Laboratory Evaluation of Control Verification Procedures for Certification of Variable-Speed Heat Pumps

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ABSTRACT

The testing and rating procedure for central air conditioners and heat pumps ("CAC/HPs") detailed in AHRI 210/240-2024 employs a steady-state test procedure where test room conditions are maintained at constant values, and the CAC/HP system is controlled to operate at specified fixed compressor speeds and indoor airflow rates. For variable-speed and multi-stage systems, it includes some specifications on selecting compressor speeds and indoor fan speeds for various ambient conditions. However, this standard does not include a process to verify whether the performance under the selected component speeds in the testing agrees with the operations of the system at the same conditions under native controls. To address this problem, a Control Verification Procedure (CVP) has recently been developed as an additional test that is described in AHRI 210/240-2024. The CVP is based on the load-based testing approach developed through CSA SPE-07:2023 that measures performance of a test unit with its native controls that interacts dynamically with a building load. In the CVP, the indoor environment is controlled to dynamically respond to the test unit behavior using a representative virtual building model that has outdoor test conditions and equipment cooling/heating rates as inputs. For the testing sequence, the outdoor condition was varied between three steady-state conditions through two transitional periods. Then, the system dynamic performance at the intermediate load condition was used to validate the operation of the native control, including verifying the system operates with variable capacity. In this paper, results and assessments associated with applying the CVP to two variable-speed heat pumps are presented. One of the primary goals is to evaluate whether CVP can serve as an indicator of whether the existing steady-state testing for AHRI 210/240 accurately reflects the unit's performance under native control and dynamic load conditions.

1.INTRODUCTION

The current rating and testing procedure in the U.S. for residential air-conditioning and heat-pump systems is based on AHRI 210/240 (2020), ASHRAE 37 (2019), and ASHRAE 116 (2010). These standards provide descriptions of the required test procedures to evaluate and rate the equipment's performance (e.g. heating/cooling capacity). The test equipment's seasonal performance (e.g., SEER, HSPF) is evaluated based on a set of steady-state tests at different indoor and outdoor conditions where the controls are overridden. However, the steady-state testing methodology does not capture the impact that embedded controls may have on performance and does not provide appropriate incentives for manufacturers to improve their controls. A study by Munk, Halford, and Jackson (2013) compared the published rating against the field performance of two variable-speed heat pump models. They found 36% lower seasonal heating performance for a 13 HSPF rated unit as well as 11% and 16% lower heating seasonal performance for two 8.9 HSPF variable-speed heat pumps. Similar discrepancies were observed for cooling seasonal performance. The higher rating based on laboratory testing was primarily attributed to extrapolation of the low compressor speed test at 47°F (8.33℃) ambient temperatures to lower temperatures and the assumption that the compressor speed is continuous between the measured minimum and maximum speed.

To address limitations of the current standard, load-based testing methodologies have recently been developed to rate equipment operating under realistic load conditions while accounting for integrated controls (Cremaschi & Perez Paez (2016, 2017); Patil et al. (2018); Hjortland and Braun (2019); Cheng et al. (2021c); Dhillon et al (2023); CSA EX07:19

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(2019): CSA SPE-07:23 (2023)). In parallel, the DOE had outlined several key issues with the current test procedures, including the representativeness of fixed speed tests for variable-speed units. As a result, a Control Verification Procedure (CVP) was developed and is included in AHRI 210-240-2024 that is based on the load-based testing methodology outlined in CSA SPE-07:23 (2023) and that is meant to evaluate whether the override of the modulating components in the steady-state regulatory tests is representative of the unit's performance under native control.

In this paper, the additional testing methodology outlined in AHRI 210/240-2024 (2024) is described and evaluated using two variable-speed heat pump units installed and instrumented at Herrick Laboratories. The performance of the units as well as potential improvements to the testing methodologies are presented. Finally, comparisons between unitary equipment steady-state and load-based testing experimental results are compared to highlight the potential of unit performance being misrepresented due to the previous testing standards.

2.CONTROL VERIFICATION TESTING METHODOLOGY

Figure 1 shows a schematic of the CVP test setup and testing approach for a split heat pump. The unit is set up in a pair of psychrometric chambers representing indoor and outdoor environments, where the temperature and humidity conditions can be controlled. During CVP tests, the test unit is controlled using its thermostat and embedded controls with indoor test room temperatures that are continuously modulated to emulate the dynamic response of a virtual building to the sensible cooling (or heating) rates generated by the tested unit, similar to the method described in CSA SPE-07:23 (2023).

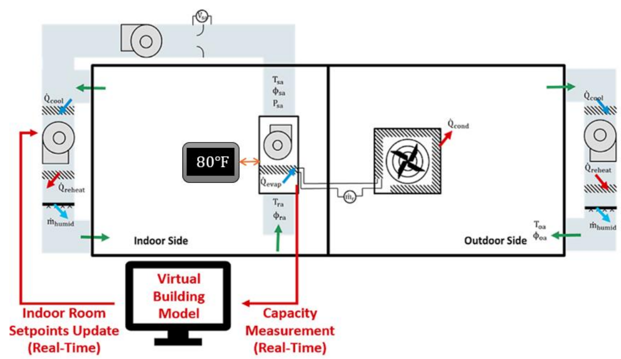


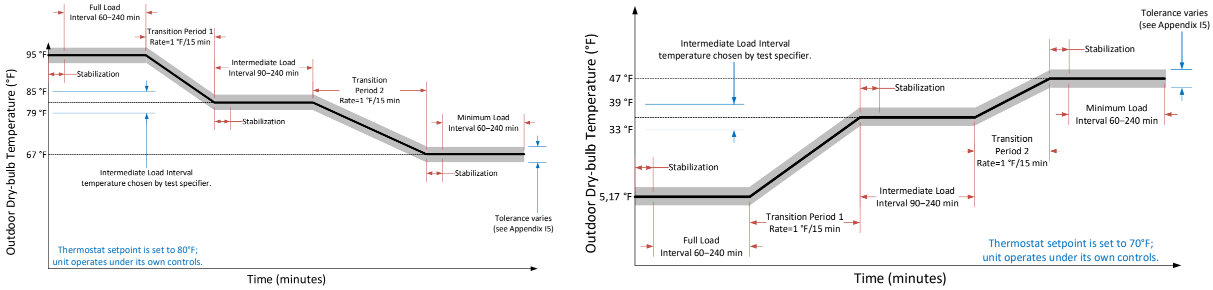
Figure 1. Testing setup and methodology for CVP

Appendix I of AHRI 210/240-2024 (2024) presents outdoor dry-bulb temperature setpoints that are employed across five CVP test intervals during cooling mode (CCVP) and heating mode (HCVP). Figure 2A illustrates the five intervals with three steady-state intervals, where the outdoor temperature remains constant at predefined levels: 95°F (35℃) for the full-load interval, 67°F (19.4℃) for the minimum-load interval, and within a selected range of 79°F (26.1℃) to 85°F (29.4℃) for the intermediate-load interval. While in the two transitional periods, the outdoor temperature decreases gradually at a rate of 1°F (0.56℃) every 15 minutes. For CCVP, section I5.1.4 of the standard specifies that the outdoor entering wet-bulb temperature is not required to be controlled for split systems that do not reject condensate to the outdoor coil. The dry-bulb temperature setpoints for the indoor chamber reconditioning system are determined based on a virtual building model that considers a sensible load and real-time sensible capacity measurements from the test unit that depend on its embedded controls. Equations 1 and 2 are used to update the indoor dry-bulb temperature setpoints for CCVP and HCVP in response to the virtual loads and sensible equipment capacities. The cooling virtual load is calculated as a linear interpolation between the sensible cooling associated with the A_{Full} and F_{Low} steady-state test conditions. In cooling tests, the indoor wet-bulb temperature is kept constant at 67°F (19.4℃) with a maximum possible indoor dry-bulb temperature of 83°F (28.3℃), and the thermostat of the test unit is set 80°F (26.7℃).

$$RAT(t+\Delta t) = RAT(t) + \frac{\Delta t[VLs(T_j) - \dot{Q}_S]}{C} \quad (1)$$

$$RAT(t+\Delta t) = RAT(t) - \frac{\Delta t[VL(T_j) - \dot{Q}_h]}{C} \quad (2)$$

The HCVP follows a similar strategy, featuring three steady-state and two transitional periods illustrated in Figure 2B. The steady-state conditions include a 17°F (-8.33℃) full-load interval, an intermediate-load interval that can employ temperatures between 33°F (0.56℃) to 39°F (3.89℃), and a 47°F (8.33℃) minimum-load interval. The heating virtual load is calculated as a linear interpolation between the sensible heating between the $H_{3,Full}$ and $H_{1,Low}$ steady-state test conditions. During the transitional periods, the outdoor temperature increases at a rate of 1°F (0.56℃) every 15 minutes, transitioning between different steady-state intervals. For HCVP, the outdoor entering wet-bulb temperature is maintained sufficiently low such that frost does not accumulate on the outdoor coil. The minimum indoor dry-bulb temperature allowed is 67°F (19.4℃) with no indoor wet-bulb temperature specified and the thermostat set to 70°F (21.1℃).



(A) (B)

Figure 2.A) CCVP **B)** HCVP Outdoor Temperature Profiles

On the completion of all test intervals, tolerances for the completion of each period are specified in section I5 of AHRI 210/240-2024 (2024). The intermediate interval is evaluated based on the total power capacity to determine if the test unit can be classified as a one-stage, two-stage, or variable-speed unit. Variable-speed classification depends on whether the standard deviation of the system's total power does not exceed 20% of mean power:

$$\sigma\left(PW_{sys}\right) \leq 20\% \cdot \mu\left(PW_{sys}\right) \tag{3}$$

where $\sigma\left(PW_{sys}\right)$ is the standard deviation of the system power; and $\mu(PW_{sys})$ is the mean of the system power.

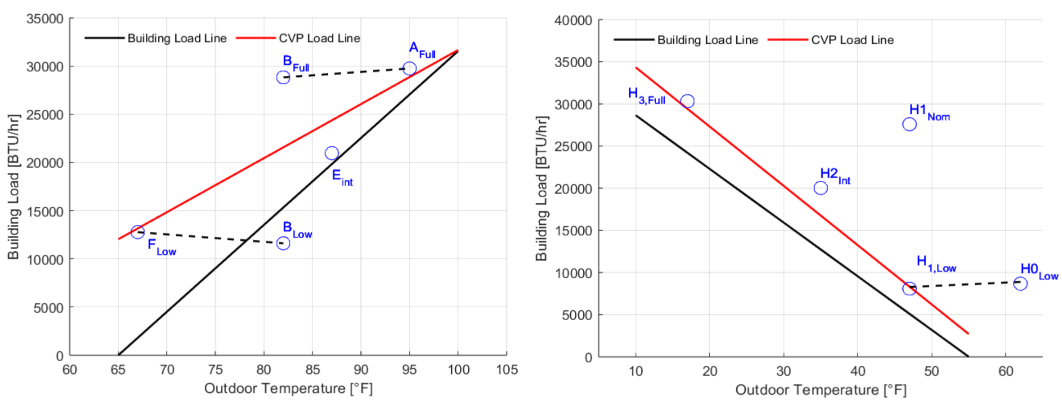
If the unit fails to meet the power criteria required to be classified as a variable-speed system, the range of capacity variation of the unit during the intermediate load period is utilized to determine its classification as a one- or two-stage system. If the capacity varies by less than 15%, the classification will be a variable-capacity certified, one-stage system. Variation of greater than 15% will result in categorization as a variable-capacity certified, two-stage system. The following equation is used to calculate the range:

$$Range\% = 100 * \frac{\dot{Q}_{Max,Int} - \dot{Q}_{Min,Int}}{\dot{Q}_{Max,Int}} \tag{4}$$

3. RESULTS

3.1 TEST UNIT A

In this section, results and analysis for CVP tests under cooling and heating mode are presented for a variable-speed 3-ton unit (referred to as Test Unit A). Figure 3A presents the CCVP load line determined from AHRI 210/240-240 steady-state A_{Full} and F_{Low} tests along with the sensible building load line associated with seasonal efficiency determinations in AHRI 210/240-2024. At the F_{Low} condition, the CVP sensible load is about 10 times the sensible building load, creating a high-load state unrepresentative of real word conditions. The HCVP load line based on steady-state $H_{3,Full}$ and $H_{1,Low}$ tests are shown in Figure 3B along with the building load line. The slope of the load lines are quite similar and representative.



(A) (B)

Figure 3. Test Unit A CVP vs AHRI 210/240 Building Load Lines: **A)** Cooling **B)** Heating

The manufacturer of the test unit indicated that there were 3 available thermostats that could be employed. The cooling CVP Test #1 was performed using a thermostat that the manufacturer indicated had a relatively slow temperature response and employed an intermediate outdoor temperature of 82°F(27.7℃) that was within the middle of allowed range. Figure 4A shows test unit sensible cooling capacity (blue), virtual sensible load (red), outdoor power (purple), and indoor fan power (yellow) as a function of time during the CVP cooling test. Figure 4B shows the outdoor and indoor temperature setpoints and measurements for the same test. The intermediate CVP test conditions were selected to be at the same outdoor condition as the B_{Full} and B_{Low} steady-state tests for comparison purposes.

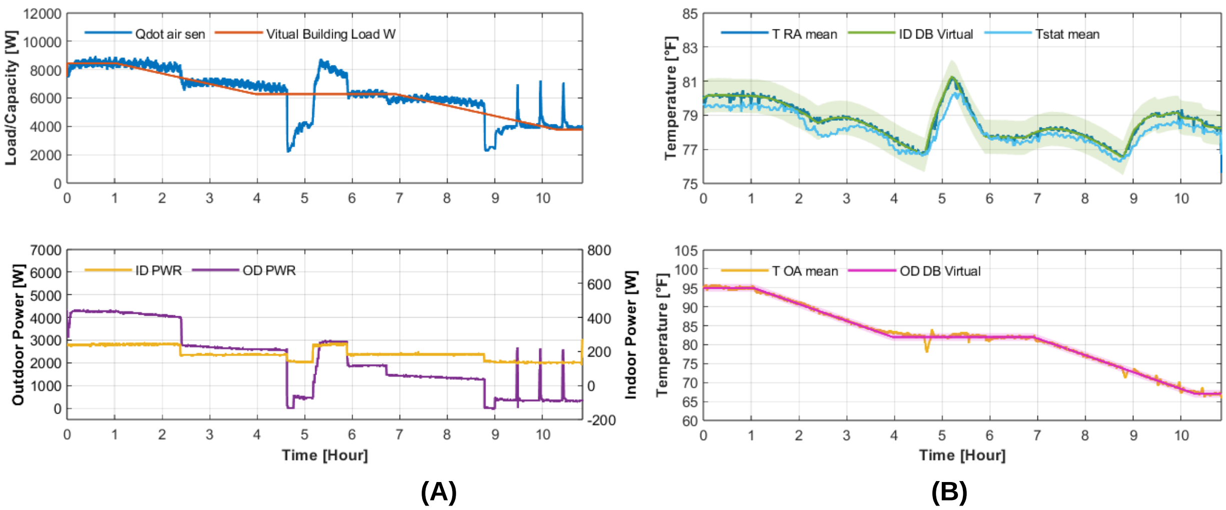


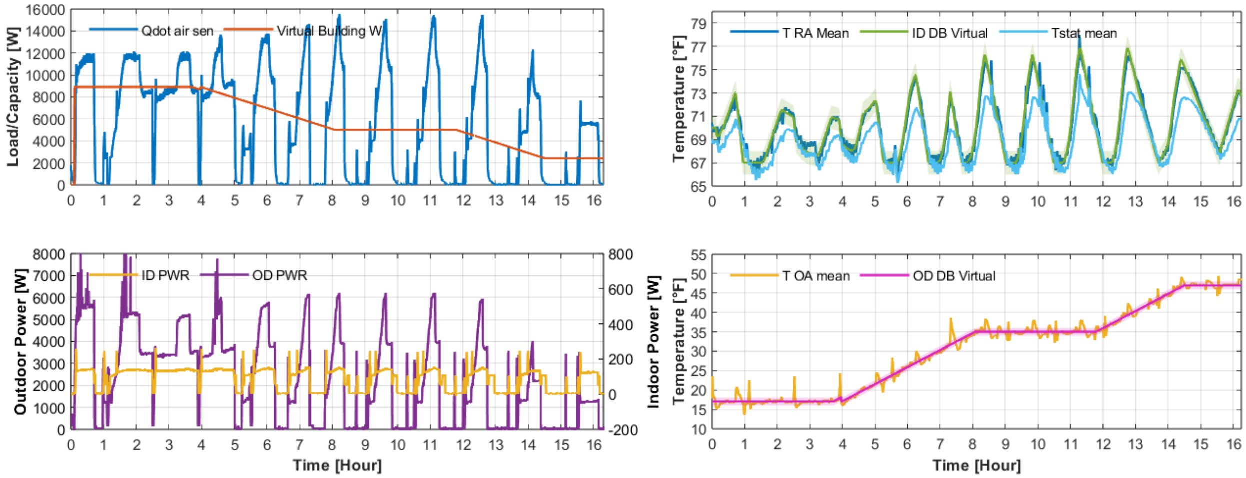
Figure 4. Test Unit A CCVP Results for **A)** Load and Power, **B)** Indoor and Outdoor Temperatures

During the tested CVP conditions, the unit demonstrated an ability to track the virtual sensible loads for most of the test periods. The unit completed the full-load interval while meeting all tolerance requirements. However, the outdoor temperature during the transition periods did not always track the set points necessary to achieve the specified ramp down rate within tolerance. Furthermore, the unit cycled off at around the 5-hour and 9-hour marks because the indoor temperature fell below 77°F (25°C) as shown in Figure 3B. The first shutdown occurred during the intermediate period, which influenced the length of the test required to meet tolerances. During shutdowns, the indoor fan continued to operate, and the compressor was turned back on after a short period, resulting in capacity not reaching zero. However, the intermediate test condition was eventually completed. In addition to not tracking building load during periods of on-off cycling behavior within the intermediate and second transition periods, the unit did not always track the load during the minimum load interval, presumably because the compressor was speeding up to provide oil return.

The indoor temperatures for the demonstrated CCVP test stayed below the 83°F (28.3°C) indoor temperature limit imposed by the CVP procedure, as illustrated in Figure 3B. Additionally, the temperature reading near the thermostat (Tstat mean) and the return air temperature (ID Room T) were in agreement during the whole duration of the test, except for periods of sudden changes. However, the thermostat display's readings (not recorded) were up to 4 °F (2.22°C) different than air temperatures measured around the thermostat using thermocouples due to the thermostat sensor dynamic lag.

In applying the CVP evaluation power criteria to the intermediate test interval, the unit had a mean total power of 2124 W (7247 Btu/h) and standard deviation of 259 W (884 Btu/h). Thus, the variable-speed unit met the requirements to be categorized as a variable-speed unit in cooling mode. The variable-speed certification must be achieved in both heating and cooling for the unit to be recognized as such.

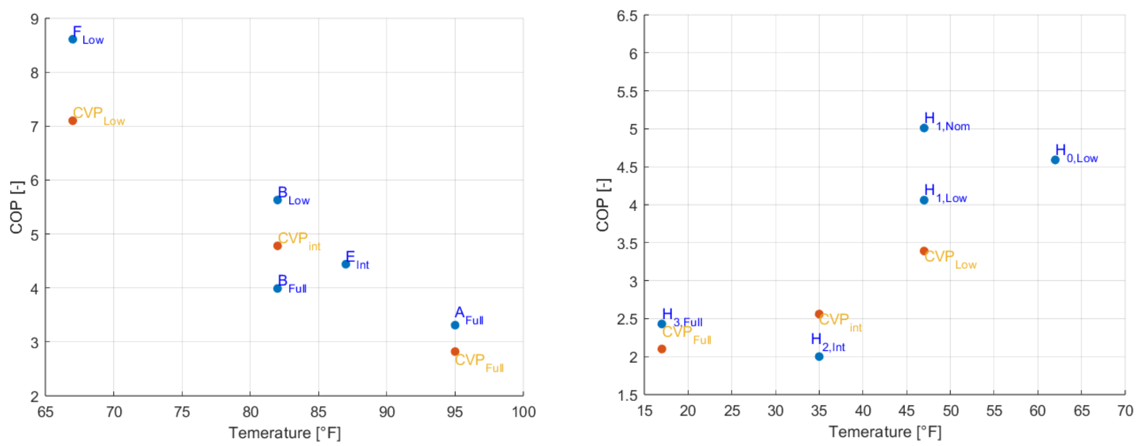
Figures 5A and 5B present results for a CVP heating test for Test Unit A with an intermediate outdoor dry-bulb temperature of 35°F (1.67℃) and a thermostat offset of 1°C (1.8°F) for heating. The unit exhibited very erratic control behavior throughout all of the test intervals, including at full load. The unit regularly cycled on and off along with varying the speed over a wide range in trying to meet load conditions. The indoor temperature oscillated over a range of more than 3°F (1.67°C). The return air temperature and the thermostat surrounding air temperature did not track each other due to the fast changing indoor condition. The test unit did not meet tolerance criteria for any section of the CVP and failed the power evaluation criteria. However, due to the high variation of the measured capacity, the unit would be classified as a variable capacity certified, two-stage system, even though the performance of the unit during the intermediate period was most similar to an on/off unit.



(A) (B)

Figure 5. Test Unit A HCVP Results for **A)** Load and Power, **B)** Indoor and Outdoor Temperatures

Figure 6A compares cooling COPs from steady-state and CVP tests at low (minimum speed for steady-state tests), intermediate, and full (maximum speed for steady-state tests) as a function of outdoor air temperature. At the full load 95°F (35°C) condition, the COP under the CVP test was about 14% lower than the A_{Full} test results. This is because the cooling capacity under the A_{Full} test with override control was 16% less than the capacity delivered under native control at that condition. At the 67°F condition, the CVP test had a lower COP (12%) compared to the F_{Low} COP due to the cycling behavior. The calculation for the minimum interval COP and capacity utilized a trapezoidal Riemann sum for the total capacity and power under one on/off cycle and normalized with respect to the length of the cycle. For the 82°F (27.7°C) test conditions, the CVP intermediate load COP was between the B_{Full} and B_{Low} COP values, as expected. Figure 6B compares heating COPs of Test Unit A determined from the steady-state and CVP tests. The steady-state and the CVP performance differed by about 13% at 17°F (-8.33°C) and around 16% difference at 47°F (8.33°C) ambient. The lower CVP performance was due to cycling behavior of the test unit, which also resulted in under heating with a 20% lower capacity for the minimum- and full-load intervals compared to the steady-state tests.

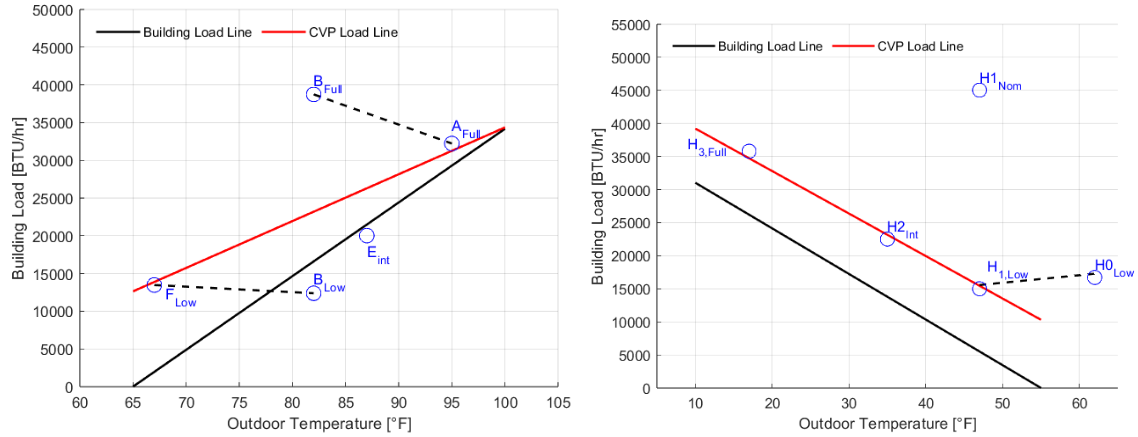


(A) (B)

Figure 6. Test Unit A comparisons of Steady-State and CVP COP Values for **A)** Cooling **B)** Heating

3.2 TEST UNIT B

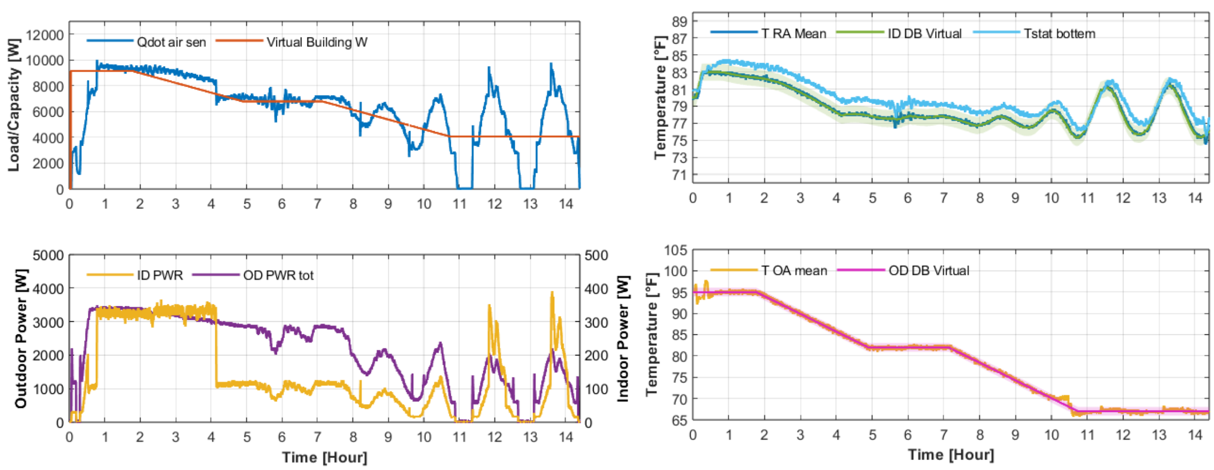
In this section, results and analysis for CVP tests under cooling and heating mode are presented for a variable-speed 4-ton unit (referred to as Test Unit B). Figure 7A compares the CVP sensible load-line determined from A_{Full} and F_{Low} tests with the AHRI 210/240-2024 sensible building load, where once again at lower ambient conditions the CVP load is significantly higher. Figure 7B compares the CVP heating load line with the building load line used to calculate HSPF. In this case, the CVP heating load line has a similar slope to the building load line, but at the 47°F (8.33℃) ambient condition the CVP load is roughly double that of the building load.



(A) (B)

Figure 7. Test Unit B CVP vs AHRI 210/240 Building Load Lines: **A)** Cooling **B)** Heating

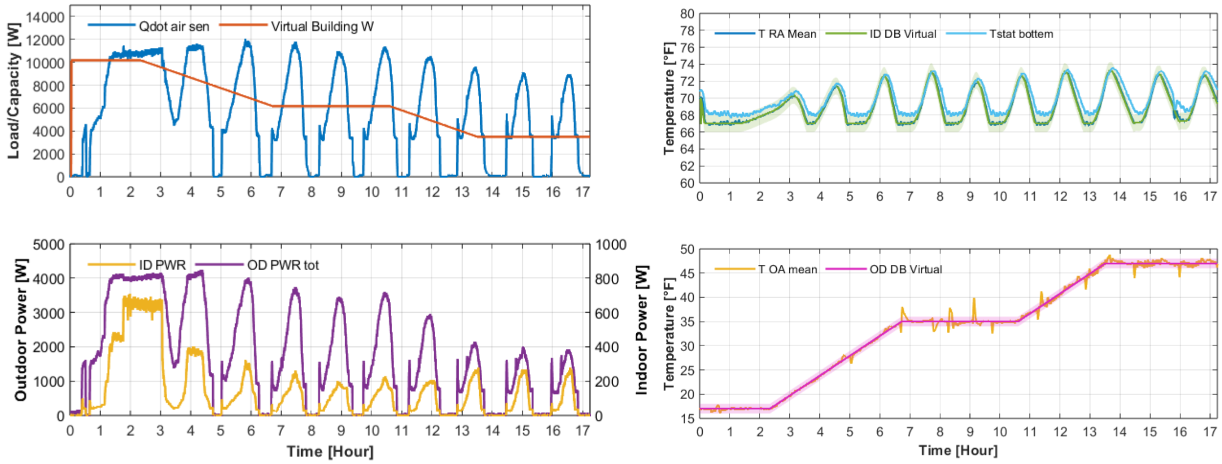
Figures 8A and 8B present the performance of Test Unit B determined under CCVP with 82°F (27.7℃) intermediate conditions. A 4°F (2.22℃) offset was employed on the thermostat to correct the steady-state error between the thermostat display and the reading of the thermocouple grid at the return. During the full load period, the unit took about an hour to ramp the compressor to full speed even though the indoor temperature had reached the 83°F (28.3℃) limit. However, when at 100% compressor speed, the load and all tolerances were met, and the interval was completed. The tolerances of the 1st transition period were also maintained with no issues. The unit reduced its cooling capacity to match the intermediate load, but slight variations of the outdoor power initially caused the indoor room tolerance to not be met. Eventually, the intermediate condition tolerances were maintained for 1 hour. However, the same cannot be said regarding the 2nd transitional period and minimum load interval as the unit exhibited cycling behavior and tolerances could not be satisfied. Also, the temperature at the inlet of the thermostat (Tstat bottom) did not track the virtual building model setpoints. When the power criteria were applied to the intermediate period, the unit had a mean total power of 2672 W (9117 Btu/h) and a standard deviation of 178 W (607 Btu/h). Thus, the requirements for a variable capacity categorization were met in cooling.



(A) (B)

Figure 8. Test Unit B CCVP Results for **A)** Load and Power Plots, **B)** Indoor and Outdoor Temperatures

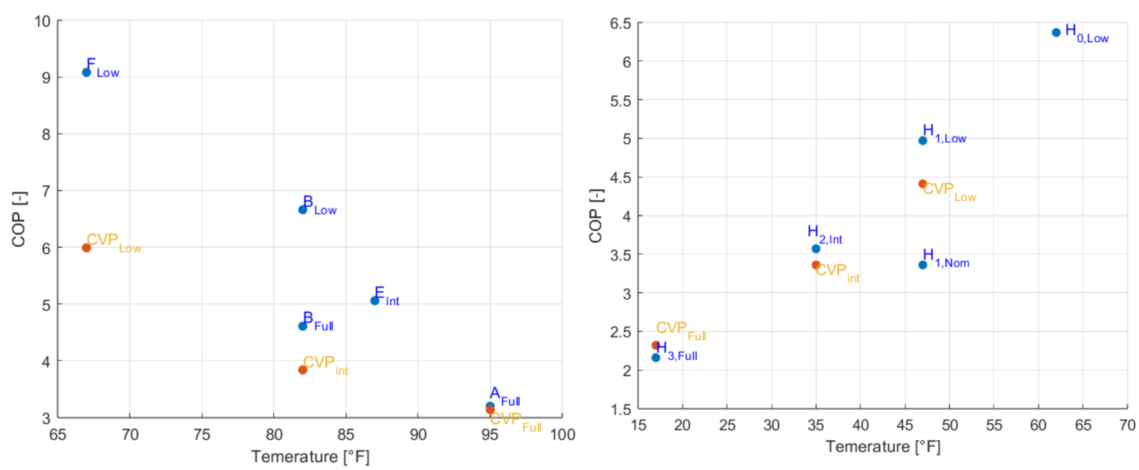
Figures 9A and 9B illustrate the performance of Test Unit B when evaluated under HCVP. The unit had a slow ramp up, but the full load interval was completed without complication. In the succeeding intervals, the test unit displayed cycling behavior with varying amplitude as outdoor temperature increased and was not able to meet the required tolerances. Furthermore, the air temperature surrounding the thermostat was not in agreement with the return air during periods of sudden change. Additionally, due to the high variation of the total power, the test unit failed to pass the power criteria, and similar to Test unit A, it was categorized as a variable-capacity, two-stage system based on capacity variation.



(A) **(B)**

Figure 9. Test Unit B HCVP Results for **A)** Load and Power, **B)** Indoor and Outdoor Temperatures

Figure 10A provides a comparison between COPs determined from steady-state and CVP tests for Test **U**nit B. In this case, the unit's COP for the full load CVP interval and A_{Full} tests were very similar (~2% difference). In contrast, the performance of the unit for the minimum load period was about 34% lower than the steady-state F_{Low} test result, presumably due to the cycling behavior. Additionally, the COP of the intermediate CVP period was below the steady-state performance of the unit for both the B_{Full} and B_{Low} condition, indicating that the behavior of the embedded controls leads to an overall performance penalty relative to overridden controls. Figure 10B presents comparisons of heating COP for the CVP and steady-state tests. In this case, the CVP unit performance was similar to the steady-state test COP even though the unit was cycling during the intermediate- and minimum- intervals. The HCVP COPs were about 7% and 11% different than the $H3_{Full}$ and $H1_{Low}$ steady-state values. However, the capacity difference at the 47°F (8.33℃) ambient condition was about 9%.



(A) **(B)**

Figure 10. Comparisons of Steady-State and CVP COP Values for Cooling of Test Unit B

DISCUSSION AND CONCLUSIONS

In this paper, two heat pumps were tested based on the CVP presented in AHRI 210/240-2024. Although both test units were able to meet the power criteria in cooling to be classified as variable-speed equipment, they were unable to meet the criteria in heating due to cycling behavior. As a result, the units would be classified as two-stage equipment leading to lower SEER and HSPF values. Furthermore, all presented tests failed to meet the full and minimum intervals capacity or efficiency requirements, 6% and 10%, as outlined by the DOE, meaning a potential reevaluation of the steady-state regulatory test results.

A number of issues were identified in the current CVP that should be addressed in future versions:

1) The current CVP fails to account for cycling behavior and does not include a procedure for the calculation of efficiency and capacity that is based on integrating performance over repeating cycles.
2) The current native controller placement on a piece of insulation less than 12 inches (30.5 cm) from the midpoint edge of the return duct is not sufficient for ensuring that the environment surrounding the native controller is within 1℉ (0.56℃) of the return entering air. Thus, the use of a Thermostat Environmental Emulator is recommended to ensure that these two temperatures are in close agreement at all times.
3) During the CCVP and HCVP testing of Test Unit B, the 83℉ (28.3℃) and 67℉ (19.4℃) return air temperature limits were found to be burdensome. The removal of these limits would permit a more realistic response from the controller and reduce the length of the tests.
4) In general, the use of instantaneous measurements for evaluation of some tolerance requirements was found to be challenging for the test unit considered in this study because of erratic controller behavior (including cycling behavior). Averaging or filtering of measurements over a short rolling window should be employed.
5) The variation of intermediate interval outdoor dry-bulb temperature as a mechanism for avoiding cheating is not thought to be adequate as there is no requirement for the unit capacity to match the load. In the current standard, the capacity in the intermediate region could be fixed at a low value that leads to the indoor dry-bulb temperature reaching the upper limit of 83℉ (28.3℃) with a capacity that is less than the load, leading to better performance. If this condition is maintained under steady-state conditions, the interval could be completed with the unit receiving variable-speed certification.
6) For the calculation of capacity range in determining the categorization of a unit as a two-stage or single-stage system, no clear equation is given. Additionally, the capacity variance requirement can result in a unit with two-stage behavior being categorized as a single-stage system and vise-versa.
7) There is a concern that the controller’s behavior may be influenced by the use of a CVP test load line that is based on the steady-state equipment tests. It was found that this CVP load line can be significantly different than the building load line used in evaluating seasonal efficiencies and may be unrepresentative of load versus ambient temperatures encountered by the equipment in the field.
8) There is a significant concern with test burden, as approximately 40 hours is required for the heating and cooling CVP tests if no transitional periods are repeated.

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