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Development and Validation of a Simulation Testbed for the Intelligent Building Agents Laboratory (IBAL) using TRNSYS

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ABSTRACT

This paper documents the development and validation of a dynamic primary cooling and thermal storage system simulation testbed. The system simulation testbed, sIBAL, is based on the Intelligent Building Agents Laboratory (IBAL) at the National Institute of Standards and Technology (NIST), which is a research infrastructure and testbed for the development, evaluation, and demonstration of intelligent control algorithms. The sIBAL testbed developed in this project will serve as a virtual twin of the real facility for future control algorithm development.

The details of the methodologies used to develop and validate the simulation testbed, which replicates the dynamic behaviors of the primary cooling and ice storage system in the IBAL facility, are presented. The simulation testbed was developed in TRNSYS using built-in component models and MATLAB functions to replicate the two water-cooled chillers, a thermal storage tank, pumps, valves and other components for four different operation modes. Experiments on IBAL components were designed and executed to generate experimental data for model development and verification of the simulation platform.

The validation of the simulation results was carried out in two phases: 1) independent component simulations for the chillers and thermal storage tank, and 2) a combined testbed simulation of the entire hydronic system. Comparison of simulation results to the experimental data obtained from the IBAL facility showed errors within 1 °C for the temperatures outputs of both the chiller and the thermal storage model. The error is within an acceptable range for further intelligent control algorithms development. The findings from the study are summarized and presented along with areas where additional research is needed. In addition, data filtering procedures and model refinement measures utilized to improve the accuracy and accelerate the computation time of the simulation are presented.

INTRODUCTION

The Intelligent Building Agents Laboratory (IBAL) has been constructed at the National Institute of Standards and Technology (NIST) as a research infrastructure and testbed for the development, evaluation, and demonstration of intelligent control algorithms for commercial heating, ventilating, and air conditioning (HVAC) equipment. However, before control algorithms are evaluated using the IBAL facility, it is important to first evaluate them using a simulated testbed to save time and cost. In this project, a simulated IBAL testbed (sIBAL) for the primary cooling system is

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Certain commercial equipment, instruments, or materials are identified in this paper in order to specify the experimental procedure adequately. Such identification is not intended to imply recommendation or endorsement by the National Institute of Standards and Technology, nor is it intended to imply that the materials or equipment identified are necessarily the best available for the purpose.

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developed that is: 1) able to accurately simulate the dynamic behaviors of the IBAL testbed hydronic loop components; and 2) easy for a third-party to use to evaluate their control algorithms. Experimental data from the IBAL facility are used to test and validate the proposed sIBAL.

IBAL Description

The hydronic system in the IBAL consists of two water-cooled chillers, one thermal storage tank (TS) and three heat exchangers. The system is comprised of three main loops: the condensing loop, the primary loop and the secondary loop. Figure 1 depicts the water loop components and their connections in the IBAL (Pertzborn 2015).

This project focuses on the primary loop, which includes Chiller 1, Chiller 2 and the water side economizer heat exchanger (WSE – labeled HX3 in the figure) connected in parallel, and a thermal ice storage tank connected in series. Each chiller and the WSE have dedicated pumps that typically operate at a single speed, but can operate as variable speed via a variable frequency drive (VFD). When the thermal storage tank is not in use, it can be bypassed by closing a control valve. The primary loop produces the cold fluid, a 30 % propylene glycol (PG) solution, in order to the meet the building load in the secondary loop. The chillers are water-cooled process chillers with scroll compressors that use refrigerant R-410A. Chiller 1 has a nominal cooling capacity of 26.4 kW (7.5 tons) and Chiller 2 has a nominal cooling capacity of 36.1 kW (10.2 tons). The thermal storage tank is an ice-on-coil design. It is specified to discharge 274 kWh (78 ton-hours) of ice over an eight-hour period with an inlet temperature of 10 °C (50 °F). The tank contains 3105 L of water (820 gallons) and is located outside of the building in which the IBAL is located. The model developed only considers the two chillers and the thermal storage tank; a Hydronic Load is used in place of the secondary loop as described later.

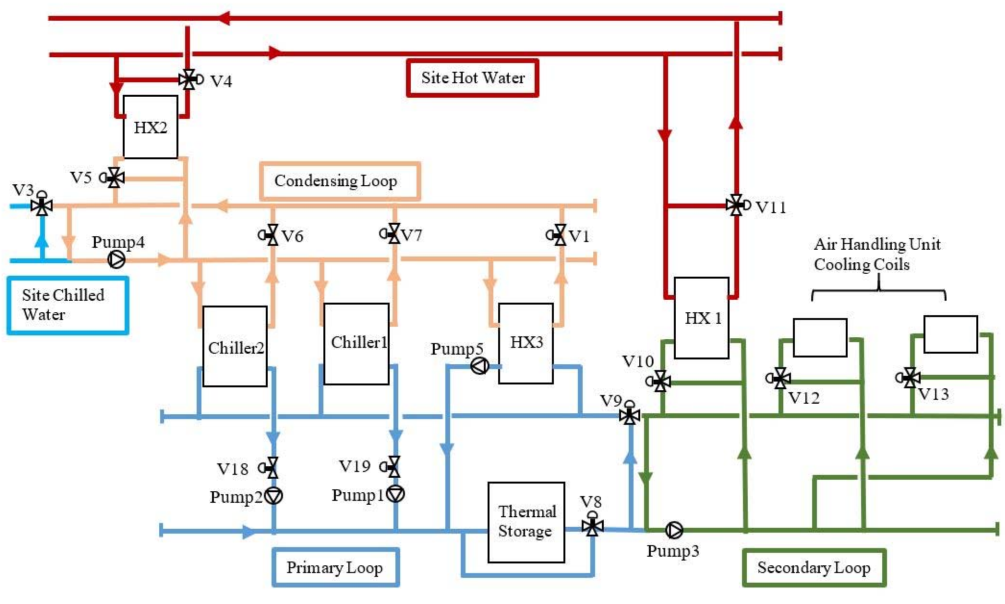

Figure 1: Schematic of the IBAL Hydronic System (Pertzborn 2015)

There are two chiller operation modes in the IBAL:

- Normal Operation: In this mode, the chiller is used as the cooling source to remove heat from a simulated building via the cooling coils in the air handling unit. In this mode the thermal storage tank can operate in discharge mode (Discharging) to meet the cooling load along with the chiller, or it can be bypassed with only the chiller used to meet the cooling load. (Note: the thermal storage tank can also be used to meet the cooling load by itself)

- Charging: The chiller is used to generate ice for the thermal storage tank in this operation mode. The thermal storage tank can be charged using either of the two chillers. In a real building, charging is usually performed during off-peak hours. There is no flow into the secondary loop when the chillers are operating in the charging mode.

SIMULATION PLATFORM DEVELOPMENT

This section describes the development of component models, data connection components and the user interface in the simulation testbed. The TRNSYS (Solar Energy Laboratory 2009) component types used for each of the models are also provided in this section.

Chiller Models

The chiller performance is different in each operating mode with respect to the chilled water outlet temperature, coefficient of performance (COP) and cooling capacity. As a result, for each chiller, two models are built for each mode in the simulation testbed, resulting in the four chiller models shown in Figure 2. Type 53 (Parallel Chiller) and Type 666 (Water-Cooled Chiller) are selected from TRNSYS's standard library to simulate Charging and Normal Operation, respectively. The two chiller models have very similar inputs and outputs as summarized here:

Inputs:
- Chilled water setpoint temperature
- Chilled water inlet temperature
- Chilled water inlet flowrate
- Cooling water inlet temperature
- Cooling water inlet flowrate

Outputs:
- Chilled water outlet temperature
- Chilled water outlet flowrate
- Cooling water outlet temperature
- Cooling water outlet flowrate
- Total chiller power
- Coefficient of Performance (COP)

For Normal Operation, Type 666 is selected as the chiller component because Normal Operation requires a detailed model with part load ratio and Type 666 satisfies this requirement. However, for Charging, the chiller operates at a very stable condition since the cooling load barely changes during the ice making process. Hence, the simplified Type 53 is suitable for describing the performance of Charging, making the modeling process very cost-effective.

Both Type 666 and Type 53 require external files that define the chiller performance curve and part-load performance curve. These performance curve data are derived from real chiller operation data obtained from experiments carried out at the IBAL facility.

Thermal Storage Tank Model

In this study, the grey-box model developed in ASHRAE research project RP-1313 is selected for the thermal storage tank discharging mode (Henze 2005, Henze 2007). This model is experimentally validated, provides an open source code, and has been adopted by other energy analysis software such as EnergyPlus. Multivariate linear regression is used on the experimentally collected data to estimate the constant parameters used in this model.

An unpublished model provided by NIST is used for the charging mode of the thermal storage tank. This model assumes a constant charge rate, which was determined through experiments in the IBAL facility. Water temperature stratification is not accounted for in the thermal storage tank models.

Both models are coded in the MATLAB environment and are called by TRNSYS through Type 155: Calling MATLAB. Based on the operation mode of the thermal storage tank, the MATLAB script calculates the temperature of the chilled water at the outlet of the thermal storage tank and the ice inventory as a percentage. TRNSYS provides the inputs to Type 155 and once the calculations are performed the outputs are passed back to TRNSYS. The inputs and outputs for Type 155 are summarized here.

Inputs:

- Thermal storage tank inlet water temperature
- Flow rate through the thermal storage tank
- Ice inventory at the start of each time step
- Specific heat of the fluid
- Operation modes as defined by the user

Outputs:

- Thermal storage tank outlet water temperature
- Flow rate through the thermal storage tank
- Ice inventory at the end of each time step

Additional Components Models

The simulation testbed also utilized the following hydronic components from the TRNSYS library to complete the primary loop: Type 3: Variable Speed Pump, Type 11d: Controlled Flow Mixer, Type 11f: Controlled Flow Diverter, and Type 31: Pipe Duct. Furthermore, since this project only focuses on developing simulation models for the primary cooling sub-system, a user-defined Hydronic Load model is used to simulate the chilled water inlet temperature for a chiller in the IBAL.

Overall Testbed

Using the TRNSYS component models presented earlier in the section, the simulation testbed shown in Figure 2 is constructed based on the schematics of the hydronic system in the IBAL. The testbed consisted of four chiller models (two Type 666 chillers for Discharging/Normal Operation, and two Type 53 chillers for Charging) and one thermal storage model that is connected to MATLAB. Two submodules, shown at the far left of the figure, are created to include the user defined inputs and experimental inputs required for the simulation. Type 9 data readers are used in both the submodules to input data from an external text file saved within the working directory.

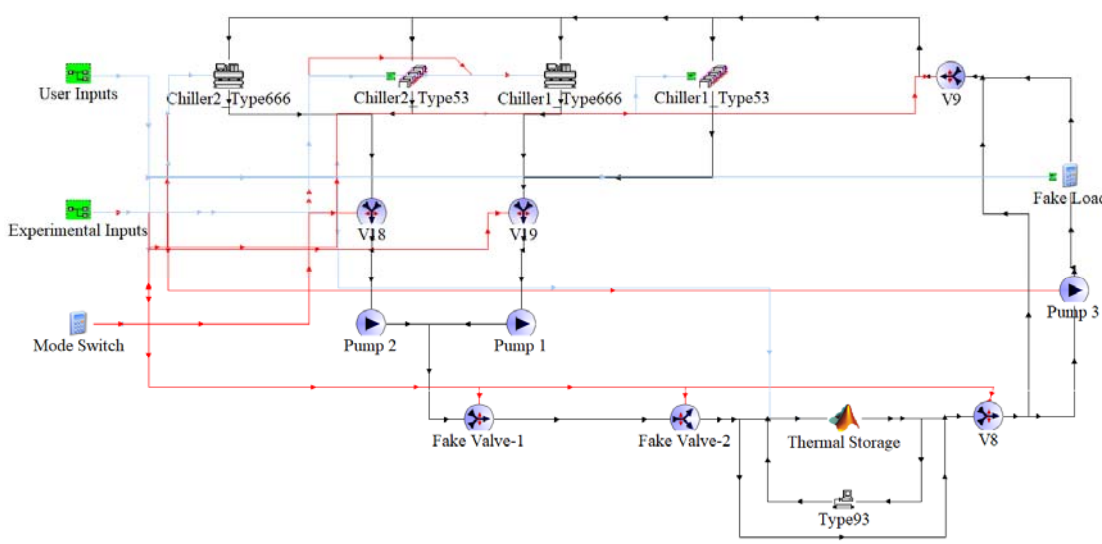

Figure 2: Simulation Testbed

EXPERIMENTAL DESIGN

This section presents the experiments that have been designed and conducted in the IBAL to generate operation data to determine the chiller performance curves and thermal storage tank parameters required in the simulation testbed.

Chiller Experiment Design

The objective of the chiller experiments is to generate chiller operation data that define the COP as a function of part load ratio (PLR) and outdoor conditions (shown by the cooling water inlet temperature). In summary, the chiller water outlet temperature setpoint, cooling water inlet temperature, and V11 (refer to Valve 11 in Figure 1) position are systematically varied following the factorial design method to vary PLR and outdoor conditions. Table 1 provides the setpoint values. The exact voltage signal and the resulting valve position for V11 are also listed in the table (note: the position of V11 determines the load met by the chillers).

Table 1: Design of Experiment for Chiller Normal Operation Mode at IBAL

Duration (hour)	Chiller Water Outlet Temperature Setpoint (°C)/(°F)	Cooling Water Inlet Temperature (°C)/(°F)	Aiming V11 Position (Open)	V11 (V)
1	4.4/40	26.7/80	~60 %	3.1
2	15.6/60			
4	10/50	21.1/70	~60 %	3.1
5		32.8/91		
7	10/50	26.7/80	~20 %	1.8
8			~100 %	4.4

Thermal Storage Tank Experiment Design

Since the thermal storage tank model is a grey-box model, the parameters of the model are calculated from thermal storage tank data from the IBAL. For the Discharging mode, six linear regression constants are required to define the model (Henze 2007), and, for Charging, the ice charging rates for the chillers are determined from experimental data.

For Discharging, three sets of experiments were designed to estimate the constant parameters. In each group of experiments, ice is discharged from approximately 100 % to approximately 0 % to ensure sufficient variation in the ice inventory for the development of the model. The inlet water temperature is varied from 7.2 °C to 15.6 °C (45 °F to 60 °F) to ensure the model experiences enough variation. For all the test cases, the flow rate is maintained constant. Table 2 shows the design of experiment for Discharging.

Table 2: Design of Experiment for Thermal Storage Tank Discharging Mode

Experiment	Inlet water temperature of ice storage tank (°C) /(°F)	Flow rate of ice storage tank (m^3/h)
1	~7.2/45	~3.4
2	~11.7/53	~3.4
3	~15.6/60	~3.4

For Charging, the thermal storage tank was charged using both chillers for different charge durations to determine the charging rates. Table 3 shows the design of experiment for Charging. Experiments 1 and 2 were carried out using Chiller 2 and experiment 3 was carried out using Chiller 1. In the following figures, the spikes in the data indicate the transition from one experiment to the next.

Table 3: Design of Experiment for Thermal Storage Tank Charging Mode

Experiment	Charge Duration (s)	Starting Ice Mass (%)	Ending Ice Mass (%)	TS Flowrate (m^3/h)	TS Cooling Demand (kW)	Chiller Flowrate (m^3/h)	Chiller Cooling Capacity (kW)	Chiller Power (kW)
1	45250	5.20	92.9	5.5	13.9	4	19.8	11.2
2	34460	2.60	92.2	3.7	16.3	5.1	21.5	11.1
3	18420	15.2	43.5	3.2	13.9	4.8	18.7	7.8

TESTBED EVALUATION

Using the data obtained from the experiments described previously, the chiller and thermal storage models are simulated independently. The results from these independent simulations are then used to test the simulation results from the combined testbed to ensure there are no connection errors in the final system (results not show here).

The simulation results mostly agree with the experimental data as quantified in Tables 4 and 5. The tables summarize the root-mean-square (RMS) error between the simulation and experiment for the chiller and thermal storage tank, respectively. The dynamic behavior of the component models captured by the simulation testbed can be observed in the figures presented in this section.

Table 4: RMS Error for Chiller Outputs

Parameter	Charging Chiller 1	Charging Chiller 2	Normal Operation Chiller 1	Normal Operation Chiller 2
Cooling Water Outlet Temperature (°C)	0.43	0.98	1.08	2.95
Chilled Water Outlet Temperature (°C)	0.38	0.86	1.83	2.53
Chiller Power (kW)	0.13	0.24	0.16	0.23

Table 5: RMS Error for Thermal Storage Tank Outputs

Parameter	Charging Chiller 1	Charging Chiller 2	Discharging
Ice Inventory (%)	2.70	15.42	0.032
TS Tank Outlet Temperature (°C)	0.70	0.91	0.57

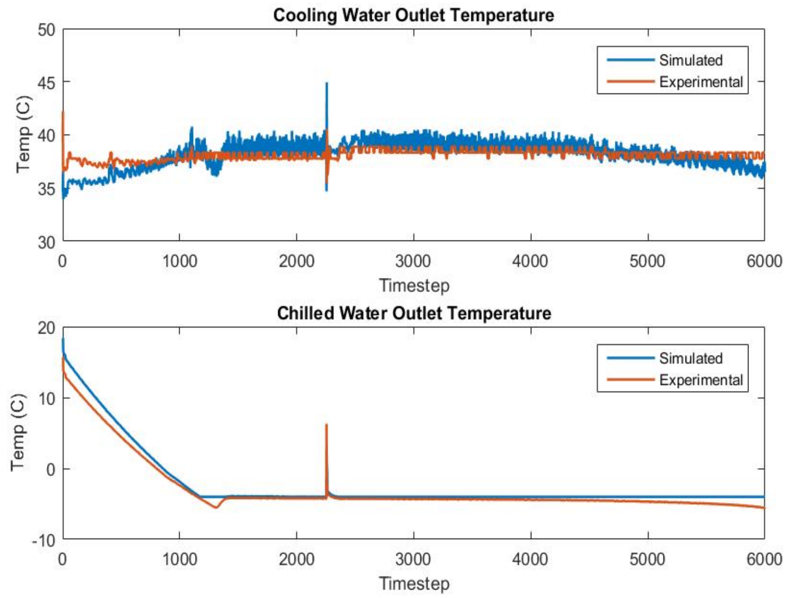

Figure 3: Chiller Outputs for Charging using Chiller 2

For Charging with Chiller 2, in Table 5, the thermal storage tank model is unable to match the experimental results at the start of the charging period (refer to Figure 5). During the experiment, for the first ~1200 timesteps, the thermal storage inlet temperature is too high for ice generation and only after the chilled water temperature coming into the thermal storage tank is less than 0 °C does ice generation begin. However, in the simulation model, this behavior was not modeled. The difference at the beginning of the charging phase causes the simulated value to be higher than the experimental value at the time when ice generation begins (at timestep 1200, the simulated value is ~25 % and the experimental value is ~15 %), leading to discrepancy throughout the process. Hence, the RMS error is high for this test run.

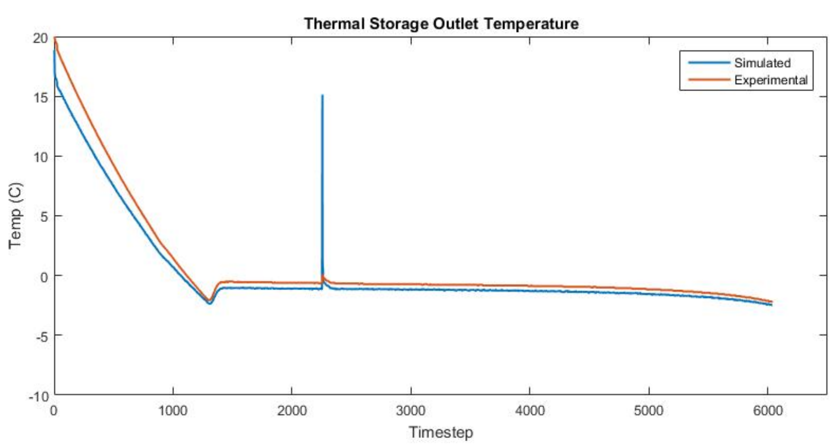

Figure 4: Thermal Storage Outlet Temperature for Charging using Chiller 2

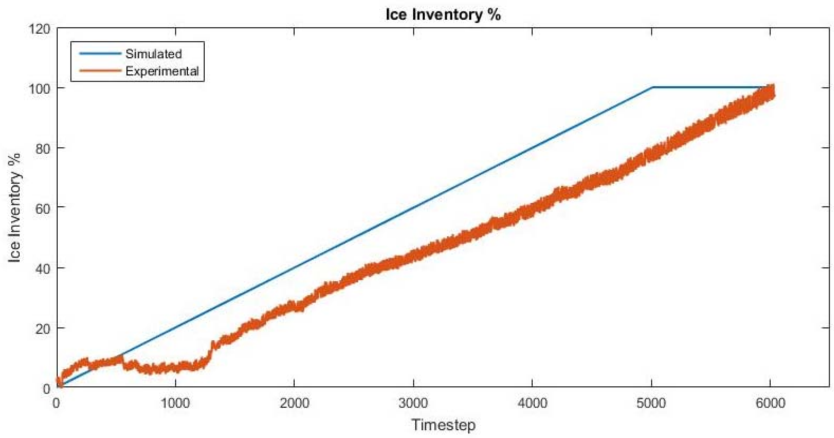

Figure 5: Ice Inventory Percentage for Charging using Chiller 2

Figures 6 and 7 present the thermal storage tank outputs for Discharging. The simulation was run for three separate tests. The thermal storage tank model showed high accuracy when compared to the experimental data (refer to Table 5 for calculated errors).

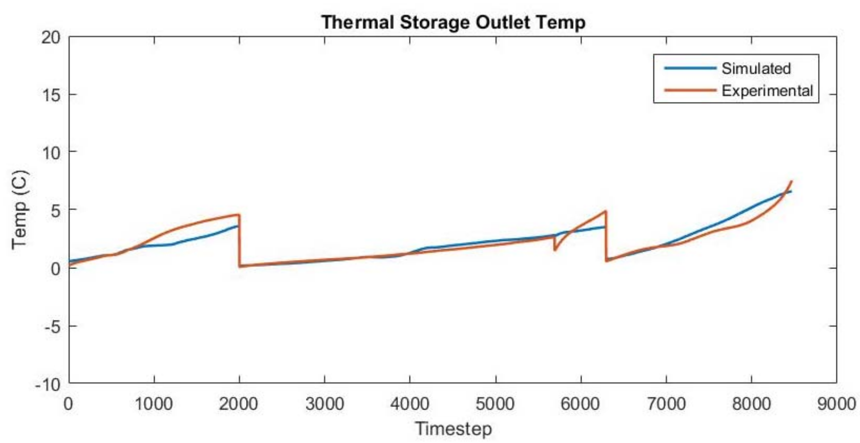

Figure 6: Thermal Storage Outlet Temperature for Discharging

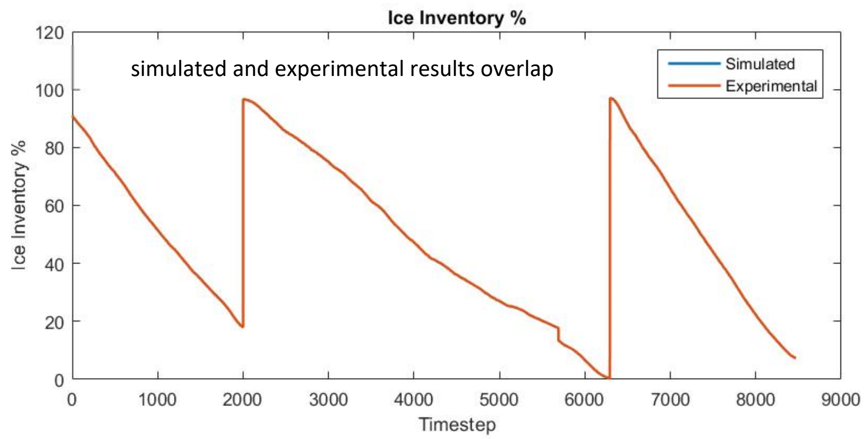

Figure 7: Ice Inventory Percentage for Discharging

CONCLUSION

Overall, the simulation testbed showed good agreement with the experimental data in different operation modes. The presented model is to be used for further intelligent control algorithm deployment at the IBAL facility.

One possible improvement that can be made to the testbed is to include a deadband for the thermal storage tank ice inventory during charging mode to account for the initial time required for the ice generation to start. Training the chiller model with additional operation data for a wide temperature range would also help improve the chiller accuracy.

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