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Heat-Pump Control Design Performance Evaluation using Load-Based Testing

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ABSTRACT

Space heating is one of the primary components of residential energy usage in the U.S., accounting for nearly 43% (EIA, 2015) of the total residential energy consumption. To reduce this energy usage, heat-pumps provide an energy-efficient alternative to currently prevalent systems such as electric heaters and gas furnaces. Advanced control strategies have the potential to further improve heat-pump system energy efficiency and comfort delivery. In recent years, advancements in the microprocessor field have made it possible to widely implement advanced energy-efficient controls within heat-pump systems. However, still only a very small fraction of residential air-conditioners and heat-pumps currently sold in the U.S. market utilize these next-generation controls (ACEEE, 2019). To facilitate an acceleration in the development and implementation of advanced control architectures within heat-pump equipment, a load-based testing methodology can be utilized. Load-based testing allows realistic dynamic behavior and performance evaluation of energy efficiency and comfort delivery for heat pumping and air conditioning equipment with embedded controls in a laboratory setting. In the load-based testing methodology, the sensible and latent loads of a representative residential building are emulated in the indoor psychrometric test room by dynamically varying the test room conditions utilizing a virtual building model. The test equipment responds dynamically to this virtual building with its embedded controls based on the thermostat sensing response. This enables engineers to evaluate the performance of a heat-pump in a controlled setting under dynamic conditions that are similar to a field application but with a significant reduction in testing time and cost. This paper demonstrates the application of load-based testing for evaluating the performance of a 5-ton split-type residential heat-pump with its integrated controls in a heating mode application. Furthermore, the effect of equipment oversizing and undersizing on the heat-pump energy consumption and comfort delivery are also presented.

1. INTRODUCTION

Improving the performance of air-conditioning and heat-pumping (ACHP) systems to meet increasing energy efficiency standards while meeting growing space conditioning and comfort demands is challenging. Research and development efforts at both the component and system levels are continuously being pursued in the industry as well as in academia. To achieve better performance, modern variable-speed ACHP systems are usually equipped with more sophisticated control capabilities than have been traditionally employed for fixed-speed systems. Advanced control algorithms have the potential to improve ACHP systems' energy efficiency while maintaining comfort delivery. However, the implementation of advanced controls has been limited in actual products (ACEEE, 2019). One reason for this is the cost and time associated with evaluating short-term and long-term seasonal performance improvements resulting from advanced controls, which is usually done with time and resource-consuming field studies.

To overcome this, a load-based testing methodology has been developed and implemented for ACHP performance tests, where the influence of system control on heating and cooling performance can be effectively evaluated for representative building and climate conditions in a test laboratory setting. Patil et al. (2018) proposed and utilized the load-based testing methodology for the estimation of seasonal performance for variable-speed residential heat-pump and air-conditioning equipment. Cheng et al. (2021) described the implementation of load-based testing for rating of a variable-speed residential heat-pump. The work of Patil et. al. (2018) and Cheng et al. (2021) demonstrated that load-based testing is beneficial for ACHP performance evaluation with the consideration of embedded controls. In addition, Hjortland and Braun (2019) implemented the load-based methodology to evaluate a packaged rooftop unit (RTU) air conditioner performance with different control modes: fixed speed on/off control, two-speed control, and variable-speed control. Their work showed that load-based testing provides an approach that can be used to compare different integrated control strategies in a manner that is representative of field application. Dhillon et al. (2021c) extended the work to develop and demonstrate a load-based testing methodology for RTYs with integrated economizers. Dhillon et al. (2018, 2021b) implemented the load-based testing approach to estimate the seasonal performance of residential heat-pump systems and compared it with the current rating approach based on AHRI 210/240. Cheng et al. (2018) presented the sensitivity analysis of virtual building parameters on load-based test results, and Dhillon et al. (2021d) compared the load-based testing results of a heat-pump in the lab to the test results from a residential house test facility at similar operating conditions to validate the load-based testing approach.

Dhillon et al. (2021a) implemented the load-based testing methodology to perform a qualitative and quantitative comparison of the dynamic performance of a 5-ton split-type residential heat-pump with two different control architectures in cooling mode. In the current work, following that of Dhillon et al. (2021a), the load-based testing methodology was implemented for performance evaluation of the same residential heat-pump with its embedded controls in a heating mode application. Furthermore, the effects of equipment oversizing and undersizing on the heat-pump energy consumption and comfort delivery were also investigated. To emulate the dynamic response of a representative building coupled to the test equipment performance, virtual building model parameters scaled to the test unit design capacity were defined. Then, the heat-pump was tested in heating mode at outdoor temperatures representative of typical mid-winter and peak-winter season days. Finally, heat-pump energy consumption and comfort delivery are analyzed and compared for different scenarios.

2. LOAD-BASED TESTING-HEATING MODE

In the load-based testing approach, a virtual building model is utilized to continuously adjust the indoor room temperature and humidity set-point of the psychrometric re-conditioning system to emulate the response of a representative building served by the heat-pump system (Hjortland & Braun, 2019). A schematic of the load-based testing approach for a heat pump is shown in Figure 1. During a heating load-based test, the heating rate of the test unit is measured in real-time and the space heating load is calculated by the virtual building model. Then, for each time step, the temperature of the virtual building is updated based on the difference in real-time measured heating rate and the calculated load. The updated virtual building model temperature is then fed into the indoor psychrometric room re-conditioning system as a set-point for the next time step. With this approach, the test unit naturally responds to a deviation in the indoor temperature from the unit thermostat set-point.

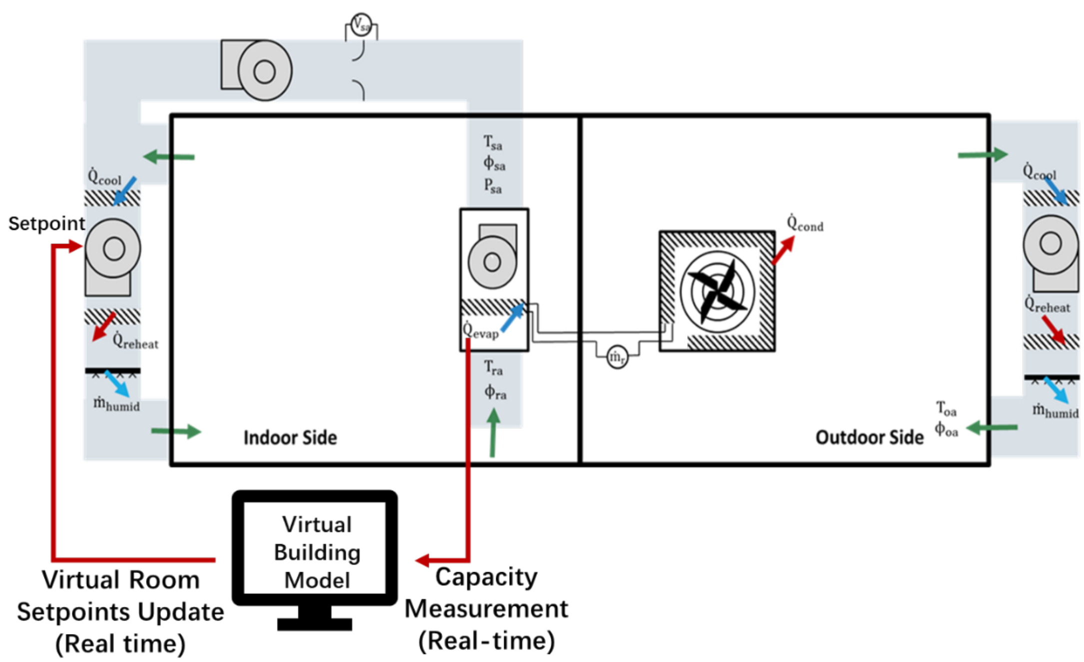

Figure 1: Load-based testing schematic of a split-type heat-pump system

The virtual building model can be defined based on the desired complexity of the representative building for the underlining experimental study. Patil et al. (2018) and Cheng et al. (2021) described a simple virtual building model for a representative residential building which was employed for the experimental study presented here. The corresponding parameters for the virtual building model are used based on CSA EXP-07 (2019). In the virtual building model for heating tests, the building heating load is calculated based on the equipment rated total cooling capacity ($\dot{Q}_{c,D}$) at design conditions as:

$$\dot{Q}_{load,h} = f \times \dot{Q}_{c,D} \times \left(\frac{T_{OD} - T_{bal}}{T_{zl} - T_{ref}}\right) \tag{1}$$

where f is a sizing factor to scale the building load based on the test unit sizing for a typical building. It should be noted that increasing the building load sizing factor is equivalent to undersizing the equipment, and similarly, decreasing the building load sizing factor is equivalent to equipment oversizing for a building design load. The building load sizing factor default value as per CSA EXP-07 (2019) is 1.15. The equipment rated total cooling capacity ($\dot{Q}_{c,D}$) is measured at design conditions with a steady-state test at constant indoor and outdoor test room conditions and the equipment running at maximum capacity. T_{OD} is the outdoor (ambient) temperature, which is determined according to a representative temperature profile. T_{zl} is the design balance point temperature for heating, and T_{ref} is the outdoor load reference temperature. T_{bal} is the balance point temperature shown in Equation (2), which is updated based on the current indoor temperature and the design indoor temperature specified as the test unit thermostat setpoint.

$$T_{bal} = T_{zl} + \left(T_{ID} - T_{ID,SP}\right) \tag{2}$$

Then based on the calculated virtual building load and the equipment measured capacity for each time interval, the virtual building temperature is updated for each next interval as:

$$T_{ID}(t + \Delta t) = T_{ID}(t) - \frac{\Delta t\left(\dot{Q}_{load,h} - \dot{Q}_{cap,h}\right)}{C_s} \tag{3}$$

where the sensible thermal capacitance (C_S) for a representative residential building is scaled with the equipment design condition sensible cooling capacity ($\dot{Q}_{c,s,D}$) as per equation (5). $\dot{Q}_{cap,h}$ is the test unit heating rate measured in real-time.

$$C_s = \frac{\dot{Q}_{c,s,D}[W] \cdot 150[s]}{\Delta T_{tstat,db}} \tag{4}$$

where $\Delta T_{tstat,db}$ is the thermostat deadband. The virtual building model continuously updates the indoor test room conditions to emulate the response of a representative building to the equipment performance based on the above described approach.

3. EXPERIMENTAL TEST METHOD

The test unit is a 5-ton split heat-pump installed in two side-by-side psychrometric test chambers at the Ray W. Herrick Laboratories. The test set-up is the same as the one utilized in the work done by Dhillon et al. (2021a). The outdoor test room temperature was varied according to a typical daily temperature profile for the heating season. Based on the model described by Mitchell & Braun (2012), an analytical relationship for monthly average hourly temperature was used to generate different diurnal temperature profiles, as shown in Equation (5).

$$T_{OD} = \left(T_{OD,max} - \frac{T_{OD,max} - T_{OD,min}}{2}\right) + \left(T_{OD,max} - T_{OD,min}\right) * (0.4632 * cos\,(\tau - 3.8051) + 0.0984 * cos\,(2 * \tau - 0.360) + 0.0168 * cos\,(3 * \tau - 0.822) + 0.0138 * cos\,(4 * \tau - 3.513)); \tag{5}$$

where $T_{OD,min}$ and $T_{OD,max}$ are the minimum and maximum outdoor temperature during the testing, respectively. Figure 2 shows the representative outdoor temperature profile for a typical mid-winter day where the outdoor temperature varies between 40°F (4.44°C) and 60°F (15.55°C) and for a peak-winter day where the outdoor temperature varies between 20°F (-6.67°C) and 40°F (4.44°C). τ is nondimensional time in radians, given by:

$$\tau = \frac{2\pi(4t - 1)}{24} \tag{6}$$

Equation (5) was modified to compress the complete daily temperature change from 24 hours to 6 hours to accelerate the testing. This is reasonable because the dynamic response of the equipment with its integrated controls is still orders of magnitude faster than the diurnal variation of the outdoor temperature (Dhillon et al., 2021a).

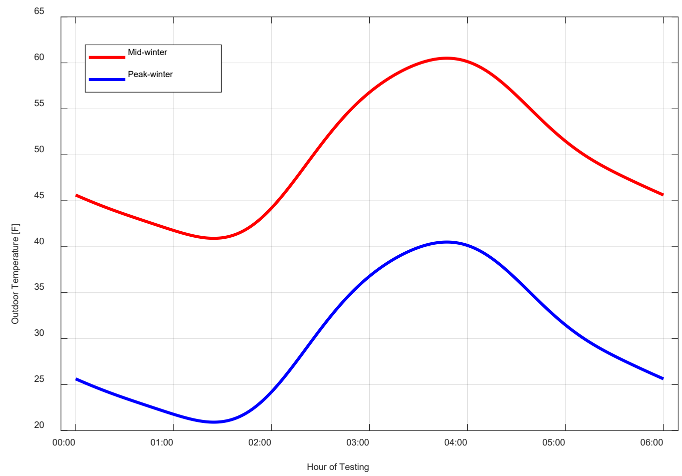

Figure 2: Outdoor temperature profile for mid-winter and peak-winter

In the load-based testing approach, the indoor temperature varies according to the response of the virtual building model as described in section 2. The virtual building model parameters derived for the tested heat-pump are presented in Table 12. The equipment was tested with three different building load sizing factor f: nominal, 20% undersized, and 20% oversized for a typical mid-winter and peak-winter day.

Table 1: Building-load sizing factor

Parameter	f		
	Oversized	Nominal	Undersized
Value	0.92	1.15	1.38

Table 2: Virtual building parameters

Parameter	$\dot{Q}_{c,D}$	$\dot{Q}_{c,s,D}$	T_{zl}	T_{ref}	$T_{ID,SP}$	$\Delta T_{tstat,db}$	C_s	Δt
	W	W	°F	°F	°F	°F	J / °F (J/°C)	second
Value	15192.6	12850.6	60	5	70	1	1927596 (1070887)	1

During the load-based testing, the outdoor room temperature varied according to the defined temperature profile as shown in Figure 2. The indoor psychrometric room temperature setpoint was updated continuously according to the virtual building temperature response based on the parameters shown in Table 1 and Table 2. In this way, the equipment dynamic performance was measured for 6-hour test durations and the results are presented in the next section.

4. RESULTS

Figure 3 and Figure 4 show the heat-pump performance for 6-hour dynamic test durations with nominal equipment sizing for typical mid- and peak-winter days, respectively. The left vertical axis corresponds to the indoor and outdoor temperature, and the right vertical axis corresponds to the virtual building model heating load and the test unit heating rate. The outdoor psychrometric room temperature followed the defined ambient temperature profiles, which varied gradually over 6 hours from 40°F to 60°F for a typical mid-winter day and from 20°F to 40°F for a typical peak-winter day. The virtual building heating load varies with the outdoor temperature profile. As the outdoor temperature decreased, the building load increased and the heat-pump run-time fraction for a cycle increased to compensate for the higher building load. A good agreement can be observed between the target indoor temperature obtained from the virtual building model and the indoor psychrometric chamber temperature with a small lag due to the test room re-conditioning system thermal dynamics. Further, the test unit heating rate and power consumption variation demonstrate the system performance as a natural response to the indoor temperature variations with its integrated control.

It can be observed from Figure 3 that for a typical mid-winter day, the variable-speed unit cycled on and off throughout the 6-hour test duration based on the thermostat interaction with the varying indoor temperature and the test unit embedded controls. The variable-speed equipment exhibited behavior similar to that of a single-stage system. When the indoor temperature was around 1°F lower than the thermostat setpoint, the equipment started to deliver heating until the indoor temperature increased to around 1°F higher than the thermostat setpoint. The test unit cycle run-time fraction decreased as the outdoor temperature increased (i.e., as the building load decreased). As the outdoor temperature increased to the design balance point temperature (T_{zl}), the building load decreased to zero and the heat-pump stayed off for a long time between the 3rd and 4th hour as shown in Figure 3. Furthermore, the building load did not follow the exact profile of the outdoor temperature because of the variations with indoor temperature deviation from its target design condition.

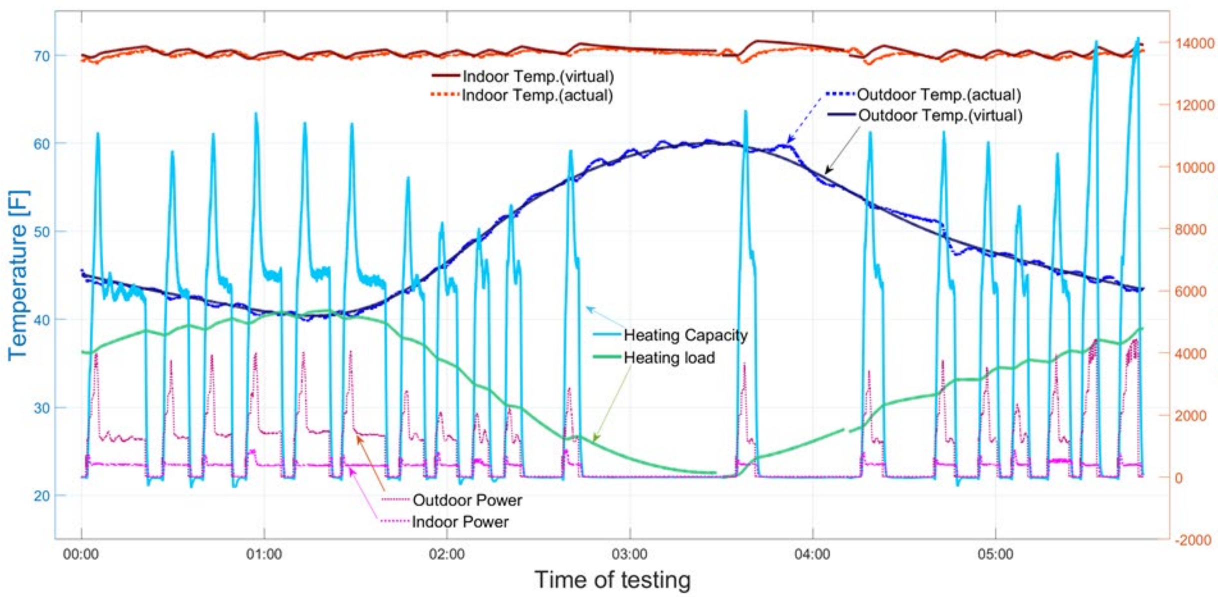

Figure 3: Equipment dynamic performance with nominal equipment sizing on a typical mid-winter day

Figure 4 represents the load-based testing results for a typical peak-winter day with nominal equipment sizing. Initially, when the building load was high at the low outdoor temperature, the heat-pump ran at its full capacity to compensate for the building load to maintain the indoor temperature above 69°F. Then, as the outdoor temperature increased and the building load decreased, the heating rate delivered by the equipment also reduced to match the smaller building load. It can be observed in Figure 4 that the psychrometric chamber control system was able to follow the virtual building model temperature setpoint better than for a typical mid-winter day (Figure 3), and the indoor temperature swings were much less compared with results for Figure 3, where the equipment cycled on and off more often. The outdoor unit power measurements, which include compressor and fan power, reveal that the unit reached a maximum value when the building load was higher at the beginning of the test, and then, the power decreased gradually with the building load before cycling off at minimum compressor speed. For the typical peak-winter day test, defrost operation was also observed during the load-based test at around 23 mins, and also at 1 hour 50 mins into the test. It can be seen that when the equipment entered the defrost cycle, the heating capacity became negative for a short period.

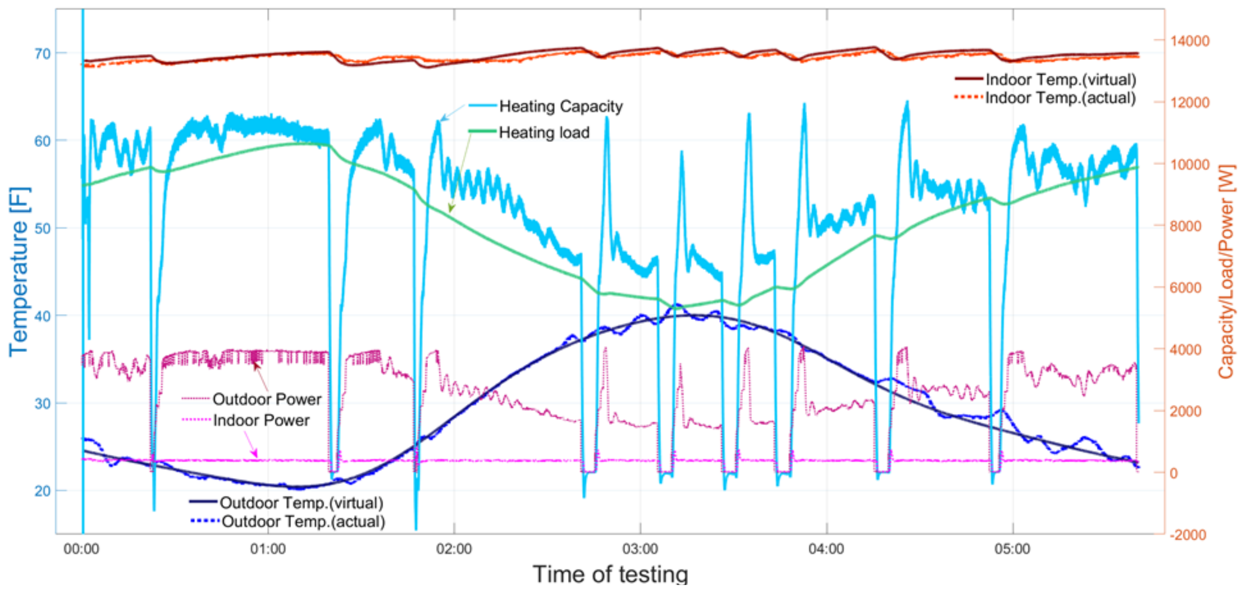

Figure 4: Equipment dynamic performance with nominal equipment sizing on a typical peak-winter day

Figure 5 and Figure 6 present heat-pump performance over 6-hour dynamic tests at typical mid-winter and peak-winter day, respectively, for an undersized equipment scenario (i.e., virtual building load is higher than the nominal sizing case at the same outdoor conditions). Comparing Figure 5 to Figure 3, the test equipment exhibited similar cycling on/off behavior but with larger cycle run-time fractions due to relatively higher building load. Furthermore, as can be seen in Figure 6, at lower outdoor temperature, the equipment ran at full capacity but still failed to meet the large building load, which resulted in indoor temperatures far below the thermostat lower dead bound of 69°F. It should be noted that at 30 mins, 1 hour 50 mins, 3 hours 55 mins, and 5 hours 30 mins of the test, the equipment utilized defrost operation, which further reduced the indoor temperature. In addition, when the outdoor temperature increased to around 40°F, the heating rate tracked the building load well and the unit operated in a variable-speed mode without cycling off, and the indoor temperature gradually increased to the thermostat setpoint. For the equipment undersized scenario, the equipment ran continuously for most of the time instead of cycling on/off, the indoor temperature was more steady but hard to maintain around the setpoint for a typical peak-winter day. Also, there was higher power consumption to provide more heating capacity for the compensation of the larger building load.

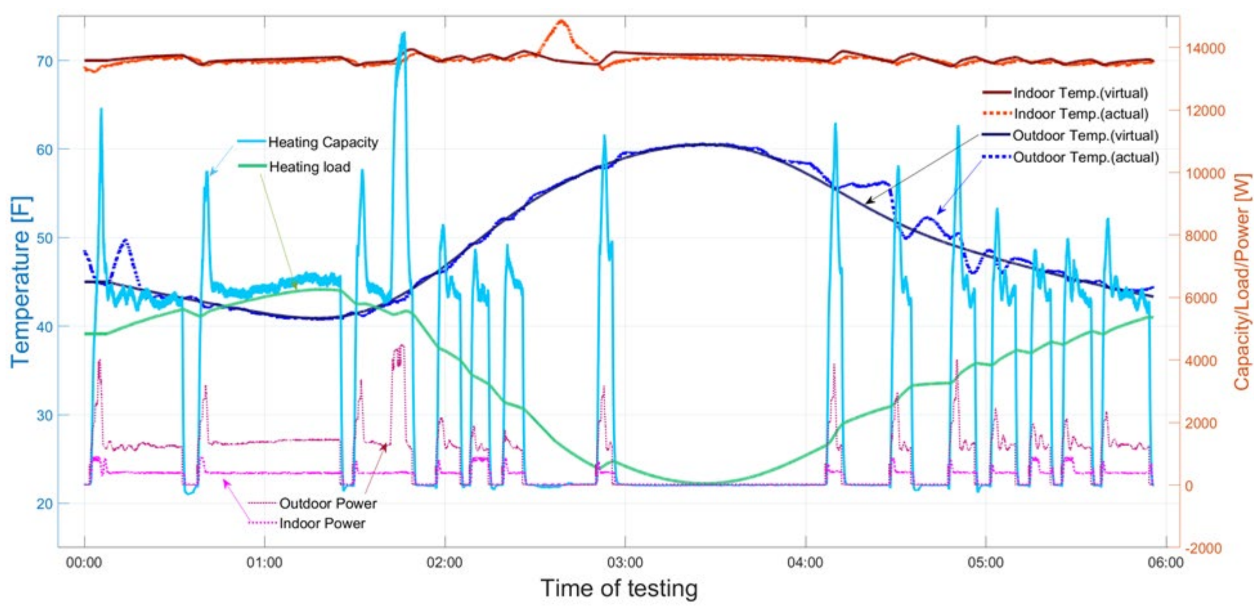

Figure 5: Equipment dynamic performance with equipment undersizing on a typical mid-winter day

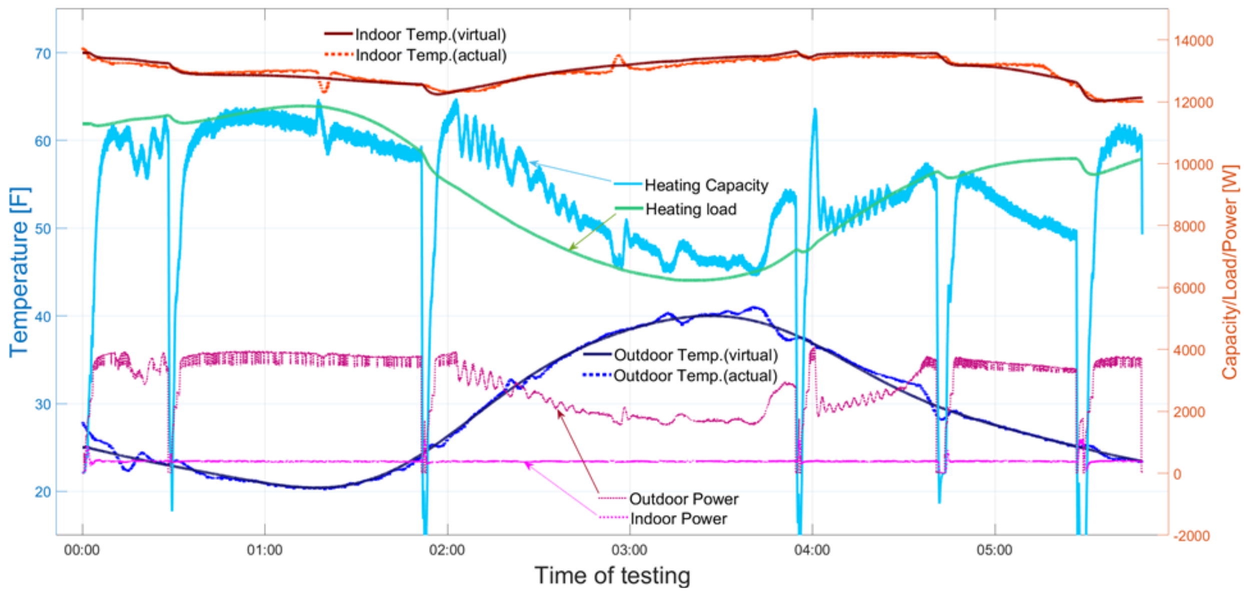

Figure 6: Equipment dynamic performance with equipment undersizing on a typical peak-winter day

Figure 7 and Figure 8 present the heat-pump performance for a 6-hour dynamic test with oversized equipment (i.e., the virtual building load is lower than the nominal sizing case at the same ambient conditions). As shown in Figure 7, the building load varied between 0 W and 4000 W with the outdoor temperature varying from 40°F to 60°F. In contrast, the building loads in the nominal sizing case and the undersizing case varied between 0W-5000W and 0W-6000W, respectively, at the same outdoor conditions. The equipment cycled on/off throughout 6 hours but with a smaller run-time fraction and larger indoor temperature swings compared to the nominal equipment sizing case as shown in Figure 3. In Figure 8 for a typical peak-winter day, the heat-pump cycled on/off instead of continuous variable-speed operation as observed in Figure 6 for the equipment undersizing scenario. In addition, the unit did not defrost for 6 hours even when the outdoor temperature was much lower than the freezing temperature, which is different from the undersized equipment test where the heat-pump utilized defrost operation four times.

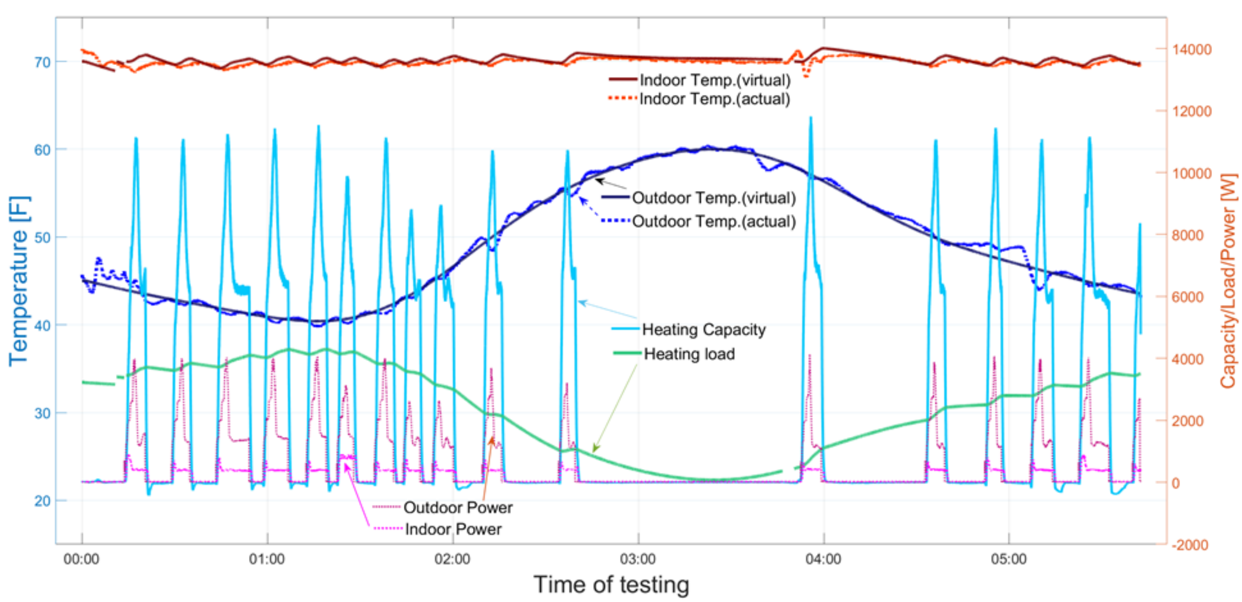

Figure 7: Equipment dynamic performance with equipment oversizing on a typical mid-winter day

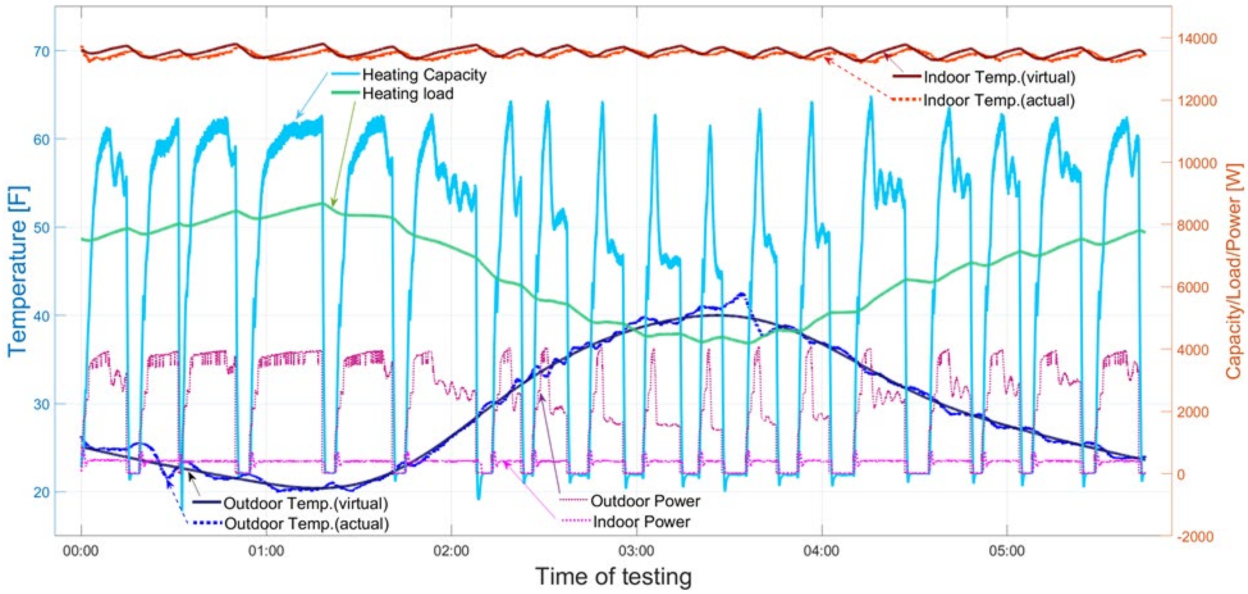

Figure 8: Equipment dynamic performance with equipment oversizing on a typical peak-winter day

In summary, the dynamic results that are presented from Figure 3 to Figure 8 illustrate the value of load-based testing in understanding the behavior of a heat pump operating with its integrated controls for a number of different scenarios. A key goal of the work was to identify any design issues for a new controller that was under development. In fact, several issues were identified and corrected prior to generating the results that are presented in this paper. In the load-based test, the indoor temperature in the psychrometric chamber was generally well-controlled based on the virtual building model response, and heat-pump responded appropriately to the indoor temperature variations with its embedded controls.

Table 3: Building Load, Heating Rate, and Power Consumption Performance Results

Test	**Season**	**Equipment Sizing**	**Virtual Building Sensible Load**	**Sensible Capacity**	**Power Consumption**	**System COP**
			Integrated			Average
			kWh	kWh	kWh	-
1	Mid-winter	Nominal	16.88	17.41	5.56	3.135
2	Mid-winter	Undersized	19.15	19.13	5.84	3.273
3	Mid-winter	Oversized	13.28	12.54	4.28	2.931
4	Peak-winter	Nominal	46.43	46.85	16.63	2.812
5	Peak-winter	Undersized	52.60	49.59	18.45	2.687
6	Peak-winter	Oversized	37.21	37.65	14.07	2.633

Based on the test data for each case, heat-pump performance indicators such as sensible capacity, power consumption, and system COP, as well as virtual building sensible load are listed in Table 3. For most tests, the virtual building sensible load was approximately equal to the heating provided by the heat-pump, except for the case of undersized equipment for the typical peak-winter ambient conditions in which the test unit failed to meet the building load. In practice, an auxiliary heater would be employed to meet the remaining load under these conditions. The results show that the system COP decreased as the outdoor temperature decreased (from the mid-winter to peak-winter day). Comparing three equipment sizing cases for a typical mid-winter day, the system COP was highest when the equipment was undersized. This is because, at typical mid-winter outdoor conditions, the heat-pump cycled on/off throughout the entire test duration for all three equipment sizing cases, with the lowest on/off cycling frequency for the oversizing case which resulted in the highest system COP due to relatively less cyclic losses. These test results showed that this equipment lower compressor turndown ratio makes it inefficient for buildings in moderate winter climates with lower building loads and direct in the areas for future improvements either through a better control approach or a better compressor model. On the other hand, for a typical peak-winter day, the system COP was highest when the equipment was nominally sized and lowest for the equipment oversizing case, where the heat-pump cycled on/off instead of continuous variable-speed operation. Thus this system is expected to perform optimally in a harsher winter climate where building loads match with the representative building load used in this work for nominal equipment sizing scenario.

In Table 4, the comfort delivery performance for six different tests is summarized. A temperature comfort violation is defined as the total number of hours, out of the 6-hour test duration, where indoor space cannot be maintained within a comfortable temperature region. In this work, as the thermostat set-point temperature was 70°F, the comfortable temperature region representing well-controlled indoor environment was defined as 70°F $\pm$ 2°F. The minimum and maximum temperatures in Table 4 indicate the bounds of the indoor temperature swings that resulted from the test equipment controls under investigation. Based on this, the only case in which the equipment failed to maintain the space temperature above 68 °F was for the equipment undersized scenario on a typical peak-winter day. In this case, the virtual building model temperature was as low as 64 °F. Overall, it can be observed that the test unit was able to maintain the indoor temperature nearly within the thermostat deadband for most of the tests.

Table 4: Comfort Delivery Performance Results

Test	**Season**	**Equipment Sizing**	**Temperature Comfort Violation**	**Virtual Building Temperature**	
				Min	Max
			Hour	°F	°F
1	Mid-winter	Nominal	0	69.6	71.6
2	Mid-winter	Undersize	0	69.3	71.2
3	Mid-winter	Oversize	0	68.9	71.5
4	Peak-winter	Nominal	0	68.3	70.6
5	Peak-winter	Undersize	2.83	64.5	70.1
6	Peak-winter	Oversize	0	68.8	70.8

5. CONCLUSIONS

This paper presented the application of a load-based testing methodology for evaluating the dynamic performance of a residential heat-pump system under conditions that are similar to a field application. A representative residential virtual building model for heating load-based tests was outlined. In the process of performing these tests for a heat pump that was employing new control algorithms, a number of controller issues were identified and corrected prior to generating the results that are presented in this paper. This is a key advantage of load-based testing compared to steady-state testing and is much less costly and time consuming than performing field evaluations. As expected, the heat-pump cycled on/off like single-speed equipment at relatively high outdoor temperatures in heating mode, but changed to continuously variable-speed operation to meet the virtual building load when the outdoor temperature decreased and the building load increased. Furthermore, for typical mid-winter day ambient conditions, the test unit was able to control the indoor temperature to the thermostat setpoint for different equipment sizing assumptions (nominal size, 20% undersized, and 20% oversized). However, the heat pump couldn't maintain comfort conditions for a typical peak-winter day with a 20% equipment undersizing case. In this case, auxiliary heat would be necessary to meet the load.

NOMENCLATURE

$\dot{Q}_{load,h}$	building heating load [W]	T_{OD}	outdoor chamber (ambient) temperature [°F]
f	building-load sizing factor [-]	$T_{OD,des}$	outdoor design temperature [°F]
T_{zl}	design balance point temperature for heating [°F]	T_{ref}	outdoor load reference temperature [°F]
$\dot{Q}_{cap,h}$	equipment heating capacity [W]	C_S	sensible building capacitance [W]

$\dot{Q}_{c,s,D}$	equipment rated sensible cooling capacity [W]	t	testing time [hour]
$\dot{Q}_{c,D}$	equipment rated total cooling capacity [W]	T_{bal}	balance point temperature [°F]
T_{ID}	indoor chamber temperature [°F]	$\Delta T_{tstat,di}$	thermostat dead bound temperature [°F]
$T_{OD,max}$	maximum outdoor temperature for testing [°F]	$T_{ID,SP}$	thermostat setpoint [°F]
$T_{OD,min}$	minimum outdoor temperature for testing [°F]	τ	nondimensional time in radians [-]

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