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Validation of a Load-Based Testing Methodology for Residential Heat Pump Performance Characterization in Heating Mode

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ABSTRACT

A load-based testing methodology has been developed to capture realistic system performance of heat pumps and air conditioners in a laboratory setting while operating under conditions comparable to field application. In this approach, a heat pump responds to a simulated virtual building model, and the dynamic performance of the test unit is measured with its embedded controls and thermostat. However, it is important to evaluate how adequately the load-based testing approach captures the overall dynamic performance of a test unit in a laboratory compared to a typical residential application. In this study, a 3-ton heat pump system was first tested in a 2-story house located within a large-scale environmental chamber with controllable ambient temperature and humidity conditions. During testing, the house was subjected to ambient loads resulting from different external conditions, and the heat pump responded to maintain the indoor temperature at the thermostat setpoint. Then, the same make and model unit was installed in psychrometric chambers and tested using the load-based testing methodology. In this paper, test unit heating mode performance and dynamic behavior comparisons are presented based on testing performed at the house and in the lab. Overall comparable COPs were measured in the lab and the residential house facility with the difference varying between -3% and 2%. However, differences in the test unit on/off cycling behavior were observed between the two test facilities.

1. INTRODUCTION

The current performance rating approaches for residential heat pumps, e.g., AHRI 210/240 (AHRI, 2020) and EN 14825 (BSI, 2018), are primarily based on steady-state tests along with a degradation factor to account for cycling losses at part-load conditions. For a test interval, indoor and outdoor test room conditions are kept at a steady state, and compressor and fan speed are fixed, typically with proprietary control settings from the manufacturer. Then, for a heat pump, the heating seasonal performance is estimated by propagating the measured performance at different ambient conditions through a temperature-bin method. The current rating approach provides a standard metric for relative performance comparison of different systems; however, it does not characterize the overall performance of a system with its embedded controls and their dynamic interactions with realistic building loads. As an alternative, a load-based testing methodology has recently been developed in which the dynamic performance of the heat pump is measured in a test lab by allowing it to respond to a simulated virtual building model.

In the load-based testing approach, the indoor test room temperature and humidity conditions are continually adjusted using a virtual building model to emulate the response of a representative building served by the heat pump. The test unit thermostat installed in the indoor test room reacts to this dynamic temperature variation from its setpoint, and the test unit controls respond accordingly. The load-based testing approach thus provides an effective method of capturing the dynamic performance of the equipment with its integrated controls and thermostat in a test laboratory setting that is reflective of its field use. Hjortland and Braun (2019), Patil *et al.* (2018), Cheng *et al.* (2021b), and Dhillon *et al.* (2022a) describe the load-based testing methodology in detail, which forms the basis for CSA (Canadian Standards Association) standard draft EXP07:2019 (CSA, 2019). Hjortland and Braun (2019) demonstrated the load-based testing approach to evaluate and compare the performance of two similar RTUs (rooftop units) with their embedded controls in three different control modes: single-stage, two-stage, and variable-speed. Patil *et al.* (2018), Cheng *et al.*

(2021b), and Dhillon *et al.* (2022a) further extended the load-based testing approach for performance evaluation of residential air conditioners and heat pumps with their embedded controls and thermostat. Cheng *et al.* (2018) presented a sensitivity study of virtual building parameters and thermostat location on load-based test results at different ambient conditions and overall seasonal performance estimation. Cheng *et al.* (2021a) developed a thermostat environment emulator (TEE) to provide standardized environmental conditions to the thermostat in the lab to improve load-based testing repeatability and reproducibility. Kim *et al.* (2022) further updated the TEE design to improve its performance and integrations with existing test facilities. Dhillon *et al.* (2022b; 2018; 2021a) used the load-based testing approach to evaluate the performance of residential heat pumps and compared the load-based test results to the current AHRI 210/240 rating approach. A repeatability and reproducibility assessment of the load-based testing approach based on was presented by Dhillon *et al.* (2022c; 2022d). Dhillon *et al.* (2021b) also proposed a load-based testing approach for RTUs with integrated economizers. As demonstrated by Dhillon *et al.* (2021c) and Ma *et al.* (2021), the load-based testing approach can also be utilized to evaluate advanced heat pump control design in a test laboratory setting.

As discussed above, there have been a number of studies describing the development, implementation, and evaluation of load-based testing for residential air conditioners and heat pumps; however, there is a lack of work in the literature to study how well the load-based testing approach characterizes overall equipment performance compared to an actual field application. For this purpose, a study was conducted to compare the performance and dynamic response of a heat pump in a residential house to that of a laboratory using load-based testing. First, a 3-ton single-stage heat-pump system was tested within the Residential Home Ecosystem (Emerson, 2022) where a 2-story house is located within a psychrometric chamber. During tests, the outdoor conditions were kept constant for each test interval, which resulted in different loads to the house and the heat pump performance was measured for each of the different ambient conditions. Then, a heat-pump system of the same make and model was tested based on the load-based testing approach in a pair of psychrometric chambers. Dhillon *et al.* (2021d) presented cooling mode comparison results from this study and observed that for cooling dry-coil tests, heat pump COPs differences were between 7% and 13%, but overall cycling dynamic behavior was similar between the two testing facilities. For humid-coil cooling tests, system COPs were comparable but the test unit cycling behavior varied. In this paper, heat pump heating mode performance and dynamic response comparisons between two test facilities are presented. An overview of the heating load-based testing approach is first presented, followed by a brief discussion of the test methodology and test setup in both facilities. The heat pump performance results from the residential house and laboratory are then presented, along with a comparison and an analysis of the differences. Finally, the conclusion provides a summary and critique of the findings, as well as recommendations for future research.

2. LOAD-BASED TESTING OVERVIEW

In the load-based testing methodology, the dynamic response of a representative building is emulated in the indoor test room by continuously adjusting its conditions using a virtual building model as illustrated in Figure 1. The virtual building model incorporates the building load and thermal mass characteristics of a representative residential building scaled to the test equipment design capacity. In this work, a simple virtual building model similar to the one described and utilized by Patil *et al.* (2018), Hjortland and Braun (2019), and Dhillon *et al.* (2022a) was implemented. Further details of the virtual building model and load-based testing approach for residential heat pumps can also be found in CSA EXP07 (CSA, 2019). For a heating mode test interval, the outdoor test room conditions are kept constant, whereas the indoor conditions are dynamically adjusted based on the interaction of the virtual building model with the test unit measured performance in real-time. At each control interval, the virtual building model temperature (T_{ID}) is updated for the next time step $(t + \Delta t)$ from the current time step (t) as per Equation (1), based on the difference between virtual building load (BL_h) and the test unit measured heating rate $(\dot{Q}_h)$ along with the effective thermal capacitance (C_s) for a representative residential building.

$$T_{ID}(t + \Delta t) = T_{ID}(t) + \Delta t \cdot \left(\frac{\dot{Q}_h - BL_h}{C_s} \right) \tag{1}$$

The virtual building model heat loss or load (BL_h) is defined as a linear function of outdoor temperature (T_{OD}) scaled to the test unit cooling capacity at design conditions $(\dot{Q}_{c,D})$ as per Equation (2).

$$BL_h = F \cdot \frac{\dot{Q}_{c,D}}{\left(T_{Bal,D} - T_{OD,D}\right)} \cdot (T_{Bal} - T_{OD}) \tag{2}$$

where F is the building load sizing factor to scale the load line, $T_{OD,D}$ 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 (3) 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.

$$T_{Bal} = T_{Bal,D} + \left(T_{ID} - T_{ID,D}\right) \tag{3}$$

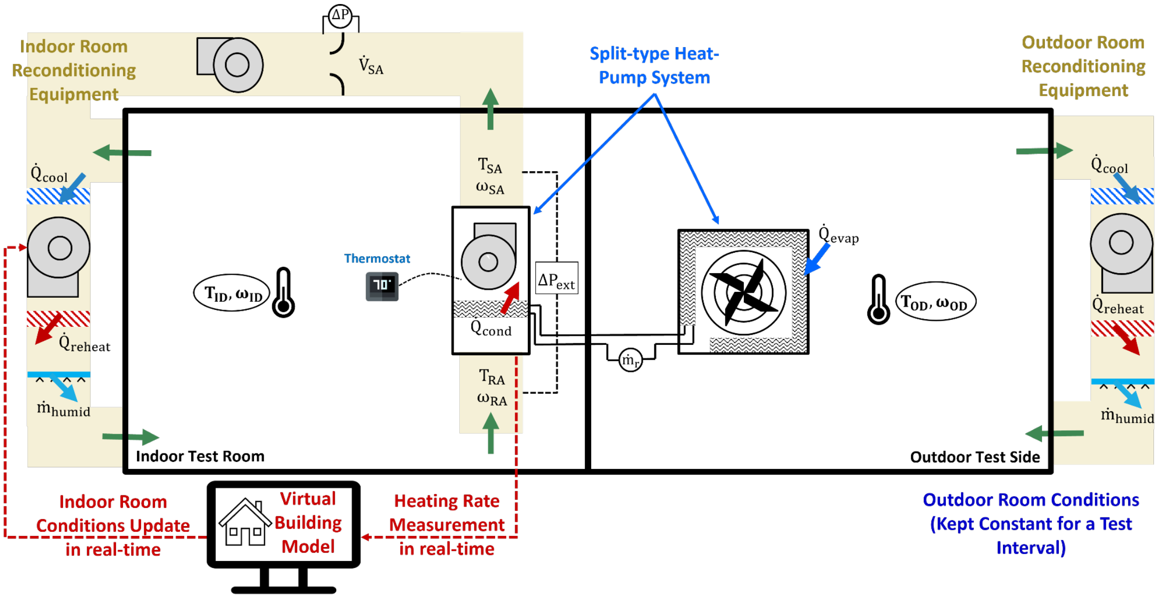

Figure 1. Load-Based Testing Schematic for a Split-Type Heat-Pump System in a Psychrometric Test Facility

To estimate the effective thermal capacitance (C_s) that captures the short time-scale dynamics associated with equipment and building interactions, Hjortland and Braun (2019) and Cheng *et al.* (2021b) presented an empirical approach based on the work of Henderson *et al.* (1991). In this approach, the effective lumped capacitance of a building is correlated to equipment maximum on/off cycling frequency (N_{max}) that occurs at a part-load ratio of 0.5, the thermostat deadband (ΔT_{db}), and the equipment design cooling sensible capacity ($\dot{Q}_{c,s,D}$) as per Equation (4). Here thermostat deadband represents the deadband of indoor temperature variation during on/off cycling. For residential buildings, Henderson *et al.* (1991) determined a maximum cycling rate (N_{max}) of about 3 cycle/h with a thermostat deadband of 2°F based on field data from multiple residential buildings in Florida.

$$C_s = \frac{1}{4} \cdot \frac{\dot{Q}_{c,s,D}}{N_{max} \cdot \Delta T_{db}} \tag{4}$$

Further, the on/off cycling rate (N) can be expressed as a function of the maximum on/off cycling rate (N_{max}) and run time fraction (X), i.e. the ratio of on-cycle time to total cycle time, as per Equation (5) (Henderson et al., 1991).

$$N = N_{max} \cdot X(1 - X) \tag{5}$$

During a heating load-based test, the virtual building temperature is continuously updated based on equations (1)-(5), which is then provided as the indoor test room setpoint. In this manner, the indoor test room mimics the response of a representative building coupled with the test unit performance. The test unit thermostat senses the dynamic indoor temperature variation, and the test unit responds accordingly with its embedded controls to maintain the space temperature near the thermostat setpoint. Thus, the dynamic performance of a heat pump is measured with its integrated controls and thermostat responding similarly to a field application.

3. TEST SETUP AND METHODOLOGY

In this section, a brief overview of the test setup, measurements, test conditions, and test methodologies is provided for both the applied ecosystem and laboratory test facilities. The reader is directed to Dhillon *et al.* (2021d) for more details. First, a 3-ton fixed-speed heat pump was tested in the 2-story house within the Residential Home Ecosystem at the Helix Innovation Center (Emerson, 2022). Then, a new heat pump with the same model and thermostat was tested with the load-based testing approach in psychrometric test rooms at Herrick Labs.

3.1 Residential Home Ecosystem

In this facility, a 2-story house is located within a large psychrometric chamber with controllable ambient temperature and humidity conditions. For this work, a 3-ton fixed-speed heat pump installed in the facility was utilized. To compare the equipment dynamic performance between the house and the lab, a number of measurements were taken in the house to replicate similar conditions in the lab. These include indoor and outdoor space temperature and humidity, heat pump air and refrigerant-side properties, power consumption, internal gains, and temperature near the thermostat. The heating test conditions at the Helix center house were chosen to be similar to those in the proposed load-based testing standard CSA EXP07 (CSA, 2019) as shown in Table 1. The heating test conditions are a combination of continental and marine outdoor test conditions with a difference in outdoor humidity. Outdoor conditions were kept constant for each test, and the test was run for a long enough time (at least 24 hours) that the load on the house from conduction and infiltration reached a steady-state (i.e., the deep thermal mass dynamics reached an equilibrium). This is analogous to the implicit assumption in the load-based testing approach, in which the virtual building model assumes that the representative building's *heavy* thermal mass dynamics and building load are at a quasi-steady state for given ambient conditions. The heat pump was controlled using a thermostat installed in the first-floor hallway of the house. Also at different ambient conditions, tests were performed with and without auxiliary heat.

Table 1. Heating Test Conditions for Residential House

Test	**Continental Outdoor Conditions**		**Marine Outdoor Conditions**		**Indoor Conditions (Thermostat Setpoint)**	
	Dry Bulb [°F]	Wet Bulb [°F]	Dry Bulb [°F]	Wet Bulb [°F]	Dry Bulb [°F]	Wet Bulb [°F]
HC	17	14.5	17	15.5	70	60 (max)
HD	34	31	34	32		
HE	47	41	47	45		
HF	54	45	54	49		

3.2 Psychrometric Test Facility

A new version of the same model of the heat pump used at the Helix Center was installed in a pair of psychrometric test rooms at the Ray W. Herrick Laboratories. The test unit was instrumented to measure its air and refrigerant-side performance as well as power consumption. Given the significance of thermostat response in load-based testing, two different thermostat installation configurations were used in lab testing to compare with residential house results. First, the thermostat was installed on the side of the indoor unit, around 3ft high from the return air inlet. Second, it was installed in a thermostat environment emulator (TEE) which provides standardized environmental conditions for the thermostat (Kim et al., 2022). First, the test unit performance was evaluated at A_{Full} test conditions (AHRI, 2020) to measure the test unit rated cooling performance. Then, the test unit was evaluated using the load-based testing methodology at the different ambient conditions specified in Table 1 to compare its performance and dynamic behavior with the performance observed in the residential house facility. For load-based testing, the virtual building model parameters were derived from the residential house test results. The external static pressure across the indoor unit was maintained at a value similar to the one observed at the residential house facility.

4. TEST RESULTS

4.1 Residential Home Ecosystem Test Results

Figure 2 shows the heat pump performance, internal gains, airflow, and temperature variation over a 24-hour duration during the heating continental test at 54°F outdoor temperature at the residential house. The upper subplot shows the sensible heating rate, total power consumption, and the internal load connected to the left vertical axis; whereas, airflow and indoor unit external static pressure are referenced to the right vertical axis. The lower subplot shows the thermostat setpoint, indoor temperature and return air temperature on the left vertical axis, with the outdoor temperature setpoint and its measured value on the right vertical axis. Here, the indoor temperature represents the measurement of a thermocouple (TC) installed around 2” below the thermostat. The return air temperature is the volumetric airflow weighted average of the TC grid installed in the first and second-floor return air ducts. The outdoor air temperature is the average of TCs installed on the outdoor unit HX (heat exchanger) inlet, which is a good representation of the overall average temperature of the outdoor space. The internal load was set at approximately 0.2 kW. The unit cycled on/off to meet the building load and it achieved a very steady cycling behavior over time similar to cooling test results (Dhillon et al., 2021d). Also, it should be noted that the indoor temperature was maintained around 73°F, 3°F higher than the thermostat setpoint, which is due to thermostat offset.

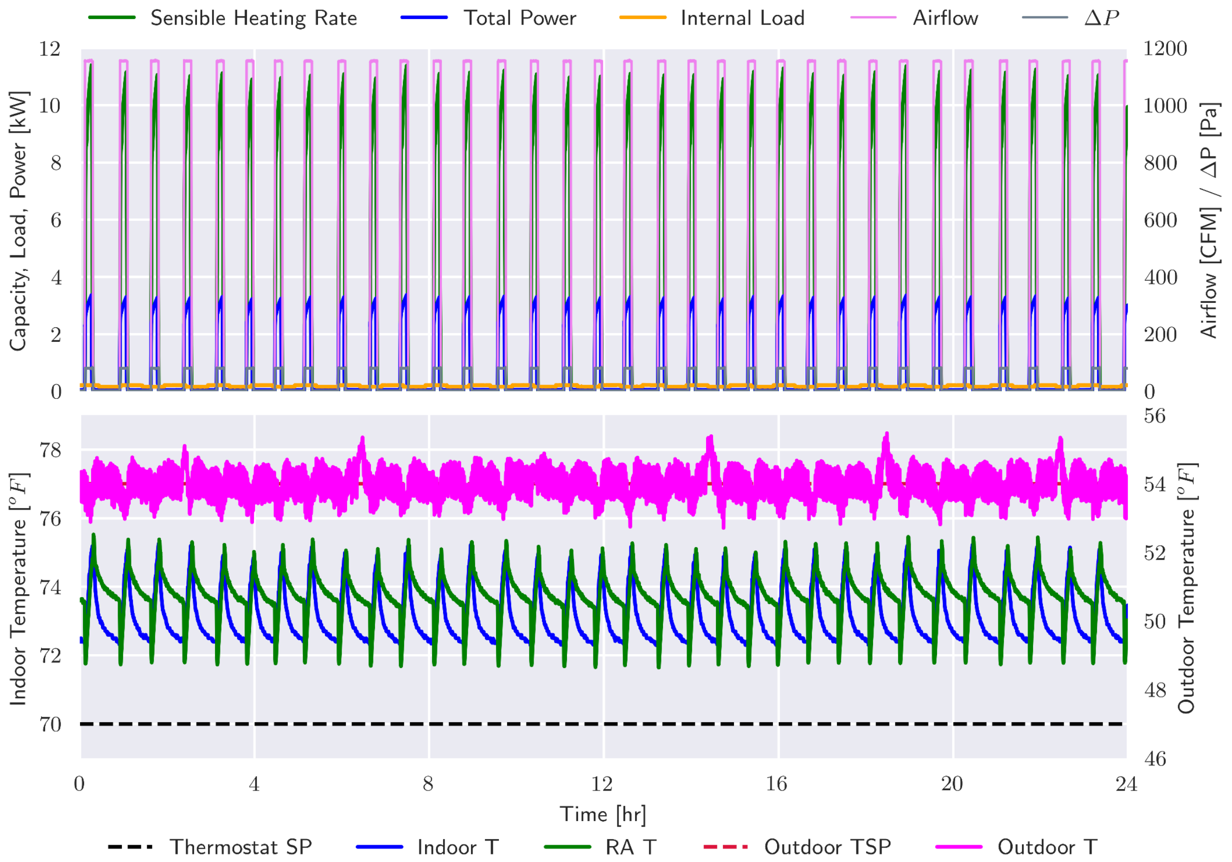

Figure 2. Heat Pump Performance and Temperature Variation during Residential House Testing (Heating Continental - HF 54°F)

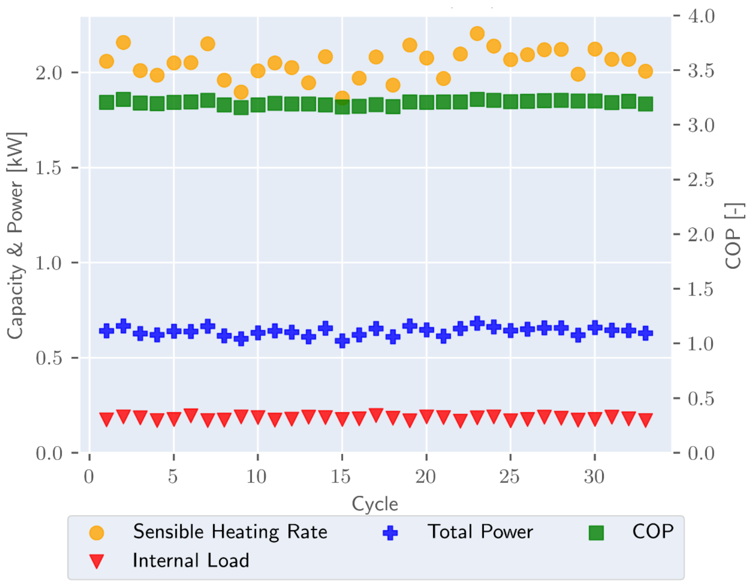

Figure 3. Average Cycle Performance during Residential House Testing (Heating Continental – HF 54°F)

Figure 3 shows the average sensible heating rate, internal load, total power, and COP for each complete on/off cycle during the heating continental test at 54°F ambient temperature. The test equipment performance was very consistent during the 24-hour test duration indicating that the house was at a steady state. Similarly, heating tests were performed for different continental and marine test intervals (Table 1) at steady ambient conditions. The test unit cycled on/off at 47°F outdoor temperature conditions. At 34°F ambient temperature, the test unit cycled on/off with intermittent defrosts at regular intervals. At 34°F outdoor temperature conditions, tests were conducted with and without activating auxiliary heat (Aux). When the unit went into defrost, the auxiliary heat kicked in to maintain the supply air temperature. This resulted in around 10% less COP compared to the case without auxiliary heat at the same ambient temperature of 34°F as shown in Figure 4. Based on the current test standards, lab tests are done without auxiliary heat, and thus there is no provision to account for the effects of auxiliary heat during defrosts on performance. However, given the impact on field performance, this should be investigated further and ultimately included in the load-based testing and seasonal performance rating methodologies. At 17°F ambient temperature, the test unit's maximum capacity without auxiliary heat was lower than the building load and it ran continuously with intermittent defrosts, equivalent to a full-load test in the load-based testing approach. Those test results are not included here, as the focus of this paper is to compare the dynamic performance between the house and the lab. Also, it is interesting to note that the test unit COP was very similar in continental and marine test intervals at the same outdoor dry-bulb temperatures. This shows that for this unit, the higher outdoor humidity in marine test intervals did not have a significant effect on the performance even for the tests where the unit was going into defrost. This is also supported by the fact that there was no visible frost buildup on the outdoor unit while testing at the house.

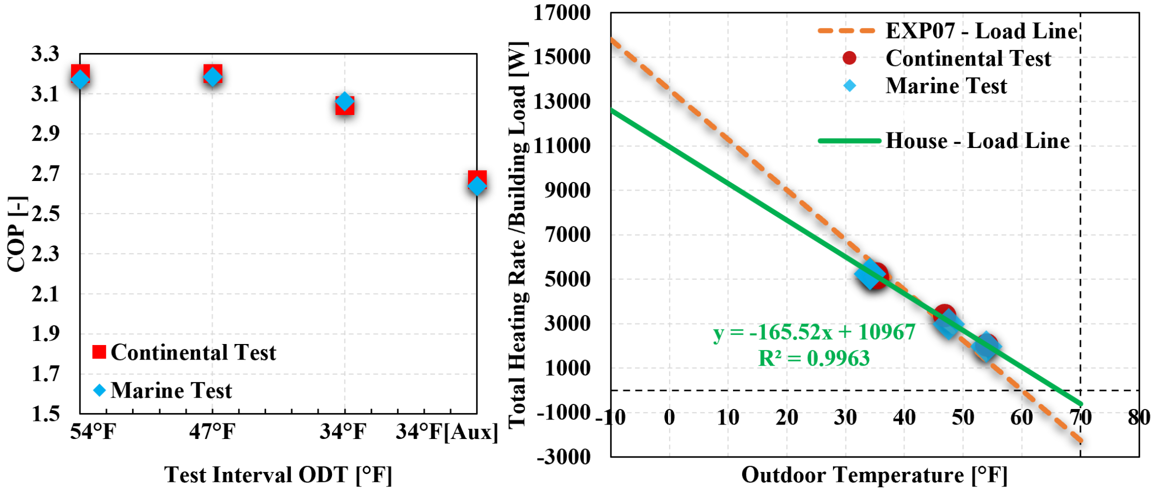

Figure 4. Overall Heating Test Results and Estimated Residential House Load Line (34°F [Aux] denotes that the test was conducted with auxiliary heat activated; other tests did not include auxiliary heat)

The building load line for heating load-based testing was estimated from the house test results using the measured average heating rates at different ambient temperatures over the 24-hour steady-periodic tests. Since the heat pump was able to maintain the indoor temperature, the average heating rates are effectively the building loads for the given indoor and outdoor conditions. Figure 4 shows the house load as a function of ambient temperature (load line) for the heating test conditions along with a representative load line based on CSA EXP07 (CSA, 2019) for a 3-ton unit. The EXP07 estimate assumes that the virtual building heating load at 5°F ambient temperature would be oversized by 15% of the test equipment cooling design capacity. In addition, the assumption in EXP07 is that the virtual building balance point temperature for heating test conditions is 60°F for the indoor design temperature of 70°F. Consequently, the load line from the residential house tests and the EXP07 standard draft differ because of differences in oversizing, balance point temperature, and indoor design temperature. Based on the estimated load line and the heat pump cycling on/off for the house at all the different ambient conditions, the heat pump is oversized compared to EXP07.

The building thermal capacitance, which governs the dynamic interaction between the building and its equipment, is an important virtual building model parameter for emulating the dynamic behavior of a realistic residential building in load-based testing. As outlined in Equations (4) and (5), the maximum cycling rate (N_{max}) is needed to define the effective capacitance, in addition to equipment sensible cooling design capacity and the thermostat deadband (ΔT_{db}) which represents the indoor temperature deadband. N_{max} was estimated by fitting the parabolic curve defined by

Equation (5) to the cycle rate (N) and run-time fraction (X) data from the residential house heating continental and marine test results as shown in Figure 5 and Figure 6, respectively. The first thing to note is that the test results (scatter points) follow a parabolic curve quite well, which is based on the simple lumped capacitance model. The other thing to note is that the fitted curves are very similar for both sets of heating tests as well as similar to what was observed for cooling tests (Dhillon et al., 2021d), which makes sense as this represents the effective capacitance of the house. The maximum cycling rate for the residential house is around 2.1 cycles/hr, which is lower than the value of 3 used within the EXP07 (CSA, 2019) virtual building model. This implies that the effective thermal capacitance of the residential house used in this study is larger with a slower building response than for the virtual building model employed in EXP07. The indoor temperature fluctuated within about a 3°F deadband in response to on/off cycling in heating tests at the residential house which was used as ΔT_{db} in the C_s estimation for load-based tests in the lab.

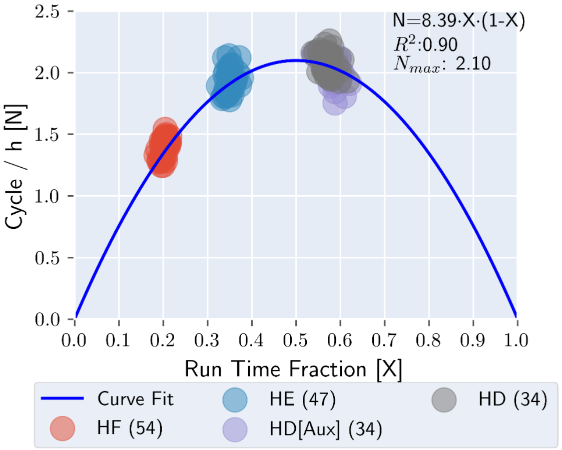

Figure 5. Cycle Rate with Run-time Fraction for Heating Continental Test Results – House

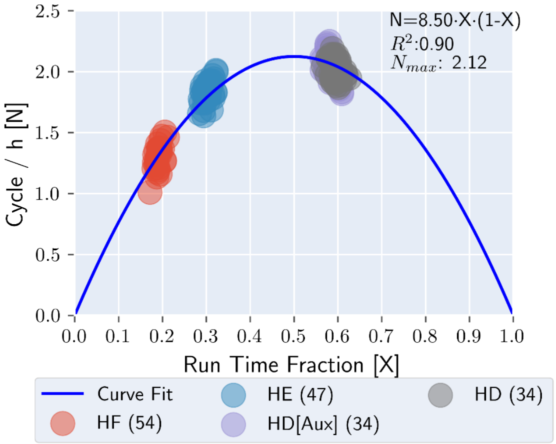

Figure 6. Cycle Rate with Run-time Fraction for Heating Marine Test Results – House

4.2 Psychrometric Facility Test Results

To evaluate and compare the performance of the same model heat-pump system in the lab using the load-based testing methodology, the virtual building parameters determined from test results for the ecosystem house were employed. The test unit design cooling rate was measured at a steady-state A_{Full} test (AHRI, 2020). Table 2 shows the virtual building parameters which were utilized with equations (1)-(5) to perform heating load-based tests at conditions similar to the residential house facility. Only continental tests were performed in the lab to compare with the residential house facility since similar performance was observed at continental and marine test conditions.

Table 2. Estimated Virtual Building Parameters from the Residential House Test Results

Parameter	$\dot{Q}_{c,D}$	$\dot{Q}_{c,s,D}$	**F**	$T_{Bal,D}$	$T_{ID,D}$	$T_{OD,D}$	N_{max}	ΔT_{db}	Δt
	W	W	-	°F	°F	°F	$1/h$	°F	s
Value	10792.5	8337.8	0.94	66.4	73	5	2.1	3	1

Figure 7 shows the heat pump performance and temperature variation during the heating continental load-based tests at 54°F ambient temperature with the thermostat mounted on the side of the test unit. In the upper subplot, the test unit sensible heating rate, virtual building sensible load, and total power consumption correspond to the left vertical axis and airflow corresponds to the right vertical axis. The lower subplot shows the virtual building indoor temperature (IDT), return air (RA) temperature, thermostat setpoint (SP), and temperature measured near the thermostat on the left vertical axis, and the outdoor temperature setpoint and its measured value on the right vertical axis. During this load-based test, the indoor unit return air temperature was controlled to the virtual building indoor temperature setpoint. The thermostat was set to 73°F for similar conditions as in the residential house, and the heat pump cycled on/off to maintain the virtual indoor (and return) air temperature near the thermostat setpoint, which was also observed in the residential house testing. The virtual indoor temperature variation (i.e., implicit deadband) was around 3°F during on/off cycles. The highlighted period (light red) shows the period of data used in the analysis and comparison. The test unit showed a defrost cycle just prior to the highlighted period that was unusual at this high ambient temperature and was not considered in the final analysis. This difference in the test unit defrost response between the house and the lab at the same outdoor temperature is possibly due to the firmware difference between the two units. As the virtual building load increased at 47°F and 34°F outdoor temperature conditions, the heat pump run-time fraction increased to compensate for the higher building load. At 34°F ambient temperature, the heat pump also showed intermittent defrosts along with on/off cycles similar to the residential house test results. Figure 7 also shows the average of two thermocouple temperature measurements taken near the thermostat. The deviation in the temperature around the thermostat from the return air temperature is due to the non-uniform temperature distribution in the psychrometric test room.

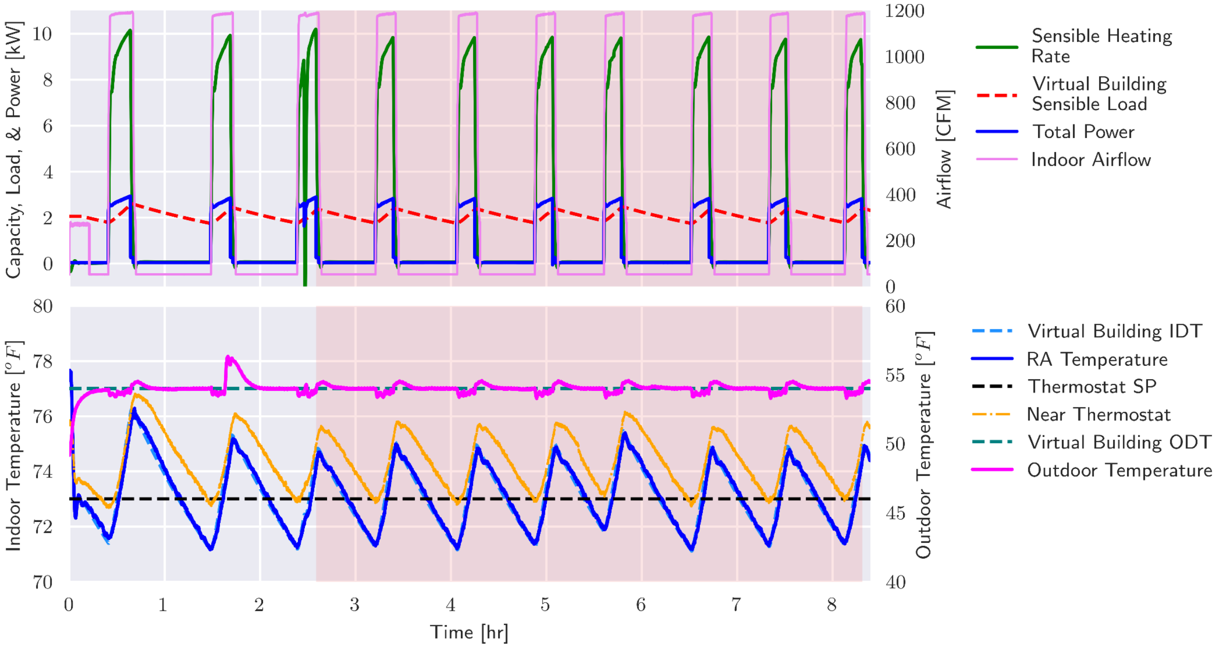

Figure 7. Heat Pump Performance and Temperature Variation for Heating Continental Load-Based Test at 54°F with Thermostat Mounted on Side of Test Unit

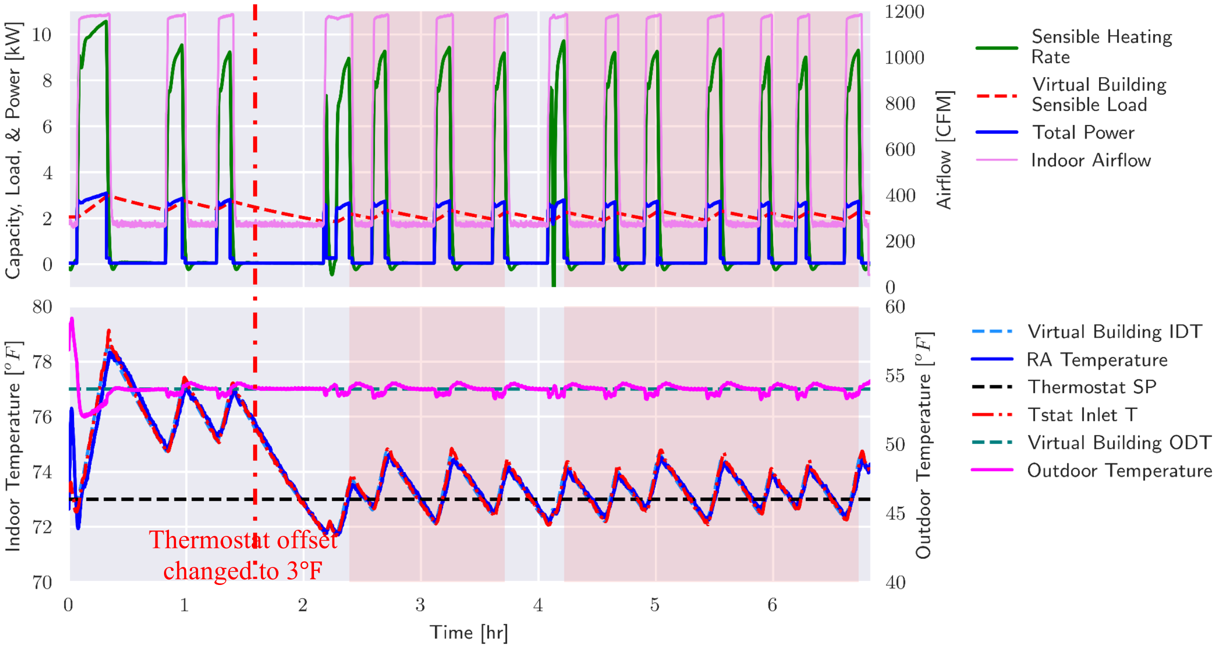

Figure 8. Heat Pump Performance and Temperature Variation for Heating Continental Load-Based Test at 54°F with Thermostat Environment Emulator (TEE)

The heating load-based tests were also repeated after installing the thermostat in a thermostat environment emulator (TEE) (Kim et al., 2022). This allowed controlling temperature conditions around the thermostat to the virtual building temperature so that both return air and thermostat inlet air temperature are maintained at similar conditions. In the TEE, the air velocity over the thermostat was controlled to around 30 FPM. Figure 8 shows the heat pump performance and temperature variation for the heating continental load-based test at 54°F outdoor temperature with the TEE. Both the test unit RA temperature and thermostat inlet air temperature were controlled to the virtual building IDT. The test unit showed a single defrost cycle in this 54°F ambient temperature test, which was not considered in the final data analysis. After installing the thermostat in the TEE, its offset needed to be set at 3°F for it to control the indoor temperature near its setpoint of 73°F as can be seen in Figure 8. This could be due to the difference in thermostat sensing response when installed inside the TEE, where the thermostat front and back are exposed to the air flowing over it, versus when installed on the side of the indoor unit, where the thermostat front is only exposed to the air flowing over it. Also, the on/off cycles in the test with the TEE were irregular and the indoor temperature variation deadband of around 2°F was smaller compared to the test with the thermostat installed on the side of the indoor unit (see Figure 7). This is also attributed to the variation in the thermostat sensing dynamic response with its installation location. The test unit performance was also measured in load-based tests at continental 47°F and 34°F outdoor temperature conditions with the TEE. Similar to tests without TEE, the test unit cycled on/off at 47°F ambient temperature, and at 34°F ambient temperature, it cycled on/off with intermittent defrosts.

4.3 Equipment Performance and Dynamic Response Comparisons

In this section, comparisons of the test unit dynamic response and overall performance between the house and the test lab results with and without the TEE are presented. Figure 9 and Figure 10 show the cycle rate (N) and run-time fraction (X) data for the heating continental load-based test results in the laboratory without and with the TEE, respectively, along with the fitted parabolic curves as per Equation (5) for lab and house test results. Similar to the house test results (Figure 5 and Figure 6), consistent on/off cycling behavior was observed in the lab test results with the thermostat installed on the side of the indoor unit (Figure 9) with a somewhat slower cycling rate in the lab. However, in the lab test results with the thermostat installed inside the TEE (Figure 10), inconsistent on/off cycles were observed with a faster cycling rate compared to the house test results. This contrasting difference in the two sets of lab test results compared to the house is due to the difference in thermostat sensing dynamics as discussed above. These findings suggest that the temperature and airflow distribution conditions around the thermostat in the house are somewhere in between the two lab testing scenarios.

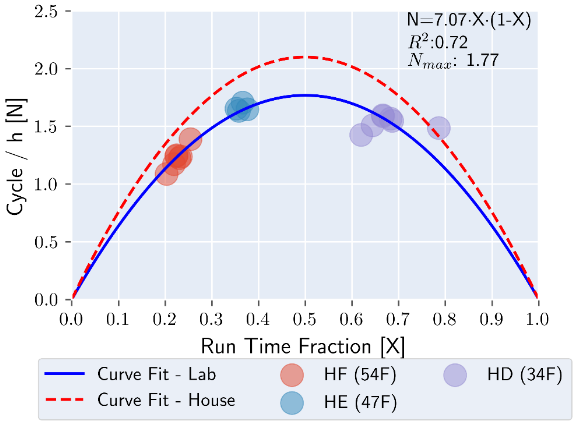

Figure 9. Cycle Rate with Run-time Fraction for Heating Continental Load-Based Test

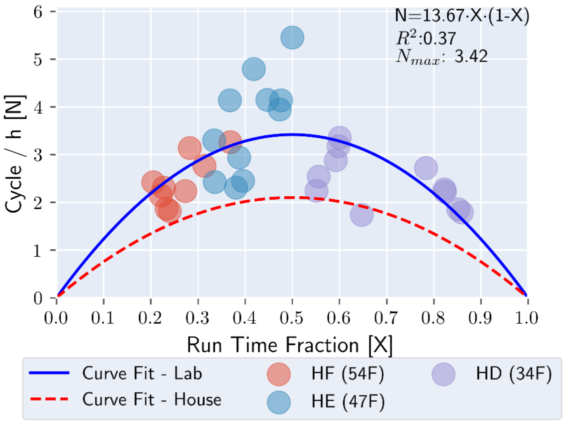

Figure 10. Cycle Rate with Run-time Fraction for Heating Continental Load-Based Test w/ TEE

Figure 11 shows performance comparisons for the heating continental tests performed at the Residential Home Ecosystem house and in the psychrometric test lab as per the load-based testing approach with the thermostat installed on the side of the indoor unit and in the TEE. The data labels show the percentage difference of lab results compared to the house results at the same test conditions. With the thermostat installed on the side of the indoor unit, the heat pump COP measured in the lab was higher than that measured at the house with a maximum difference of 2%. On the other hand, with the thermostat installed in TEE, lower COPs were measured in the lab compared to the house with a maximum difference of -3%. It is interesting to note that comparable COPs were observed between the lab and the house even with the difference in on/off cycling response. The differences in the average heating rate and total power consumption between the house and the lab test results were larger compared to COP differences for some test intervals. The performance differences between the two facilities are due to measurement uncertainties, differences in performance between the unit installed at the Helix Center and the new unit tested in the laboratory, refrigerant charge differences, differences in dynamic interaction between the equipment and load including thermostat response, and/or differences in indoor and outdoor conditions between the two facilities.

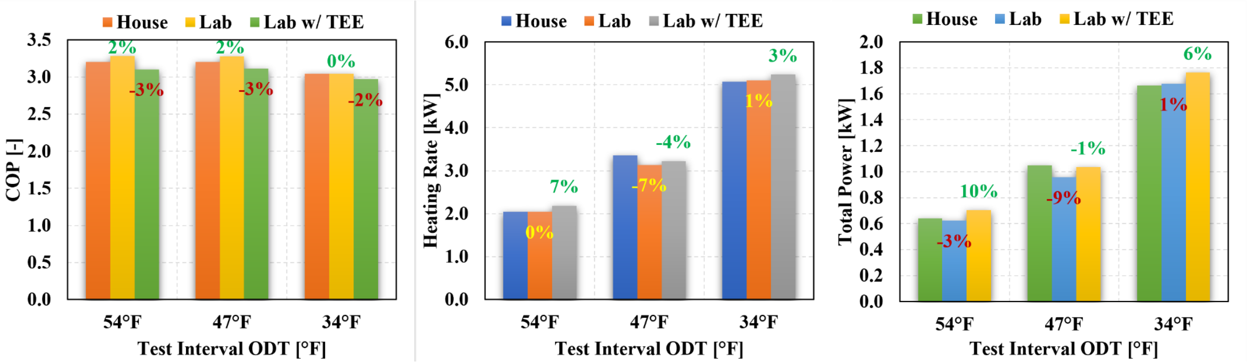

Figure 11. Heating Tests Performance Comparison between the Two Facilities

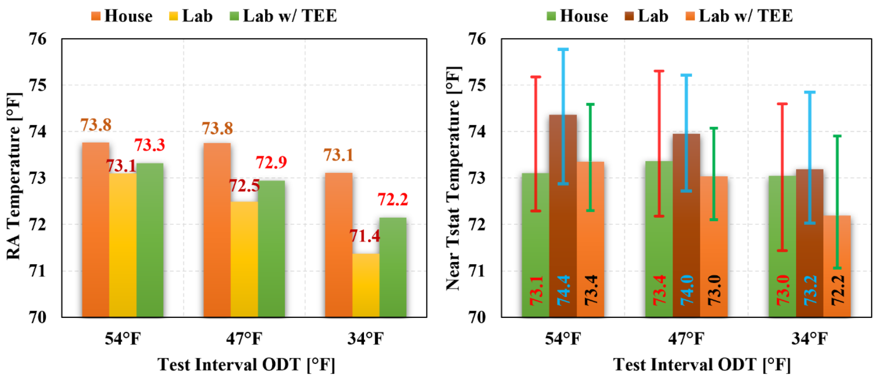

Figure 12. Heating Tests Average RA and Near Thermostat Temperature Comparison Between Two Facilities

Figure 12 shows comparisons of average return air (RA) temperature and average temperature near the thermostat between the two test facilities. The average variations in the temperature near the thermostat during on/off cycles are also shown for the tests. The average RA temperatures in the lab for both thermostat installation configurations were lower compared to the house, however, the differences were small compared to cooling results (Dhillon et al., 2021d). In the residential house testing facility, the average RA and temperature near the thermostat were similar. In the lab with the thermostat installed on the side of the indoor unit, the average temperature near the thermostat was higher than the return air temperature with differences varying from 1.3°F to 1.8°F for different test intervals. On the other hand, with the thermostat installed in the TEE, the average RA and near thermostat temperatures were comparable, similar to house test results. Further, with the thermostat installed on the side of the indoor unit, the range of temperature variation near the thermostat during on/off cycles was similar to the house test results, whereas, with the thermostat mounted inside the TEE, the temperature variation near the thermostat was smaller compared to house test results except for 34°F test interval. It should be noted that during testing in both facilities, the thermostat deadband was set to the same value of ±1°F. So, this difference in temperature variation near the thermostat during on/off cycling is due to a difference in thermostat sensing response between the two facilities as well as in the test lab between the two installation configurations, which is coupled to the test unit performance in load-based testing, as discussed above. Differences in thermostat responses could be because of the differences in the thermostat installation and airflow around the thermostat. These results also emphasize the importance of defining representative environmental conditions for the thermostat during load-based testing comparable to the field application.

5. CONCLUSIONS

This paper presents heating mode performance evaluation results for a 3-ton single-stage heat pump, tested in a 2-story house within the Residential Home Ecosystem at the Helix Innovation Center, together with load-based test results of the same model in a psychrometric test facility at the Ray W. Herrick Laboratories. The study's purpose was to gain a better understanding of how effectively the load-based testing approach characterized the dynamic performance of equipment in the lab compared to a residential building. Virtual building model parameters for load-based testing were derived utilizing the test results from the house to provide similar representative conditions to the heat pump in the test lab. The test unit performance was measured in the lab utilizing the load-based testing approach for heating continental conditions with two different thermostat installation configurations. To summarize the results, with both thermostat installation locations, comparable COPs were measured in the lab and the residential house facility with differences varying between -3% and 2%. However, differences in the test unit cycling behavior were observed between the two test facilities. In the lab, consistent on/off cycles were seen with the thermostat put on the side of the indoor unit, similar to the results in the house, albeit at a little slower rate. However, irregular on/off cycles were observed with the thermostat installed in a thermostat environment emulator (TEE) in the lab with a faster cycling rate compared to the residential house test results. Potential causes for the differences in performance and overall dynamic behavior between the two test facilities were discussed and some areas for further investigation were identified. One of the future tasks should be to define representative conditions for the thermostat in the load-based testing approach comparable to actual field applications.

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