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Demonstration of a Load-Based Testing Methodology for Rooftop Units with Integrated Economizers

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ABSTRACT

Current performance evaluation approaches for commercial packaged air conditioning and heat pump equipment (e.g. AHRI 340/360) utilize full-load steady-state performance tests to estimate system EER (energy efficiency ratio) at different ambient conditions and part-load steady-state tests to estimate an IEER (integrated energy efficiency ratio), a figure of merit for system part-load performance. There are some limitations of the current testing approaches and performance metric estimations, including that they do not consider the effects of: 1) test unit embedded controls and their realistic interactions with the building load; 2) different climate zones and building types; and 3) economizer operation. As a result, the overall performance measurement procedure does not appropriately incentivize the development of better performing controls and economizers. In this paper, an improved testing procedure applied to packaged air conditioning equipment, such as rooftop units (RTUs), that include the effects of embedded controls, economizers, climate, and building type is presented. The testing approach is based on allowing the integrated equipment system and controls to respond naturally to a "virtual building load". This is termed load-based testing and involves dynamically adjusting the indoor room temperature and humidity setpoints for the psychrometric chamber reconditioning system in a manner that emulates the response of a building's sensible and latent loads to the test equipment controls. The developed test methodology is demonstrated to evaluate the dynamic performance of a 5-ton variable-speed RTU with an integrated economizer in a psychrometric test facility.

1. INTRODUCTION

Performance rating and characterization of all unitary air-conditioning and heat-pumping systems is required to determine the energy efficiency of the system to sell in the U.S. marketplace. In the U.S., the current testing and rating procedure for small to medium size packaged unitary air-conditioners (e.g. rooftop units) is based on AHRI 340/360 (AHRI, 2019) and ASHRAE standards 37 and 116 (ASHRAE, 2010, 2019). Together these standards outline the required test procedures for establishing equipment performance (i.e., cooling capacity and power consumption), which is measured at different sets of test conditions in a psychrometric test facility. To rate any equipment based on laboratory test results, there are primarily two figures of merits for packaged air-conditioners: EER and IEER. The EER (energy efficiency ratio) is the ratio of the total cooling capacity measured to the total power consumption at a specific test condition. The IEER (integrated energy efficiency ratio) is a figure of merit for system part-load performance, calculated as a weighted average of EER at different test conditions. The current rating procedure provides an estimate of the test equipment mechanical cooling performance; however, there are a number of limitations with the current approaches. Jacobs et al. (2003) conducted field studies on 215 RTUs and observed that 64% of units had economizers that did not function properly and 24% that did not function at all. Cowen (2004) reviewed multiple field studies for RTUs and found a similar frequency of issues with economizers, consistent with the findings of Jacobs et al. (2003). Further, Hart et al. (2008), based on different field studies, pointed out that current testing and rating standards fail to capture many energy savings benefits and do not take into account the effects of outside air economizers, control configuration, fan energy during ventilation only, cycling effects, and field installation issues. Overall, the current rating approach for RTUs does not consider the effects of test unit embedded controls and their realistic interactions with the building load, different climate zones and building types, and economizer operation. As a result, the current rating procedure does not appropriately incentivize the development and integration of better performing controls and economizers. As an alternative, load-based testing methodologies have recently been developed that provide an opportunity to test and rate equipment together with their integrated controls and any other accessories that can improve performance.

Cremaschi & Perez Paez (2016, 2017) performed an experimental feasibility study of a load-based testing methodology for performance evaluation of light commercial unitary air-conditioning systems that account for cyclic effects, air circulation energy usage, economizer operation, and advanced control strategies. They tested an RTU with an economizer in a psychrometric test facility under different loads to study the relative impacts of economizer, compressor, and supply fan speed controls. This was accomplished by controlling the sensible and latent gains in the indoor psychrometric chamber and allowing the temperature and humidity to respond dynamically within the indoor test room based on the difference between the gains and the capacity delivered by the RTU with its embedded controls. However, Cremaschi and Perez Paez (2016) found repeatability and reproducibility issues with the test approach due to variations in implemented loads because of limitations with hardware control. Hjortland and Braun (2019) presented an alternative load-based testing methodology for unitary air-conditioning equipment which utilizes the existing psychrometric chamber controls and regulates the temperature and humidity to emulate the response of a representative simulated building. This test methodology involves using a virtual building model to adjust the indoor room temperature and humidity set-points for the psychrometric conditioning system in a manner that mimics the response of a real building served by the air conditioning system. In contrast to the Cremaschi & Perez Paez (2016) approach, this methodology is not affected by the test room energy losses and dynamic responses as long as the test room controls can track the dynamic temperature and humidity responses of the virtual building model. However, Hjortland and Braun (2019) did not include an integrated economizer in their RTU testing work. Patil et al. (2018) and Cheng et al. (2021) further extended the load-based testing approach for performance evaluation of residential air-conditioning equipment with their embedded controls and thermostat. For the residential load-based testing methodology, there have been several studies including a sensitivity analysis (Cheng et al., 2018), implementation for heat-pump performance evaluation and comparisons with the current rating approach (Dhillon et al., 2018, 2021b), validation based on test results from a realistic house (Dhillon et al., 2021c), and utilization of the approach as a development tool for advanced heat-pump control design (Dhillon et al., 2021a; Ma et al., 2021). However, this load-based testing methodology has not previously been extended or demonstrated for commercial building RTUs that include integrated economizers.

The motivation for this work is to develop improved rating and testing procedures applied to packaged air-conditioning equipment, such as rooftop units (RTUs), that include the effects of embedded controls, economizers, climate, and building type. The testing approach is based on allowing the integrated equipment system and controls to respond naturally to a “virtual building load”. The load-based testing methodology for commercial building equipment, presented here, is similar to the load-based testing approach for residential air-conditioning and heat-pump systems (Cheng et al., 2021; Patil et al., 2018) and unitary air conditioning equipment (Hjortland & Braun, 2019) but is extended to consider ventilation, economizer operation, and application to commercial buildings. Commercial buildings and their air conditioning equipment differ substantially from residential building applications because of the controlled ventilation requirement, greater density of internal gains, different construction materials, and the integration of economizers. Furthermore, there are substantial differences between the various commercial building types such as office, retail, and restaurants in terms of internal gains, ventilation requirements, and typical construction characteristics. Therefore, the residential load-based testing and rating approach is not directly applicable and needs to be modified to include ventilation air as well as different building dynamics and thermal load characteristics for representative commercial building types. In this paper a proposed test methodology is described, including the development of a representative and scalable virtual building model for commercial building types. Additionally, test conditions are developed based on generating representative performance conditions for different climates. Then, an outline of the testing procedure is provided together with a presentation of test results from applying the proposed methodology to a 5-ton variable-speed RTU with integrated economizer. Finally, the paper concludes with a brief summary and a discussion of future work.

2. LOAD-BASED TESTING METHODOLOGY

Figure 1 depicts the load-based testing approach for an RTU with an economizer installed in two side-by-side psychometric test chambers. The RTU is installed with an integrated economizer in the outdoor test room and connected to the indoor test chamber utilizing a return and a supply air duct. In load-based testing, the equipment performance (sensible and latent cooling rate provided to the indoor space) is measured in real time and fed into a virtual building model. The virtual building model captures representative building sensible and latent heat gains along with the dynamic responses of space temperature and moisture. The virtual building temperature and humidity responses are used as setpoints for the indoor test room reconditioning system in order to emulate the response of a representative building. The test unit thermostat senses this space temperature variation and the test unit responds to a deviation from the thermostat setpoint based on its embedded control algorithm similar to how it would behave in the field. In addition to characterizing the equipment response to integrated temperature and humidity controls for the indoor space, this approach can capture the impact of additional integrated accessories, such as an economizer, on the equipment performance. As the outdoor temperature (or enthalpy) changes during load-based testing, the integrated equipment controls naturally respond and actuate the economizer damper according to the manufacturer’s design and implementation. Consequently, overall equipment performance is measured together with its embedded controls and integrated economizer.

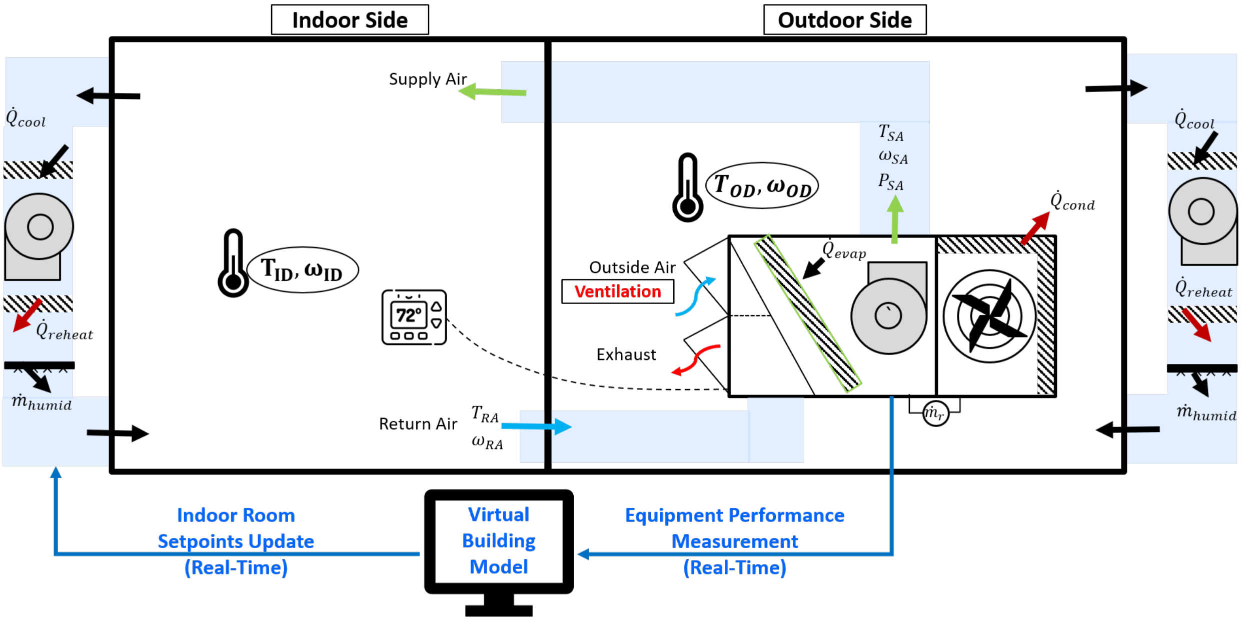

Figure 1. Load-Based Testing Schematic for a Packaged System with an Integrated Economizer

In this methodology, for each test interval, the outdoor test room conditions are kept constant, whereas the indoor conditions are continuously varied based on a virtual building model response. During a load-based test, the virtual building model temperature (T_{ID}) and humidity ratio (ω_{ID}) are updated for each time step based on the difference in the virtual building's loads and the test unit cooling rates as per Equations (1) and (2), respectively.

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

$$\omega_{ID}(t + \Delta t) = \omega_{ID}(t) + \Delta t \cdot \left(\frac{BL_{latent} - \dot{Q}_{latent,space}}{h_{fg} \cdot C_{moisture}} \right) \tag{2}$$

where $BL_{sensible}$ and BL_{latent} are the virtual building sensible and latent cooling loads. $C_{sensible}$ and $C_{moisture}$ are the virtual building effective thermal and moisture capacitances, respectively, for a representative commercial building, and h_{fg} is the latent heat of vaporization for water. $\dot{Q}_{\text{sensible,space}}$ and $\dot{Q}_{latent,space}$ are the real-time measurements of sensible and latent cooling rates provided by the equipment to the space calculated as per Equations (3) and (4).

$$\dot{Q}_{sensible,space} = \dot{m}_{supply} C_{p,air} (T_{return} - T_{supply}) \tag{3}$$

$$\dot{Q}_{latent,space} = \dot{m}_{supply} \cdot h_{fg} \cdot (\omega_{return} - \omega_{supply}) \tag{4}$$

where $\dot{m}_{supply}$ is the supply air mass flow rate and $C_{p,air}$ is the specific heat for air. T_{return} and ω_{return} are temperature and humidity measured in the return air duct; whereas T_{supply} and ω_{supply} are temperature and humidity measured in the supply air duct, respectively. It is important to note that the cooling rates in Equations (3) and (4) are not exactly a measure of the cooling rate provided by the test equipment cooling coil, but represent the overall cooling rates provided by the test equipment to the space. In addition to the space cooling loads, the equipment must also satisfy the ventilation loads (or in some cases, the ventilation loads reduce the load on the equipment).

2.1 Virtual Building Model

A virtual building model characterizes the dynamics of a representative building, including its sensible and latent loads as well as thermal and moisture dynamics, for purposes of emulating building dynamic interactions with the test equipment. To utilize a virtual building model for testing an RTU, the virtual building parameters in Equations (1) and (2): $BL_{sensible}$, BL_{latent}, $C_{sensible}$ and $C_{moisture}$; need to be determined in a manner that scales appropriately with the test unit design capacity in order to apply the approach for different size systems.

The virtual building sensible gains to the indoor space (termed cooling load), $BL_{sensible}$, which is the sum of internal (occupants, lights, equipment, and effective solar) and external (conduction and infiltration) gains, is modeled as a simple linear function of outdoor temperature (T_{OD}) based on a building representative balance point temperature (ASHRAE, 2017b) and is scaled to the test equipment sensible cooling capacity at design conditions as per Equation (5) and (6).

$$BL_{sensible} = \frac{1}{F_{Design}} * \frac{\left(1 - VALF_{Design}\right) \cdot SHR_{Design} \cdot \dot{Q}_{Design}}{\left(T_{OD,\,Design} - T_{Bal,Design}\right)} * \left(T_{OD} - T_{Bal^*}\right) \tag{5}$$

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

where $\dot{Q}_{Design}$ and SHR_{Design} are the test equipment measured cooling capacity and sensible heat ratio (SHR) at the design conditions; $VALF_{Design}$ is the minimum ventilation air sensible load fraction at the design condition defined as the ratio of the sensible load corresponding to the minimum ventilation air to the total equipment sensible cooling rate at design conditions. The overall expression with these three terms in the numerator represents the maximum sensible cooling capacity of the test equipment that is available for meeting the building sensible load at design conditions determined by subtracting the minimum ventilation air sensible load from the total sensible capacity. F_{Design} is a constant that is greater than 1 to account for equipment oversizing for a design building load. $T_{OD,Design}$ and $T_{ID,Design}$ are the design outdoor and indoor temperatures, respectively, and in a load-based test, the test unit thermostat is set to $T_{ID,Design}$. $T_{Bal,Design}$ is the design balance point temperature and T_{Bal^*} is an effective balance point temperature that accounts for the effect of indoor temperature (T_{ID}) variations from the indoor design temperature $\left(T_{ID,Design}\right)$.

The virtual building latent cooling load, BL_{latent}, is modeled as the sum of internal latent gains and external latent gains due to infiltration as per Equation (7), which is scaled to the test equipment design cooling capacity based on the virtual building floor area A_{VB} (i.e., the floor area of a representative building served by the test equipment based on its capacity at design conditions).

$$BL_{latent} = \underbrace{\frac{ILLF}{Occ_{Design}} \cdot Occ_{Ratio} \cdot A_{VB}}_{Internal\ Latent\ Gains} + \underbrace{IRF \cdot A_{VB} \cdot \rho_{air} \cdot \Delta W \cdot h_{fg}}_{Infiltration\ Latent\ Gains} \tag{7}$$

where $ILLF$, the internal latent load factor, is the representative building internal latent load per occupant, Occ_{Design} is the design occupancy for the building (floor area/occupant), and the occupancy ratio, Occ_{Ratio}, is the ratio of the building's average occupancy to its design occupancy. IRF, infiltration rate factor, is the infiltration flow rate for the representative building per unit floor area, ρ_{air} is the density of air, ΔW is the humidity ratio difference between indoor and outdoor conditions, and h_{fg} is the latent heat of vaporization of water. Virtual building floor area (A_{VB}) scaled to the test unit design capacity can be estimated as per Equation (8).

$$A_{VB} = \frac{\left(1 - VALF_{Design}\right) \cdot SHR_{Design} \cdot \dot{Q}_{Design}}{SSLF_{Design}} \tag{8}$$

where the numerator in Equation (8) represents the equipment sensible capacity that is available for meeting the building space sensible loads (internal and external) at the design condition, and $SSLF_{Design}$ is the space sensible load factor, defined as the ratio of the representative building total space load (internal and external) at the design condition to the total floor area.

For estimating an effective thermal capacitance ($C_{sensible}$) that captures the short time-scale dynamics associated with the equipment and building interactions, Cheng et al. (2021) presented an empirical approach for residential load-based testing applicable to a typical residence and that is based on work reported by 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 sensible capacity. A similar approach is utilized here to define an effective thermal capacitance, $C_{sensible}$, scalable to the test equipment design sensible capacity as per Equation (9).

$$C_{sensible} = \frac{1}{4} \frac{SHR_{Design} \cdot \dot{Q}_{Design}}{N_{max} \cdot \Delta T_{db}} \tag{9}$$

Further, the virtual building effective moisture capacitance ($C_{moisture}$) is defined based on an empirical approach similar to Hjortland & Braun (2019), which is scaling the mass of the zone air with a multiplier. The virtual building moisture capacitance scaled to the virtual building floor area served by the test equipment can be estimated as per Equation (10).

$$C_{moisture} = EC \cdot A_{VB} \cdot H_{VB} \cdot \rho_{air} \tag{10}$$

where EC, the effective moisture capacitance multiplier, captures the effect of extra moisture absorbing material in the space in addition to the zone air, H_{VB} is a representative building ceiling height for estimating the space volume utilizing the virtual building floor area, A_{VB}, and ρ_{air} is the density of air in the space.

In addition, for test equipment with integrated economizers, the minimum ventilation air requirement $\left(\dot{V}_{min,VA}\right)$ that the equipment needs to satisfy for a representative building type, scaled to the equipment design capacity can be estimated as per Equation (11).

$$\dot{V}_{min,VA} = VRF \cdot A_{VB} \tag{11}$$

where VRF is ventilation rate factor, defined as the ratio of the minimum ventilation requirement for a building type to the floor area and A_{VB} is the virtual building floor area.

The virtual building parameters for a representative small office commercial building type were derived and presented in Table 1. This building type was selected based on the building types which commonly utilize packaged air conditioning units in the U.S. as summarized by Winiarski et al. (2018) based on the Commercial Buildings Energy Consumption Survey (CBECS) data (EIA, 2012). Virtual building parameters for the small office were determined based on EnergyPlus (Drury et al., 2000) simulations of ASHRAE 90.1-2016 commercial prototype building models (Athalye et al., 2017; Goel et al., 2014) derived from DOE commercial reference building models (Deru et al., 2011). Also, field data for direct expansion (DX) HVAC systems operating in a commercial building was used in defining an approach for specifying building capacitances for small offices.

During a load-based test interval, the outdoor test room conditions are kept constant, whereas, the virtual building temperature and humidity conditions are continuously updated based on Equations (1)-(10) along with virtual building parameters from Table 1, which are then sent as setpoints to the indoor psychrometric test room for each time step. In this way, the dynamic response of a representative building is emulated by the indoor psychrometric chamber, and RTU performance is measured with its embedded controls, thermostat, and integrated economizer.

Table 1. Virtual Building Model Parameters for a Representative Small Office Building

$T_{Balance}$	$VALF_{Design}$	$SSLF_{Design}$	VRF	N_{max}	ΔT_{db}
°F	-	BTU/h-ft^2	CFM/ft^2	1/h	°F
45.0	0.13	9.77	0.08504	2	2
ILLF	Occ_{Design}	Occ_{Ratio}	**IRF**	H_{VB}	**EC**
BTU/h-occupant	ft^2/occupant	-	CFM/ft^2	ft	-
165.1	178.6	0.71	0.0187	10	2

2.2 Test Conditions

Indoor target conditions that the test unit should maintain during load-based tests are defined as 75°F dry-bulb temperature and 50% relative humidity based on typical human comfort conditions as per ASHRAE standard 55 (ASHRAE, 2017a). This defines the setpoint for the test unit thermostat and humidistat, as applicable, during a load-based test.

To measure the equipment performance at ambient conditions that are representative of a field application in a test laboratory, the outdoor test conditions were derived based on weather data from 16 representative climate zones (Athalye et al., 2017). To test a unit in cooling mode with an integrated economizer, it is important to define the representative dry-bulb and wet-bulb temperature conditions because of the impact of ventilation air on the unit, in contrast to only dry-bulb temperature conditions for residential equipment testing in cooling mode (Cheng et al., 2021). To develop representative cooling test conditions, the dry-bulb (DB) temperature data corresponding to the building's occupied hours during the cooling season was sorted into 5°F temperature bins with mean coincident wet-bulb temperature (MCWB) for all different climate zones. For this, the entire year TMY3 hourly weather data (Wilcox & Marion, 2008) was divided into three different seasons (cooling, heating, and transition) based on estimated heating and cooling balance point temperatures (Koontz et al., 1989). Then, the occupied period data was selected from cooling season hourly data based on the small office building occupancy schedules (DOE, 2019), which was then binned into 5°F temperature bins. The DB bin data with MCWB for different climate zones were grouped in three different climate zone groups based on the closeness of MCWB among different climate zones at the same DB bin. The different climate zones were grouped into three climate types: Humid, Dry, and Marine. Then, in each group, the best representative climate zone was selected from which the climate zone group test conditions were selected, as shown in Table 2.

Table 2. Cooling Mode Outdoor Test Conditions

Test	**Climate Type**					
	Humid		**Dry**		**Marine**	
	Dry Bulb Temperature [°F]	**Wet Bulb Temperature** [°F]	**Dry Bulb Temperature** [°F]	**Wet Bulb Temperature** [°F]	**Dry Bulb Temperature** [°F]	**Wet Bulb Temperature** [°F]
C1	55	49	55	45	55	51
C2	65	59	65	51	65	57
C3	75	67	75	56	75	62
C4	85	72	85	59	85	63
C5	95	74	95	61	95	63
C6	-	-	105	64	-	-

2.3 Test Procedure

Figure 2 shows an outline for the testing procedure applied to a representative building type and climate zone group test condition. First, the equipment performance at design conditions is measured by performing a steady-state cooling test at the design conditions (indoor at 75°F dry-bulb / 50% RH and outdoor at 95°F dry-bulb temperature) to measure the equipment design cooling capacity $(\dot{Q}_{Design})$ and sensible heat ratio (SHR_{Design}). In this test, indoor and outdoor room conditions are kept constant and the thermostat set-point is set such that the test unit provides maximum cooling capacity with the economizer kept closed and sealed. Then, utilizing the measured equipment performance at design conditions, the virtual building model parameters and minimum ventilation air (VA) requirement $(\dot{V}_{min,VA})$, scaled to the test unit design capacity, are estimated. The equipment economizer damper settings are then set such that this minimum VA requirement is satisfied across all different test conditions and control modes. After that, load-based tests are performed based on the representative climate zone group test conditions.

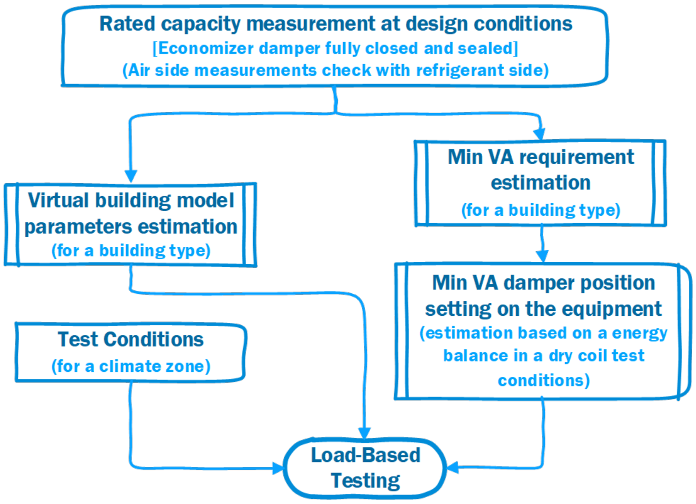

Figure 2. Testing Procedure Outline Schematic

3. TEST RESULTS

In this section, preliminary test results are presented to demonstrate the application of the proposed load-based testing methodology on a 5-ton variable-speed RTU with an integrated dry-bulb economizer; and to understand the behavior and identify areas of potential improvement to the approach. The test unit was installed in the outdoor room of two side-by-side psychrometric chambers at the Ray W. Herrick Laboratories and instrumented to measure its performance. In order to scale the virtual building loads, capacitances, and minimum VA requirement, the test unit performance at design conditions was measured. Table 3 shows the equipment design performance with scaled virtual building parameters, which were utilized in Equations (1)-(10) and Table 1 to perform load-based tests for the three different climate type test conditions outlined in Table 2. Based on the estimated minimum VA requirement, the minimum damper opening position was set at 23% and 47%, for high and low blower speed, respectively. Additionally, the economizer control setting was kept at its default *temperature offset* mode with a 10°F difference limit threshold. So, at an outdoor temperature 10°F below the indoor temperature, the unit enables economizer mode and modulates the damper based on its embedded controls. When not in economizer mode, the damper is controlled at a minimum opening position depending on the indoor blower speed to meet the ventilation requirement.

Table 3. Design Condition Performance and Scaled Virtual Building Model Parameters

Building Type	$\dot{\mathrm{Q}}_{\mathrm{Design}}$	$\mathrm{SHR}_{\mathrm{Design}}$	A_{VB}	$\dot{\mathrm{V}}_{\mathrm{min,VA}}$	$\mathrm{C}_{\mathrm{sensible}}$	$\mathrm{C}_{\mathrm{moisture}}$
	[W]	[-]	[ft^2]	[CFM]	[BTU/°F]	[lbm]
Small Office	15630	0.81	3847	327	2700	5885

At the beginning of a load-based test sequence, the test room temperature and humidity are brought to a steady state based on the defined indoor target conditions and outdoor test conditions for the test interval. After that, the thermostat is set to the indoor target comfort conditions, and the virtual building model is activated. Then, during any given test interval, the outdoor conditions are controlled to a constant setpoint and the indoor test room temperature and humidity setpoints are updated according to outputs of the virtual building model response. Subsequently, once the test unit performance reaches a steady-periodic response, the outdoor conditions are updated to the next test interval.

Figure 3 illustrates the load-based test results for the first two test intervals of the humid climate test conditions (Table 2) at 55°F and 65°F ambient temperature. The test results for the other three test intervals at 75°F, 85°F, and 95°F ambient temperature conditions are shown in Figure 4. The upper sub-plot left y-axis shows the equipment performance and load, with the test unit space sensible cooling rate (green), virtual building sensible load (red), test unit space latent cooling rate (sky blue), virtual building latent load (orange), and the test unit total power consumption (blue line); and the right y-axis shows the economizer damper opening in % (black) and economizer status (violet). The lower sub-plot left y-axis shows the virtual building (dotted line) and indoor room (solid line) temperature and humidity variation and the right y-axis show the outdoor temperature and humidity variation for different test intervals. The black dotted line shows the thermostat setpoint of 75°F. The results demonstrate that the indoor test room temperature and humidity conditions were controlled closely to the target setpoints derived from the virtual building model, indicating that the virtual building dynamic response was simulated well by the reconditioning system controls of the psychrometric chamber.

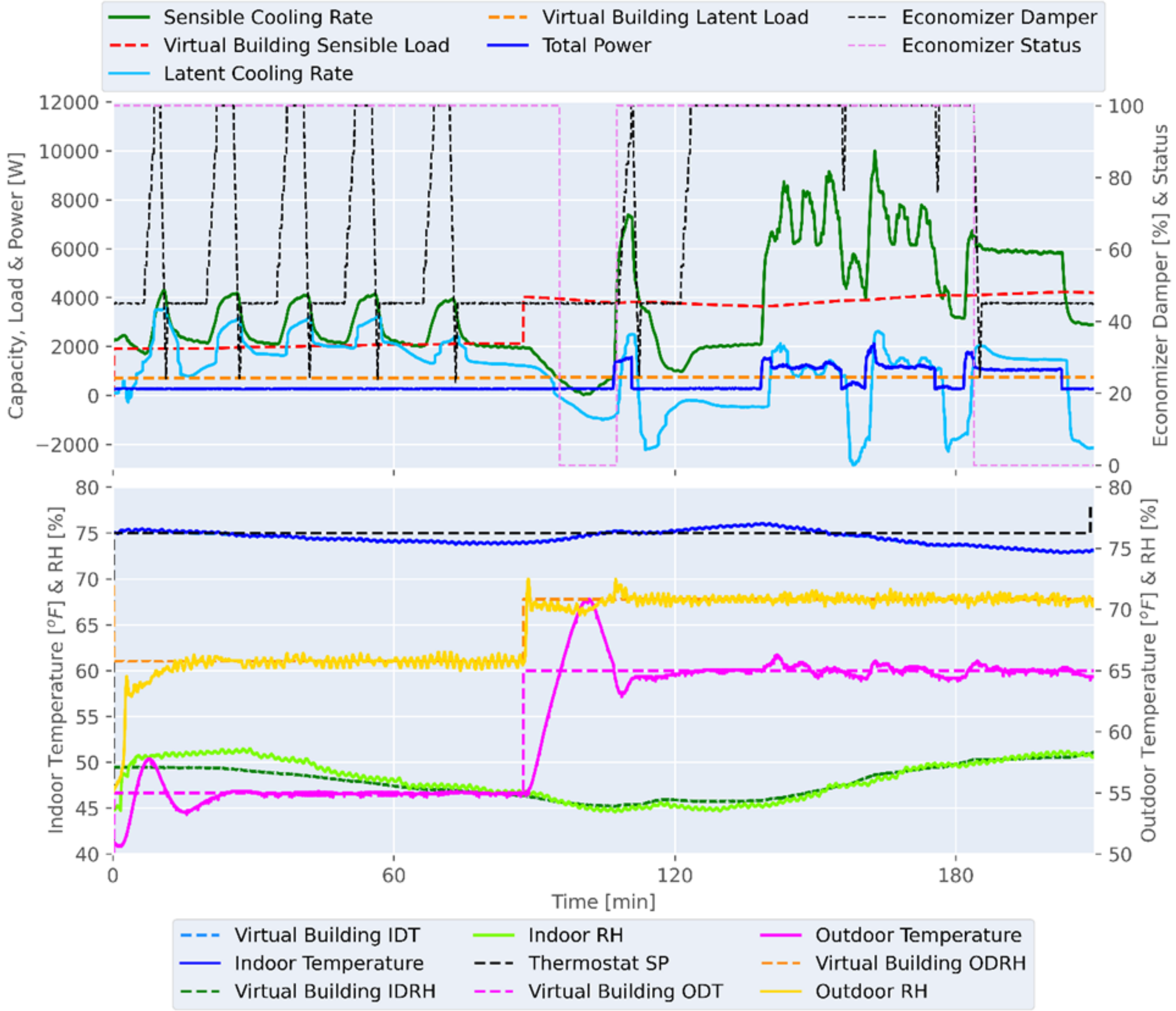

Figure 3. Load-Based Test Results for a Representative Small Office Building in Humid Climate Test Conditions at Outdoor Ambient Temperatures of 55°F and 65°F

At the lower ambient temperatures of 55°F and 65°F in Figure 3, the economizer status was *on* and the damper modulated between a minimum position of around 45% and a full opening of 100%. At 55°F ambient temperature, the building load was low and "free cooling" from the ventilation air was sufficient to compensate for the load without turning the compressor on. At 65°F outdoor temperature, to compensate for the higher building load, the compressor kicked in with a 100% outdoor damper opening. Toward the end of the 65°F test interval (~180 min), the outdoor air damper closed to the minimum position, as the test unit response overcooled the space and the difference between indoor and outdoor temperature decreased below the threshold of 10°F, thus disabling the economizer mode.

For ambient temperatures of 75°F and 85°F, the economizer was disabled and the economizer damper was controlled to the minimum damper opening of ~45% as the equipment blower was running in low-speed mode. At an ambient temperature of 95°F, toward the end of the test interval, the equipment blower mode changed to high speed to compensate for higher load, and the damper opening changed to the corresponding minimum position of ~20%.

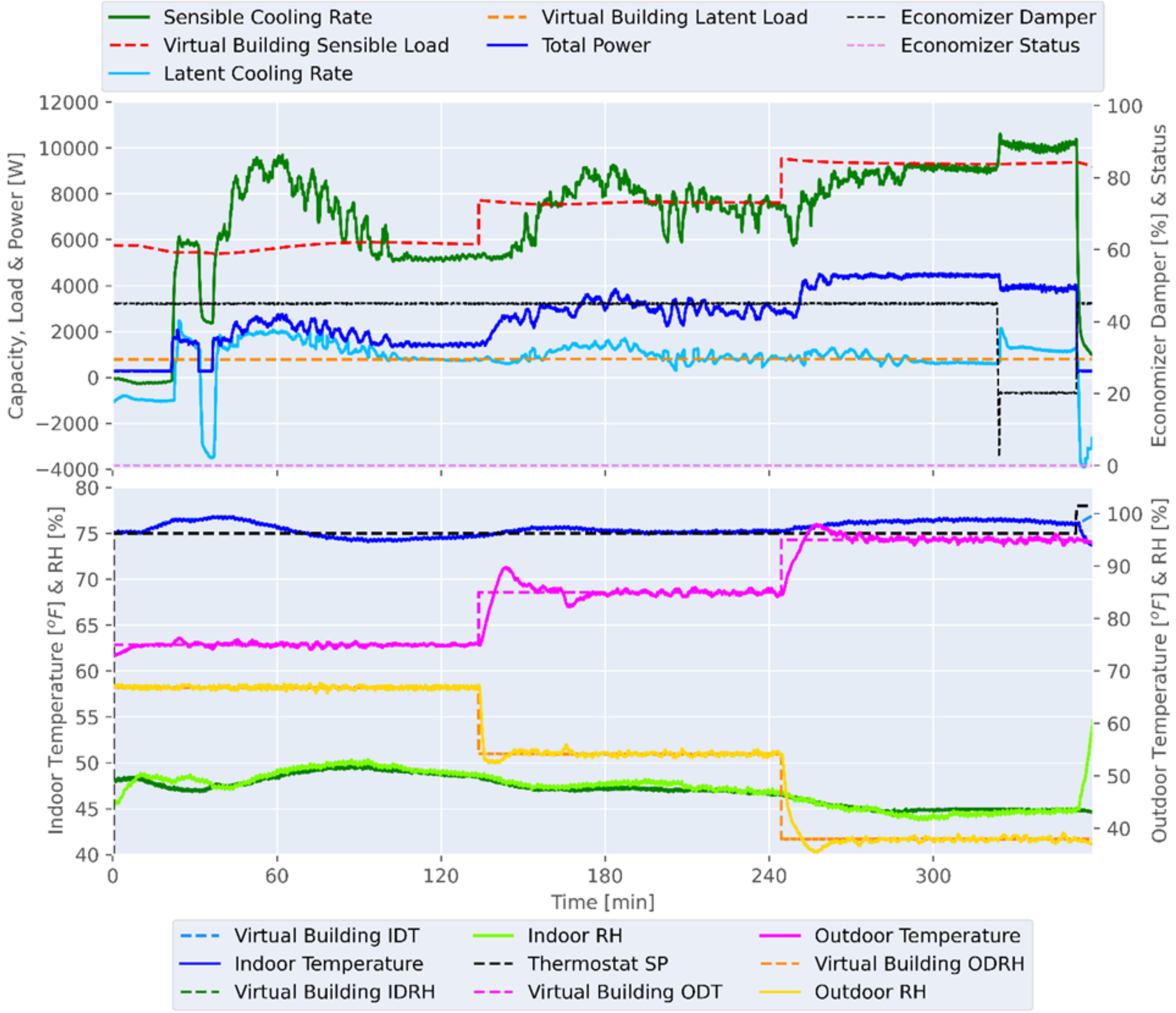

Figure 4. Load-Based Test Results for a Representative Small Office Building in Humid Climate Test Conditions at Outdoor Ambient Temperatures of 75°F**,** 85°F**,** and 95°F

The results presented in Figure 3 and Figure 4 illustrate that at low ambient temperatures, the unit was able to meet the space sensible load using the economizer alone (i.e., control of VA damper without running the compressor). The compressor cycled between *off* and minimum speed at ambient temperatures of 65°F, but then ran under variable-speed operation at 75°F, 85°F and 95°F. The equipment was able to maintain the indoor temperature and humidity near the target comfort condition of 75°F and 50%, respectively, during the entire test duration. Overall, the test results illustrate how the proposed load-based testing approach is able to capture the performance of the test equipment with its integrated economizer and embedded controls. Thus, load-based testing could be a powerful tool in assessing overall RTU performance in the laboratory for both rating and controller development purposes.

Dynamic load-based testing was also performed for the dry and marine climate test conditions as outlined in Table 2. Figure 5 shows the test equipment measured coefficient of performance (COP) at the different ambient test temperatures for all three climate types. Free cooling at lower ambient temperatures resulted in a much higher COP. However, as ambient temperature increases, the building load and the load to condition the ventilation air increase. Thus, the compressor needs to run harder to compensate for the higher load to maintain space comfort conditions and the higher condensing temperature associated with a warmer ambient, resulting in comparatively lower COP. It is worth noting that the presented COP is based on the overall cooling rate provided by the test equipment to the space rather than the total cooling rate provided by the cooling coil.

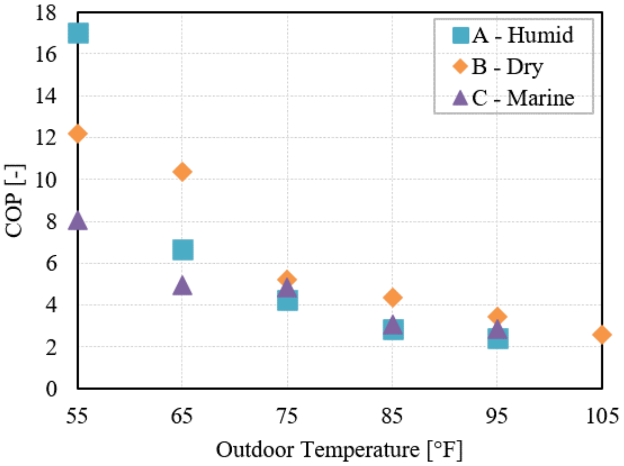

Figure 5. Test Equipment Performance (COP) at Different Climate Types Test Conditions

4. CONCLUSIONS

In this paper, a load-based testing methodology was presented which enables performance evaluation of RTUs with integrated economizers in a test laboratory under operating conditions similar to a field application for a representative building and location. A scalable virtual building model was developed to represent commercial building sensible and latent loads and the dynamic behavior of temperature and humidity within an emulated building. Virtual building parameters for a representative small office building were derived based on simulation results for a prototypical building in EnergyPlus, together with field data. Also, typical indoor and outdoor test conditions representative of equipment operation in different climate zones were defined. To demonstrate the procedure's implementation, the methodology was applied to a variable-speed 5-ton RTU with an integrated economizer using a psychrometric test facility at the Ray W. Herrick Laboratories. The RTU was tested at different ambient conditions that are representative of three different climate types. Tests at different ambient temperatures were used to characterize the test unit performance over a range that covers economizer only, economizer with compressor, and no economizer with compressor operation. At low outdoor temperature conditions, the economizer mode was enabled and provided free cooling by introducing cooler ambient air into the space, thus resulting in a relatively high COP. The test unit cycled *on/off* at low ambient temperature and operated in a variable-speed mode with the damper at its minimum setting as the load increased at higher outdoor temperature conditions. The proposed methodology presented in this paper represents a first step towards the development of improved equipment testing and rating procedures that appropriately characterize the performance of commercial building equipment and can quantify the benefits associated with advanced controls and other accessories, such as integrated economizers. Additional work needs to be done to ensure that the developed methodology captures representative equipment performance in a repeatable and reproducible fashion across different test labs.

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