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Comparison of Steady-State and Dynamic Load-Based Performance Evaluation Methodologies for a Residential Air Conditioner

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ABSTRACT

Space cooling and heating equipment account for nearly 32% of the total residential electricity consumption in the U.S. In the residential space conditioning equipment market, air-conditioning and heat-pumping systems are prevalent, so even a slight improvement in these system efficiencies can have a significant impact on reducing the overall energy consumption. Over the years, the energy efficiency benchmarks established by the U.S. Department of Energy have been successful in encouraging manufacturers to develop higher efficiency equipment. These benchmarks are based on an energy efficiency standard, and these standards are based on a rating test procedure that forms the technical basis. Currently, in the U.S., AHRI 210/240 is the rating procedure for residential air-conditioning and heat-pumping equipment, which is based on a steady-state performance measurement method with a degradation coefficient to account for the cycling losses in part-load conditions. Although it provides a standard metric to compare different equipment performances, there has been a debate that this current methodology fails to appropriately characterize the performance of systems with variable-speed compressors and advanced control design. This is largely attributed to the steady-state nature of this current testing approach, which also involves overriding the equipment native control. In contrast to this, a load-based testing methodology has been developed in which the equipment responds to a simulated virtual building load, and the system dynamic performance is measured with its integrated controls. The load-based testing methodology is described in detail by Hjortland and Braun (2019), Patil et al. (2018), and Cheng et al. (2021), which forms the basis for CSA standard draft EXP07:2019 (CSA, 2019). In this paper, these two performance measurement methodologies, steady-state and dynamic load-based, are compared for application to a 5-ton residential heat-pump system. The equipment performance was measured in cooling mode and the seasonal performance estimates based on the two testing approaches are compared. The differences in the two test methodologies' performance evaluation results are discussed with a causal analysis of the observed differences.

1. INTRODUCTION

In the U.S., the current testing and rating procedure for electric driven residential air-conditioning and heat-pumping vapor compression direct-expansion (DX) systems is based on AHRI 210/240 (AHRI, 2020) along with the method of test (MoT) outlined in ASHRAE Standard 37 and 116 (ASHRAE, 2010, 2019). Based on the current procedure, test equipment is installed in a pair of psychrometric test rooms serving as an indoor and outdoor environment, and its performance (i.e., cooling or heating capacity, and power consumption) is measured at different sets of required and optional test conditions depending on the system configuration (e.g. single-stage, two-stage or variable-speed type). For a test interval, indoor and outdoor test rooms conditions are kept at steady-state, and compressor and indoor unit fan speed are fixed, usually with proprietary control settings from the manufacturer. Measured performance at different ambient conditions is then utilized to estimate seasonal performance of equipment based on a temperature-bin method. This rating approach provides a standard metric of performance for comparing the relative performance of different available systems in the market; however, it does not characterize the overall performance of a system with its embedded controls and their dynamic interaction with representative building loads. This could result in seasonal performance estimates that may not be representative of the test unit's actual field performance. Proctor & Cohen (2006) monitored field performance for five high SEER (Seasonal Energy Efficiency Ratio) air conditioners, four with 2-stage and one with 1-stage compressor, and observed that actual energy efficiency ratios were between 59% to 84% of the rated SEER. Kavanaugh (2002) also expressed concerns on using SEER as an actual energy savings indicator for the unit because of the high indoor temperature used in the current testing approach compared to the typical field application, little consideration of dehumidification performance, and a low external static pressure requirement compared to a typical application. All of these factors could lead to an overestimation of seasonal performance. As an alternative, a load-based testing methodology has recently been developed in which the dynamic performance of a heat-pump is measured in a test facility by allowing it to respond to an emulated representative building model.

In the load-based testing approach, the indoor psychrometric test room temperature and humidity conditions are continuously adjusted using a virtual building model to emulate the response of a representative building being served by the heat-pump system. The test unit thermostat is also installed in the indoor psychrometric test room, which senses this dynamic temperature variation from its setpoint, and accordingly, equipment controls respond. In this way, the load-based testing approach enables capturing the dynamic performance of the equipment with its integrated controls and thermostat in a laboratory environment. Patil et al. (2018), Hjortland and Braun (2019), and Cheng et al. (2021) provide details on the load-based testing methodology development and implementation, which forms the basis for CSA (Canadian Standards Association) standard draft EXP07 (CSA, 2019) for residential equipment. Hjortland and Braun (2019) demonstrated the load-based testing approach to evaluate and compare two similar RTUs (rooftop units) performance with their integrated controls in three different modes – single-stage, two-stage, and variable-speed. Patil et al. (2018) and Cheng et al. (2021) further extended the load-based laboratory testing approach for residential air-conditioning equipment performance evaluation with their embedded controls and thermostat. Cheng et al. (2018) presented a sensitivity study of thermostat location and virtual building parameters on load-based test results. Dhillon et. al. (2021c) compared the cooling mode performance and dynamic behavior of a heat-pump in a residential house to that of a laboratory using a load-based testing approach at similar test conditions. Dhillon et al. (2021b) further extended this load-based testing approach for RTUs with integrated econmoizers. Another application of the load-based testing approach could be the evaluation of advanced heat-pump control design in a laboratory setting as demonstrated by Dhillon et al. (2021a) and Ma et al. (2021). Further, Dhillon et al. (2018) evaluated and compared the performance of two residential heat-pumps based on the load-based testing methodology as well as the steady-state testing approach, AHRI 210/240 (2012). They observed that, for both heat pump systems, estimates of the cooling seasonal performance based on the steady-state testing (AHRI 210/240) approach were significantly higher (15.6% to 34%) compared to the load-based testing results. These differences were due to the differences in the testing approach and test conditions between the two methodologies as well as due to the difference in building load-lines utilized for seasonal performance estimation.

The motivation for this study was to further extend the Dhillon et al. (2018) work to better understand and quantify the differences between the two test approaches utilizing a different residential heat-pump system. In this work, a 5-ton variable-speed heat-pump system was installed and tested in the psychrometric test facility at the Ray W. Herrick Laboratories using load-based testing (CSA, 2019) and steady-state testing (AHRI, 2020) approaches. First, the heat-pump performance was measured in cooling mode at the test conditions defined in EXP07 (CSA, 2019) for load-based testing and AHRI 210/240 (AHRI, 2020) for steady-state testing. The two test methodologies have different target indoor conditions, so to isolate the effect of differences in the indoor conditions from performance measurement differences, heat-pump performance was also measured based on EXP07 and AHRI 210/240 ambient test conditions but with the same target indoor conditions. Then, performance estimates from measurements based on both approaches were propagated through a temperature-bin method to estimate the seasonal performance for different climate zones. In this paper, a comparison of the test results based on the two methodologies is presented along with an analysis of the differences. In the sections below, first, an overview of the test setup and two test methodologies is provided. Then, the heat-pump performance results are presented and a comparison with an analysis of the differences is presented. Finally, the conclusions section provides a brief summary and review of the results with a discussion of future work.

2. TEST SETUP AND METHODOLOGY

A 5-ton variable-speed split-type ducted heat pump was installed in a pair of psychrometric test rooms at the Ray W. Herrick Laboratories. The indoor unit return and supply air temperatures were measured using thermocouple grids, and humidities were measured using chilled mirror dew point hygrometers. The indoor unit supply air volumetric airflow was measured using a nozzle box code-tester. To verify the air-side measurements, refrigerant-side capacity was also determined based on the refrigerant mass flow rate measured using a Coriolis-effect mass flow meter, together with pressure and temperature measurements at different state points of the cycle. The indoor and outdoor

unit power consumptions were also measured. The thermostat was installed on a wooden board around 4 ft high from the floor in the indoor psychrometric test room to control the unit during load-based testing.
First, the test unit performance was measured for cooling with dry and humid-coil test conditions as per EXP07 (CSA, 2019) using the load-based testing methodology and also for steady-state test conditions as per AHRI 210/240 (AHRI, 2020). For load-based testing, the virtual building model parameters were scaled based on the test unit full-load (i.e. maximum) capacity measured at A_{Full} test conditions (AHRI, 2020). Then, the test unit performance was also evaluated at the same load-based and steady-state test conditions except with a target indoor temperature of 75°F and relative humidity (RH) of 51.1%. Finally, the measured test results were used to estimate the cooling seasonal performance based on a temperature-bin method for the purpose of comparing performance ratings. In the sections below, an overview of the two testing and rating methodologies for residential air-conditioners is provided along with the test conditions and an overview of the seasonal performance estimation approach.

2.1 Load-Based Testing Methodology

The load-based testing methodology involves emulating the dynamic response of a representative building in the indoor side psychrometric chamber by dynamically adjusting the psychrometric chamber temperature and humidity setpoints using a virtual building model as illustrated in Figure 1. The virtual building model represents the building heat load and thermal mass characteristics of a representative residential building. In this work, a simple virtual building model similar to the one described by Patil et al. (2018), Hjortland and Braun (2019), and Cheng et al. (2021) was utilized. The load-based testing approach and virtual building model parameters were used as per EXP07 (CSA, 2019) for cooling mode performance measurement.

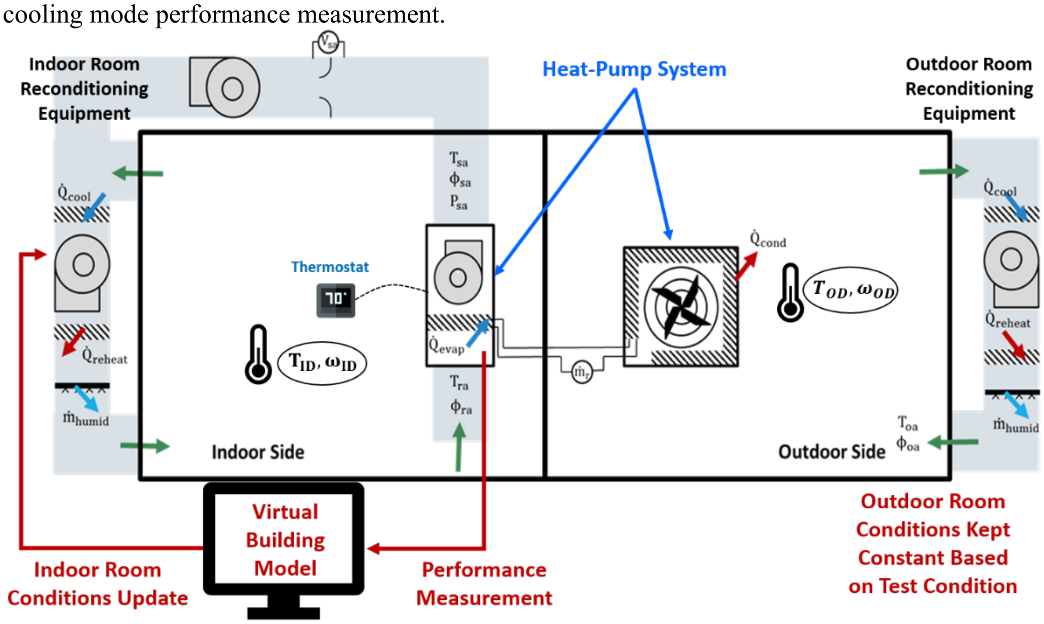

Figure 1. Load-Based Testing Schematic for a Split-Type Heat-Pump System in a Psychrometric Test Facility

In this methodology, for each test interval, the outdoor test room conditions are kept constant, whereas, the indoor conditions are continuously varied based on a virtual building model response. During a load-based test, the virtual building model temperature (T_{ID}) and humidity ratio (ω_{ID}) are updated for the next time step ($t + \Delta t$) from the current time step (t) as per Equations (1) and (2), respectively, based on the virtual building loads, sensible $\left(BL_{c,s}\right)$ and latent $\left(BL_{c,l}\right)$, together with the test unit measured cooling rates in real-time, sensible $\left(\dot{Q}_{c,s}\right)$ and latent $\left(\dot{Q}_{c,l}\right)$.

$$T_{ID}(t + \Delta t) = T_{ID}(t) + \Delta t \cdot \left(\frac{BL_{c,s} - \dot{Q}_{c,s}}{C_s}\right) \tag{1}$$

$$\omega_{ID}(t + \Delta t) = \omega_{ID}(t) + \Delta t \cdot \left(\frac{BL_{c,l} - \dot{Q}_{c,l}}{h_{fg} \cdot C_w}\right) \tag{2}$$

where C_s and C_w are the effective thermal and moisture capacitances, respectively, for a representative residential building scaled to the equipment sensible $\left(\dot{Q}_{c,s,D}\right)$ and total $\left(\dot{Q}_{c,D}\right)$ cooling capacities at design conditions as per Equation (3) and (4), and h_{fg} is the latent heat of vaporization for water.

$$C_s[J/°\mathrm{F}] = \frac{\dot{Q}_{c,s,D}[W] \cdot 300[s]}{\Delta T_{db}[°\mathrm{F}]} \tag{3}$$

$$C_w[kg] = \frac{\dot{Q}_{c,D}[W]}{12.9\ [W/kg]} \tag{4}$$

where ΔT_{db} is the thermostat deadband defined as the difference between upper and lower bounds. The virtual building model sensible heat gain or load $\left(BL_{c,s}\right)$ for cooling mode testing is defined as a linear function of outdoor temperature $\left(T_{OD}\right)$ scaled to the test unit cooling capacity at design conditions $\left(\dot{Q}_{c,D}\right)$ as per Equation (5).

$$BL_{c,s} = \frac{1}{F} \cdot \frac{\dot{Q}_{c,D} \cdot SHR_{Building}}{\left(T_{OD,D} - T_{Bal,D}\right)} \cdot \left(T_{OD} - T_{Bal}\right) \tag{5}$$

where F is the building load sizing factor to scale the load-line, $SHR_{Building}$ is the building cooling load sensible heat ratio, $T_{OD,D}$ is the outdoor design temperature, and $T_{Bal,D}$ is the design balance point temperature. T_{Bal} is the effective balance point temperature, which is updated as per Equation (6) to account for the variation in building load due to a change in indoor temperature (T_{ID}) from the indoor design temperature $(T_{ID,D})$, which is also the thermostat setpoint.

$$T_{Bal} = T_{Bal,D} + \left(T_{ID} - T_{ID,D}\right) \tag{6}$$

The virtual building latent load $\left(BL_{c,l}\right)$ is defined based on the simple assumption of maintaining a constant building load sensible heat ratio $(SHR_{Building})$ as per Equation (7).

$$BL_{c,l} = BL_{c,s} \cdot \left(\frac{1}{SHR_{Building}} - 1\right) \tag{7}$$

During a load-based test, the virtual building temperature and humidity conditions are continuously updated based on equations (1)-(7), which are then sent as setpoints to the indoor psychrometric test room for each time step. In this way, the dynamic response of a representative building is emulated in the indoor side psychrometric chamber and heat-pump performance is measured with its integrated controls and thermostat.

Table 1. Load-Based Testing Methodology Cooling Mode Test Conditions (CSA, 2019)

Test	**Humid Test Conditions**			**Dry Test Conditions**		
	Outdoor Temperature [°F]	Indoor Temperature [°F]		Outdoor Temperature [°F]	Indoor Temperature [°F]	
	Dry Bulb	Dry Bulb	Wet Bulb	Dry Bulb	Dry Bulb	Wet Bulb
A	N/A	74	63	113	79	56 (maximum)
B	104			104		
C	95			95		
D	86			86		
E	77			77		

In load-based testing for cooling, a test unit's performance is evaluated at two different sets of test conditions, dry and humid, as given in Table 1. In a load-based test, the indoor conditions represent the target comfort conditions set as the test unit thermostat and/or humidistat setpoint, whichever is applicable. For dry coil tests, only sensible building loads are simulated with indoor humidity levels low enough such that there is no dehumidification at the indoor unit cooling coil. For humid test conditions, both sensible as well as latent loads are simulated, and test equipment sensible and latent cooling performance is measured. At test conditions where the unit fails to maintain the indoor temperature to the target thermostat setpoint due to the maximum capacity being less than the building load, a full-load test is conducted. In a full-load test, indoor and outdoor test rooms conditions are maintained at steady-state and the equipment performance is measured by running it full-out at maximum capacity with the test unit thermostat setpoint set below the target indoor condition. To scale the virtual building parameters, the test unit design cooling capacity was measured by running a full-load test at A_{Full} indoor and outdoor test conditions (AHRI, 2020). In addition to the test conditions shown in Table 1, heat-pump performance was also evaluated for dry and humid-coil ambient conditions but with a target indoor temperature of 75°F along with relative humidity (RH) of 51.1% for humid-coil tests. For these load-based tests, virtual building parameters were scaled based on the design cooling capacity measured at A_{Full} outdoor test conditions, but with indoor conditions of 75°F dry-bulb temperature and 51.1% RH.

2.2 Steady-State Testing Methodology

In the steady-state testing methodology based on AHRI 210/240 (AHRI, 2020), heat-pump performance is measured utilizing a test setup similar to the one shown in Figure 1 (i.e., in two side-by-side psychrometric test chambers). For variable-speed system performance measurements, Table 2 shows the 5 required humid-coil test conditions for cooling mode based on AHRI 210/240. Note that, in addition to indoor and outdoor test room conditions, compressor speed and indoor unit volumetric airflow rate requirements are also defined for each test interval. In this work, the compressor speeds and airflow rates were set based on proprietary test settings provided by the manufacturer, overriding the system's native controls. Similar to load-based testing, heat-pump performance was also evaluated at steady-state test outdoor conditions shown below but with indoor conditions of 75°F dry-bulb temperature and 51.1% RH.

Table 2. Steady-State Methodology Cooling Mode Test Conditions (AHRI, 2020)

Test	**Indoor Conditions**		**Outdoor Conditions**		**Compressor Speed**	**Air Volume Rate**
	Dry Bulb [°F]	Wet Bulb [°F]	Dry Bulb [°F]	Wet Bulb [°F]		
A_{Full}	80	67	95	75	Maximum	Full Load
B_{Full}			82	65	Maximum	Full Load
E_{Int}			87	69	Intermediate	Intermediate
B_{Low}			82	65	Minimum	Minimum
F_{Low}			67	53.5	Minimum	Minimum

2.3 Seasonal Performance Estimation

Both test methodologies utilize a temperature-bin method (ASHRAE, 2017; Knebel, 1983) to estimate the cooling and heating seasonal performance based on the measured performance at different ambient temperature conditions. For more details, the reader is referred to AHRI 210/240 (AHRI, 2020) for steady-state testing and EXP07 (CSA, 2019) for the load-based testing approach. For a climate zone, cooling seasonal coefficient of performance ($SCOP$) is estimated as the ratio of the weighted average of cooling load with the bin-hour fractions to the weighted average of estimated power consumption with the bin-hour fractions at different bin temperatures. AHRI 210/240 defines cooling season bin-hour fractions for a single climate zone, whereas EXP07 defines values for 7 different cooling climate zones. For the load-based seasonal performance evaluation methodology, Table 3 summarizes the load-based testing results that are used for each climate zone in the $SCOP$ calculation.

Table 3. EXP07 (CSA, 2019) Cooling Climate Zones and Test Results used for **$SCOP$** Estimation

Climate Zone	***Very Cold***	***Cold/Dry***	***Cold/Humid***	***Marine***
Cooling Test Type used	Humid Tests	Dry Tests	Humid Tests	Dry Tests
Climate Zone	***Mixed***	***Hot/Humid***	***Hot/Dry***	
Cooling Test Type used	Humid Tests	Humid Tests	Dry Tests	

3. TEST RESULTS

3.1 Load-Based Testing Results

For scaling of the virtual building loads and capacitances, the test unit design cooling rate was measured at a steady-state A_{Full} test (AHRI, 2020) condition with the indoor test room at 80°F dry-bulb / 67°F wet-bulb (51.1% RH), the outdoor test room at 95°F dry-bulb temperature conditions, and the heat pump running at full-capacity in cooling mode. Table 4 shows the virtual building parameters for dry as well as humid-coil cooling test conditions that were utilized with equations (1)-(7) to perform load-based tests as per EXP07.

Table 4. Virtual Building Parameters for Load-Based Testing as per EXP07

Parameter	$\dot{Q}_{c,D}$	$\dot{Q}_{c,s,D}$	**Dry-Coil**			
			$SHR_{Building}$	$T_{OD,D}$	$T_{Bal,D}$	$T_{ID,D}$
	W	W	-	°F	°F	°F
Value	16212	12692	1	105	72	79
Parameter	ΔT_{db}	F	**Humid-Coil**			
			$SHR_{Building}$	$T_{OD,D}$	$T_{Bal,D}$	$T_{ID,D}$
	°F	-	-	°F	°F	°F
Value	2	1.2	0.8	95	67	74

To compare the load-based and steady-state test results with similar indoor conditions, the heat-pump performance was also evaluated with load-based testing at the same dry and humid-coil ambient conditions as per Table 1 but with a target indoor temperature of 75°F and RH of 51.1%. For these load-based tests, virtual building parameters were scaled based on the equipment design cooling capacity measured for a full-load test with the indoor test room at 75°F dry-bulb / 63°F wet-bulb (51.1% RH) and the outdoor test room at 95°F dry-bulb temperature conditions. Table 5 provides the virtual building parameters that were updated from Table 4 for these load-based tests.

Table 5. Updated Virtual Building Parameters for Load-Based Testing with 75°F Indoor Target Temperature

Parameter	$\dot{Q}_{c,D}$	$\dot{Q}_{c,s,D}$	**Dry-Coil**	**Humid-Coil**
			$T_{ID,D}$	$T_{ID,D}$
	W	W	°F	°F
Value	14483	11585	75	75

Figure 2 shows the heat-pump performance, temperature, and humidity variation for cooling humid-coil load-based tests at 4 different ambient temperature conditions. In the upper subplot, the test unit sensible and latent cooling rate, virtual building sensible and latent load, and total power consumption correspond to the left vertical axis and indoor unit airflow corresponds to the right vertical axis. The lower subplot shows the virtual building indoor temperature (IDT) and relative humidity (RH), actual indoor temperature and relative humidity, and thermostat setpoint (SP) on the left vertical axis, and the outdoor temperature setpoint and its measured value on the right vertical axis. During this load-based test sequence, the indoor temperature and relative humidity measured at the AHU (air handling unit) return air inlet were controlled to the virtual building temperature and RH setpoint, and it can be seen that the test room re-conditioning system was able to track the virtual building conditions very well. The thermostat was set to 74°F for this humid-coil cooling load-based test, and the heat pump cycled on/off at its minimum compressor speed at the low ambient temperature condition of 77°F where building loads were relatively small. As the ambient temperature increased, the heat-pump operated in variable-speed mode at the moderate building load outdoor test conditions of 86°F and 95°F, and ran out of capacity to meet the building load at the 104°F ambient test condition. A full-load test was performed at the outdoor test condition of 104°F by setting the indoor temperature at a fixed value of 74°F and forcing the unit to run at maximum capacity by lowering the thermostat setpoint. During the full-load test, virtual building sensible load model was deactivated, however, the latent load model was still implemented and relative humidity converged to around 60%. The test equipment controlled the indoor temperature around the thermostat setpoint, however, indoor relative humidity increased above 60% at the low load test interval when the unit was cycling on/off. Another thing to note is that this variable-speed unit effectively operated as a two-stage unit.

Figure 3 shows the heat-pump performance and temperature variation for cooling dry-coil load-based tests at different outdoor temperature conditions with a target indoor temperature of 75°F (thermostat setpoint). In dry-coil cooling load-based tests, the virtual building latent load model was deactivated and the indoor temperature was controlled based on the virtual building sensible load model response. The test unit cycled on/off at the outdoor test condition of

77°F, 86°F and 95°F, ran in variable-speed mode at 104°F ambient conditions and failed to maintain the indoor temperature close to the thermostat setpoint at 113°F outdoor test condition. A full-load test was performed for the 113°F test interval, which is not shown in this plot. In this test, as the outdoor temperature increased and the unit started utilizing a high-stage mode, the variations in the indoor temperature increased significantly which might be uncomfortable for an occupant in a house. For each test interval, the test unit performance was determined based on the convergence criteria outlined in EXP07 (CSA, 2019) and Cheng et al (2021). Overall, these results illustrate the application of the load-based testing methodology to measure the dynamic performance of a heat-pump with its embedded controls and thermostat.

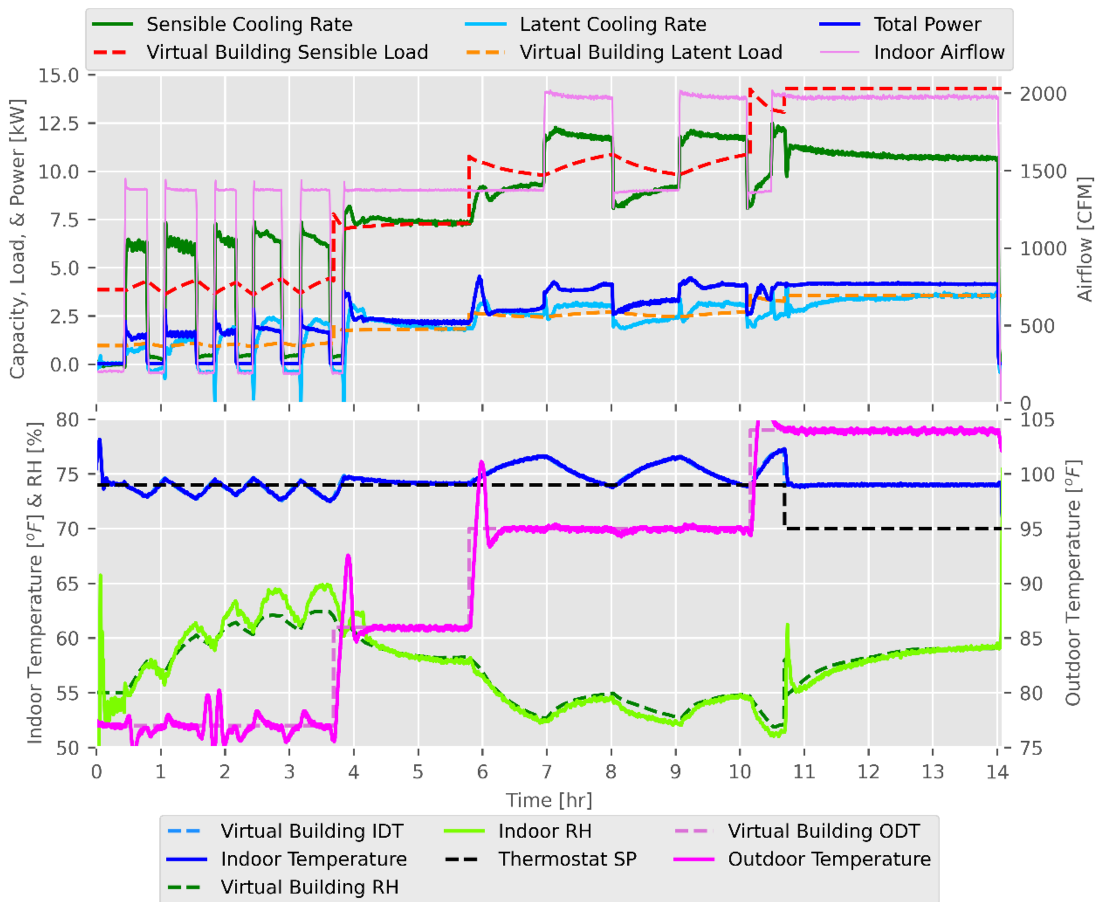

Figure 2. Heat-pump Performance, Temperature, and Humidity Variation for Cooling Humid-Coil Load-Based Test with target indoor temperature of 74°F

Figure 4 and Figure 5 show overall cooling dry and humid-coil load-based test results for COP (coefficient of performance) along with the test unit behavior during different outdoor condition test intervals with target indoor conditions as per EXP07 (Table 1) and with target indoor conditions of 75°F and 51.1% RH, respectively. In both plots, "cycling" refers to the test unit cycle on/off behavior during load-based tests. For both sets of tests, humid-coil tests had higher COP compared to dry-coil tests in general except at the 104°F outdoor condition test interval with indoor target temperatures as per Table 1, i.e. 79°F for dry-coil and 74°F for humid-coil tests. For dry-coil tests, COPs with a 75°F target indoor temperature were around 4% to 8% lower compared to the 79°F indoor temperature, except for the 95°F ambient condition test where the test unit cycling on/off behavior was different, resulting in different cycling losses. On the other hand, for humid-coil tests, COPs were comparable for 77°F and 104°F outdoor test conditions, and around 3% lower for 86°F and 5% higher for 95°F ambient test conditions with a 75°F indoor target compared to the indoor target conditions of 74°F. As the indoor conditions were comparable, this variation was mainly due to the change in loads between two sets of tests which resulted in the different dynamic behavior of the unit to compensate for that load.

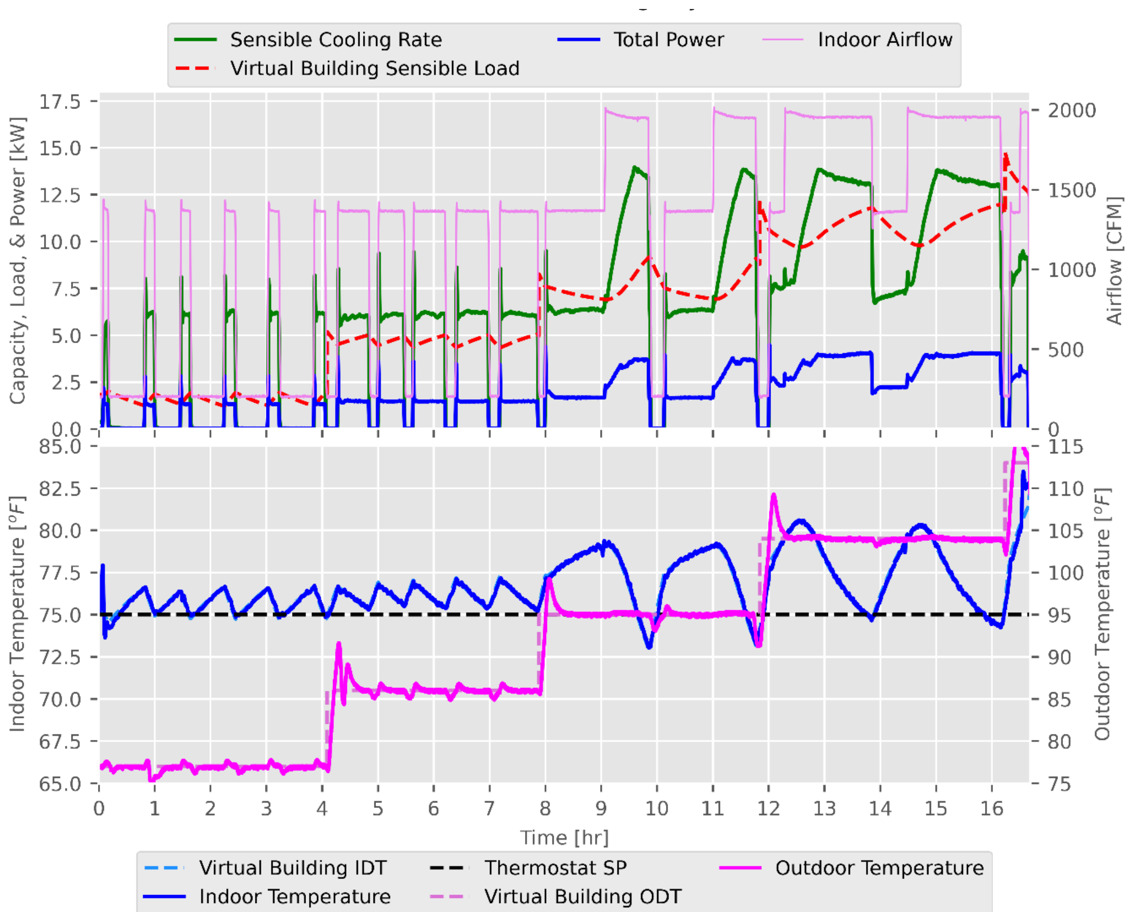

Figure 3. Heat-pump Performance and Temperature Variation for Cooling Dry-Coil Load-Based Test with Target Indoor Temperature of 75°F

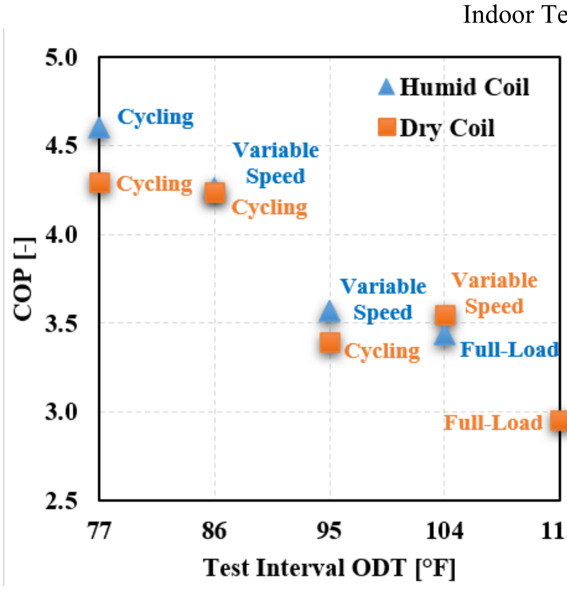

Figure 4. Cooling Load-Based Tests COP and Unit Behavior with EXP07 (Table 1) Indoor Target Conditions

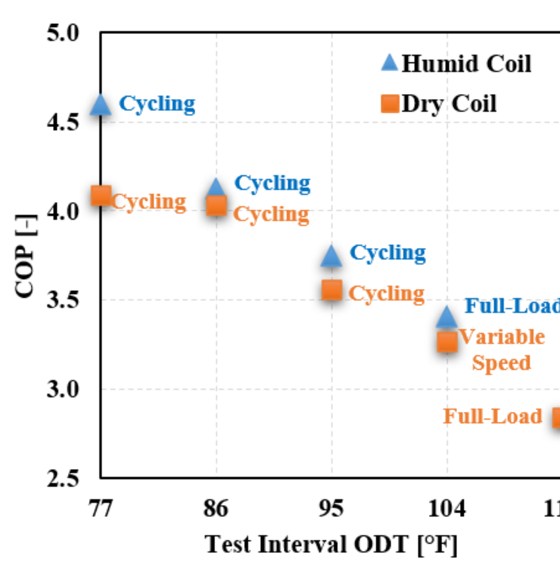

Figure 5. Cooling Load-Based Tests COP and Unit Behavior with 75°F and 51.1% RH Indoor Target Conditions

3.2 Steady-State Testing Results

Figure 6 and Figure 7 show steady-state (AHRI 210/240) results for COP at different outdoor temperatures and compressor speeds with the indoor temperature conditions of 80°F and 75°F, respectively. During these tests, proprietary control settings from the manufacturer were utilized to set the compressor speeds and indoor airflow at different test conditions as per AHRI 210/240. As expected, at the same ambient temperature, the test unit COP decreased with increasing compressor speed and at the same compressor speed, COP decreased with increasing outdoor temperature for the cooling tests. At the same ambient test conditions with the indoor temperature of 75°F, COP was lower (9% to 18%) compared to the tests at the indoor temperature of 80°F due to a decrease in the evaporator inlet air temperature.

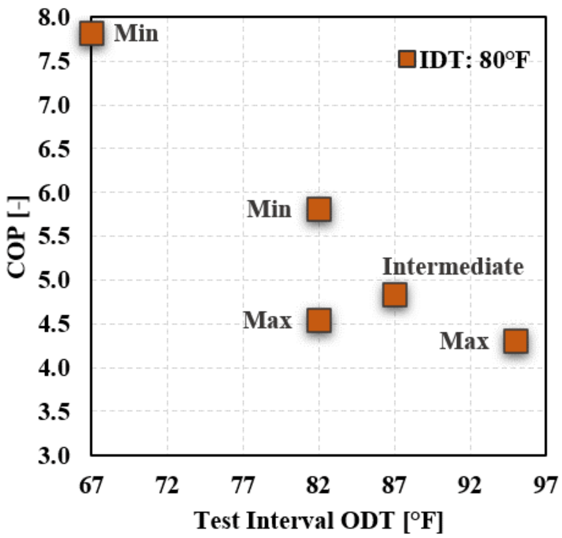

Figure 6. Cooling Steady-State Tests COP with 80°F and 51.1% RH Indoor Conditions

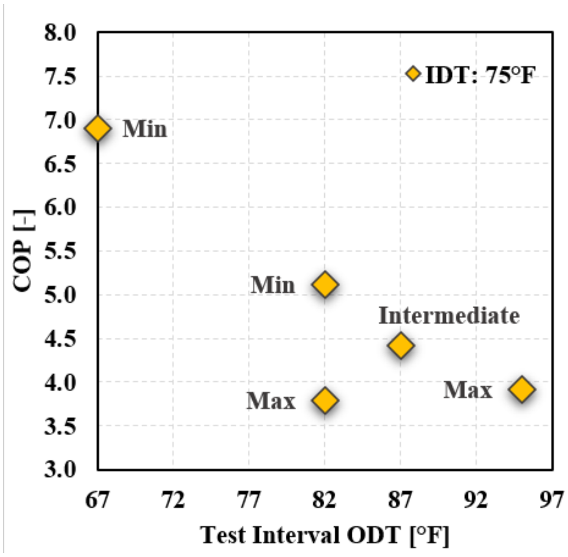

Figure 7. Cooling Steady-State Tests COP with 75°F and 51.1% RH Indoor Conditions

3.3 Seasonal Performance Comparisons

The measured performance results at different outdoor temperature conditions for the load-based and steady-state testing methodologies were propagated through a temperature-bin method to determine seasonal performance. The cooling seasonal coefficient of performance (SCOP) was calculated based on the AHRI 210/240 (AHRI, 2020) standard using steady-state test results with a default degradation coefficient of 0.25 for cycling losses and also based on the CSA EXP07 (CSA, 2019) standard draft using load-based test results. These two standards define different climate zones and also different cooling season temperature bin-hour fractions for those climate zones. To mitigate the effect of different temperature bin-hour fraction data in the performance comparisons, consistent climate data were used for the comparisons. Seasonal performance values for both standards were calculated using both AHRI 210/240 and CSA EXP07 temperature bin-hour data.

Figure 8 shows comparisons of estimated cooling SCOP based on the load-based testing approach (EXP07) utilizing the load-based test results and the steady-state testing approach (AHRI 210/240) utilizing the steady-state test results at corresponding ambient conditions as provided in Table 1 and Table 2, respectively. The steady-state test method estimates a higher SCOP compared to the load-based test method with a difference varying from 22% to 27% across different climate zones. The differences are similar for use of either CSA EXP07 or AHRI 210/240 bin-hour temperature data. Since the same climate zone and bin-hour fraction data were utilized, the differences associated with the steady-state and load-based testing methodologies results were due to the differences in the methods used for test unit control during testing (feedback versus overriding control), differences in test conditions, differences in the approach used to interpolate and extrapolate measured performance at different bin temperatures, and differences in the building load lines. In cooling mode steady-state testing (humid-coil tests), the indoor temperature is kept constant at 80°F; whereas, in the load-based testing, the indoor temperature varied around the target of 74°F for humid-coil cooling tests and 79°F for dry-coil cooling tests. To isolate the effect of differences in indoor conditions, SCOP estimates were also compared between two methodologies utilizing the load-based and steady-state test results at the same indoor test conditions of 75°F and 51.1% RH (for humid-coil tests only) as shown in Figure 9. Still, SCOP estimates based on the steady-state method were higher, but the differences decreased by 6% to 10% compared to the results with different indoor test conditions (Figure 8).

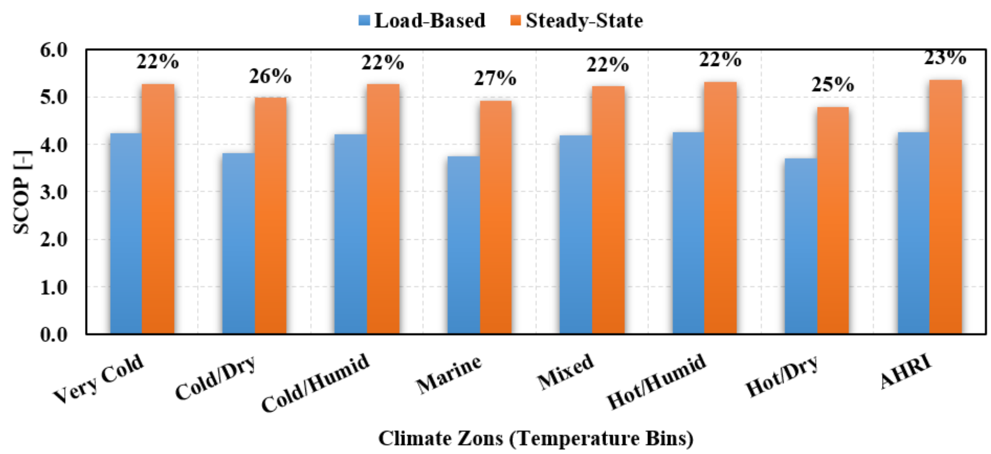

Figure 8. Cooling Seasonal Performance Comparisons for Load-Based and Steady-State Tests with Indoor Target Test Conditions as per CSA EXP07 (Table 1) and AHRI 210/240 (Table 2)

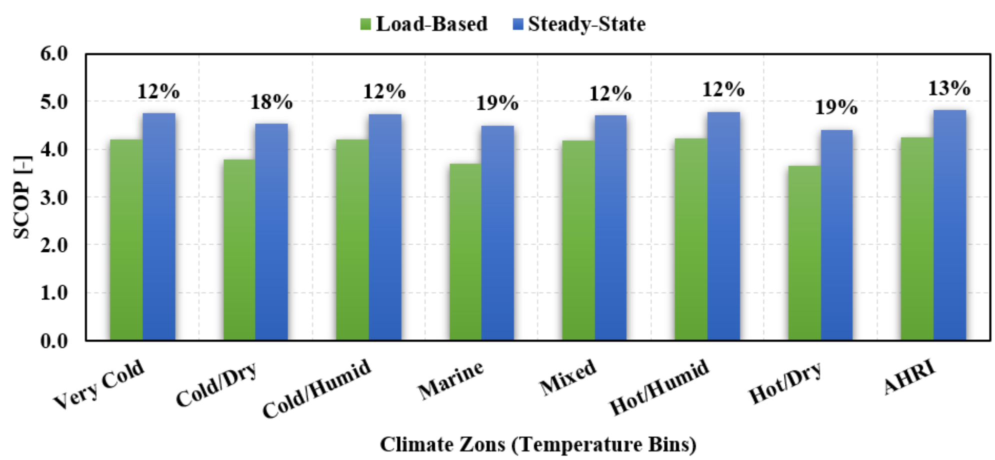

Figure 9. Cooling Seasonal Performance Comparisons for Load-Based and Steady-State Tests with same Indoor Target Test Conditions of 75°F and 51.1% RH

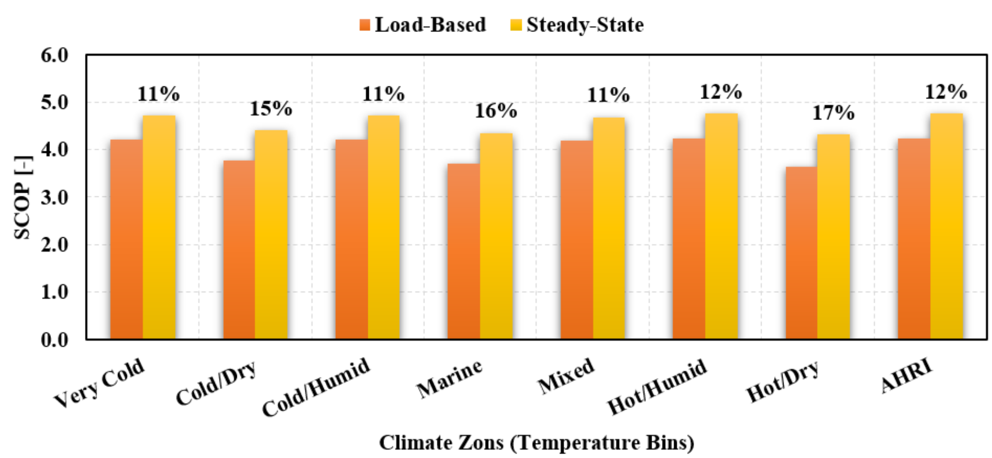

Figure 10. Cooling Seasonal Performance Comparisons for Load-Based and Steady-State Tests with same Indoor Target Test Conditions and same Load Lines

In addition, a comparison of SCOP estimates using the test results with the same target indoor conditions and the same load lines employed for the load-based testing methodology was performed as shown in Figure 10. Utilizing the same load lines further decreased the COP differences by 1% to 3%, bringing the overall differences to around 11% to 17%, with the steady-state testing approach predicting higher performance. The differences are mainly due to the differences in the fundamental test approach (i.e., dynamic with embedded controls vs steady-state with overriding native controls), differences in ambient conditions at which performance is measured, and differences in the interpolation and extrapolation approach of measured performance to different bin temperatures.

4. CONCLUSIONS

This paper presented a comparison of cooling mode performance results for a 5-ton variable-speed residential heat-pump system evaluated based on a new load-based testing methodology (CSA EXP07) and the existing steady-state testing approach (AHRI 210/240). In load-based testing, the heat pump operated in response to a simulated building load at different test conditions in cooling mode. In steady-state testing, test unit performance was measured by keeping the indoor and outdoor test room conditions at steady-state and fixing the compressor and fan speeds to specifications provided by the standard. Heat-pump performance comparisons between the two standards were presented for use of two different sets of indoor test conditions: 1) the defined indoor test conditions from EXP07 and AHRI 210/240 and 2) the same indoor target conditions of 75°F and 51.1% RH for both testing approaches. Cooling seasonal performance was estimated for different climate zones based on a temperature-bin method utilizing the measured performance at different ambient conditions for both testing approaches. Using the specified indoor test conditions from the two standards, estimates of the cooling seasonal performance based on the steady-state testing approach were significantly higher (22% to 27%) compared to the load-based testing methodology. The differences in seasonal performance estimates based on the two testing approaches decreased to around 11% to 17% when utilizing test results obtained using the same target indoor conditions and same load lines. However, estimates based on the steady-state testing method were still higher compared to the load-based testing method. The primary reasons for these differences in seasonal performance estimates are the differences between the two testing methodologies (steady vs dynamic), outdoor test conditions, and the approach used to estimate equipment performance at different bin temperatures. One of the next steps will be to perform a similar comparative study in heating mode for the two test methodologies.

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