Modelica Models for the Control Evaluations of Chilled Water System with Waterside Economizer

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Abstract

Chilled water system with waterside economizer is a common cooling system used for large commercial buildings and data centers. To evaluate the design and control of the cooling system, modeling and simulation techniques are essential. This paper presents an equation-based modeling package for chilled water cooling system and a library of system- and equipment-level control. Then a case study is conducted to evaluate performance of the system-level control under different climate zones. Simulation results show that both temperature and humidity of the climate zone have influences on the economizing hours of the system, which thus influences the energy consumption.

Keywords: Chilled Water System, Waterside Economizer, Control Evaluation

1 Introduction

Commercial buildings have large cooling loads that are removed by Heating Ventilation and Air Conditioning system. American Society of Heating Refrigeration, and Air-Conditioning Engineers (ASHRAE) standards 90.1 states the requirements of the cooling system with waterside economizer for different climate zones.

Modeling and simulation is a cost-effective way to evaluate of the design and operation of the cooling systems. Modeling refers to the process that the real physical system is represented as mathematical models. Different physical systems (thermal, electrical, and electromagnetic, etc.) with different time-scaled dynamics are involved. This usually leads to high-indexed differential algebraic equations. Simulation is then conducted to numerically solve the mathematical equations in order to calculate the unknowns, which involves computer representation of models, different numerical solvers, solution procedures etc.

Many tools have been developed in academia and industry to perform computer modeling and simulation of the cooling systems in buildings. For example, eQuest (Lee and Chen, 2013), EnergyPlus (Pan et al., 2008) (Ham and Jeong, 2016), TRNSYS (Agrawal et al., 2016), and some customized simulation tools such as Energy Modeling Protocol (Shehabi et al., 2008) have been used to study the cooling systems with waterside economizers (WSEs) and airside economizers (ASEs) in data centers. Most of these traditional tools are based on imperative programming languages such as FORTRAN, C/C++ etc.

These imperative programming language based tools have exposed several challenges in the context of modeling, simulation and optimization. They have limited capacity when it comes to control designs and evaluations. For instance, EnergyPlus adopts idealized controls to reduce computation time(Fu et al., 2018). Although TRNSYS has dynamic control models, its constant time step poses numerical challenges(Kim et al., 2013). Further, conventional tools often intertwine model equations and numerical solvers in their source codes; this makes it difficult to extend these programs to support control-oriented cases.

Equation-based language such as Modelica (Elmqvist et al., 1998) can provide solutions to the above-mentioned issues. Modelica separates physical equations and numerical solvers wherever possible. The separation can mitigate the risks of intertwinement, and can fully take advantages of different expertise from different domains(Wetter et al., 2016; Fu et al.). For example, model developers can concentrate on how to develop efficient high-fidelity physical models, while computer engineers can focus on the development of robust numerical solvers. Also, the State Graph package in Modelica can be used to perform discrete control which contains dead band or delay time. The rich library of numerical solvers in Modelica can be chosen for different systems and different use cases.

In this paper, we present a Modelica-based package for the chilled water system with waterside economizers. The cooling component models are built on Modelica Buildings library(Wetter et al., 2014), and the control logic of the cooling system are adopted from engineers' experience. We first introduce the chilled water system with waterside economizers, and then discuss the Modelica models for the above-mentioned cooling and control system. In Section 4, we perform an comprehensive evaluation of the mentioned cooling mode control for different climate zones. The conclusions are discussed in Section 5.

2 Chilled Water System with Waterside Economizer

Chilled water system is usually used for commercial buildings. A typical chilled water system includes chillers,

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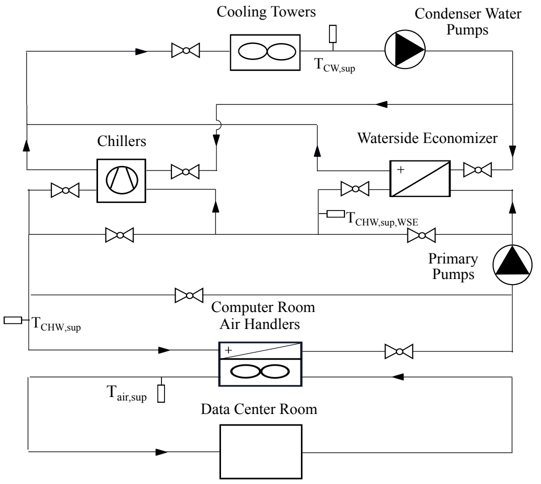
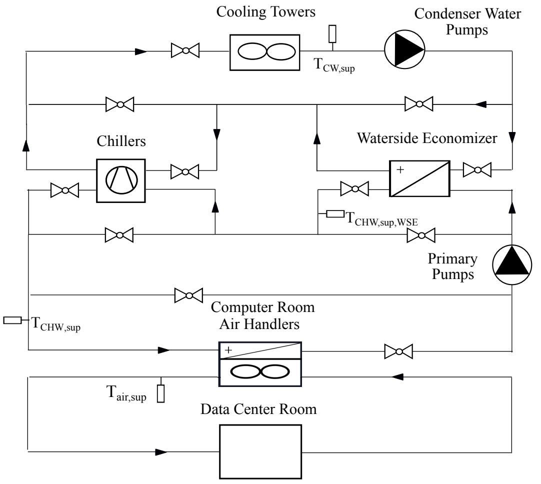


(a) Parallel



(b) Series

Figure 1. Primary-only chilled water system with integrated WSE

air handling units (AHUs), pumps, and cooling towers (Huang et al., 2016). The heat generated in the building is first transferred to the chilled water through AHUs, and the chillers then transfer the heat in the chilled water loop into the condenser water loop through a refrigeration system. The cooling towers at last reject the the heat in the condenser water loop to the outdoor environment.

Waterside economizers (WSE) can also be installed to provide auxiliary cooling when outdoor condition allows. It can be configured with chillers in different ways. For example, the WSE can be integrated with chillers, meaning that the economizer can meet all or some of the load while the chiller meets the rest of the load, or non-integrated, meaning the economizer can only operate when it can meet the entire load.

Two common configurations of the chiller plant with integrated WSEs are shown in Figure 1. The WSE is located on the load side of the common leg rather than plant side in the chiled water loop, which can guarantee that the WSE can meet the warmest return chilled water and maximize the economizing hours. On the condenser water side, the WSE can be installed in parallel (Figure 1(a)) or in series with chillers (Figure 1(b)). The chiller plant with integrated WSEs 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 cooling mode of the cooling system is determined by a cooling mode controller, and achieved by manipulating the associated isolation valves and the bypass valves of the chillers and the WSE.

3 Modelica Models

In the following section, Modelica models for the cooling system and the controls are elaborated.

3.1 Cooling System

In this section, the implementation of equipment models such as the chiller, WSE, and the cooling tower is first presented. Then, the subsystem models for two system configurations are illustrated.

3.1.1 Chiller

We developed a chiller model that supported the head pressure control and could model numbers of identical electric chillers. A group of identical chillers are modeled by vectorising existing chiller models in the Moelica Buildings library. The vectorized equipment model is assigned with the same design parameters but different performance curves if needed. A partial class of the chiller model is instantiated through vectorization with a number *num* by specifying the length of the array chiller, which can be redeclared with a detailed chiller model later. Medium used in the chillers, design parameters such as the design capacity, and performance curves of each chiller are specified. Note that although the chillers have identical nominal conditions, they can have different performance curves specified in performance data *per*. In addition, we add isolation valves in the vectorized models to avoid circulating flow among components.
The head pressure control in this model is achieved by modulating the isolation valve on the condenser water side to maintain a minimum temperature difference between evaporator and condenser, such as 11°C.

3.1.2 WSE

The waterside economizer model consists of a heat exchanger with outlet temperature control and two isolation valves on both medium sides. This waterside economizer model can be used in two different control scenarios: (1) the outlet temperature at chilled water side is controlled by a built-in PID controller and a three-way valve by setting the parameter *use_controller* as true. (2) the outlet temperature at chilled water side is NOT controlled by a built-in controller by setting the parameter *use_controller* as false.

Hence, an outside controller can be used to control the temperature. For example, in the free-cooling mode, the speed of variable-speed cooling tower fans can be adjusted to maintain the supply chilled water temperature around the set point.

The user can select different heat exchanger models according to the data availability and modeling requirement. In this model, the heat exchanger model uses the nominal approach temperature and heat capacity as its critical design parameters. The heat exchanger model has various efficiency, which changes based on the *UA* value under off design conditions. The part-load *UA* value in this model is based on the ratio of the fluid mass flowrate to its nominal flowrate. The principles of the heat exchanger model is shown as the following equations,

$$PLR_1 = \dot{m}_1/\dot{m}_{0,1}, \tag{1}$$

$$PLR_2 = \dot{m}_2/\dot{m}_{0,2}, \tag{2}$$

$$UA = UA_0 * PLR_1^a * PLR_2^b, \tag{3}$$

$$C_{min} = min(\dot{m}_1 * Cp_1, \dot{m}_2 * Cp_2), \tag{4}$$

$$C_{max} = max(\dot{m}_1 * Cp_1, \dot{m}_2 * Cp_2), \tag{5}$$

$$NTU = UA/C_{min}, \tag{6}$$

$$C_r = \frac{C_{min}}{C_{max}}, \tag{7}$$

$$Q_{max} = C_{min} * (T_{i1} - T_{i2}), \tag{8}$$

$$eff = f(NTU, C_r), \tag{9}$$

$$Q = eff * Q_{max}, \tag{10}$$

where *PLR* is the part load ratio, expressed as normalized flow rate, $\dot{m}$ is the mass flow rate. The subscripts 0,1 and 2 represent nominal condition, fluid 1 and fluid 2 respectively. C_{min}, C_{max} and C_r are the minimum, maximum and ratio of the flow thermal capacity. Cp is the specific thermal capacity. NTU and eff denote the number of heat transfer units and effectiveness. The function f expresses the relationship between NTU,C_r and eff for different flow configurations. Q is the heat transfer rate and Q_{max} is the maximum possible heat transfer rate. The function f is a formula related to the flow configuration of the heat exchanger, which can be referred in (DoE, 2010). T_i is the inlet temperature. The superscripts a and b are the curve coefficients.

3.1.3 Cooling Tower

The model is based on the York regression model in the Modelica Buildings library and it is integrated with an electric heater to provide auxiliary heating for the cooling tower when the weather is very cold. To compute the thermal performance, this model takes as parameters the approach temperature, the range temperature and the inlet air wet bulb temperature at the design condition. Along with the design mass flow rate (of the chiller condenser loop) as parameter, these parameters define the rejected heat. For off-design conditions, the model uses the actual range temperature and a polynomial to compute the approach temperature for free convection and for forced convection, i.e., with the fan operating.

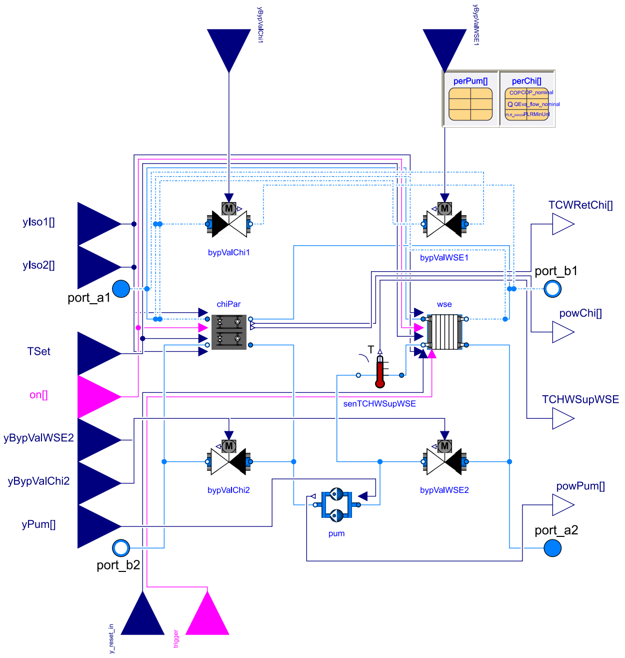


Figure 2. Implementation of the two piping configurations on the condenser water side

The heater is controlled by an on/off controller. The controller is activated when the outlet temperature of cooling tower is lower than the anti-freezing temperature setpoint *antFreTem*. Otherwise, the heater is deactivated. For the details of cooling tower and electric heater model, please see the model in the Modelica Buildings library.

3.1.4 Subsystem

In the following section, we implemented two configurations of integrated WSE on the load side of the primary-only chilled water system, with both series and parallel piping on condenser waterside and series piping on chilled water side. A partial model is built which could link the piping connection based on the condition whether it is series or parallel configuration on the condenser side. That said, the selection of the piping on the condenser waterside is achieved by setting the Boolean variable *parallelCondenserWater* by extending this partial model. The implementation of this model is depicted in Figure 2. The outputs of this model can be the temperature of leaving condenser water in chillers, electric power consumed by chiller compressor, chilled water supply temperature in the waterside economizer and the electrical power consumed by the pumps. Users can model multiple chillers with only one integrated WSE.

Integrated in Series on Condenser Water Side The series piping on condenser waterside is achieved by extending the partial model discussed in Section 3.1.4 and setting *parallelCondenserWater* to false.

Integrated in Parallel on Condenser Water Side The parallel piping on condenser waterside is achieved by extending the partial model discussed in Section 3.1.4 and setting *parallelCondenserWater* to true.

3.2 Control System

In this section, the implementation of cooling model controls and equipment-level local controls is described respectively.

3.2.1 Cooling Mode Control

Based on the operational status of chillers and WSEs, the chiller plant with WSEs can operate in three cooling modes, including Free Cooling (FC) mode when only WSEs are enabled for cooling, Partial Mechanical Cooling (PMC) mode when both chillers and WSEs are triggered, and Full Mechanical Cooling (FMC) mode when only chillers are activated. To consider the condition when the system is off, we introduce an unoccupied mode. Different sets of implementable control sequences for transitioning among different cooling modes are available in literature and industry applications for the chiller plant with WSEs. In this paper, we use one control logic from Meakins and Griffin from their research to showcase the implementation of the cooling mode controller using state-graph package in Modelica. Figure 3 depicts the schematics of the control sequence in the form of a state graph as well as the implementation of this cooling mode controller. It is noted that this general implementation approach could be extended and applied to other sets of the cooling mode controller.

As shown in Figure 3(a), the initial state of the cooling system is in unoccupied mode, where the whole system is off. When the system is operated, it will transition to the FC mode. The chiller is switched on if

$$T_{sup,CW,WSE} > T_{sup,CHW,set} \, and \, \Delta t_{chiller,off} > \Delta t_{thr}, \quad (11)$$

and switched off if

$$T_{sup,CW,WSE} < T_{sup,CHW,set} \, and \, \Delta t_{chiller,on} > \Delta t_{thr}, \quad (12)$$

where $T_{sup,CW,WSE}$ is the supply condenser water temperature, $T_{sup,CHW,set}$ is the supply chilled water temperature setpoint, $\Delta t_{chiller,on/off}$ is the elapsed time since the chillers were on/off, and Δt_{thr} is a waiting time threshold. The WSE is enabled when

$$T_{sup,CW,WSE} < T_{ret,CHW,WSE} - 3^oF \, and \, \Delta t_{WSE,off} > \Delta t_{thr}, \quad (13)$$

and switched off if

$$T_{sup,CW,WSE} > T_{ret,CHW,WSE} + 2.5^oF \, and \, \Delta t_{WSE,on} > \Delta t_{thr}, \quad (14)$$

where $T_{ret,CHW,WSE}$ is the chilled water return temperature upstream of WSE, $\Delta t_{WSE,on/off}$ is the elapsed time since the WSE was on/off, and Δt_{thr} is a waiting time threshold. 2.5^oF or -3^oF is an adjustable offset temperature difference.

Figure 3(b)shows the Modelica implementation of the above control sequence. On the left are the connectors for the control input signals expressed as real and boolean number, such as *TSupCWWSE* (Supply condenser water temperature at downstream of WSE), *TRetCHWWSE* (Return chilled water temperature at downstream of WSE), *TSupCHWSet* (Suppy chilled water temperature setpoint) and occupancy mode *uOcc* (True if the room is occupied). The modules *timGre* and *timLes* count and output the time when the signal u is over/below the offset temperature difference as shown in Eq.(11) - Eq.(14).In the middle is the state graph implemented in Modelica State graph 2. There are four states in this controller, indicated by the squared block icons. The states are FC mode, PMC mode, FMC mode, and the unoccupied mode. The initial state is set to the unoccupied mode when simulation starts. The transitions between the states are represented by the horizontal black bars, and each transition has exactly one preceding state and one succeeding state, and is set accordingly based on the transition conditions. On the right are the *mulSwi* module which converts the stage number to the output *y*.

3.2.2 Equipment-level Control

Chiller plants with WSEs require different equipment-level local controls of components compared with conventional chiller plants without WSEs. The selection of the local controls for different components is critical to the performance of the whole system. The local controls we selected are based on the inputs from the dicussion with the experienced industry engineers in this field. In this section, the equipment-level control sequences are described.

Chiller Control The chiller control involves a load-based stage control. Stage control of chiller is usually based on the supply chilled water temperature, chiller loads or partial load ratio (PLR), and chilled water pump speed. In this logic, chillers are

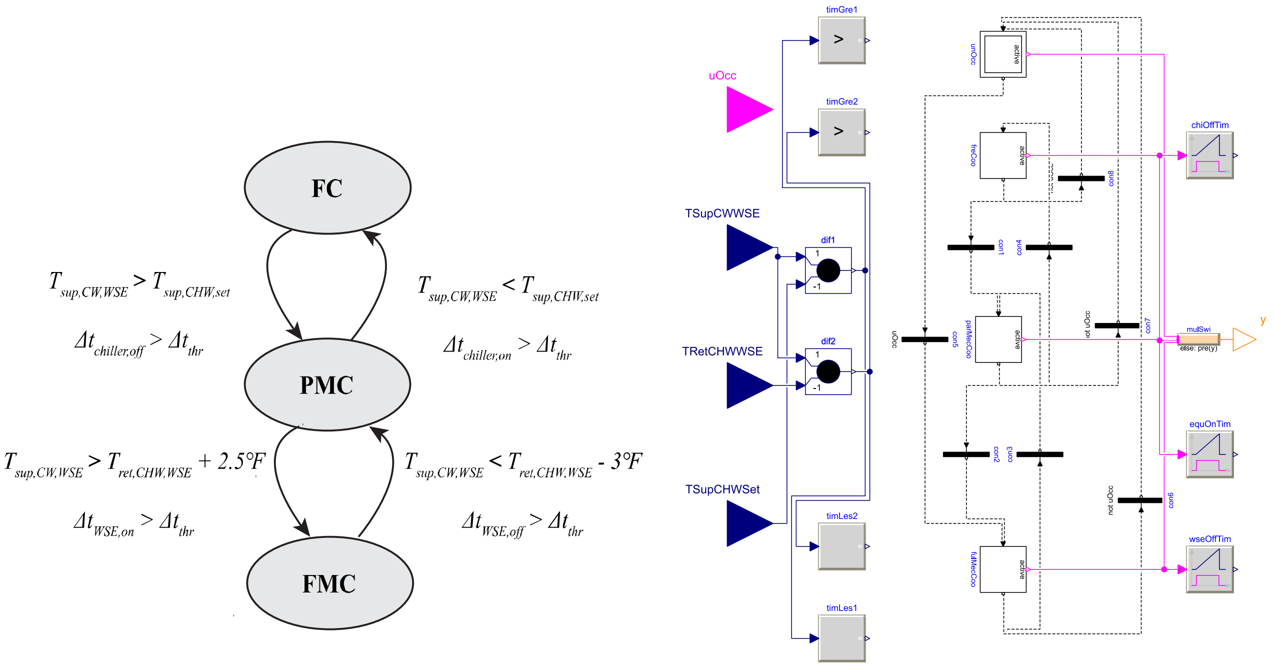
- staged up if current stage has been active for at least 30 minutes and the PLR for any active chiller is greater than 80 % for 10 minutes
- staged down if current stage has been activated for at least 30 minutes and the PLR for any active chiller is less than 25 % for 15 minutes.

It is noted that the threshold and delay time are adjustable.

Chilled Water Pump Controls The chilled water pump controls involve a stage control and a speed control.

Chilled water pumps stage up or down based on measured flowrate. The thresholds and delay time are also adjustable as shown in the following logic. Pumps are

- staged up if current stage has been active for at least 15 minutes and the measured flowrate is larger than



(a)

(b)

Figure 3. Implementation of the cooling mode control (a) Schematics (b) State-graph in Modelica

85% of the total nominal flowrate of the active pumps for 2 minutes.

- staged down if current stage has been active for at least 15 minutes and the measured flowrate is less than 45% of the total nominal flowrate of the active pumps for 15 minutes.

The chilled water pump speed is adjusted by a PID loop to maintain the differential pressure (DP) signal at a setpoint. All pumps receive the same speed signal. Minimum speed setpoint is prescribed based on the system configuration.

Temperature Reset Control In this control logic, both the chilled water supply temperature setpoint and the chilled water loop DP setpoint are reset based on the difference between the actual and set temperature of the supply air in the part load condition. A single reset control point should be used to control both setpoints. When the plant includes a WSE, the reset should lead with pressure to keep the water temperature as high as possible to maximize WSE operation (see Figure 4). The setpoint reset strategy is to first increase the different pressure DP of the chilled water loop to increase the mass flow rate. If DP reaches the maximum value and further cooling is still needed, the chiller temperature setpoint, $T_{sup,CHW,set}$ is reduced. If there is too much cooling, $T_{sup,CHW,set}$ and DP will be changed in the reverse direction.

Cooling Tower Controls The local controls related to the cooling tower are the cell stage control and fan speed control.

In the cell stage control, the tower cells are staged based on measured condenser water flowrate.

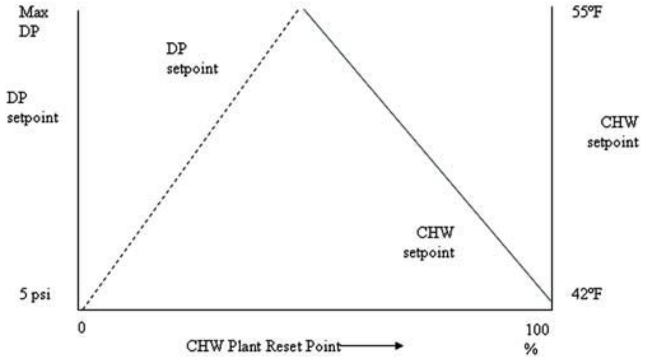


Figure 4. Principle of temperature reset control

- One additional cell stages on if average flowrate through active cells is greater than a stage-up threshold for 15 minutes
- One additional cell stages off if average flowrate through active cells is lower than a stage-down threshold for 5 minutes.

A minimum tower cell number reset control based on the different cooling modes is commonly used to support the stage control.

- In unoccupied mode, the minimum number is 0.
- In FC mode, the minimum number of active cooling towers should be equal to the number of active condenser water pumps.
- In PMC mode, the minimum number of active cooling towers should be equal to the total number of

cooling towers, which means all the cooling towers should be commanded on.

- In FMC mode, the minimum number of active cooling towers should be equal to the number of active condenser water pumps.

The cooling tower fan speed is also controlled to satisfy the requirement of temperature setpoint, and fan speed shall not exceed the maximum speed.

- In unoccupied operation mode, the fan is turned off.
- In FC mode, the fan speed is controlled to maintain a predefined chilled water supply temperature at the downstream of the economizer, and not exceed the predefined maximum fan speed.
- In PMC and FMC modes, the fan speed is controlled to maintain the supply condenser water at its setpoint.

The maximum fan speed is reset based on cooling modes and operation status.

- In unoccupied mode, the maximum speed is not reset.
- In FC mode, if all condenser pumps are enabled, the maximum fan speed is reset to full speed 100%; otherwise the maximum fan speed is reset to a lower speed, e.g. 90%.
- In PMC mode, the maximum fan speed is set to a high speed, e.g. 100%.
- In FMC mode, if all the condenser water pumps are active, the maximum fan speed is reset to full speed 100%; otherwise it is reset to a lower speed, e.g. 90%.

Condenser Water Pump Controls The condenser water pump controls include a pump stage control and a speed control.

The condenser water pump stage control have different logics according to operational mode. Here assume the number of condenser pumps and that of the chillers are identical.

- In unoccupied mode, the condenser pump should be turned off.
- In FC mode, the number of operating condenser water pumps is staged based on the cooling tower fan speed signal.When the fan speed signal exceeds 80% for 5 minutes, then stage up one condenser pump. When the fan speed signal is below 45% for 10 minutes, then stage down one condenser pump.
- In PMC mode, if not all chillers are active, the number of active condenser water pumps should be one less than the total condenser water pumps, else all the condenser pumps are commanded to run.
- In FMC mode, the number of active condenser water pumps should be equal to the number of active chillers.

The condenser water pump speed control sequence is shown as follows.

- In unoccupied mode, the pump is turned off.
- In FC mode, the condenser water pump speed is equal to a high signal select of a PID loop output and a minimum speed (e.g. 40%). The PID loop outputs the cooling tower fan speed signal to maintain chilled water supply temperature at its setpoint.
- In PMC and FMC modes, the condenser water pump speed is equal to a high signal select of the following three: (1) a minimum speed (e.g. 40%); (2) highest chiller percentage load; (3) CW system differential pressure PID output signal.

Valve Controls Four local controls related to the valves in the cooling system are considered. They are controls for the modulating isolation valve, the two position valves, the chiller bypass valve, and the WSE bypass valve.

Modulating Isolation Valve Control. The modulating isolation valve is usually installed on the condenser water side of a chiller to perform head pressure control during cold climate. The modulating isolation valve is modulated to control variables such as chiller temperature/pressure lift between evaporator and condenser. The logics for different operational modes are as follows.

- When chiller is not enabled, the isolation valves are closed.
- When chiller is enabled, the isolation valves on the condenser side are fully opened at the beginning. Then after a stable time delay, the valve is modulated to control variables such as temperature lift or pressure lift in a chiller.

Two Position Valve Control. The two position valve controls the on/off of the equipment.

Chiller Chilled Water Bypass Control. Bypass valves are used to switch the cooling system among different operation modes, and maintain desired differential pressure through the equipment such as evaporators or condensers. The control sequence of chiller chilled water bypass is as follows.

- In unoccupied operation mode, the bypass for chillers and economizers are closed.
- In FC mode, the bypass valve on chiller side is fully opened.
- In PMC mode, the chiller bypass valve is modulated to maintain the differential pressure through the active evaporators at its setpoint such as design differential pressure.

- In FMC mode, the chiller bypass is modulated to maintain the differential pressure through the active evaporators at its setpoint such as design differential pressure.

WSE Chilled Water Bypass Control. Bypass valves for economizers are used to switch the cooling system among different operation modes, and maintain desired differential pressure through economizers. This model can be used for both chilled and condenser water side. The control sequence of WSE chilled water bypass is as follows.

- In unoccupied operation mode, the bypass valves for economizers are closed.

- In FC mode, the bypass valve on economizer side is modulated to maintain differential pressure across their respective economizers at a setpoint, such as design differential pressure.

- In PMC mode, the bypass valve on economizer side is modulated to maintain the differential pressure through the economizer at a setpoint such as design differential pressure.

- In FMC mode, the bypass valve on economizer side is fully opened.

4 Case Study

4.1 Case Description

We perform a case study utilizing Modelica models to comprehensively evaluate performance of the cooling mode control logic mentioned in Section 3.2.1 in all ASHRAE climate zones. There are in total 19 thermal climate zones in ASHRAE Stanadard 169-2013, which categorizes different areas based on their historical weather data such as heating degree days, average temperatures, and precipitation. The climate zones and their representative cities are shown in Table 1. The index 0 means extremely hot area, while index 8 means arctic area. The index A, B and C mean humid, dry and marine area.

Table 1. ASHRAE climate zones

Index	*City*	*Index*	*City*
0A	Singapore	4B	Albuquerque
0B	Riyadh	4C	Salem-McNary
1A	Miami	5A	Chicago
1B	Kuwait	5B	Boise
2A	Houston	5C	Bremerton
2B	Phoenix	6A	Burlington
3A	Memphis	6B	Helena
3B	EI Paso	7	Duluth
3C	San Francisco	8	Fairbanks
4A	Batimore		

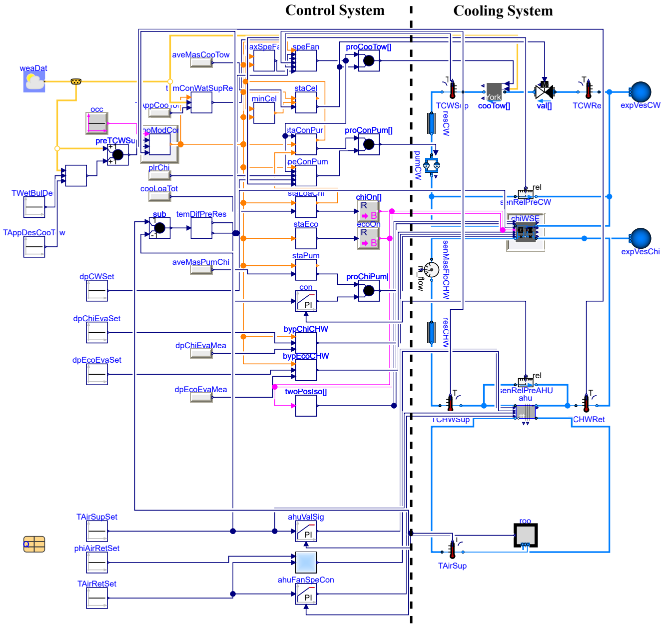


Figure 5. Modelica implementation of a chilled water system with waterside economizer

The Modelica model is built as shown in Figure 5. The chilled water system with waterside economizer is designed for a virtual data center. The data center room has a nominal cooling load of 2000kW but operates at a part load ratio 0.65. Two identical chillers with a cooling capacity of 1000kW for each, and one WSE that can provide 2000kW under the design condition are provided as cooling sources. The waterside economizer is integrated with chillers on the chilled water side, and in parallel with chillers on the condenser water side. The pumps, cooling towers and air handling units are sized accordingly based on the design cooling load. The cooling mode and equipment-level control are described in Section 3.2.

4.2 Simulation Results

An annual simulation is performed for each climate zone. The energy consumption of the cooling system are shown in Figure 6. The economizing hours in different climate zones when the WSE is activated to provide cooling are shown in Figure 7.

Both the dry bulb temperature and humidity can influence the energy consumption of the chilled water system with WSEs. In the humid area (A), as the dry bulb temperature decreases from 0A to 6A, the total energy decreases from 151 MWh to 139 MWh. This means with, similar humidity, the higher the dry bulb temperature is, the more energy is consumed by the cooling system. The reason is with a higher outdoor dry bulb temperature, the cooling system has less economizing hours during annual operation, as shown in Figure 7. In hot climate zone 1, as the humidity reduce, the cooling system operates under more economizing hours. The reason is that given similar dry bulb temperature, dryer air means lower wet bulb temperature. As a consequence, the cooling towers can

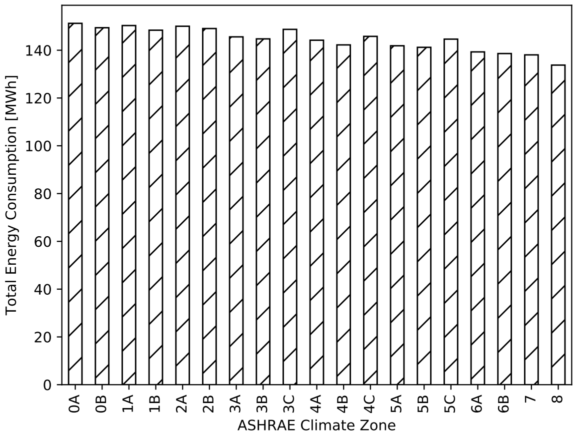


Figure 6. Total energy consumption for the cooling system in all climate zones

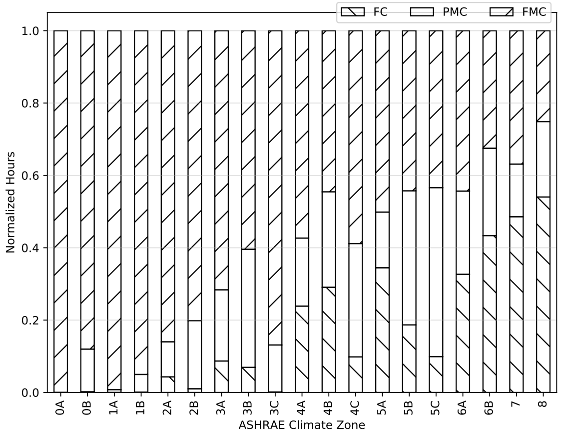


Figure 7. Normalized economizing hours in all climate zones

produce cold condenser water temperature for a longer period, which then can help extend the economizing hours.

5 Conclusions

We presented a Modelica-based tool for the modeling and simulation of the chilled water system with waterside economizers. The cooling component models and control models are also discussed in details. These Modelica models are then used to perform a case study to evaluate the energy and control performances of the cooling mode control in different climate zones. Simulation results show that the cooling mode control has different performances in different climate zones. Both the temperature and the humidity can influence the system performance.

6 Acknowledgement

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