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Task 2.3: Title 24 Credit for Efficient Evaporative Cooling

Model Validation

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1 Document scope:

This document presents:

1. The method used to build characteristic performance curves from field measurements for the Coolerado H80.
2. Validation of these performance curves by comparison to field measurements.
3. Results from implementation of these curves in our Hybrid-Black-Box model (HBBM).

This document is intended to be read with a clear understanding of the preceding document Task 2.3: Title 24 Credit for Efficient Evaporative Cooling:Project Plan.

2 Methods

2.1 Method summary

We performed the validation of a functional EnergyPlus model for the Coolerado H80 in three steps.

First, we used field data from two separate installations of the Coolerado H80 to develop an empirical model of the performance for each major system component. The empirical formulae to describe each component were necessary because the field observations from the two sites did not span a comprehensive range of conditions and operating modes. Our previous attempt to build regression models directly from the field data failed because the resulting equations were not well constrained for operating scenarios that were not experience by in field operation.

Second, we use the empirical characterization for each component in a parameterized numerical model of the complete system to generate a partially synthetic set of performance data for each mode of operation over comprehensive range of operating and environmental conditions. We then used this partially synthetic data set develop the second order polynomial performance curves required to populate the HBBM.

Prior to testing the HBBM with these performance curves, we validated the empirical characterizations directly against measured field data by using the independent variable conditions observed to predict equipment performance. We then compared these predictions to measured performance values.

Last, we implemented the second order polynomial performance curves within the HBBM operating in EnergyPlus. Appropriate function of the HBBM was tested for a simple set of inputs, then the HBBM was used to predict equipment operation for the independent conditions that were observed during field evaluation, and predicted performance was compared against the performance measured in the same period. We compared the electricity use and delivered sensible cooling capacity predicted by the HBBM to the field data at identical environmental conditions.

2.2 Component-by-component empirical model for Coolerado H80

We developed a parameterized numerical model of the Coolerado H80 using empirical formulae to describe the performance of each component. This model was used to generate a comprehensive data set of performance by mode, which was subsequently used to generate polynomial curves for the HBBM.

We created our empirical model by separating performance data for the indirect evaporative cooler from data for the two stage compressor, and then by developing separate second order polynomial formula to describe the supply air temperature, supply air humidity and component power draw. These separate relations were then combined in a parameterized numerical model to estimate equipment performance for any desired scenario.

We used field data of the Coolerado H80 operating in an "*Indirect Evaporative Only*" cooling mode to develop the empirical model for the indirect evaporative heat exchanger. Mixed air conditions at the inlet of the heat exchanger, and supply airflow rate were used as the input variables for a polynomial formula to predict power draw for the fans, and product air conditions at the heat exchanger outlet. We developed these formulae using least squares regression.

We used field data from the Coolerado H80 with its compressor active to develop models of the vapor compression system in each stage of operation. Power draw and cooling performance for the vapor compression system was modeled as an independent component separate from the indirect evaporative heat exchanger, and separate from the system's fans. Independent curves were generated for stage one and stage two. The empirical model for the indirect evaporative heat exchanger was used to process the mixed air conditions and to estimate the input conditions seen at the inlet of the evaporator coil. The curve predictions for the power draw of the indirect evaporative cooler were subtracted from the measured power draw for the entire system in order to asses compressor power draw independently.

2.2.1 Development of Second-Order Performance Curves to define system for HBBM

The component-by-component model of the Coolerado H80 was used to generate performance data for the whole system across a wide range of possible operating conditions. This comprehensive matrix of performance data was used as input to a least squares regression to generate the second order polynomial curves required for definition of the system in the HBBM.

In this process, it was determined that the polynomial maps would provide a better data fit if they predicted supply air temperature and humidity instead of capacity and sensible heat ratio. It is generally more stable to predict fundamental characteristics of a system instead of calculated metrics (such as capacity and sensible heat ratio), which can be highly sensitive to small and large input values. Format of the HBBM inputs for system definition were adapted to suit this, and the HBBM was adapted to calculate the appropriate performance metrics (such as sensible room cooling capacity) from these new parameters instead of from the previous polynomial predictions.

Three curves that give the supply air temperature, the supply air relative humidity and the unit power consumption were generated for each of the three cooling modes for the Coolerado H80 (resulting in 9 curves in total). In order to allow for user scaling of nominal equipment capacity, the curves for power describe system power draw relative to nominal cooling capacity.

2.3 Validation of HBBM Predictions Compared to Field Measurements

We used the performance curves developed in section 2.2.1 and the appropriate nominal capacity to define a model configuration for the HBBM. We then used 300, 1 minute averaged, measured environmental conditions from field evaluation and measured cooling loads as inputs to our model to compare HBBM model predictions to behavior and performance for the real system.

2.4 Test of HBBM Model Operation within EnergyPlus Simulation

We then used the model to provide cooling to a single zone model in EnergyPlus to verify that the model selects an appropriate mode of operation for the cooling load conditions, and that cooling set points are met. We modeled high internal loads and ventilation rates based on California Title-24, using climate zone 15 weather file.

3 Results

3.1 Validation of Component-by-Component empirical model for Coolerado H80

Figure 1 through **Error! Reference source not found.** plot predictions of the component-by-component empirical model against the recorded field data at identical input conditions. Points that lie on the line passing through the origin with a slope of 1 indicate points where the model accurately predicts the system performance that is observed in the field. Points that lie far from this line indicate that some system performance characteristic(s) for the real system are not accurately captured by the model.

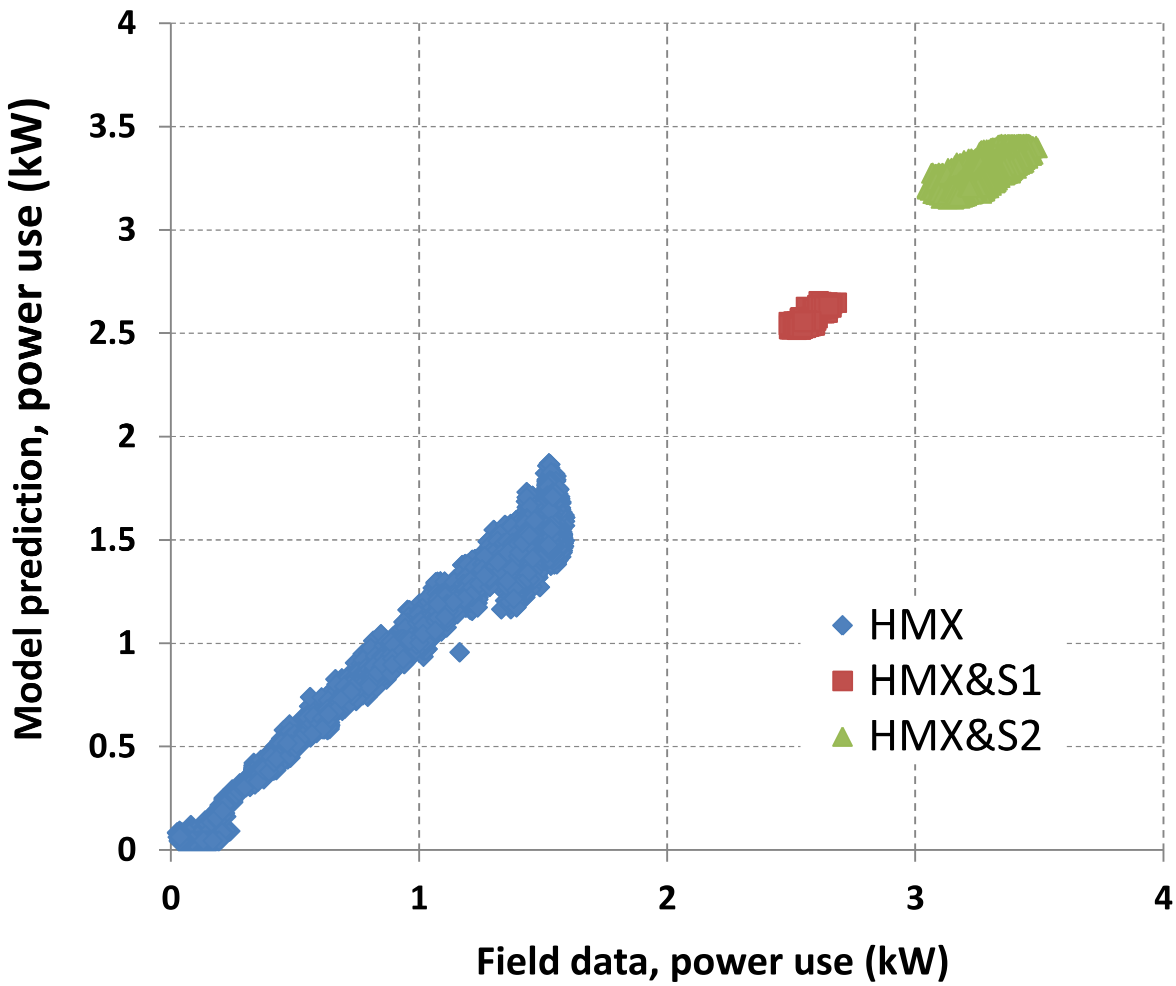

Figure 1 – Power consumption predicted by the component level model versus power consumption observed in the field

As shown in Figure 1 the component level model accurately predicts the system power consumption in all three modes.

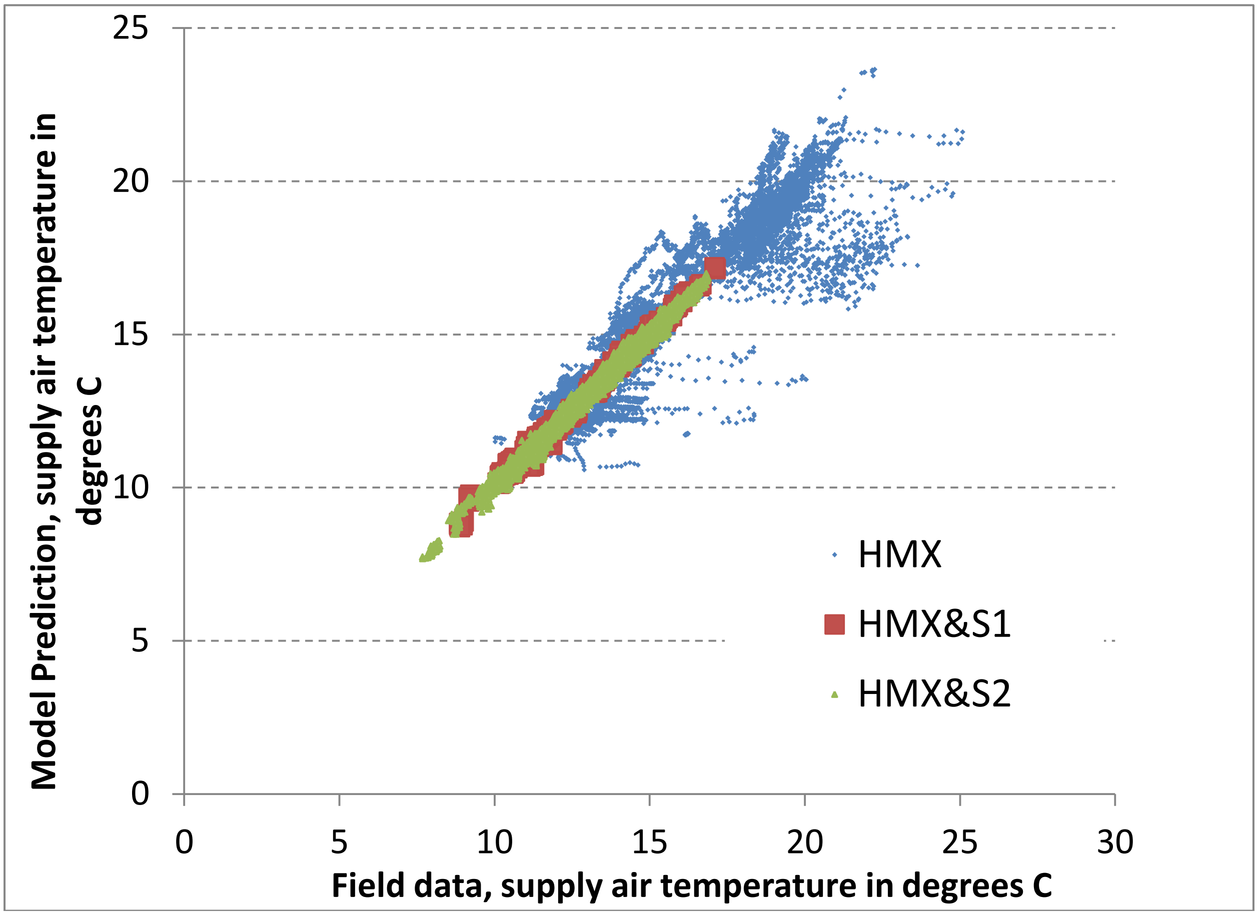

Figure 2 – Supply air temperature predicted by the component level model versus Supply air temperature observed in the field

Figure 2 shows that the empirical component-by-component model predicts the supply air temperature with a high degree of accuracy in HMX&S1 and HMX&S2 operating modes. However, there is some deviation for operation in the "*Indirect Evaporative Only*" mode. This was unexpected, because the component level approach uses the output of the indirect evaporative heat exchanger as input for the model to predict the input conditions to the Stage 1 and Stage 2 compressor models. Thus, any error inherent in the HMX model should propagate through to the stage 1 and stage 2 compressor models. This indicates that there exists a phenomenon, present when the HMX operates independently but absent when the compressors are operating, that is not being fully captured. These points account for a very small fraction of the measured minutes of operation; for now we have decided to proceed with the empirical formulae developed here, despite the minor intermittent disagreement with field data.

3.2 <u>Validation of Second-Order Performance Curves to define system for HBBM</u>

Figure 3 compares electricity demand in each operating mode predicted by the second-order performance curves to the measured observations at the same input conditions.

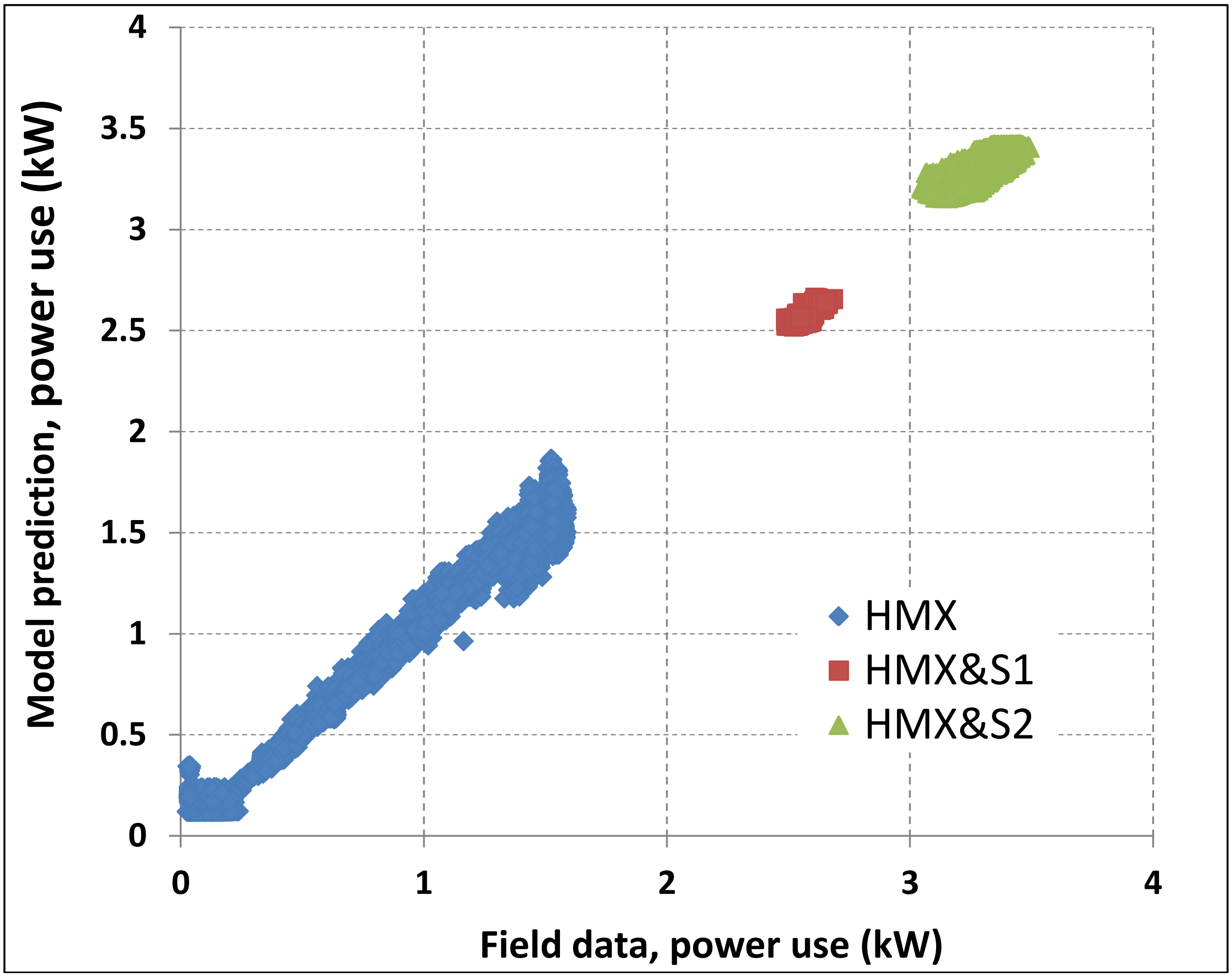

Figure 3 Comparison of second order polynomial model and field data

3.2.1 <u>Error analysis</u>

We performed error analysis to determine how well the model agreed with the measured field data. When the model is operating in HMX mode, the second order curve for the supply air temperature had a root mean error of 1.03 degrees C compared the average measured temperature of 15.5 degrees C. This analysis was repeated for each of the three curves and three operation modes, with the results given in Table 1.

Table 1 Root mean square errors

	Supply air temp. (°C)	Supply air HR (g/g)	Power (kW)
HMX	1.029	0.001	127.796
HMX&S1	1.854	0.003	20.716
HMX&S2	0.558	0.002	41.774

We also calculated the Pearson product-moment correlation between the measured and modeled predictions for the three curves and three operation modes given in Table 2.

Table 2 Pearson product-moment correlation coefficient

	Supply air temp. (°C)	Supply air W (g/g)	Power (kW)
HMX	0.868	0.677	0.985
HMX&S1	0.662	0.349	0.749
HMX&S2	0.915	0.377	0.713

Validation of HBBM

Figure 4 gives the predicted and measured sensible cooling capacity for 300 sample data points. Points that lie closer to the ideal model line represent more accurate predictions.

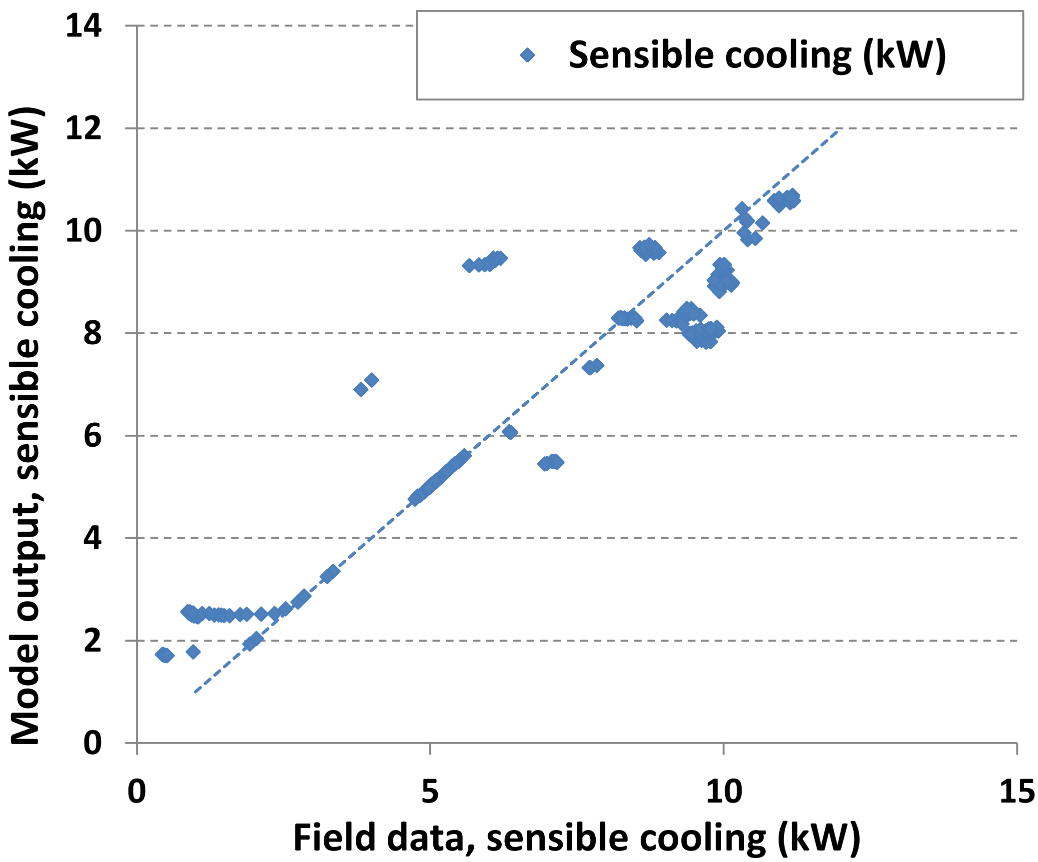

Figure 4 Comparison of modeled and predicted sensible capacity

For 70% of the time HBBM predicted the same mode of operation that was observed for equipment operation in the field. The modeled sensible cooling and power consumption are highly dependent on which mode of operation the model chooses. On average our model predicted a 13% lower delivered sensible cooling capacity, and14% higher electricity use than the real system. On average mass flow rates were predicted to be 11% lower than observed.

Disparities at this stage are believed to result from three main factors. First, the model is not designed to mimic the exact control logic for the Coolerado. Instead, the HBBM chooses the mode and functional operating conditions that will meet the sensible room cooling load and ventilation requirements with the smallest energy input. Second, the inputs fed to our model are averages rather than the real time environmental conditions that were experienced by the system observed. Finally, the model deliberately does not assess transient effects that occur when the equipment switches from one operating mode to another. These effects can include sensible cooling effects from water evaporation off of the DX evaporator coil after a compressor shuts off, or dynamic behaviors associated with “warm-up” of system components.

We anticipate that more detailed analysis will lead to incremental improvements in the model implimentation.

3.3 Validation of an EnergyPlus Simulation

Figure 5 shows the indoor temperature of our test single zone model rising when the cooling model is off up to 9 in the morning. When the cooling model activates, indoor temperatures are shown to fall to below the cooling set point of 25 degrees C. As the daytime outdoor temperatures rise to a peak of 46 degrees, cooling loads increase, and the cooling model is shown to step up from mode 1(HMX only) up to mode 2 (HMX with single stage cooling), and then finally up to mode 3 (HMX with stage 2 cooling).

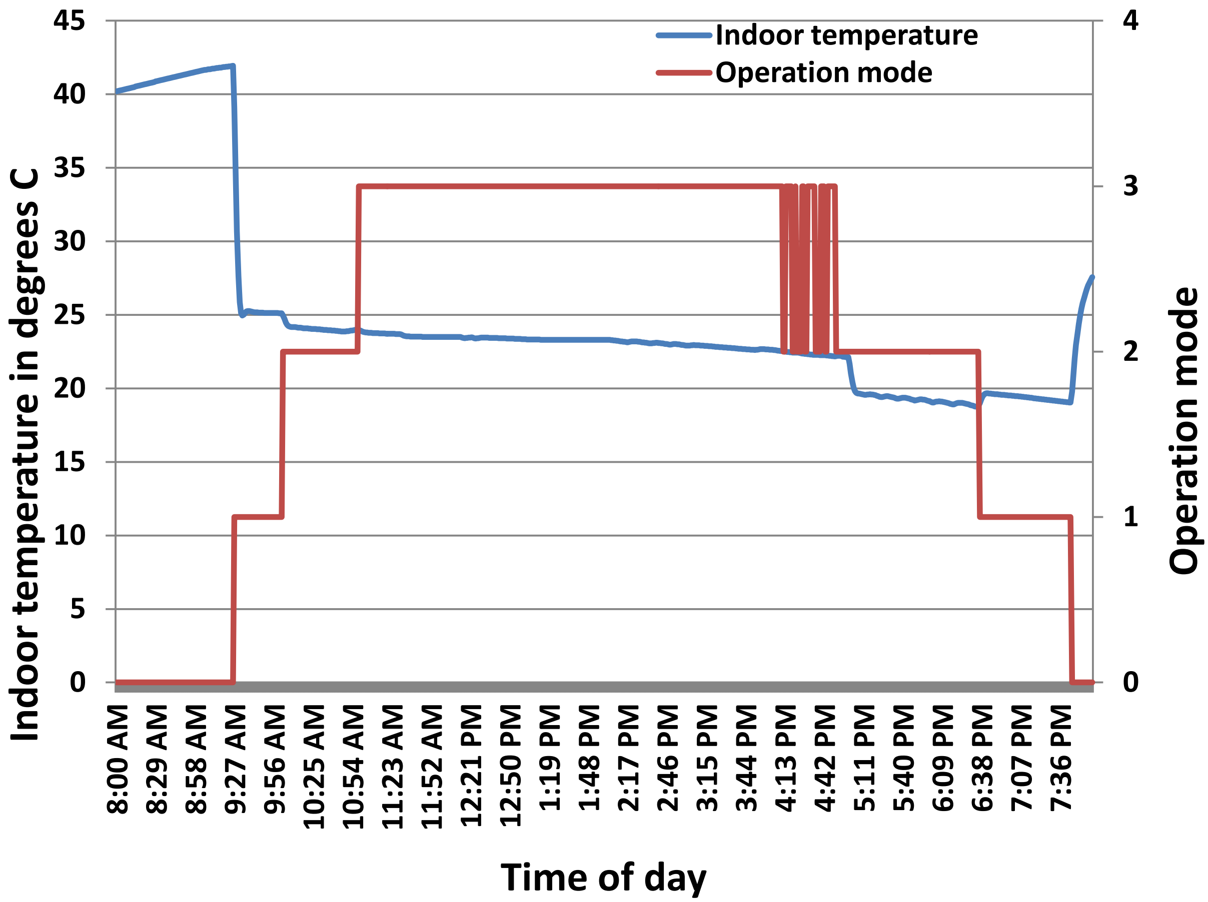

Figure 5 Indoor temperature and operation mode of the Coolerado H80 model.

This initial testing has highlighted some control issues that will need to be addressed. Towards the end of the day the model was shown to flutter between modes. This was considered a likely issue during the design of the model, and we will likely use a delay in the mode control to prevent the model from changing modes too rapidly. For this initial test, the HBBM also predicts a pattern of behavior that causes cooling well below the set point throughout the day.

4 Conclusions

The second order performance curves developed for the Coolerado H80 compared well with the field data. A comparison of the predicted and measured performance characteristics found average correlations of 0.81 for supply air temperature, 0.47 for supply air humidity and 0.82 for power draw. These figures verify that the second order curves used to define our Coolerado H80 model are sufficiently accurate. It should be reiterated that our objective in developing the Coolerdo model is for the purpose of testing the HBBM framework, and that the accuracy of this Coolerado model is only significant in that it provides us with a realistic test model to verify that the HBBM functions as intended.

When these curves are used within the HBBM framework and tested using input data from our field study, the model predicted mode selection and delivery of sensible cooling to an acceptable level of accuracy. We believe that significant improvements can be made for the HBBM by tuning variables such as timing within the logic and minimum runtime for each mode.

We also stress tested the model in our EnergyPlus implementation. For a simple single zone EnergyPlus building model, our Coolerado H80 model delivered sufficient cooling to meet the cooling load requirements of the space. This demonstrates that the HBBM functions within in EnergyPlus, although some control issues were identified in testing that we will be addressed before release of the model.

Further analysis of these results will be performed, the model operation will be further improved, and documentation will be developed in order to allow others to use the model.