# Validation of a Load-Based Testing Method for Characterizing Residential Air-Conditioner Performance

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# Validation of a Load-Based Testing Method for Characterizing Residential Air-Conditioner Performance

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## ABSTRACT

Seasonal performance assessments of air-conditioning and heat-pump systems are typically carried out based on performance measurement of equipment in a test laboratory. The performance ratings that arise from these assessments are important in providing information to consumers, and in influencing policymakers to determine appropriate incentives for high-efficiency equipment in the marketplace. The current testing and rating approach for performance evaluation of residential air-conditioning and heat-pump systems is based on steady-state performance measurements, with a degradation coefficient to account for the cycling losses that occur during part-load operating conditions. However, this current methodology fails to appropriately characterize the true performance characteristics of these systems in the field, and as a consequence, SEER (seasonal energy efficiency ratio) improvements have not resulted in proportional savings in energy. As an alternative, a load-based testing methodology has been developed with the motivation of capturing realistic equipment performance in a laboratory setting while operating similar to field application conditions. In this approach, the equipment responds to a simulated virtual building load, and the system dynamic performance is measured with its integrated controls and thermostat. However, there is a lack of field-testing data to characterize how well the load-based testing approach captures equipment performance and dynamic behavior compared to a typical field application. To fill this gap, a 3-ton heat pump system was tested within the Residential Home Ecosystem at the Helix Innovation Center where a 2-story house is located within an environmental chamber that can vary external ambient temperature and humidity conditions. During tests, the house was subjected to cooling loads resulting from different outdoor temperature conditions, and its air conditioning system responded accordingly. Similar cooling equipment was also tested within psychrometric chambers at the Ray W. Herrick Laboratories using the load-based testing methodology. A comparison of the test equipment performance and its dynamic behavior in cooling mode between testing performed at the Helix Center and at the Herrick Laboratories is presented in this paper.

## 1. INTRODUCTION

The current performance rating approach for residential air-conditioners and heat-pumps in the U.S., AHRI 210/240 (AHRI, 2020), is primarily based on steady-state performance measurements with a degradation coefficient to account for cycling losses at part-load conditions. Test equipment performance is measured at different ambient conditions by overriding its native control, usually with proprietary control settings from the manufacturer, and forcing the unit to run at fixed compressor and fan speeds. Measured performance is then propagated through a temperature-bin method to estimate cooling and heating seasonal performance. Although this rating approach provides a standard performance metric for comparing the relative performance of different equipment, it does not characterize the overall performance of the equipment with its embedded controls and their dynamic interactions with representative 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 facility by allowing it to respond to a simulated virtual building model.

Hjortland and Braun (2019), Patil et al. (2018), and Cheng et al. (2021b) describe the load-based testing methodology in detail, which forms the basis for CSA (Canadian Standards Association) standard draft EXP07:2019 (CSA, 2019).

In this methodology, a virtual building model is utilized to continuously adjust the indoor psychrometric test room temperature and humidity conditions in a manner that mimics the response of a representative building being served by the heat-pump system in a typical field application. The test unit thermostat is allowed to respond naturally to this dynamic temperature variation, and controls the equipment in response to a deviation from its setpoint. In this way, the load-based testing approach provides an effective means for capturing the dynamic performance of equipment that is representative of its field application with its integrated controls and thermostat in a test laboratory environment. Hjortland and Braun (2019) demonstrated the load-based testing approach in evaluating and comparing 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), and Cheng et al. (2021b) further extended the load-based laboratory testing approach for performance evaluation of residential air-conditioning equipment 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 on overall seasonal performance estimation. Dhillon et al. (2018, 2021b) implemented the load-based testing approach for evaluating residential heat-pumps, and compared the load-based test results with results based on the current rating approach AHRI 210/240. Dhillon et al. (2021c) further investigated a load-based testing approach for RTUs with integrated economizers. The load-based testing approach can also be used for the evaluation of advanced heat-pump control design in a test laboratory setting as demonstrated by Dhillon et al. (2021a) and Ma et al. (2021).

Despite a growing number of studies describing development, implementation, and evaluation of load-based testing for packaged and residential air-conditioners and heat-pumps, there has been no detailed study that compares the performance and dynamic response of a test unit in a residential house to that of a laboratory using load-based testing. The motivation for this study was to fill this gap by testing a heat-pump in a residential house and then testing similar equipment in the laboratory with load-based testing to compare the equipment dynamic behavior and overall performance. In this work, first, a 3-ton single-stage heat-pump system was tested within the Residential Home Ecosystem at the Helix Innovation Center where a 2-story house is located within a psychrometric chamber where the external temperature and humidity can be closely controlled. During tests, the outdoor conditions are kept constant for each test interval, which results in different loads to the house for each of the different ambient conditions, and the corresponding heat-pump performance is measured. Then, a similar heat-pump system was installed and tested in the psychrometric test facility at the Ray W. Herrick Laboratories using the load-based testing approach. In this paper, a comparison of the heat-pump performance in the residential house and test laboratory is presented for cooling mode operation. In the sections below, first, an overview of the load-based testing approach is provided followed by a description of the test methodology and test setup in both facilities. Then, the heat-pump performance results are presented from the residential house as well as from the laboratory and a comparison with an analysis of the differences is presented. Finally, the conclusion gives a brief summary and critique of the findings with a discussion on future work.

## 2. LOAD-BASED TESTING OVERVIEW

Figure 1 illustrates the load-based testing setup and methodology for split-type heat-pump systems installed in two side-by-side psychrometric test chambers. In this methodology, for each test interval, the outdoor test room conditions are kept constant, whereas, the indoor conditions are continuously varied to emulate the dynamic response of a representative residential building coupled with the test equipment performance using a virtual building model. The test unit thermostat senses the dynamic temperature variation, and the test unit responds accordingly with its embedded controls based on the space temperature deviation from the thermostat setpoint. 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 responding similarly to a field application.

The virtual building model incorporates the building heat load and thermal mass characteristics of a representative residential building scaled to the test equipment design capacity. The complexity of the virtual building model can be defined based on the requirements of the underlying study. 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 Cheng et al. (2021b) was implemented. Further details of the virtual building model and load-based testing approach for residential heat-pump systems can also be found in CSA EXP07 (CSA, 2019). For cooling operation mode testing, the virtual building model defines the building sensible heat gain or load $\left(BL_{c,s}\right)$ as a linear function of outdoor temperature $(T_{OD})$ scaled to the test unit rated cooling capacity at design conditions $\left(\dot{Q}_{c,D}\right)$ as per Equation (1).

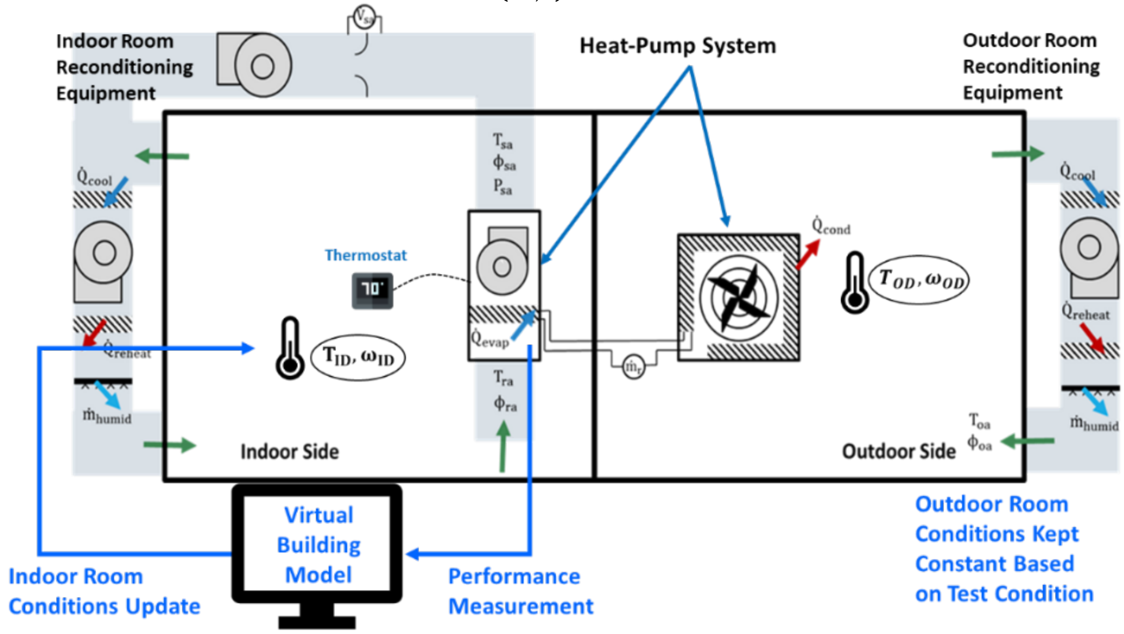


**Figure 1.** Load-Based Testing Schematic for a Split-Type Heat-Pump System in a Psychrometric Test Facility

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

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 (2) to account for the variation in building load due to a change in indoor temperature $(T_{ID})$ from the indoor design temperature $(T_{ID,D})$. Also, during a load-based test, the test unit thermostat is set to the target $T_{ID,D}$.

$$T_{Bal} = T_{Bal,D} + \left(T_{ID} - T_{ID,D}\right) \tag{2}$$

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 (3).

$$BL_{c,l} = BL_{c,s} \cdot \left(\frac{1}{SHR_{Building}} - 1\right) \tag{3}$$

During a load-based test, the virtual building model temperature $(T_{ID})$ and humidity ratio $(\omega_{ID})$ are updated for the next time step $(t + \Delta t)$ from the current time step $(t)$ as per Equations (4) and (5), respectively, and utilizing the virtual building loads together with the test unit cooling rates, sensible $\left(\dot{Q}_{c,s}\right)$ and latent $\left(\dot{Q}_{c,l}\right)$, measured in real-time.

$$T_{ID}(t + \Delta t) = T_{ID}(t) + \Delta t \cdot \left(\frac{BL_{c,s} - \dot{Q}_{c,s}}{C_s}\right) \tag{4}$$

$$\omega_{ID}(t + \Delta t) = \omega_{ID}(t) + \Delta t \cdot \left(\frac{BL_{c,l} - \dot{Q}_{c,l}}{h_{fg} \cdot C_w}\right) \tag{5}$$

where $C_s$ and $C_w$ are the effective thermal and moisture capacitances, respectively, for a representative residential building scaled to the equipment cooling capacities at design conditions, and $h_{fg}$ is the latent heat of vaporization for water. Hjortland and Braun (2019) and Cheng et al. (2021b) presented an empirical approach for estimating the effective thermal capacitance, that captures the short time-scale dynamics associated with equipment and building interactions, of a typical residential building 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 ($\Delta T_{db}$), and the equipment design cooling sensible capacity ($\dot{Q}_{c,s,D}$) as per Equation (6). 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.

$$C_s = \frac{1}{4} \cdot \frac{\dot{Q}_{c,s,D}}{N_{max} \cdot \Delta T_{db}} \tag{6}$$

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 (7) (Henderson et al., 1991).

$$N = N_{max} \cdot X(1 - X) \tag{7}$$

The effective moisture capacitance ($C_w$) is defined based on a simple empirical approach by scaling the mass of the virtual building zone air (Cheng et al., 2021b) as per Equation (8).

$$C_w[kg] = \frac{\dot{Q}_{c,D}[W]}{12.9\ [W/kg]} \tag{8}$$

During a load-based test, the virtual building temperature and humidity conditions are continuously updated based on the equations (1)-(8), which are then sent as setpoints to the indoor psychrometric test room for each time step. This allows emulation of the response of a representative building coupled to the test unit performance in the indoor test room as long as the test chamber reconditioning system tracks the varying setpoints reasonably well.

## 3. TEST SETUP AND METHODOLOGY

In this section, an overview of the test setup, measurements, test conditions, and test methodologies is provided for both the applied ecosystem and laboratory test facilities. In this work, a heat-pump system was first tested in the 2-story house within the Residential Home Ecosystem at the Helix Innovation Center. A new heat-pump with the same model and thermostat was installed and tested with the load-based testing 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 where ambient temperature and humidity conditions to the house can be controlled over a wide range. This allows a controlled study of the dynamic behavior and performance measurement of a heat-pump system in a residential building which would typically not be possible in a residential house in the field. For this work, a 3-ton fixed-speed heat-pump installed in the facility was utilized. To replicate similar conditions in the lab and enable a comparison of the equipment dynamic behavior between the house and the laboratory, and to understand the thermostat behavior, a number of measurements were taken in the house during the Helix Center tests. These include, indoor and outdoor side space temperature and humidity, heat-pump air and refrigerant side performance, power consumption, internal gains, and temperature near the thermostat. Moreover, temperature and humidity measurements were taken throughout the house to study the overall response of the house as well as to evaluate whether steady-state conditions had been achieved for concluding a test and moving to the next one.

To compare the test unit performance and dynamic behavior at the house to laboratory results obtained using load-based testing, the cooling test conditions at the Helix center were chosen to be very similar to those of the load-based testing standard draft CSA EXP07 (CSA, 2019). The cooling test conditions are defined as a set of dry-coil and humid-coil test conditions as shown in Table 1. Since there were no internal moisture gains in the house, the outdoor humidity was controlled to provide suitable indoor humidity conditions through infiltration gains. For dry-coil tests, the humidity was kept sufficiently low as to eliminate dehumidification at the indoor AHU coil; whereas, for the humid-coil test it was increased with a target to maintain the indoor RH variation at around 50-60%. For each test, ambient conditions were held constant and the test was carried out for a long enough duration (at least 24 hours) such that the load on the house due to conduction and infiltration was at steady-state (i.e., the deep thermal mass dynamics reached an equilibrium). This is similar to the inherent assumption in the load-based testing approach, in which the virtual building model assumes the representative building's *heavy* thermal mass dynamics and building load for given ambient conditions are at steady-state. Furthermore, as the house was not occupied, heaters were utilized to represent an internal load of about 2 kW. The heat-pump was controlled using a thermostat installed in the $1^{st}$-floor hallway of the house.

**Table 1.** Cooling Test Conditions for the Residential House

| Test | Dry-Coil Conditions | | | Humid-Coil Conditions | | |
|---|---|---|---|---|---|---|
| | Thermostat Setpoint [°F] | Outdoor Drybulb [°F] | Outdoor RH [%] | Thermostat Setpoint [°F] | Outdoor Drybulb [°F] | Outdoor RH [%] |
| **A** | 79 | 77 | Such that there is no dehumidification at the indoor AHU coil | 74 | 77 | Such that indoor RH is around 50-60% |
| **B** | 79 | 86 | | 74 | 86 | |
| **C** | 79 | 95 | | 74 | 95 | |
| **D** | 79 | 104 | | 74 | 104 | |
| **E** | 79 | 113 | | N/A | | |

### 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 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 same model thermostat used in the residential house testing was installed on the side of the AHU, around 3 ft high from the return air inlet, in the indoor psychrometric test room to control the unit during load-based testing.

First, the test unit performance was evaluated at $A_{Full}$ test conditions (AHRI, 2020) to verify and ensure various measurements with air and refrigerant-side energy balances, and also to measure the test unit rated cooling performance. Then, the test unit was evaluated using the load-based testing methodology 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 to ensure a virtual building that is representative of the actual house for better comparison between the test results of the two facilities. The test unit cooling mode performance was evaluated with the load-based testing approach at the different ambient conditions specified in Table 1. During load-based testing in the laboratory, the indoor AHU external static pressure was maintained at a value similar to the static pressure determined through testing 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 cooling humid-coil test at 77°F outdoor temperature at the residential house. The upper subplot shows the sensible cooling rate, latent cooling 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. As mentioned before, the internal load was set at approximately 2 kW, and the unit cycled on/off in order to meet the load. The equipment achieved a very steady cycling behavior over time.

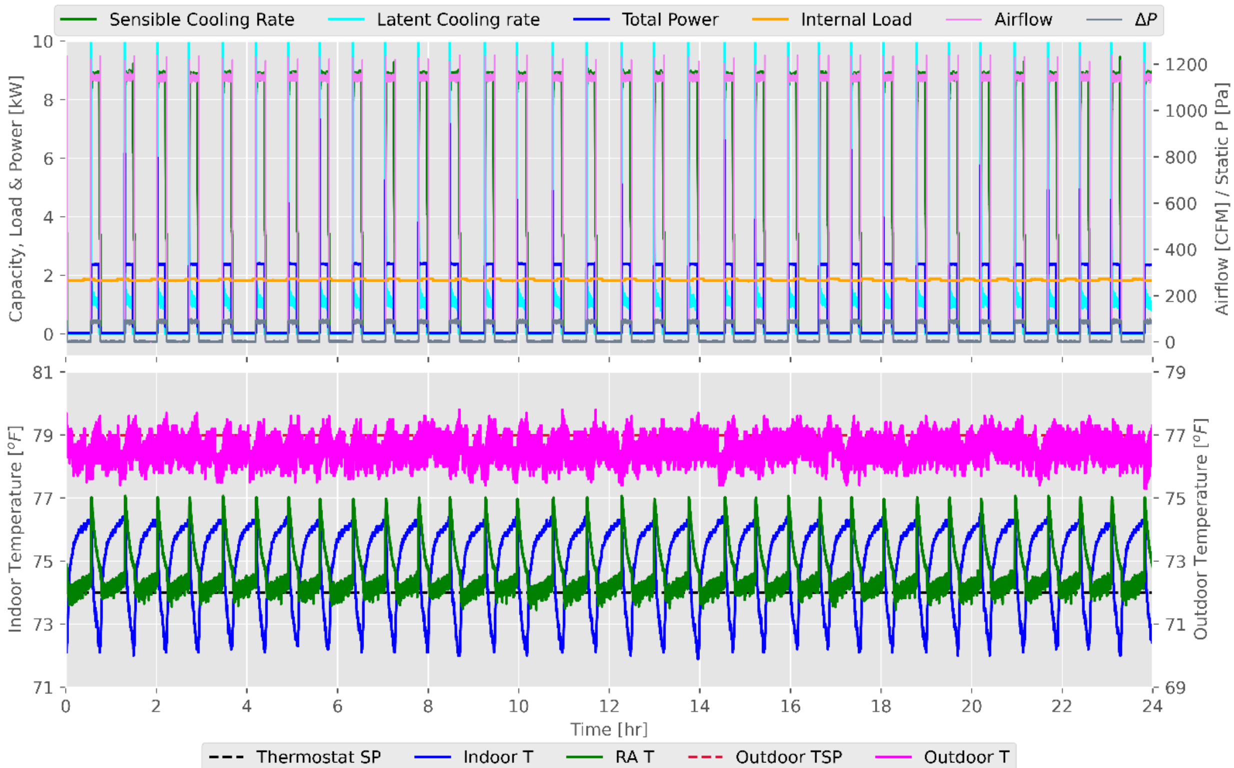


**Figure 2.** Heat-pump Performance and Temperature Variation during Residential Home Ecosystem Testing (Cooling Humid Coil - A 77°F)

Figure 3 shows the average sensible and latent cooling rate, internal load, total power, and COP for each complete on/off cycle during the cooling humid-coil test at 77°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. For these humid-coil tests, the latent cooling rate was estimated based on differences between total refrigerant-side and air-side sensible cooling rates. The estimated latent cooling rate compared well with estimates from condensate measurements.

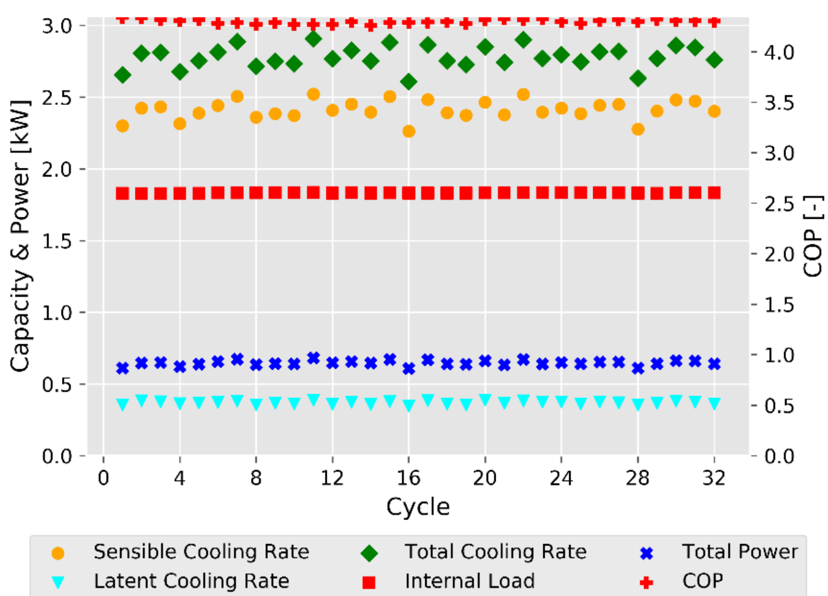


**Figure 3.** Average Cycle Performance during Residential Home Ecosystem Testing (Cooling Humid Coil – A **77**°F)

Cooling tests were performed for all the 5 dry-coil and 4 humid-coil test conditions at steady ambient conditions. For the humid coil tests, the outdoor humidity was controlled to maintain an indoor RH in the 50-60% range. However, at low ambient temperature, even with the high outdoor RH, it was not possible to maintain the indoor RH in the desired range. This is because the only moisture gain to the house was due to infiltration. So, at low outdoor temperature conditions as the moisture carrying capacity of the air decreases, the moisture gain to the house also decreases. The building load lines for load-based testing were estimated from the house testing for both dry-coil and humid-coil cooling test conditions using the measured average cooling rates at different ambient temperatures over the 24-hour steady-periodic tests. Since the heat-pump was able to maintain the indoor temperature across all the ambient conditions, the average cooling rates are effectively the building loads for the given indoor and outdoor conditions. Figure 4 shows the house loads as a function of ambient temperature (load lines) for the cooling dry-coil and humid-coil test conditions along with representative load-lines based on CSA EXP07 (CSA, 2019) for a 3-ton unit. The EXP07 estimate assumes that the test equipment would be oversized by 20% at 95°F ambient temperature. In addition, the assumption in EXP07 is that the virtual building balance point temperature for cooling dry-coil test conditions is 72°F and 67°F for humid coil test conditions. Also, the building load sensible heat ratio is assumed to be 1 for dry-coil and 0.8 for humid-coil test conditions in EXP07. Consequently, the load lines from the residential house tests and the EXP07 standard draft differ because of differences in oversizing and balance point temperatures. 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.

In order to emulate the dynamic behavior of a representative residential building within load-based testing, an important virtual building model parameter is the building thermal capacitance, which dictates the dynamic interaction between the building and its equipment. As outlined in Equation (6) and (7), 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. Here, $N_{max}$ is estimated by fitting the parabolic curve defined by Equation (7) to the cycle rate ($N$) and run-time fraction ($X$) data from the residential house cooling dry-coil and humid-coil 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 tests, which makes sense as this represents the effective capacitance of the house. The maximum cycling rate for the residential house is around 2, 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.

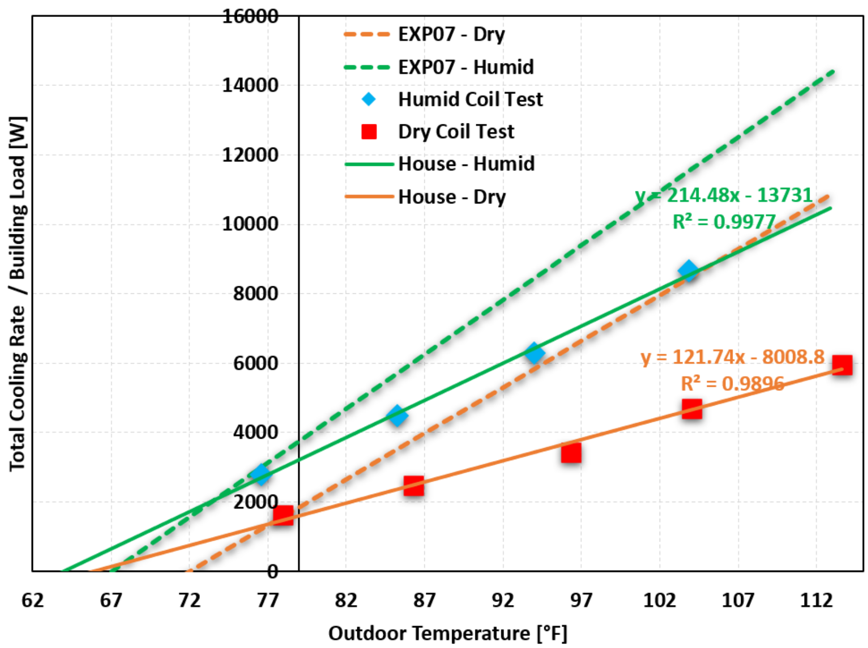


**Figure 4.** Overall Cooling Test Results and Estimated Residential House Load Lines

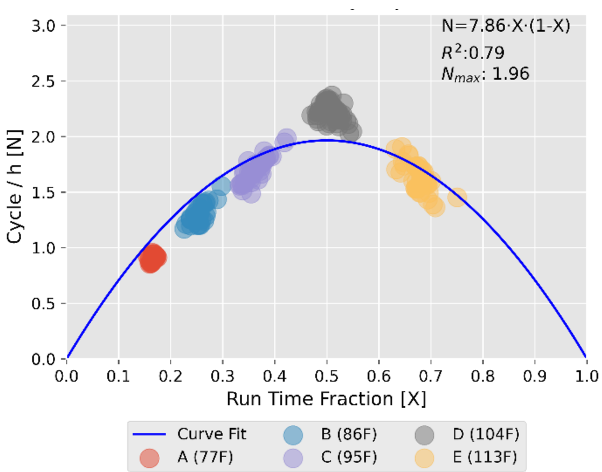


**Figure 5.** Cycle Rate with Run-time Fraction for Dry-Coil Cooling Test Results – House

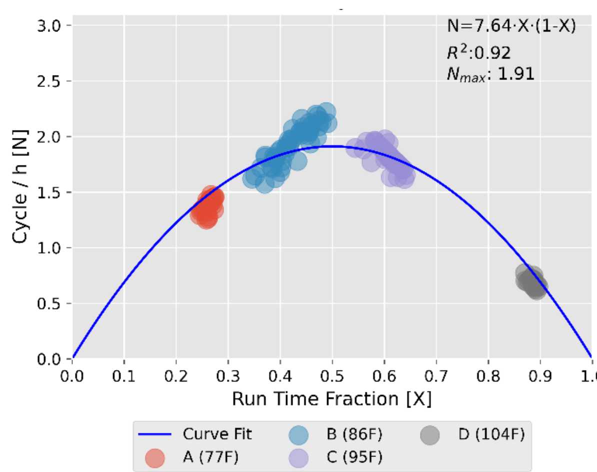


**Figure 6.** Cycle Rate with Run-time Fraction for Humid-Coil Cooling Test Results – House

## 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 were updated from the CSA EXP07 (CSA, 2019) based on the above test results such that the virtual building loads and dynamics are representative of the applied ecosystem house. The test unit design cooling rates were measured for a steady-state $A_{Full}$ test (AHRI, 2020) with the indoor test room at 80°F dry-bulb / 67°F wet-bulb, the outdoor test room at 95°F dry-bulb temperature conditions, and the heat pump running at full-capacity in cooling mode. Table 2 shows the virtual building parameters for dry as well as wet-coil cooling test conditions which were utilized with equations (1)-(8) to perform load-based tests.

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

| **Parameter** | $\dot{Q}_{c,s,D}$ | $\dot{Q}_{c,D}$ | $\Delta T_{db}$ | $\Delta t$ | **Dry-Coil** | | | |
|---|---|---|---|---|---|---|---|---|
| | | | | | $F$ | $SHR_{Building}$ | $T_{OD,D}$ | $T_{Bal,D}$ |
| | $W$ | $W$ | °F | s | - | - | °F | °F |
| **Value** | 8337.8 | 10792.5 | 2 | 1 | 2.26 | 1 | 105 | 65.8 |
| | **Dry-Coil** | | **Humid-Coil** | | | | | |
| **Parameter** | $T_{ID,D}$ | $N_{max}$ | $F$ | $SHR_{Building}$ | $T_{OD,D}$ | $T_{Bal,D}$ | $T_{ID,D}$ | $N_{max}$ |
| | °F | $1/h$ | - | - | °F | °F | °F | $1/h$ |
| **Value** | 79 | 1.96 | 1.62 | 0.85 | 95 | 64 | 74 | 1.91 |

Figure 7 shows the heat-pump performance and temperature variation during the cooling dry-coil load-based tests at 5 different ambient temperature conditions. In the upper subplot, the test unit sensible cooling rate, virtual building sensible load, and total power consumption correspond to the left vertical axis and AHU 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 AHU return air temperature was controlled to the virtual building indoor temperature setpoint, and it can be seen that the test room re-conditioning system was able to track the virtual building temperature very well as both are overlapping.

The thermostat was set to 79°F for the dry-coil cooling load-based test, and the heat pump cycled on/off at all the 5 ambient conditions to maintain the indoor temperature near the thermostat setpoint, which was also observed in the residential house testing. As the virtual building load increased, the heat-pump run-time fraction increased to compensate for the higher building load. The heat pump cycled on/off even at higher outdoor temperature conditions with higher building load due to the oversizing of the heat-pump compared to the defined virtual building load. 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 possibly due to the non-uniform temperature distribution in the psychrometric test room.

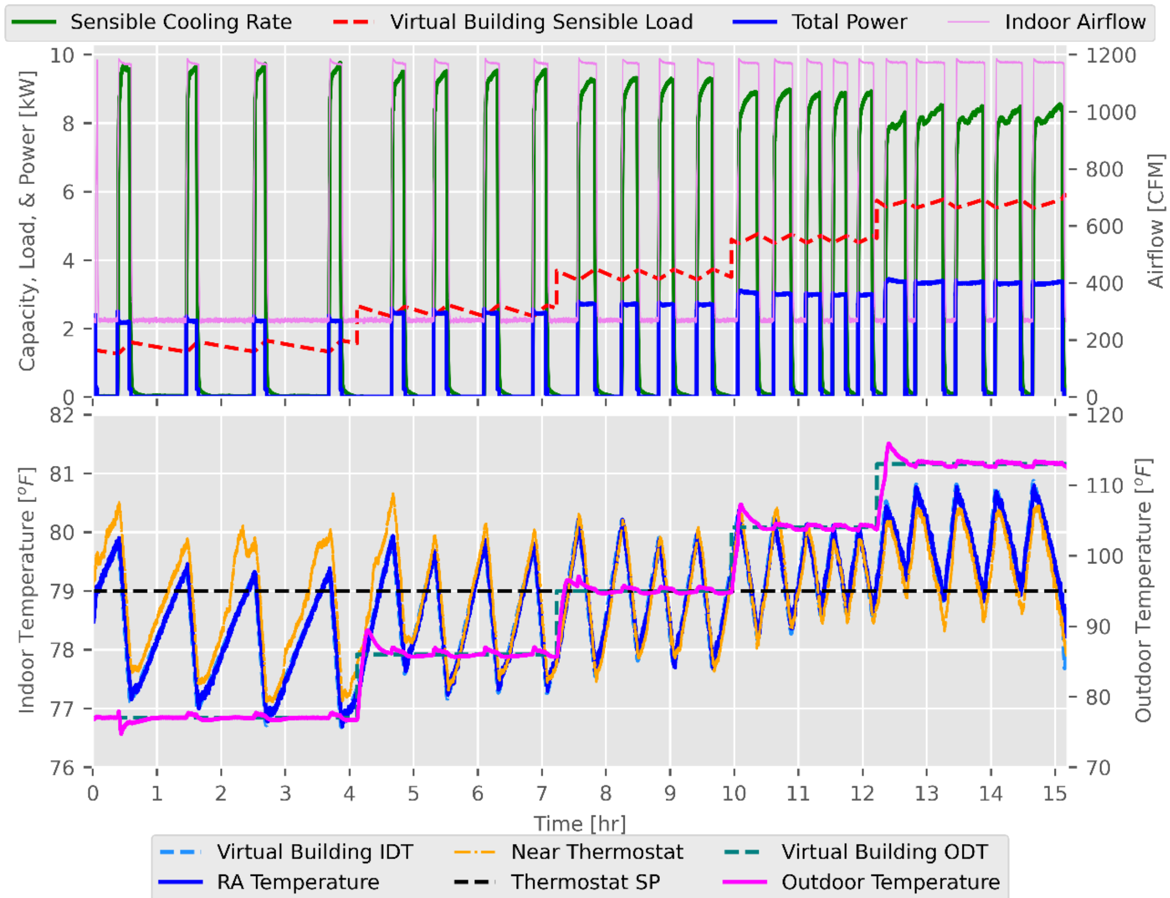


**Figure 7.** Heat-pump Performance and Temperature Variation for Cooling Dry-Coil Load-Based Test

Figure 8 shows the heat-pump performance, temperature, and humidity variation for the cooling humid-coil load-based tests at 4 different outdoor temperature conditions. In humid-coil cooling load-based tests, the return air relative humidity (RA RH) was controlled based on the virtual building latent load model response, in addition to the return air dry bulb temperature. For each test interval, the COP (coefficient of performance) for at least the last two cycles converged according to the primary convergence criteria outlined in (CSA, 2019), prior to moving on to the next test interval. The average return air temperature also converged for different cycles; however, the return air humidity did not converge, especially for the first test interval. This requires further investigation into how the indoor humidity convergence affects the overall performance measurement in load-based tests. As shown in the upper subplot of Figure 8, a negative latent cooling rate was measured when the heat-pump cycled off due to a condensate re-evaporation effect. The re-evaporation effect was somewhat intensified in the current test setup due to a small airflow over the coil in fan off-mode conditions. This is because the nozzle code-tester is connected to the facility re-conditioning system air circulation loop. In future testing, a shutoff damper will be installed in the AHU supply air duct. Furthermore, similar to the dry-coil test results, the average indoor temperature increased as the building load increased and a small difference in the return air temperature and temperature around the thermostat can be observed.

Figure 9 and Figure 10 shows cycle rate $(N)$ and run-time fraction $(X)$ data for the cooling dry-coil and humid-coil load-based test results in the laboratory, along with the fitted parabolic curve as per Equation (7) and also the curve obtained from the house test result. In contrast to the house test results (Figure 5 and Figure 6), there is a significant difference in the overall cycling behavior between dry-coil and humid-coil load-based tests in the lab. Also, the results from dry-coil tests are comparable among the two facilities, but not for the humid-coil cooling tests.

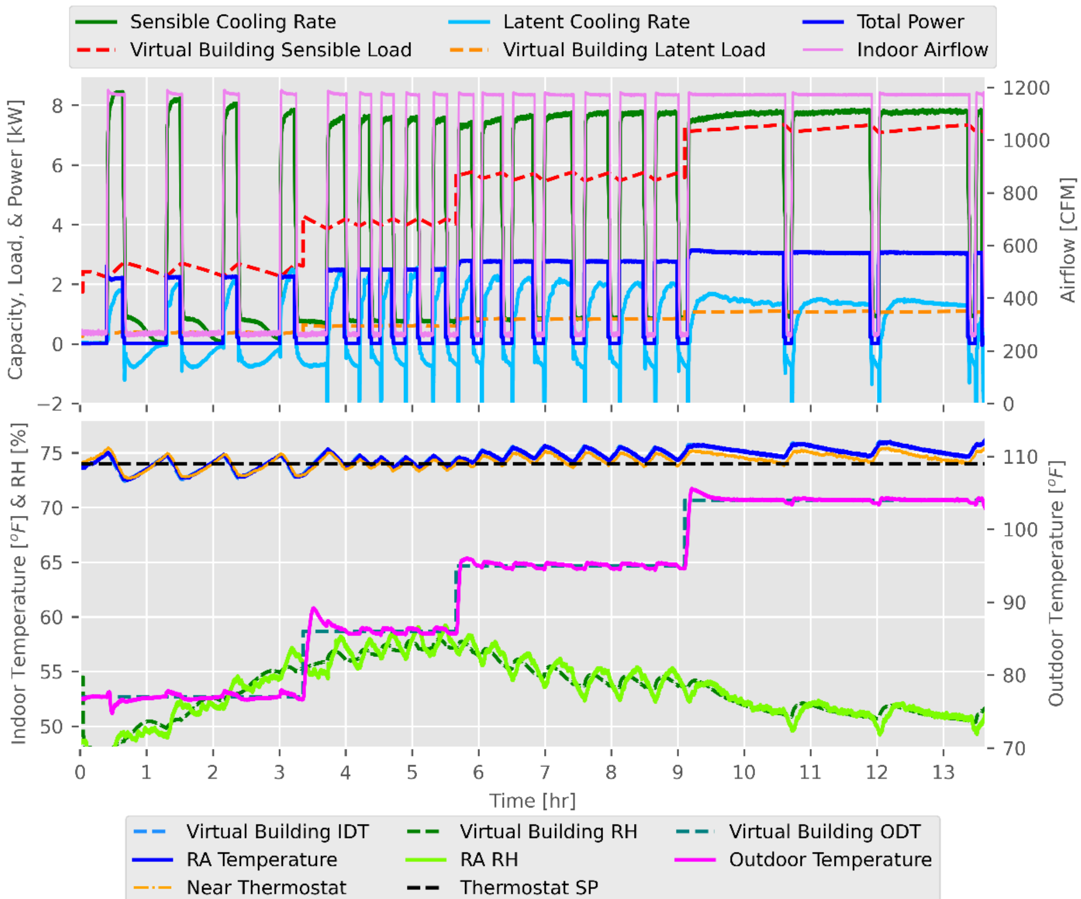


**Figure 8.** Heat-pump Performance, Temperature, and Humidity Variation for Cooling Humid-Coil Load-Based Test

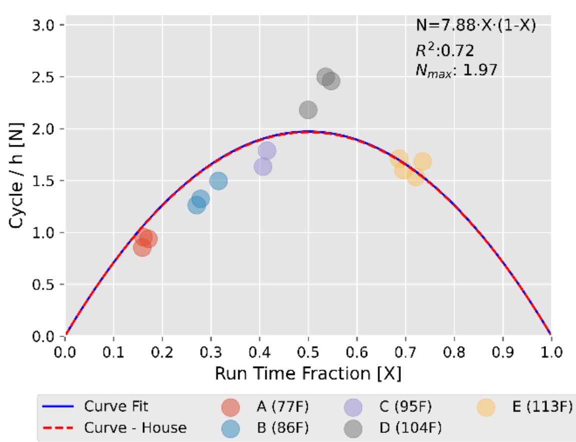


**Figure 9.** Cycle Rate with Run-time Fraction for Dry-Coil Cooling Load-Based Test

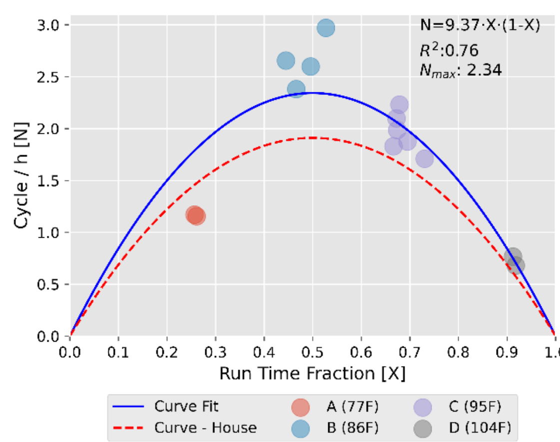


**Figure 10.** Cycle Rate with Run-time Fraction for Humid-Coil Cooling Load-Based Test

## 4.3 Equipment Performance Comparisons

Figure 11 shows COP comparisons for the dry-coil and humid-coil cooling tests performed at the Residential Home Ecosystem house and in the psychrometric test lab as per the load-based testing approach. For dry-coil cooling tests, the heat-pump COP measured in the lab was higher than that measured at the house, with a difference varying from 7% to 13% at different test intervals. These differences may be due to measurement uncertainties, differences in performance between the unit installed at the Helix Center and the new unit tested in the laboratory, differences in dynamic interaction between the equipment and load, and/or differences in indoor and outdoor conditions between the two facilities. In dry-coil tests, the average cooling provided by the heat-pump was similar in both test facilities with a variation of only around 5%. However, the average outdoor power consumption in the house was anywhere from 5% to 17% higher, indicating a disparity in the compressor performance. For example, at the 95°F outdoor temperature test condition in the house, the outdoor power consumption during the system ON period was observed to be around 2.9kW, compared to only 2.5kW in the test lab. In addition to the variations in operating conditions and refrigerant charge, this difference could also be because of heat-pump compressor performance degradation at the house over the years, whereas, the test unit in the lab was a new one.

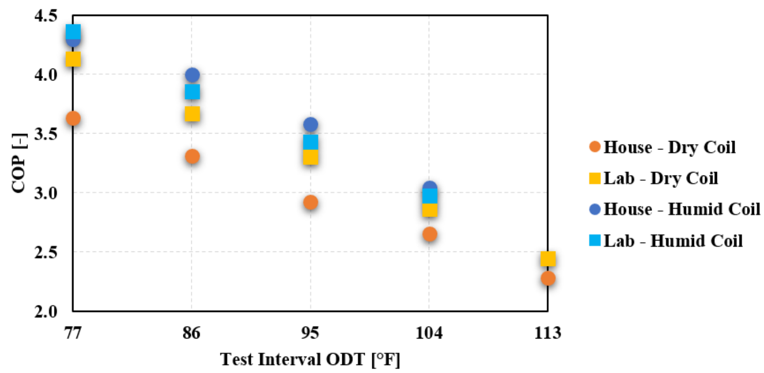


**Figure 11.** Cooling Tests COP Comparison Between Two Facilities

Another factor that could cause performance differences is differences in average return air temperature (RA T) between the two test facilities as shown in Figure 12. The 2-story house was controlled based on a single thermostat installed on the first floor, whereas the average return air temperature to the equipment is the result of return air ducts on both floors. As a result, the return air temperature increased with ambient temperature, which improved the heat-pump performance in cooling mode compared to the test lab where the average return air temperature remained relatively constant. However, this effect would not explain differences in performance results since increasing the return air temperature for the lab tests would lead to greater differences in performance. Figure 12 also shows the average temperature near the thermostat between the two test facilities, along with its average variation during on/off cycling indicated with error bars. In the house, the average temperature near the thermostat was maintained around 0.7°F to 1.6°F higher than in the test lab, with higher temperature swings of around 4.8°F (-2.7°F to 2.1°F) compared to the 2.3°F (-1.2°F to 1.1°F) swings in the lab. During testing in both facilities, the thermostat deadband was set to the same value of ±1°F. Differences in thermostat responses could be because of the differences in the thermostat installation and airflow around the thermostat in the two facilities. In the psychrometric test room, the airflow is relatively high compared to the house, which could lead to a faster response in thermostat sensing and smaller temperature swings. On the other hand, for dry-coil tests, overall heat-pump dynamic behavior of on/off cycling rate with run-time fraction was observed to be fairly similar in both test facilities, as can be seen in Figure 5 and Figure 9.

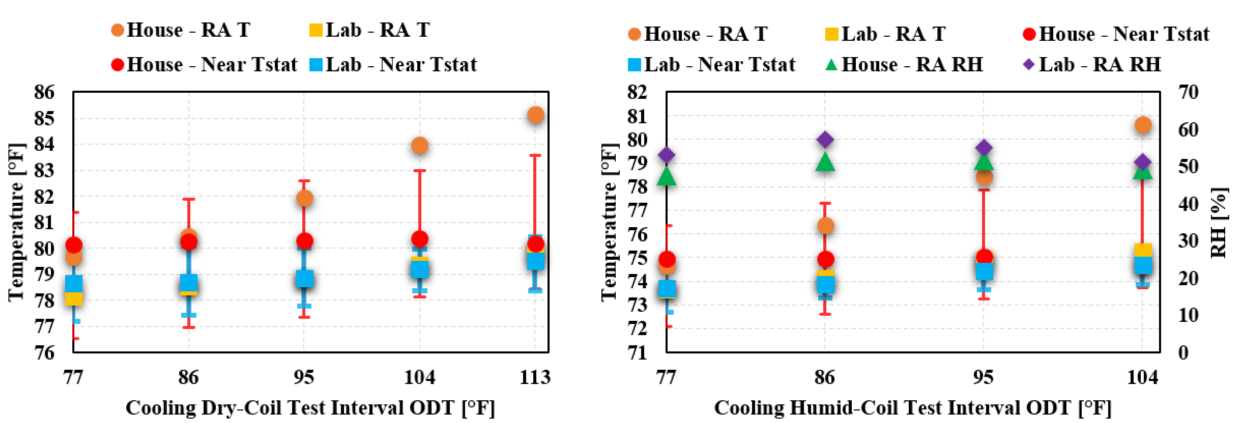


**Figure 12.** Colling Tests Average Temperature and RH Comparison Between Two Facilities

In humid-coil cooling tests, differences in the heat-pump COP between the two facilities were relatively small as compared to the dry-coil tests, varying from only 1% to 4%, with COP measured lower in the load-based tests at the lab. The overall equipment on/off cycling behavior with run-time fraction was somewhat different between the two facilities, as can be seen in Figure 6 and Figure 10. This difference was mainly caused by the test unit behavior at the 86°F and 95°F outdoor conditions load-based tests. Comparing the fitted curve from both facilities' test results, at the same run-time fraction (part-load ratio), the test unit cycled on/off more frequently during the lab load-based tests. One of the possible causes for this is a difference in the thermostat sensing response due to different thermostat airflow and temperature conditions in the two facilities. As the right plot in Figure 12 shows, the average temperature around the thermostat was similar between the two test facilities; however, similar to dry-coil tests during on/off cycles, larger temperature swings of around 4.3°F (-1.8°F to 2.4°F) were observed in the house compared to around 1.5°F (-0.8°F to 0.7°F) in the lab. For humid-coil tests, these temperature variations around the thermostat were even smaller than the dry-coil tests. A possible contributory factor for these differences is differences in sensible cooling rate provided by the equipment for the humid-coil and dry-coil tests. These results emphasize the importance of providing standardized environmental conditions to the thermostat during load-based testing. Figure 12 also shows that similar to the dry-coil tests, the average return air temperature increased with ambient temperature in the house, whereas in the lab it was fairly constant among the different test intervals and very close to the average temperature around the thermostat. The average return air relative humidity levels were observed to be around 2% to 6% lower in the house compared to the load-based tests in the lab. In humid-coil cooling test intervals, the average sensible cooling rate was lower and the average latent cooling rate higher compared to the load-based test results. These effects tended to increase overall system COP in the house test results leading to better agreement with the lab results than for the dry coil tests. Another possible reason for better agreement in the humid-coil test COP's is the comparable power consumption by the compressor during the system ON period in the two test facilities. This is likely attributable to the fact that before performing humid-coil tests, the heat-pump at the house was retrofitted with a new identical model compressor due to failure of the original compressor.

Based on the test results and comparisons, further testing and investigation will be carried out in the lab to test the unit with more comparable conditions to the house, such as return air temperature and conditions around the thermostat, in order to have an apples-to-apples comparison and to gain a better understanding of the root causes of performance differences. In future load-based tests in the lab, a thermostat environmental emulator (Cheng et al., 2021a) will be used to provide temperature and airflow inlet conditions for the thermostat that are similar to those experienced in the house.

## 5. CONCLUSIONS

This paper presents cooling 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 a same model in a psychrometric test facility at the Ray W. Herrick Laboratories. The goal of the study was to gain a better understanding of how well the load-based testing approach characterizes the dynamic performance of equipment in the lab as compared to an actual 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, and then the system was tested for dry-coil and humid-coil cooling conditions. To summarize the results, it was observed that for the dry-coil tests, the heat-pump COPs differed by between 7% and 13%, but the overall cycling dynamic behavior was similar for the two test facilities at the different test conditions. On the other hand, for humid-coil tests, the system COPs were comparable but the test unit cycling behavior varied, especially at 86°F and 95°F outdoor test conditions. Possible causes for the differences in performance and overall dynamic behavior between the two test facilities were studied and some areas for further investigation were identified to reduce differences in performance and to better understand the root causes of the differences, including reducing differences in return air temperature and humidity conditions, compressor performance, and temperature and airflow conditions around the thermostat. One of the next steps will be to perform load-based testing on the heat-pump with a thermostat environmental emulator (Cheng et al., 2021a) to have more representative conditions in the lab similar to the testing at the house. Additionally, similar comparisons will be performed for heating mode testing.

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