airside properties such as temperature, humidity and static pressure at the inlet and outlet of the indoor unit were measured using thermocouple grids, a dew point monitor, and static pressure sensor respectively. The volumetric flow rate of air was measured using a hot wire anemometer for capacity calculation using air enthalpy method.

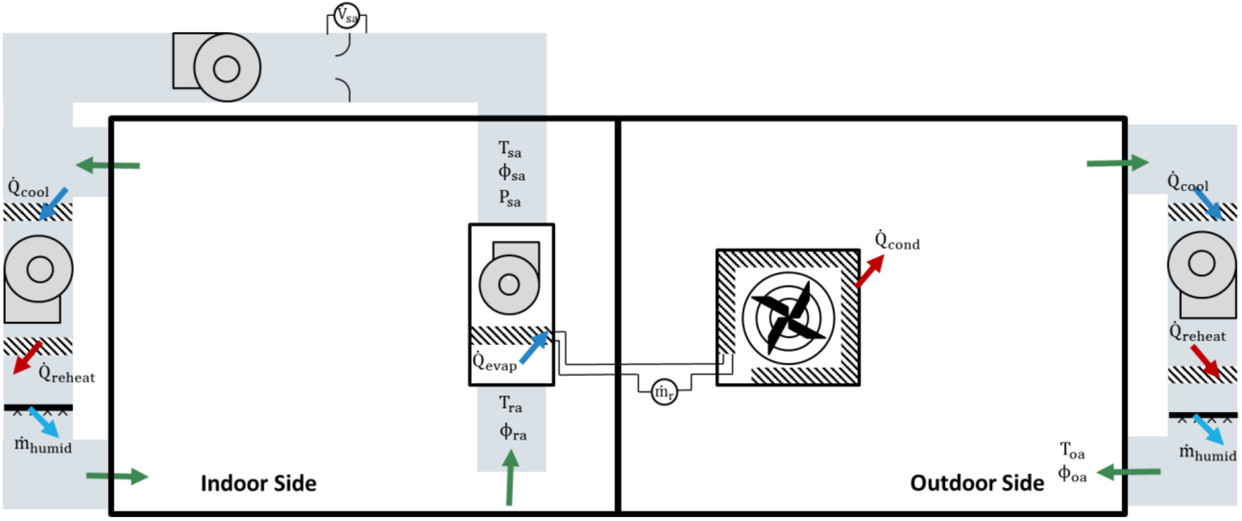

Figure 1: Psychrometric chamber equipment layout used to test split-type variable-speed heat pump systems

For measuring the mass flow rate of refrigerant, a Coriolis-effect based mass flow meter was installed in the liquid line. Immersion pressure and temperature sensors were installed to measure the refrigerant side properties at different state points of the cycle. Figure 2 shows a schematic of the heat pump system along with locations of measurement points for the air and refrigerant.

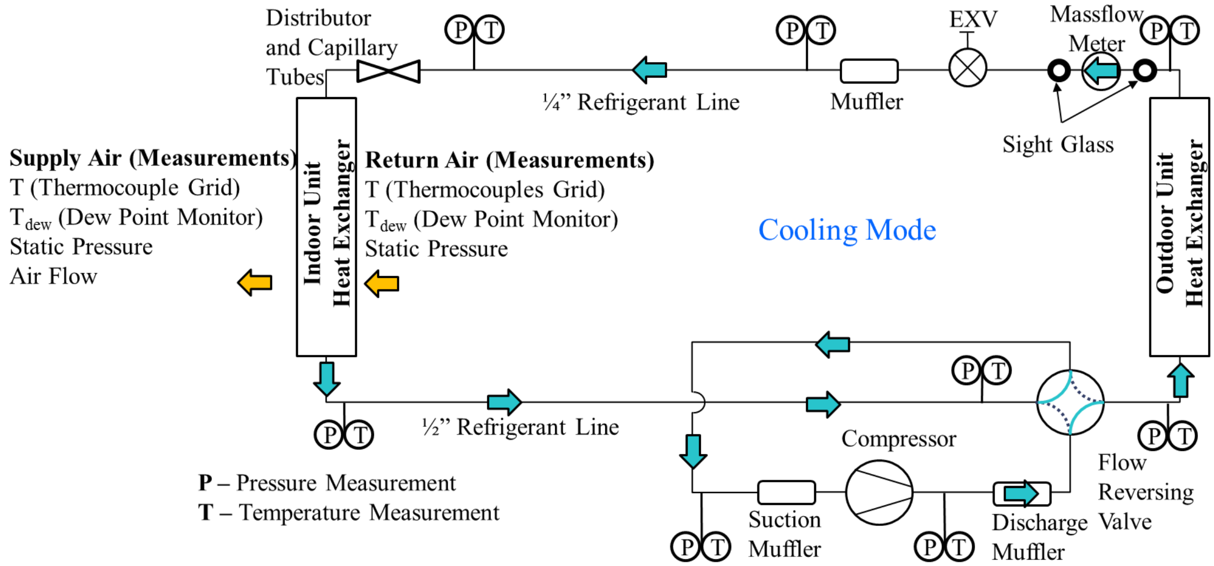

Figure 2: Schematic of split-type heat pump system showing the location of air and refrigerant side measurements

3.2 Test Procedure

Performance of two residential variable-speed heat pump systems, a 1.5-ton mini-split ducted system (Heat Pump 1) and, a 2-ton ducted system (Heat Pump 2), were evaluated based on the load-based testing methodology in both cooling and heating mode. The indoor room temperature and humidity setpoints were updated using the virtual building model as described in section 2 and outdoor room conditions were kept constant as per the test conditions defined in Table 1 and Table 2. For test conditions where the building load exceeded the unit maximum capacity, full load tests were performed by maintaining the indoor and outdoor side at constant test conditions and making the unit run at full capacity by resetting the thermostat setpoint (low value for cooling, high value for heating). Performance of both these heat pump systems was also evaluated at steady-state test conditions as per AHRI 210/240-2008 for comparing the seasonal performance of load-based test methodology with the current ratings procedure.

4. LOAD-BASED TEST RESULTS

4.1 Cooling Mode Tests

For cooling mode load-based tests, an automated testing methodology was implemented in which test conditions are transitioned to the next test point in the sequence when the performance of the unit converges. First, the steady-state high-temperature cooling mode test (A_2 test) was performed to calculate the load line using Equation (1). Based on the load-line, dry coil and humid coil cooling mode load-based tests were performed on heat pump 1 (HP1) and heat pump 2 (HP2).

Table 3: Cooling mode steady-state high-temperature A_2 test results

System	$\dot{Q}_c(95)$ [W]	SHR [-]
Heat Pump 1	4281	0.68
Heat Pump 2	10243	0.67

Figure 3 shows the automated dry coil cooling load-based test results for HP1. The outdoor temperature was varied according to the 5 dry coil test conditions of Table 1. The test unit thermostat was set at 79°F for this dry climate test, while the indoor psychrometric chamber setpoint changed in response to the virtual building model based on Equations

(1)-(4). The indoor temperature varies based on the difference between the unit capacity and building load. At a low outdoor temperature of 77°F when building load was lower than minimum unit capacity, HP1 cycled on and off. As outdoor temperature increased to 86°F and 95°F i.e. medium building load conditions, HP1 behaved as a variable-speed system and tried to match the building load with unit capacity. At 86°F and 95°F, HP1 had sufficient capacity to meet the load, but its thermostat failed to bring the room temperature to the setpoint. HP1 did not have sufficient cooling capacity at 104°F and 113°F outdoor temperature test conditions and the room temperature converged to a value more than 2°F above the set point of 79°F. In this case, full load tests were performed for test conditions A and B of Table 1. A similar unit behavior can be observed from HP2 test results in Figure 4. HP2 cycled on and off at outdoor temperature of 77°F and 86°F, behaved as variable-speed system at 95°F and 104°F, and ran out of capacity at 113°F outdoor temperature. The difference in variations of indoor temperature of HP1 and HP2 was observed due to the difference in thermostat dynamics and control design of two units. Table 4 summarizes the behavior and performance results for dry coil cooling load-based tests of HP1 and HP2.

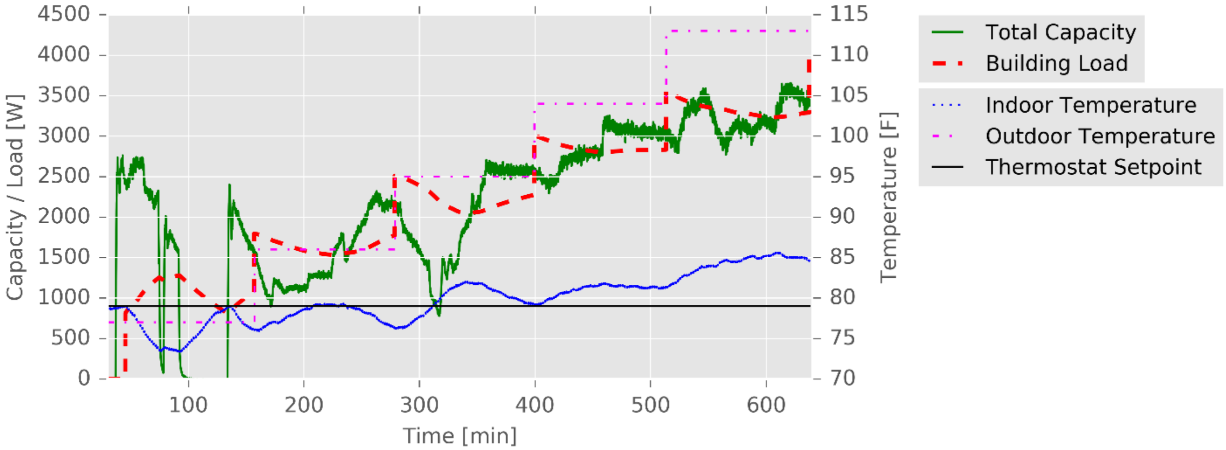

Figure 3: Dry Coil Cooling Load-based Test Performance of HP1

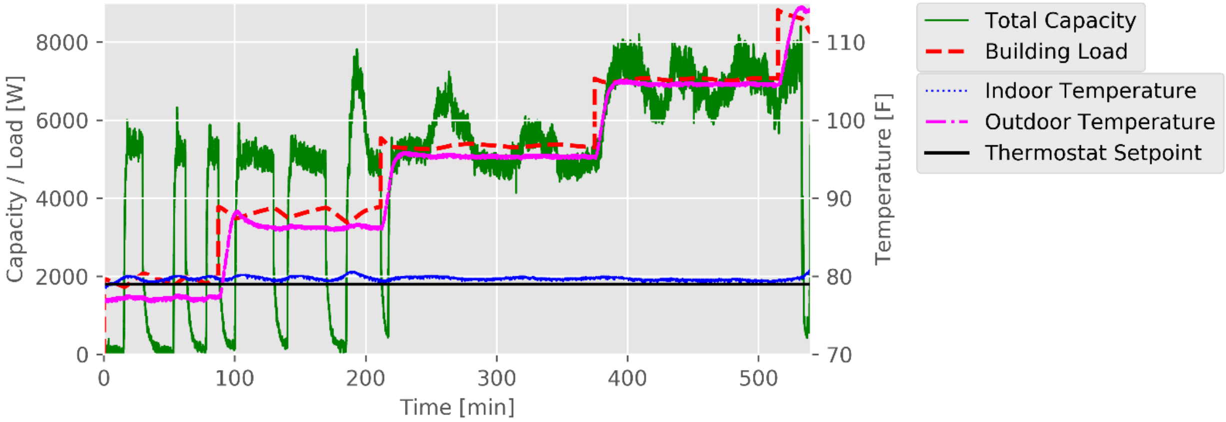

Figure 4: Dry Coil Cooling Load-based Test Performance of HP2

Table 4: Dry Coil Cooling Load-based Test Behavior and Performance results of HP1 and HP2

Outdoor Temperature	**77°F**	**86°F**	**95°F**	**104°F**	**113°F**
Heat Pump 1	Cycling	Variable-speed mode	Variable-speed mode	Insufficient capacity	Insufficient capacity
COP	4.84	4.24	2.52	1.91	1.62
Heat Pump 2	Cycling	Cycling	Variable-speed mode	Variable-speed mode	Insufficient capacity
COP	6.75	6.28	4.97	4.02	3.36

A similar unit behavior to dry coil test was observed for HP1 and HP2 in humid coil cooling load-based tests. Outdoor temperature was varied according to the 4 test conditions of Table 1. Table 5 summarizes the HP1 and HP2 behavior and performance results for the humid coil cooling load-based tests. In the humid coil tests, the units were subjected to both sensible and latent building loads. HP1 cycled on and off at a low building load outdoor temperature of 77°F and 86°F but ran out of capacity at 95°F and 104°F outdoor temperature test conditions. HP2 cycled on and off at 77°F outdoor temperature, behaved as a variable-speed unit at 86°F and 95°F and ran out of capacity at 104°F outdoor temperature.

Table 5: Humid coil cooling load-based test behavior and performance results of HP1 and HP2

Outdoor Temperature	**77°F**	**86°F**	**95°F**	**104°F**
Heat Pump 1	Cycling	Cycling	Insufficient capacity	Insufficient capacity
COP	6.69	3.89	2.74	2.15
Heat Pump 2	Cycling	Variable-speed mode	Variable-speed mode	Insufficient capacity
COP	6.87	6.50	5.25	4.20

Table 4 and Table 5 show that at the same outdoor temperature conditions, HP1 and HP2 system performance (COP) improved for humid-coil tests compared to dry-coil tests. The additional mode of latent heat transfer on the indoor unit coil in the humid coil tests leads to somewhat higher evaporating temperatures and better performance. In dry coil and humid coil tests, as the building load (outdoor temperature) increased, the system COP for both HP1 and HP2 decreased.

4.2 Heating Mode Tests

Heating mode load-based tests were performed on HP1 and HP2 for both standard and marine outdoor test conditions. The outdoor temperature was varied based on the test conditions of Table 2. The unit thermostat was set at 70°F and the indoor temperature floated in response to the heating mode virtual building model of Equations (5)-(7).

In the standard outdoor conditions heating load-based tests at outdoor temperatures of 54°F and 47°F, the unit minimum heating capacity was higher than that of the building load and both HP1 and HP2 cycled on and off. At the medium ambient temperature condition (34°F) both systems exhibited both defrost and on/off cycles as shown in Figure 5.

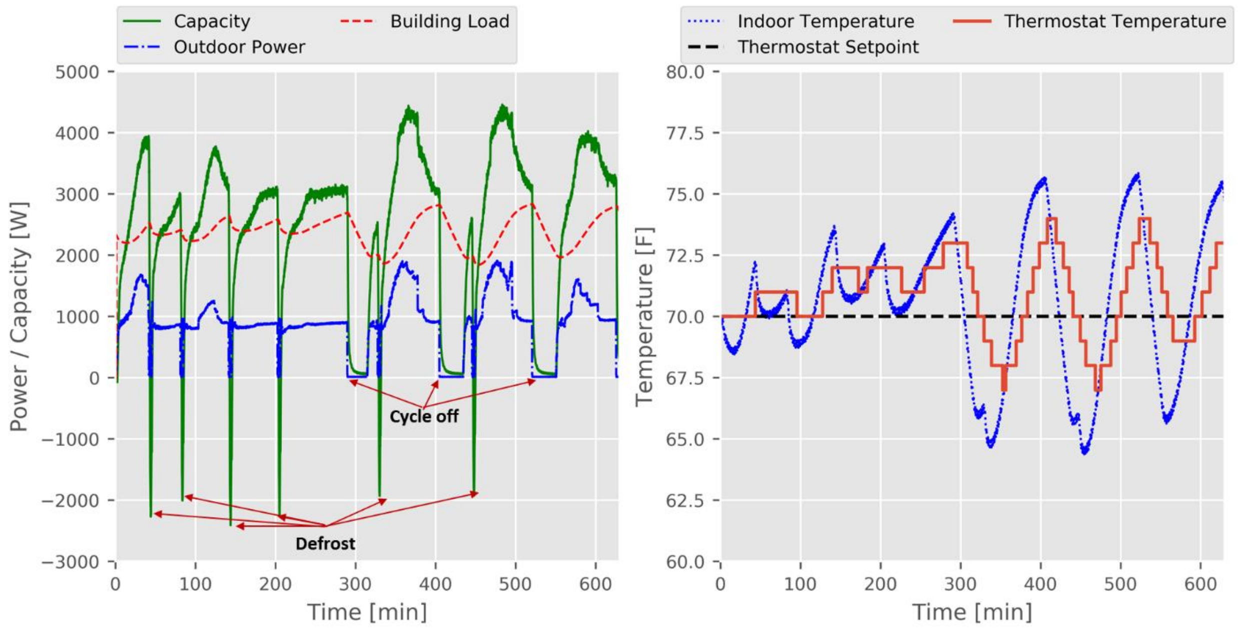

Figure 5: Heating load-based test performance and temperature variation at 34°F standard outdoor condition of HP1

At lower ambient temperatures (17°F and below), HP1 was not able to maintain the indoor side temperature above the thermostat setpoint limit and therefore full-load tests were conducted at these temperature conditions. At the 17°F outdoor condition, HP2 was able to maintain the indoor temperature within the thermostat setpoint limit and ran in a variable-speed mode with periodic defrost cycles. HP2 failed to match the building load with the unit capacity at low outdoor temperatures (5°F and below) and the indoor side temperature drifted to values less than 2°F below the thermostat setpoint. At these conditions, full load tests were performed on HP2. The heating load-based test behavior and performance of HP1 and HP2 at the standard outdoor conditions are summarized in Table 6. It is interesting to note that over the entire range of the test conditions, the only variable-speed operation occurred for HP2 at the ambient temperature of 17°F.

Table 6: Heating load-based test behavior and performance results of HP1 and HP2 at standard outdoor conditions

Outdoor Drybulb [°F]		**54**	**47**	**34**	**17**	**5**	**-5**	**-15**
Outdoor Wetbulb [°F]		**45**	**41**	**32**	**15**	**4**	**-6**	**-15**
Heat Pump 1	Unit Behavior	Cycling on/off	Cycling on/off	Cycling on/off, defrost	Full-load test, defrost	Full-load test, defrost	Full-load test, defrost	Full-load test, defrost
	COP	3.18	3.06	2.63	1.62	1.43	1.52	0.67
Heat Pump 2	Unit Behavior	Cycling on/off	Cycling on/off	Cycling on/off, defrost	Variable-speed mode, defrost	Full-load test, defrost	Full-load test, defrost	Full-load test, defrost
	COP	6.21	6.2	5.14	3.43	2.51	1.78	0.3

In heating load-based tests at marine outdoor conditions, a similar pattern to the standard outdoor conditions in HP1 and HP2 performance behavior was observed which is summarized in Table 7. Both HP1 and HP2 cycled on and off at a high outdoor temperature (54°F and 47°F), and as outdoor temperature decreased to 34°F, both systems started to utilize defrost operation and also cycled on/off. At a low ambient temperature of 17°F, both systems failed to maintain the indoor side temperature within thermostat setpoint limit and the full-load test was performed at this condition. Over the entire range of conditions considered, there was no variable-speed operation.

Table 7: Heating load-based test behavior and performance results of HP1 and HP2 at marine outdoor conditions

Outdoor Drybulb [°F]		**54**	**47**	**34**	**17**
Outdoor Wetbulb [°F]		**49**	**45**	**33**	**16**
Heat Pump 1	Unit Behavior	Cycling on/off	Cycling on/off	Cycling on/off, defrost	Full-load test, defrost
	COP	3.00	2.89	2.27	1.60
Heat Pump 2	Unit Behavior	Cycling on/off	Cycling on/off	Cycling on/off, defrost	Full-load test, defrost
	COP	5.49	5.76	4.82	3.02

Comparing the results in Table 6 and Table 7 the higher outdoor humidity for the marine outdoor condition tests led to lower COP for both systems at the same outdoor dry-bulb temperature. COP decreased significantly with decreasing outdoor temperature for both units and sets of test conditions.

5. COMPARISON WITH STEADY-STATE TESTS

For assessing the benefits of the load-based testing methodology, steady-state tests were performed on HP1 and HP2 based on AHRI 210/240-2008. A comparison of the seasonal performance estimates based on load-based tests and steady-state tests is presented in this section.

5.1 Steady-state Test Results

For steady-state tests, indoor and outdoor room conditions were set based on the AHRI 210/240 test conditions. HP1 was run at the different AHRI test conditions with the compressor and indoor fan speed set according to the test requirements by overwriting the unit control settings using an interface tool from the manufacturer. Since an interface tool was not available for HP2, the unit was run at different constant capacities using the service mode. In cooling mode, the unit was run at a minimum capacity of 63% and intermediate capacity of 75% compared to maximum capacity. In heating mode, the unit was run at minimum capacity 57% and intermediate capacity 70% of maximum capacity. Even though the steady-state tests on HP2 were not conducted exactly as per the AHRI test procedure unit settings, the test results are still useful for comparison between unit steady-state and load-based test performance. As the main motivation was to compare the two test methodologies based on the difference in test conditions and unit operation mode in the unit performance measurement tests, no other test setup modifications were done compared to the load-based tests such as changes to the indoor side external static pressure and so on. Table 8 and Table 9 show the steady-state test results of HP1 and HP2 based on AHRI-210/240 for cooling and heating mode, respectively.

Table 8: Steady-state cooling tests results of HP1 and HP2 based on AHRI 210/240

Test	**Heat Pump 1**				**Heat Pump 2**			
	Total Power [W]	Sensible Capacity [W]	Total Capacity [W]	COP	Total Power [W]	Sensible Capacity [W]	Total Capacity [W]	COP
A2	1624	2986	4601	2.83	1655	7008	9021	5.45
B2	1367	3070	4764	3.48	1424	7449	9618	6.76
EV	483	1864	2648	5.48	986	5248	7233	7.33
B1	200	1262	1477	7.4	718	4445	5706	7.95
F1	149	1346	1701	11.42	544	4979	6383	11.73

Table 9: Steady-state heating tests results of HP1 and HP2 based on AHRI 210/240

Test Description	**Heat Pump 1**			**Heat Pump 2**		
	Total Power [W]	Total Capacity [W]	COP	Total Power [W]	Total Capacity [W]	COP
H01 (required, steady)	247	1510	6.11	1591	12847	8.08
H12 (required, steady)	1381	4768	3.45	2602	14011	5.38
H11 (required, steady)	255	1162	4.57	1428	9550	6.69
H1N (optional, steady)	1374	4767	3.47	N/A		
H22 (optional)	1755	4294	2.45			
H2V (required)	875	3166	3.62	1882	10917	5.8
H32 (required, steady)	2195	3758	1.71	3059	12536	4.1

5.2 Seasonal Performance Comparison

The seasonal coefficient of performance (SCOP) of the two heat pumps was calculated and compared based on both the AHRI 210/240-2008 standard using steady-state test results and the CSA standard draft using load-based test results. These two standards define different cooling season and heating season temperature bin fractions. So, to mitigate the effect of different temperature bins in the performance comparisons, the seasonal performance based on both standards was calculated using the temperature bins of AHRI 210/240 as well as CSA standard draft.

Table 10: Load-based and Steady-state tests cooling seasonal performance ($SCOP_c$) comparison of HP1 and HP2

	Test Method	**Climate Zones (Temperature Bins)**							
		CSA Standard Draft							**AHRI**
		Very Cold	Cold/ Dry	Cold/ Humid	Marine	Mixed	Hot/ Humid	Hot/Dry	AHRI
HP 1	**Steady-State**	5.56	4.56	5.48	4.32	5.32	5.64	3.97	5.75
	Load-based	4.34	3.43	4.29	3.22	4.19	4.43	2.99	4.44
	%(Steady – Load-based)	**28.3%**	**32.9%**	**27.7%**	**34.0%**	**26.9%**	**27.3%**	**32.9%**	**29.4%**
HP 2	**Steady-State**	7.38	6.87	7.33	6.68	7.25	7.37	6.40	7.43
	Load-based	6.35	5.72	6.31	5.54	6.25	6.37	5.31	6.35
	%(Steady – Load-based)	**16.3%**	**20.0%**	**16.2%**	**20.5%**	**16.0%**	**15.6%**	**20.6%**	**16.9%**

In Table 10, Table 11 and Table 12, the columns under the “CSA standard Draft” used the CSA standard draft temperature bins data for different climate zones, whereas the columns under “AHRI” used the AHRI-210/240 temperature bins data. The rows corresponding to “Steady-State” show the SCOP results based on AHRI-210/240 using steady-state test results, whereas the rows “Load-Based” show the SCOP results based on the CSA standard draft using load-based test results. The rows “%(Steady - Load-based)” show the percentage differences in SCOP estimates based on steady-state testing compared to load-based testing.

Table 10 shows the cooling seasonal performance ($SCOP_c$) comparisons for HP1 and HP2. The steady-state test method estimates a higher $SCOP_C$ compared to the load-based test method with a difference varying from 26.9% to 34% for HP1 and 15.6% to 20.6% for HP2 depending on climate zone. The differences in $SCOP_C$ for HP2 were smaller than the differences for HP1, which may be due to fact that unit control settings for steady-state testing of HP2 did not follow the exact AHRI standard required unit settings. Table 11 and Table 12 show the comparisons of heating seasonal performance ($SCOP_h$) of HP1 and HP2 for the AHRI and CSA standard draft climate zones, respectively. For HP1, the steady-state test method estimates a higher $SCOP_h$ compared to the load-based test method for all different climate zones with differences varying from 35.3% to 64.2%. For HP2, the steady-state test method estimates significantly higher $SCOP_h$ than the load-based test method in cold climates with the differences decreasing in the warmer climates. The differences in $SCOP_h$ estimates for HP2 are very sensitive to the choice of climate zone, varying from -5% to 80.2%. For AHRI climate zone 1 (Florida region), the estimates of $SCOP_h$ of HP2 for the load-based test methodology were 5% higher than steady-state test method.

Table 11: Load-based and Steady-state tests heating seasonal performance ($SCOP_h$) comparison of HP1 and HP2 based on AHRI climate zone temperature bins

	Test Method	**Climate Zones (Temperature Bins)**					
		AHRI 210/240-2008					
		I (Hot-Humid)	II (Hot-Humid)	III (Hot-Dry / Mixed-Humid)	IV (Cold-Humid / Cold-Dry)	V (Very Cold)	VI (Marine)
HP1	**Steady-State**	4.52	4.13	3.75	3.16	2.52	4.33
	Load-based	2.92	2.74	2.53	2.13	1.74	2.64
	%(Steady - Load-based)	**54.5%**	**50.5%**	**48.3%**	**48.6%**	**44.6%**	**64.1%**
HP2	**Steady-State**	5.53	5.45	5.43	5.36	4.83	5.56
	Load-based	5.82	5.47	4.97	3.96	2.74	5.30
	%(Steady - Load-based)	**-5.0%**	**-0.3%**	**9.2%**	**35.2%**	**76.7%**	**4.9%**

Table 12: Load-based and Steady-state tests heating seasonal performance ($SCOP_h$) comparison of HP1 and HP2 based on CSA standard draft climate zone temperature bins

	Test Method	**Climate Zones (Temperature Bins)**							
		CSA Standard Draft							
		Subarctic	Very Cold	Cold/ Dry	Cold/ Humid	Marine	Mixed	Hot/ Humid	Hot/Dry
HP1	**Steady-State**	1.95	2.46	3.02	2.73	4.20	3.32	4.00	3.83
	Load-based	1.44	1.76	2.09	1.91	2.56	2.31	2.67	2.57
	%(Steady - Load-based)	**35.3%**	**39.7%**	**44.3%**	**42.9%**	**64.2%**	**43.5%**	**49.7%**	**49.2%**
HP2	**Steady-State**	3.32	4.36	5.07	4.95	5.47	5.38	5.35	5.36
	Load-based	1.84	2.69	3.76	3.23	5.17	4.48	5.33	5.08
	%(Steady - Load-based)	**80.2%**	**62.0%**	**34.9%**	**53.0%**	**5.8%**	**19.9%**	**0.3%**	**5.6%**

Since the same weather data was utilized for the comparisons, the differences in seasonal performance associated with the steady-state and load-based testing approaches were due to the differences in unit performance measurements and the building load lines. In cooling mode, the steady-state testing (humid coil tests) indoor temperature setpoint was

80°F, whereas in the load-based humid coil cooling tests the indoor temperature was set at 74°F. This improved the performance of the unit in the steady-state cooling test. Also, the steady-state tests involved keeping the indoor side conditions constant and running the unit at a constant compressor and fan speed for each test point. While in load-based testing, the unit responded to a building load and indoor temperature floated as per the difference in building load and unit capacity. These results show that the current steady-state test based rating standard estimates a higher seasonal performance of a heat pump system than the load-based testing methodology. In the future, comparing the seasonal performance based on both testing approaches with actual field data of a unit can provide further insights into the efficacy of the two standards.

6. CONCLUSIONS

This paper presents performance results of two variable-speed residential heat pump systems evaluated based on a new load-based testing methodology. The heat pump operated in response to a building load at different test conditions in heating and cooling mode. At low building loads, the units cycled on and off. As the test conditions changed to medium building loads, the units tried to match the capacity with the building load utilizing variable-speed operation. At high building loads, the units operated at full capacity. The load-based testing captured unit performance and dynamics of both system and controls, which is similar to actual field operation. AHRI-210/240 steady-state tests were also conducted on both heat pump systems in order to provide comparisons of seasonal performance for the two approaches. For both heat pump systems, estimates of the cooling seasonal performance based on steady-state testing approach were significantly higher (15.6% to 34%) compared to the load-based testing methodology. The heating seasonal performance estimates based on steady-state testing compared to load-based testing were higher for heat pump 1 in all climate zones and in cold climate zones for heat pump 2. In warm climate zones, both of these methodologies estimated comparable heating seasonal performance for heat pump 2. In addition to enabling more representative performance ratings of heat pumping and air conditioning equipment, load-based testing is a valuable tool for testing advanced controls as part of a development process for future equipment designs.

NOMENCLATURE

AHRI	Air-conditioning, Heating & Refrigeration Institute	HVAC	Heating, Ventilation and Air-conditioning
HVAC	Heating, Ventilation and Air-conditioning	RTU	Rooftop Unit
CSA	Canada Standard Association	BL	Building Load (W)
$\dot{Q}_c$	Cooling Capacity	SHR	Sensible Heat Ratio
ODB	Outdoor Drybulb temperature (°F)	IDB	Indoor Drybulb temperature (°F)
OWB	Outdoor Wetbulb temperature (°F)	IWB	Indoor Wetbulb temperature (°F)
HP	Heat Pump	COP	Coefficient of Performance
SCOP	Seasonal Coefficient of Performance		

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