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MODELICA MODELS FOR DATA CENTER COOLING SYSTEMS

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ABSTRACT

This paper presents a package of Modelica models, which are dedicated to data center cooling systems and recently added to the Modelica Buildings library. To demonstrate the usage of this package, we modeled a chilled water system with an integrated wateside economizer, and an air-cooled direct expansion system with an airside economizer. These models are then applied to evaluate the control performance. After that we performed a detailed comparison in terms of system-level energy efficiency, economizing hours and supply air conditions for the two cooling systems. The advantages and disadvantages of this package are finally summarized and discussed.

INTRODUCTION

Data centers in the US consume about 2% of the nation's electricity and approximately half of that is used for data center cooling. Simulation can be an effective way to assist the design and operation of data centers. Many tools have been developed in academia and industry to perform computer simulation of cooling systems in data centers. For example, eQuest (Lee and Chen 2013), EnergyPlus (Ham and Jeong 2016), TRNSYS (Agrawal, Khichar et al. 2016), and some customized simulation tool such as Energy Modeling Protocol (Shehabi, Horvath et al. 2008) have been widely used to study the cooling systems with waterside economizers (WSEs) and airside economizers (ASEs) in data centers.

The abovementioned tools utilize imperative programming languages such as FORTRAN, C/C++, which makes the tools less extensible. In such programs, models usually tightly couple physical equations, input/output routines with numerical solution methods, by making the numerical solution procedure part of the actual model equations (Wetter 2009). This intertwinement makes it difficult to extend these programs to support various use cases (Wetter, Bonvini et al. 2016), co-simulations with each other (Radosevic, Hensen et al. 2006, Trcka, Wetter et al. 2007) and effective optimization (Wetter 2009). What's more, some energy simulation tools are not suitable for evaluating the system dynamics and the semantics of their control has little in common of how actual control works. For example, in EnergyPlus, the commonly used PI control loop is assumed to be ideal, i.e., there will be no overshoot (Wetter 2011). EnergyPlus also idealizes dead band or waiting time, which are frequently used in the building control process. Moreover, many equipment models have built-in idealized control that requests flow rates, and flow rates are ideally distributed within a system rather than the results of friction-based flow distribution for a given valve or pump control signal. This makes it difficult to model, test and verify actual control.

To address these problems, the equation-based language Modelica can be used to model and simulate the system, instead of imperative programming language such as C/C++. Details about Modelica and how it can benefit system modeling and optimization can be found in previous publications (Fritzson 2014, Wetter, Bonvini et al. 2016).

The Modelica Buildings library (MBL) has been developed by Lawrence Berkeley National Laboratory to support various use cases regarding to HVAC systems in buildings (Wetter, Zuo et al. 2014). MBL is an open-source, free library with component and system models for building energy and control systems. Besides the conventional energy analysis, this library can also provide support for rapid prototyping (Wetter 2010), modeling of arbitrary HVAC system topologies (Wetter 2010), evaluation of the stabilization of feedback control and Fault Detection and Diagnostics at the whole building system level (Wetter 2009, Lee, Lee et al. 2015). It can also be used in the design and operation of cooling systems for data centers (Wetter, Zuo et al. 2014).

However, MBL still needs to be extended to support fast modeling of the cooling systems for data center applications, although it includes the major component models such as chiller, heat exchanger, and cooling tower. For example, when users want to evaluate different configurations of the chilled water system with WSEs for the data center during the design phase, they need to assemble all the components into the studied configuration one by one. When the number of the configurations is large, the modeling processing could be time consuming.

In this paper, we implement a package in the MBL to support fast modeling of commonly-used cooling systems in data centers. To introduce this package, we first give a brief description of the configurations of the commonly-used cooling systems in data centers. In Section 3, we give an introduction to the data center package. We also compare the energy efficiency and control performances of two different cooling systems: the chilled water system with an integrated WSE, and the direct expansion (DX) system with an ASE in Section 4. In the end, the advantages and disadvantages are discussed.

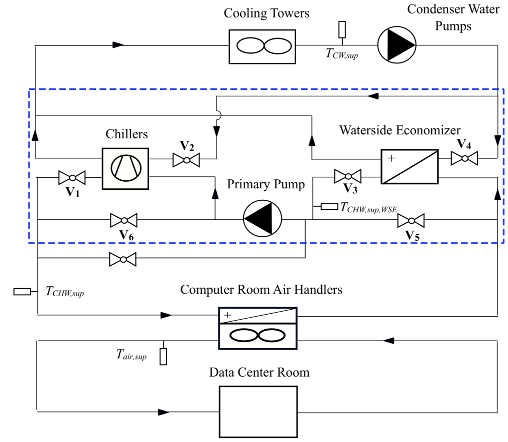
TWO COMMONLY-USED COOLING SYSTEM FOR DATA CENTERS

Chilled Water System with WSEs

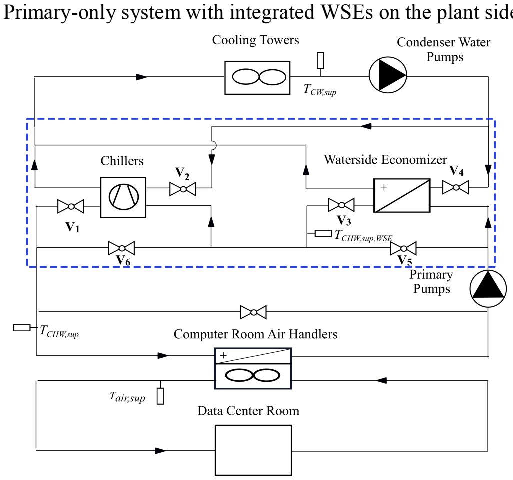
A commonly-used cooling system in data centers is the chilled water system with differently configured WSEs. The WSE can be integrated, meaning the economizer can meet all or some of the load while the chiller meets the rest of the load, or nonintegrated, meaning the economizer can only operate when it can meet the entire load. A brief survey shows that the chiller plant with WSEs usually have the following configurations: integrated WSEs on the load side of the common leg in a primary-only chilled water system (Figure 1(a)), integrated WSEs on the plant side of the common leg in a primary-only chilled water system (Figure 1(b)), integrated WSEs on the load side of the common leg in a primary-secondary chilled water system (Figure 1(c)), and nonintegrated WSEs (Figure 1(d)) that can be installed in both a primary-only and a primary-secondary system.

Figure 1(a) shows an integrated WSE in a primary-only chilled water system, where the WSE is in series with the

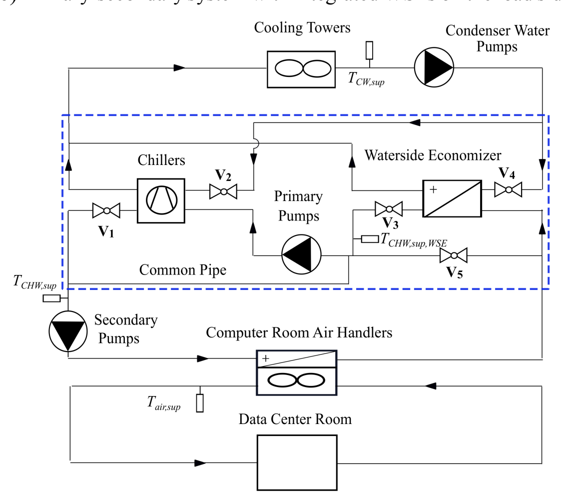
(a) Primary-only system with integrated WSEs on the load side



(b) Primary-only system with integrated WSEs on the plant side



(c) Primary-secondary system with integrated WSEs on the load side



(d) Primary-secondary system with nonintegrated WSEs

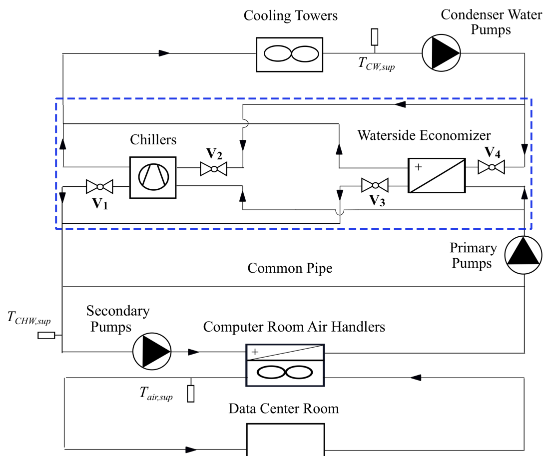


Figure 1. Chiller plant with WSEs

chillers on the chilled water return side and in parallel with the chillers on the condenser water side. The WSE is located on the load side of the common leg, which allows the WSE to see the warmest return chilled water from the Computer Room Air Handlers (CRAHs) and thus maximizes the hours when the WSE can operate. This is also the reason why the WSE on the load side is more efficient than that on the plant side (Figure 1(b)).

Figure 1(d) shows a primary-secondary system with a nonintgrated WSE. The WSE is in parallel with chillers on both the chilled and condenser water side. The nonintegtrated WSE should be shut off if it cannot meet the entire cooling load. Otherwise, when the chillers and nonintegrated WSE work simultaneously, the supply chilled water will be a blend of the cold water leaving the evaporators and the relatively warm water leaving the WSEs, and possibly exceed the chilled water temperature setpoint.

DX System with ASEs

A typical configuration of a DX system with an air-cooled Computer Room Air Conditioner (CRAC) and an ASE is shown in Figure 2. The data center room can be cooled by the ASE, or the air-cooled CRAC or both of them. The transition among three cooling states is achieved by regulating the dampers D1 ~ D4. For instance, when only the ASE is needed for cooling, the damper D4 is fully opened and the air-cooled CRAC is switched off. The supply air temperature is maintained by adjusting the damper D1 ~ D3. When both the ASE and the CRAC are needed for cooling, the damper D1 and D3 is fully open and the CRAC is switched on, while the damper D2 and D4 are fully closed. When only the CRAC is needed, the damper D2 is fully open and the CRAC is switched on, while the damper D1, D3 and D4 are fully closed.

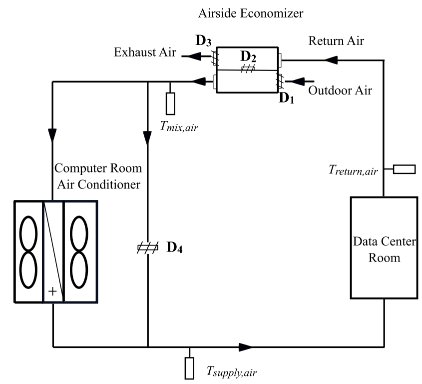


Figure 2. Air-cooled DX system with an ASE

DATA CENTER PACKAGE IN MODELICA BUILDINGS LIBRARY

The data center package is released in the MBL 5.0.0., and contains component models for the abovementioned two commonly-used cooling systems in data centers. This package has the same class hierarchy as the MBL, and contains various reusable base classes. These base classes together with the inheritance and instantiation in the object-oriented modeling language Modelica facilitate modeling and simulation of data center cooling systems.

Chilled Water System with WSEs

General Description

A group of identical chillers and pumps can be modeled by vectorising existing chiller and pump models respectively. The vectorized equipment model is assigned with the same design parameters but different performance curves if needed. The pseudo-code of vectorization of chillers in Modelica is shown in Figure 3. First, a partial class of the chiller model is instantiated through vectorization with a number *n* by specifying the length of the array *chiller*, which can be redeclared with a detailed chiller model later. Line 3 specifies the medium used in the chillers. Line 4 defines the identical design parameters for the identical chillers with the keyword “each” in Modelica, such as the design capacity. Line 5 defines the performance curves of each chiller by obtaining different curves from a performance curve array. The same instantiation method is also used to model a group of pumps. In addition, we add isolation valves in the vectorized models to avoid circulating flow among components.

The CRAH model is created using existing component models in the MBL with control logics added. The CRAH consists of a cooling coil model, an electric reheater model, a steam humidifier model, and a variable speed fan model. The control logic is designed to avoid simultaneously heating and cooling in the CRAH.

```
replaceable Fluid.Chillers.BaseClasses.PartialElectric chiller[n]
constrainedby  Fluid.Chillers.BaseClasses.PartialElectric(
   redeclare each final replaceable package Medium = Medium,
   each final parameters = parameters,
   final performanceCurve = performanceCurveArray)
"Identical chillers";
```

Figure 3 Pseudo-code of vectorization of chillers in Modelica

The WSE model is built on a heat exchanger model with constant effectiveness, and a three-way valve model. The three-way valve is on the chilled water side, and can be adjusted to control the chilled water supply temperature by a built-in PI(D) controller. The three-way valve and the PI(D) controller can be activated or deactivated based on user's needs. For example, if the chilled water supply temperature at the downstream of the WSE is controlled by regulating the speed of cooling tower fans in free cooling, then the three-way valve and the built-in PI(D) controller should be deactivated. The switch between activation and deactivation is implemented using a Boolean parameter.

Detailed Models: WSE Configurations

This package implements four different configurations of a chiller plant with WSEs, whose schematic drawings are shown in the dashed boxes in Figure 1.

The chiller plant with integrated WSEs (Figure 1(a)~(c)) can operate in three modes: Free Cooling (FC) mode when only WSEs are enabled for cooling, Partial Mechanical Cooling (PMC) mode when the chillers and WSEs are both triggered, and Fully Mechanical Cooling (FMC) mode when only the chillers are activated. The transition among each cooling mode is achieved by manipulating the associated isolation valves. For example, in Figure 1(a), when the cooling system is in the FC mode, the isolation valves V1 and V2 in chillers, and V5 for bypassing the WSE are shut off. The isolation valves V3 and V4 in WSEs, and V6 for bypassing the chillers are fully opened so that the chilled water can flow through the WSE, and then be delivered by the primary pumps to the CRAHs. In the PMC mode, V1~V4 are fully open, V5 and V6 are shut off. In the FMC mode, while V3, V4 and V6 are shut off, V1, V2 and V5 are fully open to deliver the chilled water through the primary pumps, chillers, and then CRAHs.

The chiller plant with nonintegrated WSEs (Figure 1(d)) only have the FC mode and FMC mode. In the FC mode, the WSE is on and the isolation valves V3 and V4 are fully open, while the chillers and the associated valves V1 and V2 are off. As opposite to the FC mode, the FMC mode requires that the chillers and their associated valves be open.

DX System with ASEs

One major component in the DX system is CRAC. Air-cooled CRAC and water-cooled CRAC with single speed, multiple speed or variable speed compressors are modeled using the DX coil model located in *Fluid.HeatExchanger.DXCoil*. These models are based on performance curves, and detailed formulas can be found in the reference (Shen, New et al. 2017).

Validation

Each component is verified in a simulation example, following the conventions of the MBL mentioned in Wetter, Zuo et al. (2014). Due to the class hierarchy in the MBL and the object-oriented language Modelica, we built the data center package based on the base classes and ready-to-use component models in the MBL. We validated the data center package using comparative testing and analytical verification, which has also been used to validate all individual component models in the MBL. For example, comparative testing is used to validate the water-cooled CRAC model, which compares the simulation results of Modelica with EnergyPlus. The WSE model is validated by analytical verification, which compares its results with analytical solutions that are derived for certain steady-state or transient boundary conditions.

EXAMPLES

To demonstrate this package, we analyzed two cooling systems for a data center. One is a primary-only chilled water system with an integrated WSE on the load side, and the other is a DX cooled system with an ASE. We then compared the system performances of the two different designs.

System Models

The data center, located in a dry and cold climate zone, has a design cooling load of 1000 kW, but operates at a 50%-part-load condition. Two cooling systems are designed to provide cooling for the data center: System 1 is a primary-only chilled water system with an integrated WSE on the load side of the common leg (Figure 1(a)), and System 2 is a DX cooled system with an ASE (Figure 2).

The data center room is modelled using a mixed air volume with a heat source. The heat transfers and air infiltration through envelope are neglected because they are insignificant compared with the heat generated by the computers. No humidifiers are activated in both systems.

System 1

The WSE has a constant effectiveness of 0.8, and the built-in controller and three-way valve to control the outlet water temperature in the WSE are deactivated. The chiller model is based on performance curves and has a variable speed compressor. The cooling towers use a performance curve to calculate the approach temperature at off-design conditions. The sizing of each component is based on the method introduced in Taylor (2014).

The transition among each cooling mode is determined by the control sequences described by Stein (2009) and its state graph is shown in Figure 4. The initial state of the cooling system is in FC mode, where the WSE is switched on and the chiller is switched off. The chiller is switched on if

$$\Delta t_{chi,off} \geq 20\, min \text{ and}$$
$$T_{chw,sup,wse} > T_{chw,sup,set} + \delta T_1, \quad (1)$$

and switched off if

$$\Delta t_{chi,on} \geq 20\, min \text{ and}$$
$$T_{chw,sup,wse} < T_{chw,sup,set} - \delta T_1, \quad (2)$$

where $\Delta t_{chi,off}$ is the time of the chiller in off status, $\Delta t_{chi,on}$ is the elapsed time since the chiller was switched on, $T_{chw,sup,wse}$ is the temperature of the supply chilled water at the downstream of the WSE, $T_{chw,sup,set}$ is the chilled water supply temperature setpoint, and δT_1 is a dead band temperature.

The WSE is enabled when

$$\Delta t_{wse,off} \geq 20\, min \text{ and}$$
$$T_{chw,ret,wse} > T_{wb} + T_{app,ct,pre} + \delta T_3, \quad (3)$$

and is disabled when

$$\Delta t_{wse,on} \geq 20\, min \text{ and}$$
$$T_{chw,ret,wse} < T_{chw,sup,wse} + \delta T_2, \quad (4)$$

where $\Delta t_{wse,off}$ is the time of the WSE in off status, $\Delta t_{wse,on}$ is the elapsed time since the WSE was switched on, $T_{chw,ret,wse}$ is the temperature of the return chilled water at the upstream of the WSE, T_{wb} is wetbulb temperature of the outdoor air, $T_{app,ct,pre}$ is the predicted approach temperature of the cooling tower, δT_2 and δT_3 are the offset temperature. In our application, we set $T_{app,ct,pre}$ as the nominal approach temperature in the cooling tower, although many other prediction algorithms can be used such as using a detailed cooling tower model (Stein 2009), or engineering experience (Taylor 2014). The offset δT_2 is set to 0.5°C, and δT_3, which represents the approach temperature of the WSE, is set to 1.5°C.

For the control of cooling towers, the fan speed is regulated to maintain the condenser water supply temperature at its setpoint in the FMC mode, but it is adjusted to control the temperature of the supply chilled water leaving the WSE in the FC mode. In the PMC mode, the fan speed is set as 90% rather than 100% (Stein 2009). The reason is the last bit of fan speed from 90% to 100% does little to lower the condenser water supply temperature but increases the fan energy significantly, although at full speed the cooling tower can make the condenser water as cold as possible and maximize the WSE output.

The chilled water supply temperature is controlled at 8°C. The speed of the primary pumps is adjusted to maintain a constant differential pressure of the chilled water loop. The two-way valve on the waterside of the cooling coil is manipulated to control the temperature of the supply air leaving the CRAH at 18°C. The speed of the supply air fan is modulated to control the room temperature at 25°C. The setpoint reset strategy and head pressure control in the chillers are not considered.

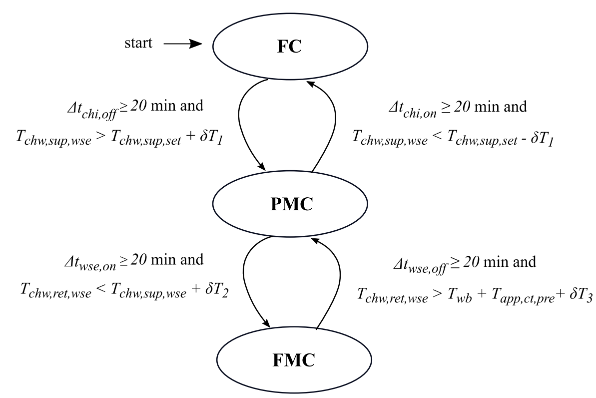


Figure 4. State graph of the cooling mode control in the System 1

System 2

System 2 contains an air-cooled, variable-speed CRAC with an ASE. The supply air temperature is controlled at 18°C by modulating the speed of the compressor in the CRAC in the PMC mode and FMC mode, and by adjusting the outdoor air damper position in the FC mode. The outdoor air damper is fully open during the PMC mode and fully closed in the FMC mode.

A temperature-based sequence is used to control the ASE. The state graph is shown in Figure 5. The CRAC is enabled if

$$\Delta t_{crac,off} \geq 20\, min \text{ and}$$

$$T_{db,OA} > T_{air,sup,set} + \delta T, \quad (5)$$

and disabled if

$$\Delta t_{crac,on} \geq 20\, min \text{ and}$$

$$T_{db,OA} < T_{air,sup,set} - \delta T, \quad (6)$$

where $\Delta t_{crac,off}$ is the time of the CRAC in off status, $\Delta t_{crac,on}$ is the elapsed time since the CRAC was switched on, $T_{db,OA}$ is the drybulb temperature of the outdoor air (OA), $T_{air,sup,set}$ is the supply air temperature setpoint, and δT is a dead band temperature. The ASE is switched on when

$$T_{db,OA} < T_{db,RA} - \delta T, \quad (7)$$

and switched off when

$$T_{db,OA} > T_{db,RA} + \delta T, \quad (8)$$

where $T_{db,RA}$ is the drybulb temperature of the return air. δT in conditions (5) ~ (8) is set to 1.1℃.

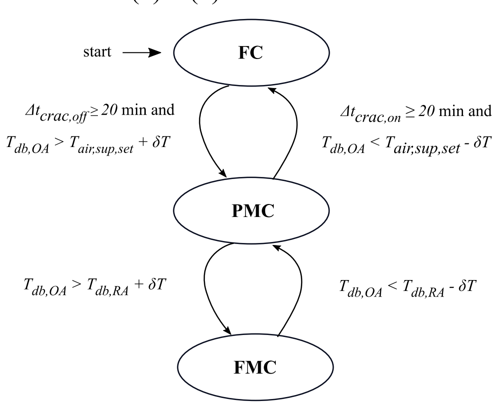


Figure 5. State graph of the cooling mode control in the System 2

System Performance

This section compares the system performance in terms of energy efficiency, economizing hours, and supply air conditions in both systems.

Energy Efficiency

PUE, power utilization effectiveness, is commonly used to quantify the energy efficiency of the cooling system in data centers. The definition of PUE is shown in (9).

$$PUE = \frac{E_{total}}{E_{IT}}, \quad (9)$$

where E_{total} is the total energy consumed by the whole data center, including energy consumption of the IT equipment E_{IT}, the cooling system, and lighting system, and energy losses in the power system etc. The lower the PUE, the less energy is consumed by non-IT equipment, hence energy efficient data centers have a low PUE.

Here we only consider the energy consumption of the IT equipment and the cooling system when calculating the total energy. The calculated PUE for the System 1 and System 2 is 1.13 and 1.06 respectively. System 2 is more energy efficient because it does not need pumps and cooling towers.

Economizing Hours

Figure 6 shows for the two systems the normalized hours of the cooling system status in each month for a whole year. Figure 7 shows the hexagon binning plots over the OA dry bulb temperature and the OA wet bulb temperature for each cooling mode. Such a bivariate histogram can describe the relationship between the outdoor weather conditions and the cooling system mode control. The color ramp of the hexagons indicates the count in each bivariate bin. The darker the color is, the larger the count is.

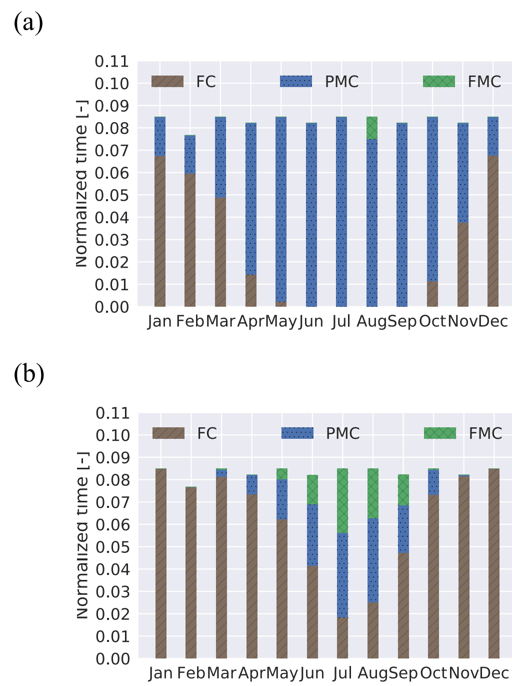


Figure 6. Normalized operating time of different cooling modes in: (a) System 1 and (b) System 2

In the dry and cold climate zone, System 1 operates less in the FC and FMC mode than System 2 for each month, because the cooling mode controller in the System 2 has a broader activation range for the FC mode and FMC mode than System 1 in terms of the OA dry bulb temperature and wet bulb temperature (Figure 7). For example, System 2 activates the FC mode when the OA dry bulb temperature is lower than the supply air temperature setpoint of 18℃, while System 1 only operates in the FC mode when the OA dry bulb temperature is lower than about 10°C, and the OA wet bulb temperature is lower than approximately 5°C.

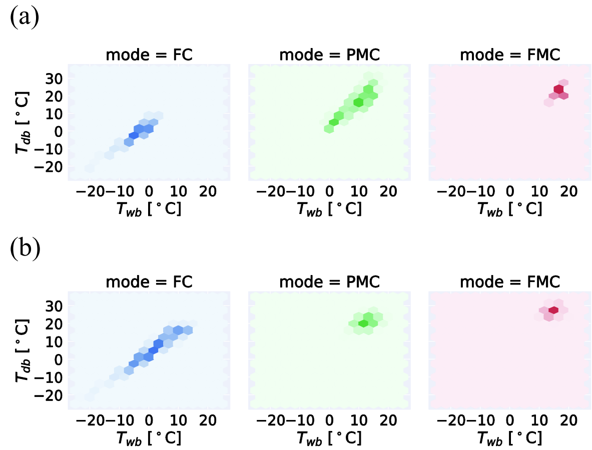


Figure 7. Hexagon bins of the OA dry bulb and wet bulb temperature in each cooling mode for: (a) System 1, (b) System 2

Supply Air Conditions

Figure 8 shows the scatter plot of the temperature and relative humidity (RH) of the supply air leaving the cooling coils in each cooling mode for both systems. The supply air temperature in System 1 and System 2 can be controlled at round its setpoint of 18°C, but the RH varies in a different range.

The supply air temperature can be controlled at 18°C during the PMC and FMC mode in both systems, but slightly loses control in the FC mode, wherein the supply air temperature varies between 18°C and 19°C.

The loss of control of the supply air temperature in the FC mode in both systems is temporary, which is caused by the waiting time in the cooling mode controller (Figure 4 and Figure 5). Take the System 2 as an example. If the OA dry bulb temperature suddenly increases to the supply air temperature setpoint of 18°C at the moment when the cooling system works in the FC mode and the CRAC has been switched off for less than 20 minutes, then the cooling system will still work in the FC mode rather than switch to the PMC mode. Hence, the supply air temperature will be greater than 18°C for a while until the fire condition for switching from the FC mode to the PMC mode in Figure 5 is satisfied.

The RH in System 1 varies within the range of 50% to 90%, while that in System 2 fluctuates from around 5% to 85% during the whole year. The reason is that the ASE in the System 2 frequently introduces the dry outdoor air to the data center room, which contributes to the humidity disturbance.

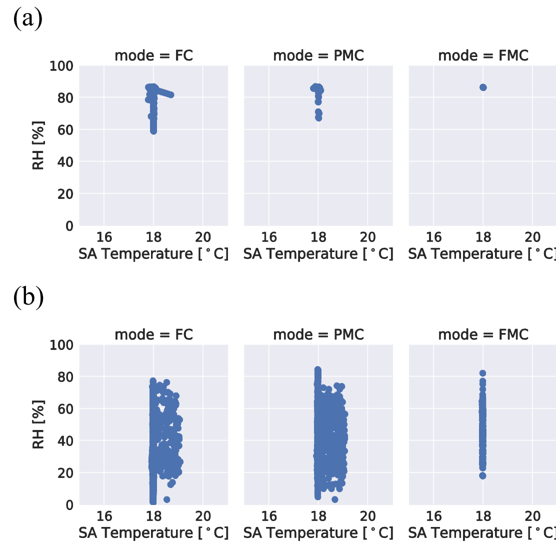


Figure 8. Supply air conditions in each cooling mode for: (a) System 1 and (b) System 2

Discussions

This package has the following advantages: first, it can inherit the advantages of the Modelica language and MBL. Modelica-based modeling platforms provide some important features such as object-oriented, and acausal modeling, and support a rich library of numerical solvers for Ordinary Differential Equation, and Differential Algebraic Equation systems. MBL provides several associated tools to support an automated workflow, coupled simulation with legacy building simulation programs, or connections to hardware (Wetter, Zuo et al. 2014).

Second, it supports fast modeling of the chilled water and DX cooling systems in the data center. This package is built on the MBL, which provides a rich library of base and ready-to-use HVAC equipment models. Besides that, we have added different configuration models of the chiller plant with WSEs, which can be used to quickly build a system-level model using the drag & drop.

Third, it supports the analysis of dynamic processes in the cooling and its control system. Through the analysis of the control, we can identify deficiencies of the control system. For example, in System 1, the transition conditions in terms of dry bulb temperature and wet bulb temperature do not have a clear boundary for the FC mode and PMC mode (Figure 7). When the OA wet bulb temperature and the dry bulb temperature are both in the range of 0°C to 10°C, the system can operate in both the FC and PMC mode for a long time. It means that the system sometimes is controlled to run in the PFC mode when it could run in the FC mode, which hence does not maximally utilize the cold outdoor air to cool the data centers.

However, currently only a few system configurations have been implemented. For other configurations, users need to assemble system models component-wise by instantiating, through drag & drop modeling, components of mechanical equipment and control blocks, and connect them to form a system model.

CONCLUSIONS

To support fast modeling of cooling systems in data centers, we implemented in the Modelica Buildings library a data center package that contains major component models for chilled water plants and direct expansion cooling systems. This package has been shown to be able to perform detailed analysis of cooling systems in terms of energy efficiency as well as control evaluations for data centers.

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