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Thermostat Environment Emulator Design Update and Assessment for Load-Based Testing Methodology

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ABSTRACT

In current testing and rating approaches for estimating seasonal energy efficiency (e.g., SEER) of residential heat-pump systems, the embedded controls of the unit under test (UUT) are overridden. As a result, the rated performance does not fully capture part-load operation and degradation effects that occur due to interaction of the integrated controls, equipment, and building dynamics, and does not incentivize the implementation of improved controllers. To address this deficiency, a load-based testing methodology has been developed for estimating the seasonal performance of residential heat pumps based on their dynamic performance measurement in a lab. The load-based testing methodology emulates the response of building sensible and latent loads to the equipment controls in a psychrometric test chamber by continuously updating the room temperature and humidity based on a virtual building model. The test unit thermostat naturally responds to dynamic temperature variations and controls the equipment capacity in response to a deviation from its setpoint. Since the thermostat response is integral in load-based testing, it is critical to provide representative and reproducible conditions to the thermostat. For this, a thermostat environment emulator (TEE) was developed to provide a standardized environment for the thermostat during load-based tests in order to ensure repeatability and reproducibility. This paper presents an updated design of a thermostat environment emulator that was previously presented by Cheng *et al.* (2021a) to improve performance and applicability across different test facilities. First, design updates to the TEE are discussed in detail, and then performance assessment results of the TEE are presented. Finally, performance and operation characteristics evaluation results of the TEE are discussed based on load-based tests with a 2-ton variable-speed heat pump.

1. INTRODUCTION

AHRI 210/240 (AHRI, 2020) defines the current testing and rating procedure for residential air conditioners and heat pumps in the US. Based on this methodology, heat pump performance is measured in a pair of psychrometric chambers representing indoor and outdoor environmental conditions. The current testing method generates a standard figure of merit that can be used to compare the relative efficiency of different equipment; however, it could be contended that this rating method does not adequately characterize the overall dynamic performance of systems with advanced controls. This is because, in the current testing approach, heat pump performance is measured by keeping both the test rooms, indoor and outdoor, at a steady state and fixing compressor speeds and airflow rates during a test interval with proprietary control settings specified by the manufacturer for that test condition. Thus, the current rating approach does not consider dynamic interactions of equipment embedded controls with representative building loads and might not be representative of the system's actual field performance. A load-based testing methodology has been recently developed as an alternative for evaluating the dynamic performance of residential heat pumps and air conditioners in a laboratory with their integrated controllers and thermostats. In this approach, a test unit responds dynamically to emulated building loads in real-time by continuously adjusting the indoor test room conditions based on a virtual building model. The test unit thermostat, installed in the indoor test room, naturally responds to the dynamic temperature variation and controls the equipment capacity as it would in an actual installation. Hjortland and Braun (2019), Patil *et al.* (2018), Cheng *et al.* (2021b), and Dhillon *et al.* (2022a) describe the load-based testing methodology in detail, which forms the basis for CSA (Canadian Standards Association) standard draft EXP07:2019 (CSA, 2019).

Dhillon *et al.* (2022b; 2018; 2021a) implemented the load-based testing approach to evaluate the performance of different residential heat pumps and compared load-based test results to results based on AHRI 210/240. They observed significant differences between seasonal performance estimations based on load-based testing and steady-state testing (AHRI 210/240) and provided a root cause analysis of the observed differences. Further, load-based testing repeatability and reproducibility assessment was presented by Dhillon *et al.* (2022c; 2022e) based on comparisons of multiple equipment test results in the same and different labs along with recommendations to improve the load-based testing approach. Dhillon *et al.* (2021d; 2022f) conducted a study to assess how well the load-based testing approach characterizes heat pump performance in a lab compared to an actual residential building. They compared test results of a heat pump tested in a 2-story residential house to that of a laboratory using the load-based testing approach for both cooling and heating mode. Cremaschi and Perez Paez (2017) performed a feasibility study of a load-based testing methodology for unitary equipment with integrated economizers. Dhillon *et al.* (2021b) proposed an alternative load-based testing methodology for RTUs (rooftop units) with integrated economizers based on the virtual building model approach. Ma *et al.* (2021) and Dhillon *et al.* (2021c) further investigated the application of the load-based testing approach to develop and evaluate the performance of advanced heat pump control design in a laboratory setting.

Cheng *et al.* (2018) performed a sensitivity study of thermostat location on load-based test results by conducting load-based tests with three different thermostat installation locations in the indoor test room: 1) indoor test unit return air inlet, 2) on the side of the indoor test unit, and 3) in a corner of the test room. They observed significantly different performance and unit dynamic behavior due to the variation in airflow and temperature distribution around the thermostat which affects its response dynamics. This variation in airflow and temperature distribution can be significantly larger among different test facilities, so to ensure load-based test results repeatability and reproducibility across different labs, it is important to provide reproducible conditions for the test unit thermostat. Since the thermostat is integral to the test unit performance in load-based testing, it is also important to provide representative conditions to it in order to measure field representative equipment performance. For this, Cheng *et al.* (2021a) designed and built a thermostat environment emulator (TEE) which provides standardized and reproducible environmental conditions to the thermostat. The TEE independently controls and provides representative air velocity and temperature conditions over the thermostat during load-based tests.

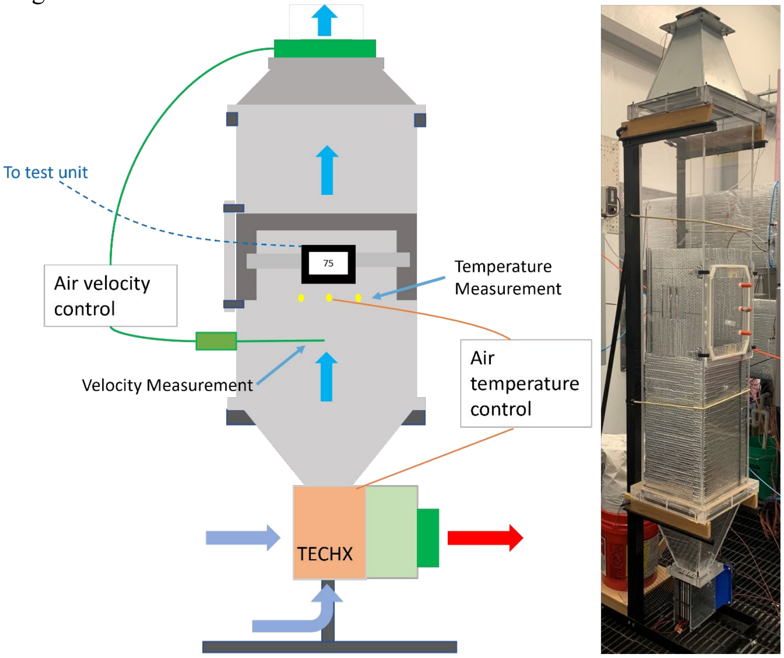


Figure 1: 1st generation thermostat environment emulator schematic and built prototype (Cheng *et al.*, 2021a)

Figure 1 shows a schematic and finished prototype of the 1st generation TEE developed by Cheng *et al.* (2021a). The TEE is composed of three main parts: 1) thermostat apparatus enclosure, 2) thermostat inlet air velocity control, and 3) thermostat inlet air temperature control. The apparatus enclosure consists of a main plenum with a 1ft x 1ft cross-section and transition parts at both ends to have a uniform airflow through the plenum. The thermostat is installed at the center of the plenum and the fan on the top draws air through the opening at the bottom of the apparatus from the indoor test room. During load-based testing, the fan is controlled based on feedback from the air velocity measurement upstream of the thermostat to have a constant air velocity of 30 FPM (0.15 m/s) over the thermostat as per the NEMA DC 3 (NEMA, 2013) recommendation. Further, the thermostat inlet air temperature is controlled to the virtual building temperature by reconditioning the sampled air using a TECHX (Thermoelectric Cooler Heat Exchanger) installed at the bottom. The TECs (Thermoelectric Coolers) installed in the TECHX work as heat-pump devices between the crossflow air streams and can provide cooling as well as heating. The TECHX is controlled based on the virtual building temperature as the setpoint and temperature measurements upstream of the thermostat as feedback. Figure 2 depicts the load-based test setup and virtual building model concept for a split-type heat pump along with the TEE for the thermostat. The TEE provides independent control of the air temperature over the thermostat to track the virtual building temperature, while the psychrometric chamber re-conditioning system is used to control the indoor test unit return air conditions to the virtual building conditions. The 1st generation TEE maximum temperature difference between the TECHX inlet air temperature and thermostat inlet air temperature was around 2.3°F in cooling, while around 17°F in heating. In both cooling and heating modes, TECHX was powered at 100% and the fan was controlled to maintain the air velocity at 30 FPM.

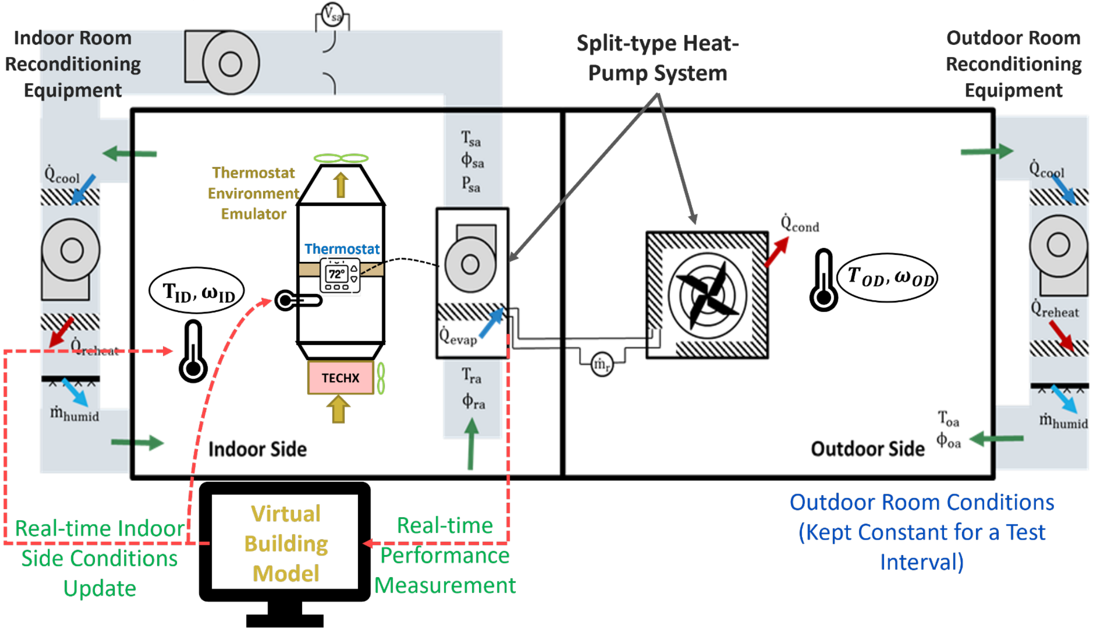


Figure 2: Load-based testing schematic for a split-type heat-pump system with the TEE in a psychrometric test facility

In this work, a 2nd generation TEE was designed and built to improve its maximum performance, robustness, and applicability across different test facilities along with some other design improvements. The primary objective of this paper is to present the design of the 2nd generation TEE along with a performance assessment and application in load-based testing. The focus of the design was on improving the TECHX performance, reducing the overall size of the TEE, and simplifying the installation and setup for use in other laboratories. In the subsections below, first, the TEE updated design is presented followed by the test setup and methodology to assess its maximum performance, temperature distribution inside the plenum, and application with load-based testing. Then, TEE test results are presented along with a discussion on its performance.

2. THERMOSTAT ENVIRONMENT EMULATOR DESIGN

2.1 Updated Design

Figure 3 shows a schematic and picture of the 2nd generation TEE. The overall dimensions of the re-designed thermostat environment emulator are 14" x 14" x 75", around 23" shorter than the 1st generation TEE. Reducing the TEE height was important for application in some other laboratory test facilities. To make the thermostat apparatus lightweight, the overall support structure is built with 1.5" hollow aluminum extrusions in a modular design consisting of different parts that can be assembled on-site using latches and screws. Three main parts of the thermostat environment emulator are: 1) head plate with fan; 2) main body with plenum; 3) bottom part with TECHX (thermoelectric cooler heat exchanger).

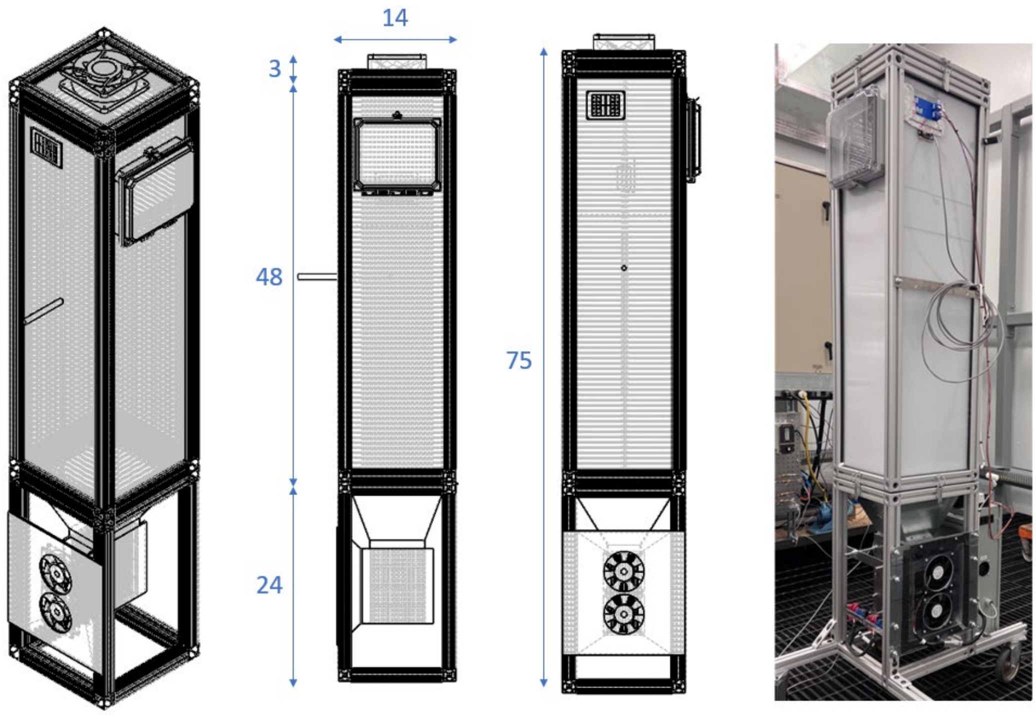


Figure 3: Drawings and prototype of 2nd generation TEE (dimension in inches)

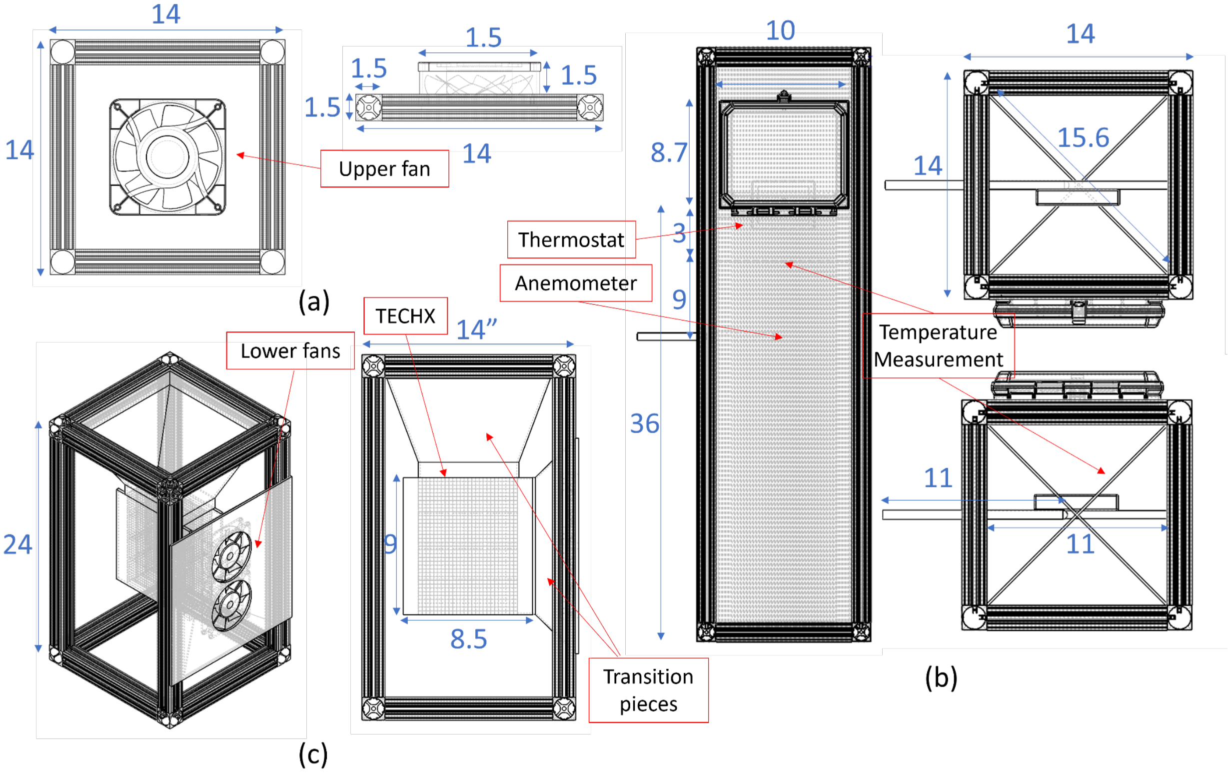


Figure 4. Drawings of (a) head part (b) main body part (c) bottom part with TECHX (dimension in inches)

The head part design is shown in Figure 4(a) with overall dimensions of 14" X 14" X 3". An axial fan is installed at the center of the head part with an acrylic panel to maintain air velocity around 30 FPM over the thermostat installed inside the TEE. The head part is attached to the main body using four latches installed on the aluminum extrusions for an airtight assembly. Figure 4(b) shows the design of the main body plenum. The main body plenum's overall dimensions are 14”x14”x48” with a 12”x12” internal cross-section for airflow inside the plenum. In order to realize a robust, insulated, and lightweight design, hollow polycarbonate panels with an air gap are used for plenum walls. Rubber gaskets are used between polycarbonate panels and aluminum extrusions to make the overall assembly airtight. A single layer of bubble wrap reflective insulation was also installed inside the plenum to decrease the heat loss and heat gain. The thermostat is installed at the center of the plenum cross-section on a thermostat mounting panel located 36” above the plenum bottom. The thermostat mounting panel is made of polycarbonate that is lightweight and easy to mount. At 3” below the thermostat center, 4 thermocouples are installed to measure the thermostat inlet air temperature, and further 9” below, a hot-wire anemometer is installed to measure the thermostat inlet air velocity. Thermostat inlet air temperature and velocity are used in feedback control of the TECHX and the top fan, respectively. A transparent door with a latch and airtight rubber seal was installed to have easy access for thermostat installation and allow visual checks of the thermostat display during testing if needed. Figure 4(c) depicts the bottom part with the TECHX. The bottom part dimensions are 14” x 14” x 24” and it incorporates the TECHX, two 24VDC axial fans, and two transition parts. The vertical transition piece connects the TECHX to the body plenum, and the horizontal transition piece connects the TECHX to the two fans mounted on the flange. Two fans discharge the crossflow exhaust air with 300 cfm ($0.142\ m^3/s$). For the best performance of the TECHX, the fans are operated at full speed.

Figure 5 presents details of the TECHX with overall dimensions of 6.5” x 3.3” x 9” constituting 4 horizontal airflow channels, 3 vertical airflow channels, and 72 TECs in 6 layers. Figure 5(a) depicts the complete TECHX assembly, Figure 5(b) illustrates that 12 TECs are located in a single layer between the two airflow channels in a 4 x 3 array, and Figure 5(c) shows the TEC layout in each layer. The TECs and airflow channels are assembled with thermal conductive tape and thermal paste to maximize thermal contact and heat transfer. The conditioned air passing through the vertical channels flows over the thermostat installed inside the main plenum, while the air flowing through the horizontal channels acts as a heat source or sink depending on TECs operating mode. Both vertical and horizontal airflow channels are constructed with 30-gauge (0.01”) copper sheets and also copper fins are installed in the channels to increase the heat transfer surface area. The air gaps between the TECs for wiring, 0.26” in the vertical direction and 0.34” in the horizontal direction, were filled with silica gel to block the airflow and provide insulation between hot and cold side channels.

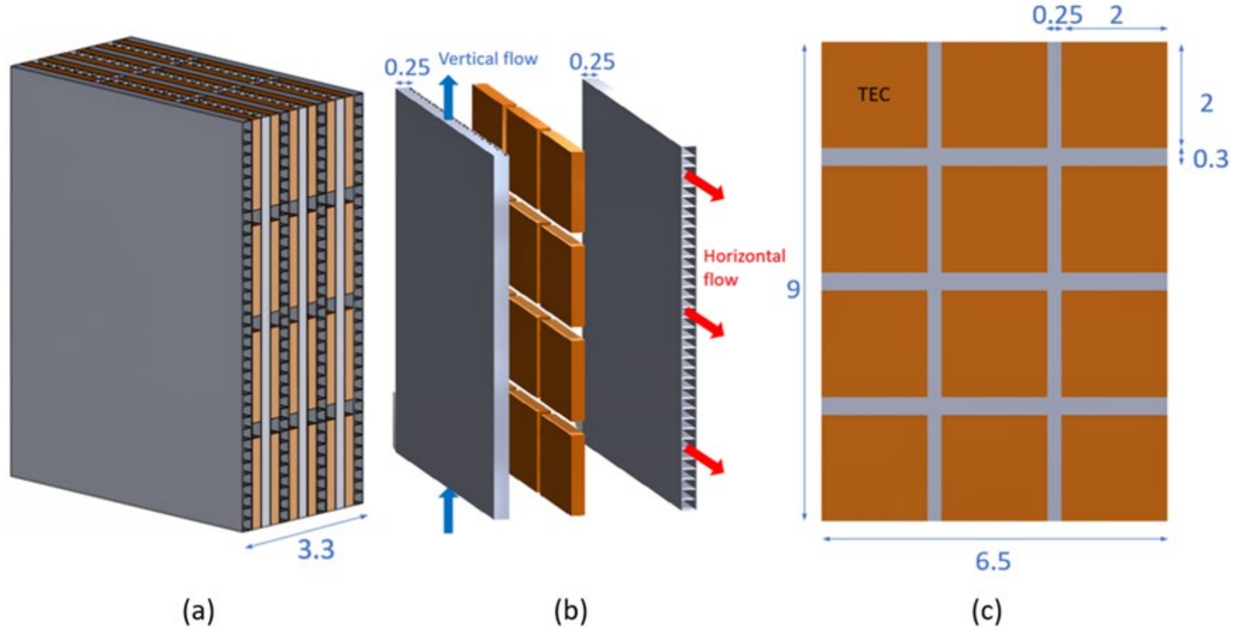
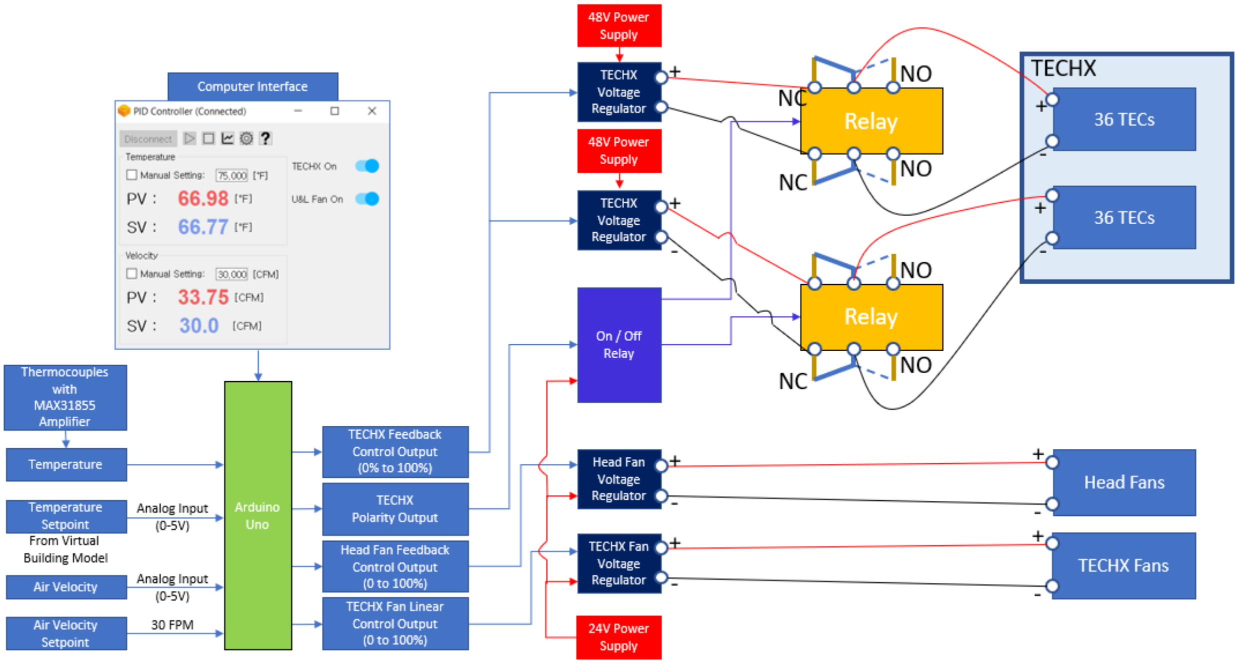


Figure 5. (a) Overall schematic of TECHX (b) TECs with two channels (c) 2D TECs arrangement

2.2 Control Configuration

During load-based testing, the TECHX is controlled based on a PI feedback controller to maintain the thermostat inlet air temperature to the virtual building model temperature. The TECHX feedback controller compares the measured thermostat inlet air temperature to its setpoint and controls the DC voltage amplitude and polarity supplied to the TECs modules. The air velocity over the thermostat is maintained at 30 FPM (0.15 m/s) by controlling the top fan voltage using a feedback controller based on the measured thermostat inlet air velocity using a hot-wire anemometer. The control schematic for the TEE is shown in Figure 6. Two 48 VDC power supplies are used to power the TECs and one 24 VDC power supply for the top fan and TECHX fans. Each 48 VDC power supply supplies one set of 36 TECs, therefore, 72 TECs are controlled with two 48 VDC power supplies in total. Voltage amplitudes to the TECs and fans are controlled using voltage regulators which linearly scale the power supply input voltage from 0% to 100% based on a 0 to 5 VDC control signal. Further, the TECHX is switched between cooling and heating mode by changing the polarity of the voltage supplied to the TECs using a DPDT (Dual Pole Dual Throw) relay. The DPDT relay is controlled by a binary control signal from the TECHX feedback controller using an on/off relay. An Arduino Uno is used as hardware for control implementation and an independent software package was developed to operate the thermostat environment emulator (TEE). The TECHX and head fan feedback controls are accomplished with PI algorithms that were implemented in the software. A MAX31855 amplifier is used to collect and amplify the signals from thermocouples (TCs). The thermostat inlet air temperature setpoint is read by the Arduino as a 0-5V analog input (AI) signal. The 0-5V AI signal is converted to the thermostat inlet air temperature setpoint range based on the user input temperature range.


PID Controller (Connected)

Temperature
☐ Manual Setting: 75.000 [°F]
PV : 66.98 [°F]
SV : 66.77 [°F]

Velocity
☐ Manual Setting: 30.000 [CFM]
PV : 33.75 [CFM]
SV : 30.0 [CFM]

TECHX On ●
U&L Fan On ●

Figure 6. 2nd generation TEE control and electronics schematic

3. TEST SETUP AND METHODOLOGY

3.1 Maximum Performance Testing

After initial commissioning of the 2nd generation TEE, maximum performance tests were performed in cooling and heating modes. For these tests a thermocouple (TC) grid with 9 thermocouples was installed upstream of the thermostat and 2 thermocouples were installed at the TECHX inlet to measure ambient air temperature. Each thermocouple was placed 3 inches apart as shown in Figure 7. During the maximum performance tests, the TECHX was powered to 100% capacity in cooling and heating modes, and the air velocity over the thermostat was controlled at 30 FPM.

3.2 Load-Based Testing

After the maximum performance assessment tests, load-based tests were performed with a 2-ton variable-speed split-type heat pump as per CSA EXP07 and utilizing the TEE to provide standardized environmental conditions for the thermostat. The motivation for these tests was to assess the performance of the TEE in application with load-based testing across varied cooling and heating mode test conditions. For heat pump performance assessment, return and supply air temperature and humidity, indoor unit airflow and external static pressure, and indoor & outdoor unit power were measured along with refrigerant-side properties for secondary performance measurement. First, an AHRI 210/240 A_2 steady-state test was conducted to measure the test unit design cooling capacity and to perform a secondary energy balance check with the refrigerant side capacity. Table 1 summarizes the A_2 steady-state test results. The energy balance difference was around 3%, which fulfills the CSA EXP07 standard of less than 6%. The total cooling capacity of the unit is 6002W, which is used to scale the virtual building model parameters for load-based testing.

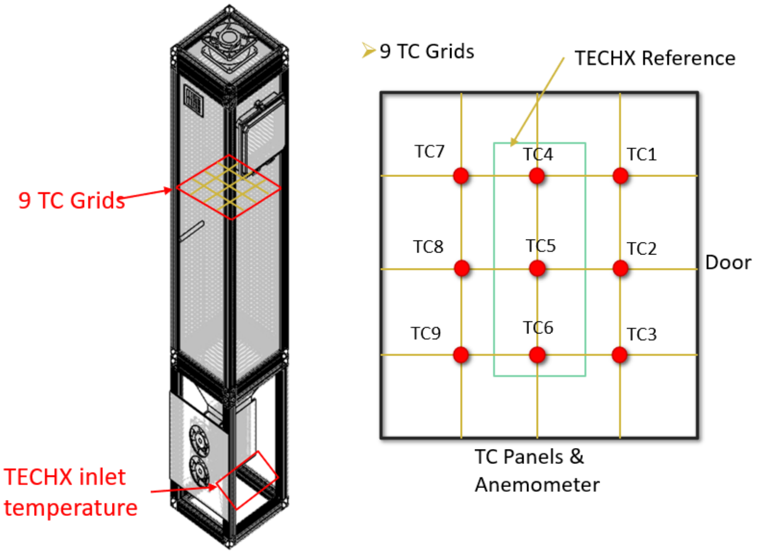


Figure 7. Temperature measurements for maximum performance test

Table 1: AHRI 210/240 A_2 steady-state test performance results

Indoor dry-bulb temperature	Indoor wet-bulb temperature	Outdoor dry-bulb temperature	Airside total capacity	Total power	Air flowrate
80 °F	67 °F	95 °F	6002.4 W	1603 W	658.7 CFM

4. TEST RESULTS

4.1 Maximum Performance Test Results

The TEE cooling maximum performance test results are shown in Figure 8. The plot on the left illustrates the temperature variation measured at the thermostat inlet grid (TC1 to TC9) along with the TECHX inlet temperature which is the mean of two thermocouples. The figure on the right shows the average of 9 TCs at the thermostat inlet after the temperatures converge. The temperature at the thermostat inlet varied from 65°F at the center to 68°F in the corner with an average temperature of 66.3°F for an average TECHX inlet temperature of 73.2°F. This resulted in a maximum temperature difference between the thermostat inlet temperature and TECHX inlet temperature of 6.8°F, more than twice the 1st generation TEE maximum cooling performance.

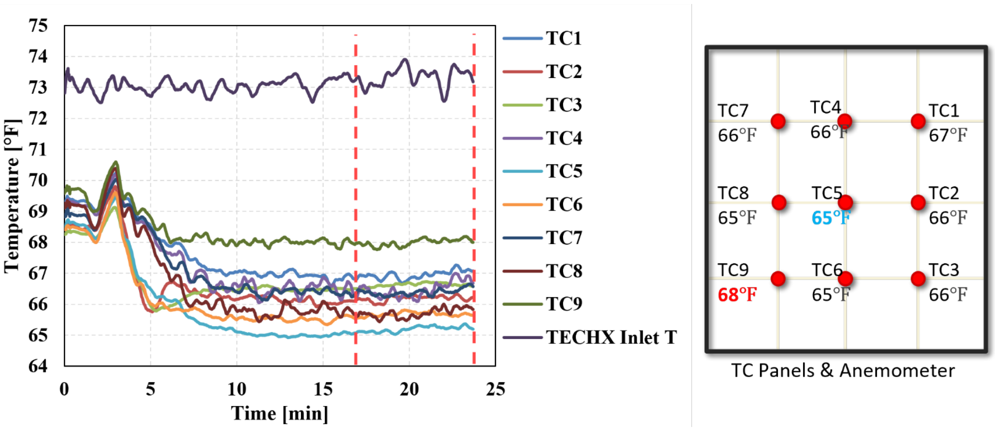


Figure 8. Cooling maximum performance test results

Figure 9 shows heating maximum performance test results. The temperature distribution of the 9 thermocouples at the thermostat inlet ranged from 108°F to 121°F with TC9 in the bottom left corner having the lowest value (108°F) and TC5 at the center having the highest value (121°F). The average temperature at the thermostat inlet was 115°F and the maximum temperature difference between the temperature at the thermostat inlet and the TECHX inlet (73.1°F) was 41.9°F, showing that the TECHX has a significantly larger heating capacity compared to cooling. Even though there was some large variation in temperature at the thermostat inlet location between the center and corner of the 1ft x 1ft cross-section, it was decided that this is acceptable for this application as the thermostat is installed in the center and its inlet temperature is controlled based on 4 nearly placed thermocouples installed at the center as discussed above. Overall, the 2nd generation TEE performance met the initial design goal of increasing its cooling capacity by more than twice the 1st generation TEE capacity.

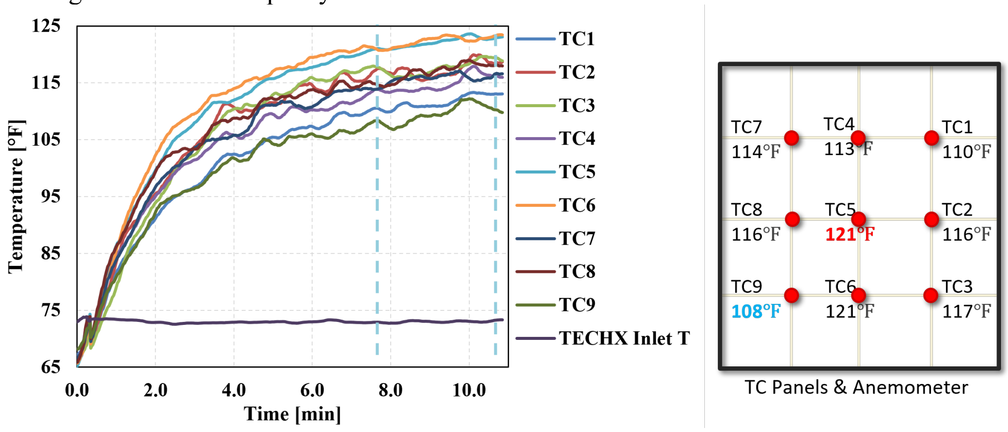


Figure 9. Heating maximum performance test results

4.2 Load-Based Test Results

Figure 10 shows test unit performance and temperature variations for cooling dry-coil load-based tests at 5 different ambient temperature conditions with the thermostat installed in the TEE. The upper subplot shows the unit's sensible cooling rate, total power, indoor airflow, and virtual building load. The lower subplot depicts the thermostat setpoint, virtual building indoor temperature (IDT), test unit return air temperature, thermostat inlet temperature, virtual building outdoor temperature, and measured outdoor temperature. In this test, the thermostat setpoint was set at 79°F, and the test unit operated in different modes to maintain the indoor (test unit return and thermostat inlet air) temperature near the thermostat setpoint. In the 1st and 2nd test intervals, the unit cycled on/off to meet the building load, operated in a variable-speed mode in the 3rd and 4th intervals, and ran out of capacity to meet the building load in the 5th interval in which a full-load test was performed. The indoor test unit return air and thermostat inlet air temperature were controlled to the virtual building indoor temperature (IDT) by the test room re-conditioning system and the TEE, respectively. The TEE was able to track the virtual building temperature quite well, thus satisfying its main design objective.

Figure 11 presents the TEE overall control variables. The upper subplot shows the virtual building indoor temperature, thermostat inlet temperature, test unit return air temperature, thermostat inlet air velocity setpoint, and thermostat inlet air velocity. The root mean square error between the virtual building indoor temperature and thermostat inlet temperature for the complete test duration was around 0.13°F, while that of the virtual building indoor temperature and the return air temperature was around 0.17°F, indicating that the thermostat inlet air temperature tracked the virtual building temperature slightly better than the return air temperature. The thermostat inlet air velocity was controlled around its setpoint of 30 FPM with ±4 FPM fluctuation. The lower subplot displays TECHX control voltage, head fan control voltage, and TECHX heating status. This plot demonstrates that the TECHX only utilized 40% of its cooling capacity in this test and TECHX mainly operated in cooling mode. This can be attributed to the fact that the psychrometric chamber is also conditioned based on the virtual building temperature setpoint.

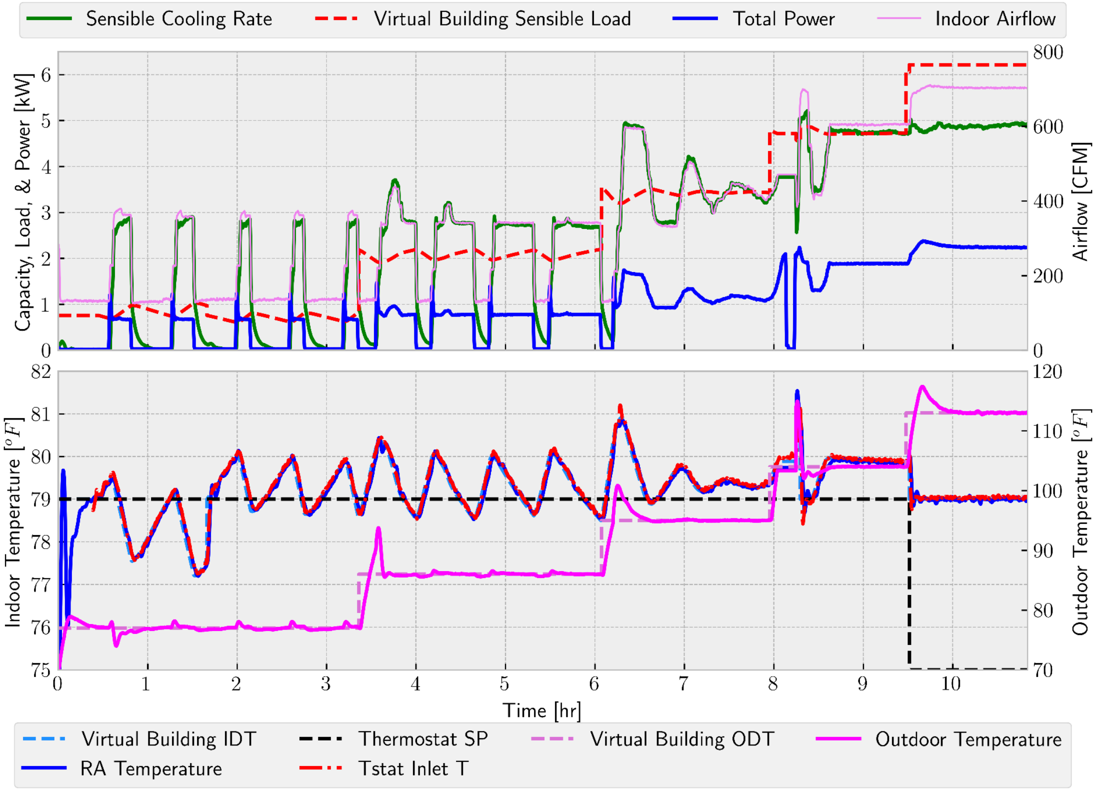


Figure 10. Cooling dry-coil load-based test results with the thermostat mounted in the TEE

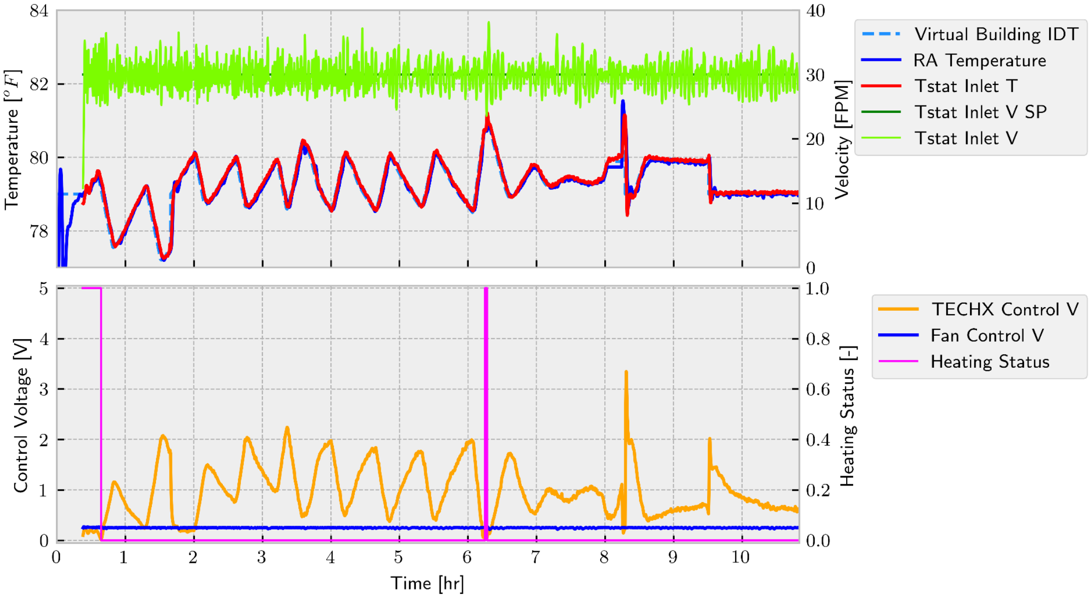


Figure 11. TEE performance results for cooling dry-coil load-based tests

The TEE performance and operation were also evaluated in heating load-based tests. Figure 12 shows the TEE temperature control response with its control variables for the heating marine test interval at 17°F outdoor temperature. In this test interval, the test unit operated in variable-speed mode with intermittent defrosts, and the virtual building indoor temperature variation was larger compared to the cooling test. Nonetheless, the TEE was able to track the virtual building temperature well. The thermostat inlet air velocity fluctuated around ±8 FPM, somewhat higher than for the cooling test. These high fluctuations in air velocity could be due to air turbulence in the TEE which affects the hot-wire anemometer reading. Currently, this issue is being resolved. It is interesting to note that the TECHX operated mostly in cooling mode for this heating test interval, which could be due to the airflow and temperature distribution characteristics for this particular test facility, and it might vary in a different test room. Overall, the TEE performed well in cooling as well as heating test intervals. For further discussion on the TEE performance across varied heating and cooling load-based test conditions, the reader is referred to a companion paper by Dhillon *et al.* (2022d).

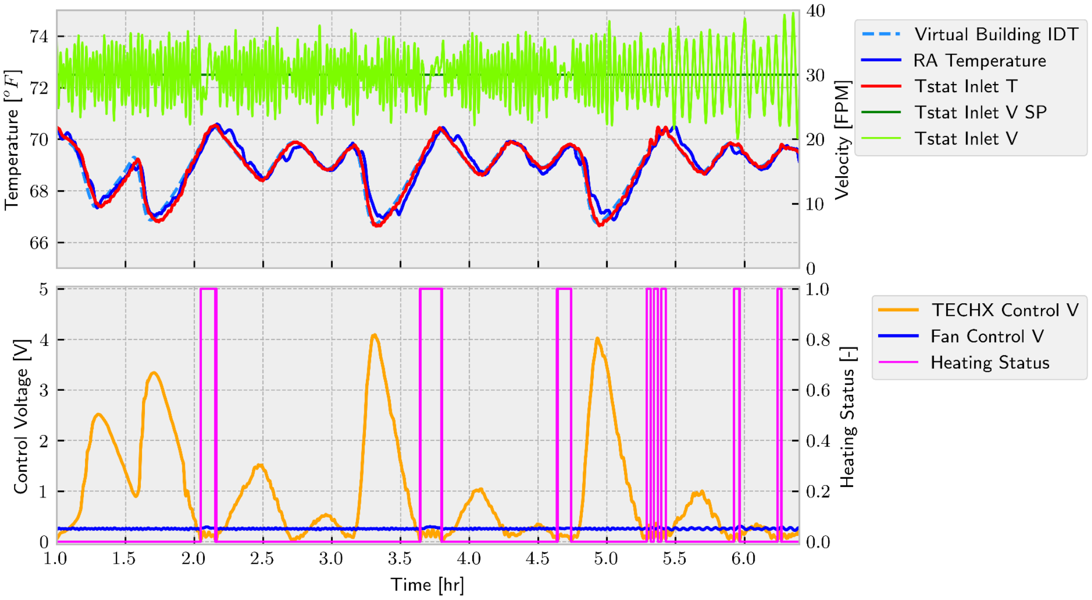


Figure 12. TEE performance results for heating marine test interval at 17°F outdoor temperature

5. CONCLUSIONS

In this work, an updated design of a previously developed thermostat environment emulator (TEE) that provides standardized environmental conditions to the thermostat in load-based testing was presented and assessed. This 2nd generation TEE was designed and built to improve its performance and applicability across different test facilities compared to the 1st generation TEE. The overall structure was built with aluminum extrusions and polycarbonate panels for a lightweight and easy-to-assemble design. An Arduino Uno is used to control the electronic components with a software package that was developed to provide independent control and easy implementation within existing test facilities. With the TEE running at maximum cooling capacity and the air velocity maintained at 30 FPM over the thermostat, the device was able to cool down the ambient inlet air by 6.8°F and for heating, it was able to raise the air temperature by 41.9°F. In contrast, the 1st generation TEE was only able to achieve a maximum temperature drop of 2.3°F in cooling mode and a maximum temperature rise of 17°F in heating mode. After initial design assessment tests, load-based tests were performed for a 2-ton variable-speed heat pump utilizing the TEE for both cooling and heating mode test conditions. For all of the tests, the thermostat inlet air temperature closely tracked the virtual building indoor temperature and the TEE performed well and met its design goals.

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