Energy Efficient Design for Hotels in the Tropical Climate using Modelica

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Abstract

For hotels located in the tropical climate, a significant amount of energy is attributed to the domestic hot water (DHW) usage and the space cooling. To improve the energy efficiency of hotels in the tropical climate, we proposed a heat recovery system that could utilize the waste heat from the space cooling system to pre-heat the city water supplied to the DHW system. To support the system design, we selected Modelica to model the heat recovery system and its control, which is difficult to be simulated by conventional building simulation tools. The Modelica *Buildings* library and the *Modelica_StateGraph2* library were employed to build the system model. A hotel in Miami, Florida, U.S. was selected for the case study. The simulation results showed that the proposed heat recovery system could save up to around 30% boiler energy use in the DHW system.

Keywords: energy efficient design, hotel, tropical climate, Modelica

1 Introduction

In the U.S., hospitality facilities, such as hotels and resorts, account for 7% of the primary energy consumption of all commercial buildings (U.S. Department of Energy), which is equivalent to approximately 1.3% of primary energy consumption in the nation. In an average hotel, the Heating, Ventilation and Air Conditioning (HVAC) system accounts for around 50% of electricity usage and up to 86% of natural gas consumption (U.S. Environmental Protection Agency, 2008). Due to their significant energy consumption, improving energy efficiency of the HVAC systems in hospitality facilities is of great interests to the society.

The conventional HVAC system for the hospitality facilities consists of two parts: the Domestic Hot Water (DHW) system and the space conditioning system. The DHW system provides the hot water to the kitchen and the guestroom. It obtains the supplement water from the municipal water network, which is called "city water". The city water is then heated by heating equipment such as boilers. The space conditioning system provides cooling \ heating to the space. In the cooling condition, the heat from the building is extracted by the space conditioning system and usually dumped to the ambient environment. The dumped heat is called "waste heat". In the heating condition, the space condition system extracts heat from the ambient environment or boilers and then injects the heat into the hotel space.

The same HVAC systems are also implemented for hotels in the tropical climate. However, the space cooling in tropical climate is the dominant usage of the space conditioning and there is a significant amount waste heat generated from the space cooling all the year. Thus, it is possible to save the energy consumption by the heating equipment in the DHW system if we can recover the waste heat from the space conditioning system and use it to preheat the city water before it enters into the heating equipment.

In addition, if there is a capacity control in the heat rejection of the space conditioning system (e.g. variable speed fan control in the cooling tower), we can also reduce the energy consumption by the heat rejection since the waste heat injected by the heat rejection system decreases if the heat recovery occurs. Besides the energy saving, we also have other benefits from the heat recovery: it can extend the life of both the heating equipment and the heat rejection system by reducing their usage. If the cooling towers are employed in the heat rejection system, the heat recovery can also further help the environment by reducing the usage of evaporative cooling at the cooling towers, which requires make-up water and chemicals for treating the make-up water.

On the other side, there are some potential negative impacts associated with the heat recovery: adding an extra piping system to connect the space conditioning system and the DHW systems requires additional initial cost in equipment, such as pipes, heat exchangers, pumps and valves, and labor for installation. It will also need additional pump energy to cycle water between two systems to enable the heat recovery. Finally, controlling the heat recovery can be a challenge since the system operates under various conditions with complicate flow loops.

Overall, the heat recovery seems to be promising since it is not just economically beneficial but environmentally as well. However, to find a balance in terms of costs and benefits, it is necessary to quantitatively evaluate the performance of the proposed heat recovery design.

In this paper, we presented our research in designing and modeling a heat recovery system for the Grand Beach Hotel in Miami, Florida, U.S. We first introduce the detailed design of the heat recovery system. Then we evaluate the energy performance of the heat recovery system with simulation. In the simulation, Modelica was used to establish the system model. After showing the simulation results of different operating scenarios, we discuss the future work for the project.

2 Design of the Heat Recovery System

As shown in Figure 1 and Figure 2 are the DHW system and the space condition system of the Grand Beach hotel, respectively. The DHW system contains a group of three identical boilers with a combined total capacity of 350kW and they are represented by a single boiler (Boiler-1), a group of three identical domestic hot water tanks with a total capacity of 3000 L and they are also represented by a single DHW tank (HW Tank). The DHW system provides hot water at 60°C. Part of the 60 °C hot water would be directly supplied to the kitchen and the rest would be mixed with the city water to provide a 43.3°C hot water to the guestroom. To ensure the quick delivery of the hot water, the hot water is continuously circulating within the distribution network. The space conditioning system is made up of two heat pumps, two cooling towers, one heat exchanger and one small (102.4kW) boiler (Boiler-2). Boiler-1 is the dedicated main boilers that provide the heat for both the DHW system and the space conditioning system. Boiler-2 is a backup boiler that operates only when Boiler-1 is not able to meet the heating demand.
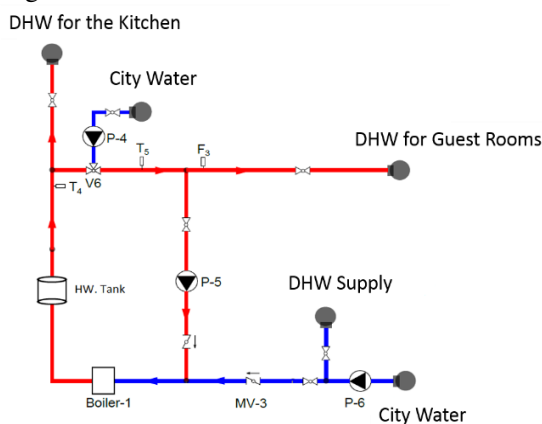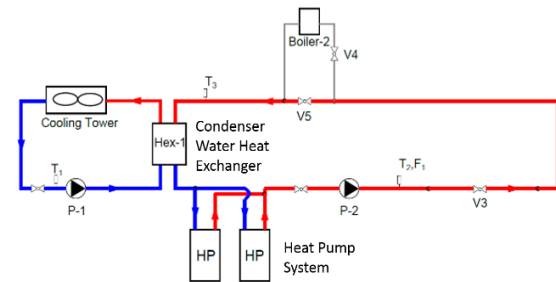

Figure 1. Schematic of the DHW system

Figure 2. Schematic of the space conditioning system in the space cooling mode

As mentioned in the introduction, we can save the energy consumption of both the DHW system and the system conditioning system by recovering the waste heat from the latter to the former. In fact, Miami provides an ideal environment for the use of the heat recovery. The climate in Miami is considered to be tropical or sub-tropical. According to the ASHRAE standard 169 (ASHRAE, 2006), Miami is located in Climate Zone 1A, which is very hot and humid. Thus, there is a large amount of waste heat from the space cooling throughout the year. With that in mind, we proposed to use a connection loop, which recovers the heat from the space conditioning system to the DHW system through a heat exchanger (Hex-2 in Figure 3a).

There are seven possible operating states for the whole system varying from the space heating to the space cooling. In the winter of Miami, there are occasionally a few cold days, especially during the morning that the space heating is needed. Since hotel guests tend to take shower in the morning, the DHW demand may also be high at the same time when the space heating is needed. If the DHW demand is extremely large that requires the full capacity of Boiler-1, the space conditioning and the DHW systems will run independently (State 1). The purpose is to guarantee the supply of the DHW. In this case, the heat recovery system will stop working.

When the DHW demand drops and Boiler-1 has additional capacity to meet a partial demand of the space heating, the system will operate at State 2 that use both Boiler-1 and Boiler-2 for the space heating through the connecting loop. This is anticipated to be the typical operating state for the space heating. The flow direction in the connection loop at State 2 is shown in Figure 3a.

If the combined demand for the space heating and the DHW drops to a level that can be met by Boiler-1, Boiler-2 will be turned off and the system will operate at State 3.

State 4 happens when there is no need for the space heating or cooling, which seldom happens. At this state, the DHW system and the system conditioning system are disconnected and no space heating or cooling will be provided. This state is used as a transitional period between the space heating and the space cooling.

At State 5, a moderate space cooling and a large amount of the DHW is provided at the same time. The waste heat from the space cooling is used to heat the cool city water before it is further heated by Boiler-1. The demand for the DHW is sufficiently large so that the DHW subsystem can absorb all the waste heat from the space conditioning system.

If the DHW subsystem cannot absorb all the waste heat from the space conditioning system because either the large demand for the space cooling or insufficient demand for the DHW, the cooling towers are kicked on to eject the remaining waste heat to the ambient
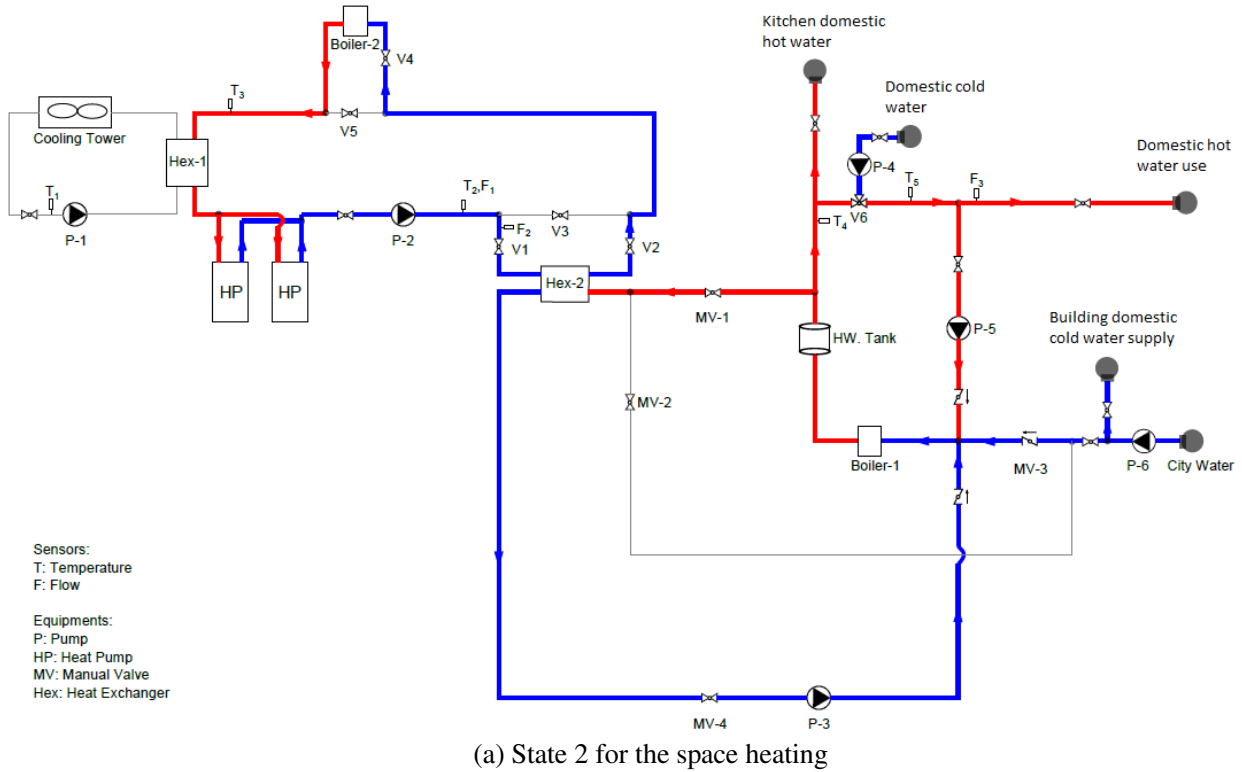

(a) State 2 for the space heating

(b) State 6 for the space cooling
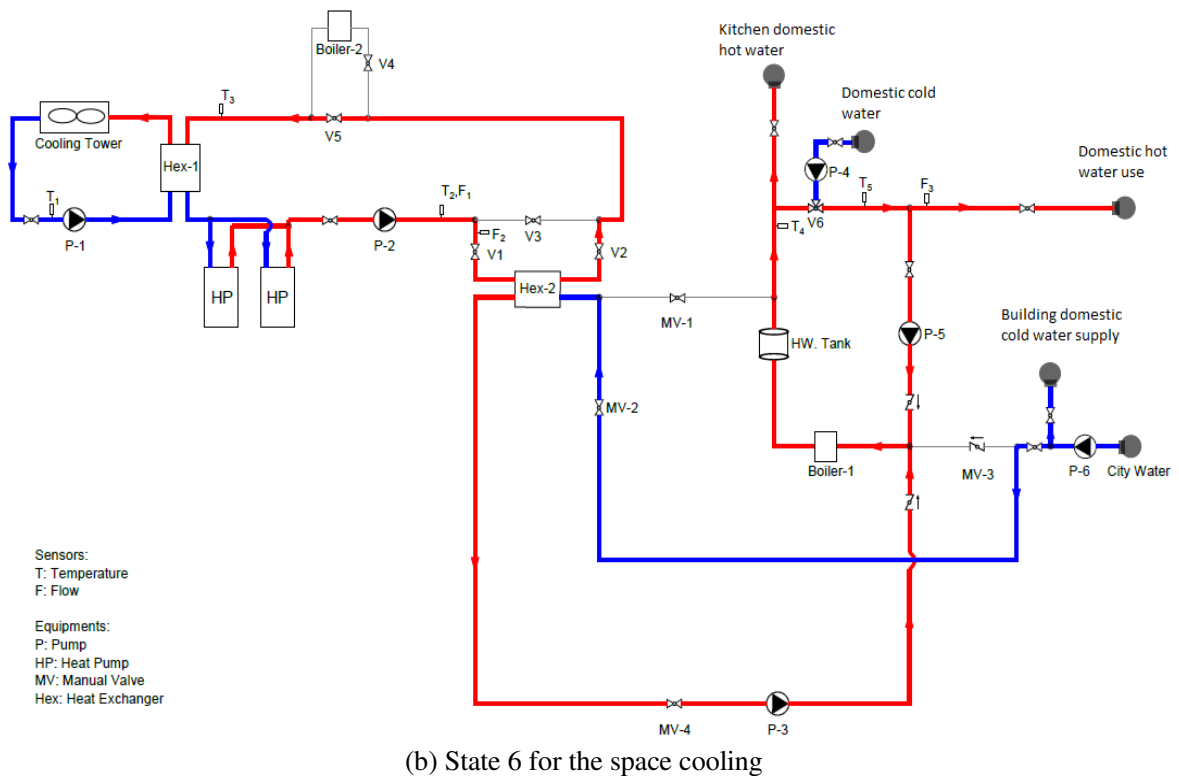
Figure 3. Two typical operating states of the proposed HR system

environment (State 6). This is anticipated to be the typical operating state for the space cooling since the DHW demand in the hotel mainly occurs in the early morning and late afternoon. For the rest of the day, the DHW demand is small but the cooling demand can be large. The flow direction in the connection loop at State 6 is shown in Figure 3b.

If it is hot and the DHW demand is too small (such as at night), it is not worth of running the heat recovery system. In that case, the DHW system and system conditioning system will operate independently at State 7.

The above analysis shows that the two subsystems operate jointly at State 2, 3, 5 and 6. However, the energy saving due to the heat recovery would only occur at State 5 and 6.

The transition between the states is achieved by employing a state machine (shown in Figure 4). In the state machine, temperatures, temperature differences and flow rates are used to indicate the different states of the whole system. The dead band and waiting time are employed to avoid short cycling.
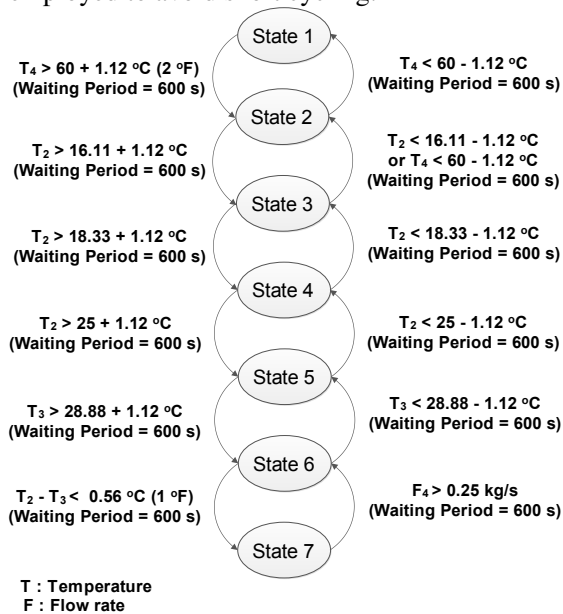

Figure 4. Supervisory control described by the state machine (the location of the temperature sensor and flow meter can be refered to Figure 3)

3 Evaluation

3.1 System Model

A commonly used method for the quantitative evaluation is to perform computer simulations (Gregor P. Henze, Clemens Felsmann *et al*, 2004; Hien, Poh *et al*, 2000). The widely used modeling tools in the building industry include EnergyPlus (Crawley, Lawrie *et al*, 2001) and TRNSYS (Klein, Duffie *et al*, 1976). However, it is difficult to use EnergyPlus to model the proposed heat recovery system because it does not support the unconventional system topology and tends

to highly idealize the control process (Huang and Zuo, 2014; Piette, Granderson *et al*, 2012; Wetter, 2009; Wetter, Zuo *et al*, 2011). TRNSYS is also not suitable for this case due to two limitations. First, TRNSYS is not effective in simulating such large system as the proposed design because it doesn't supply hierarchical modeling, which is essential for the debugging and model reuse (Wetter and Haugstetter, 2006); second, the pressure-driven flow distribution in the connection loop is hard to be modeled with TRNSYS. On one side, the flow direction in the connection loop varies by the operational states. On the other side, TRNSYS requires fixed and prescribed flow directions in the hydraulic system modeling (Kim, Zuo *et al*, 2013).

To overcome these challenges, we chose Modelica in the system modeling. The Modelica *Buildings* library (Wetter, Zuo *et al*, 2014; Wetter, Zuo *et al*, 2011) was used to build the physical system while *Modelica_StateGraph2* (Otter, Årzén *et al*, 2005) was employed to simulate the control system. The simulation platform is Dymola 2015 FD01.

Figure 6 shows the diagram of the top-level model for the whole system. It consists of five components: the DHW system, the connecting loop, the heat pump for the space conditioning, the condenser water loop, and the supervisor control system. Solid blue lines are pipes connecting the components and dashed lines are input or output signals for controls. We use the DHW system and the supervisor controller as examples to show the details of the Modelica models.
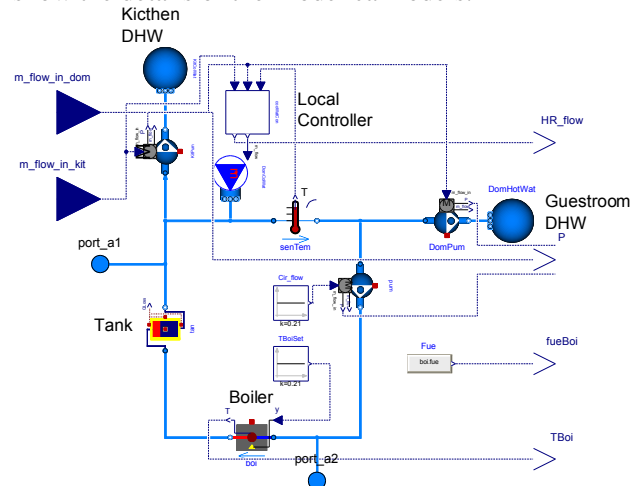

Figure 5. Diagram of the model for DHW system

Figure 5 is the model for the DHW system. The similarity between the system schematic (Figure 1) and Modelica models (Figure 5) allows a quick identification of modeling error. The DHW system model consists of physical equipment, such as a boiler (Boiler-1), a tank, and pumps, and the local controller for the temperature of DHW supplied to the guestrooms. This controller is committed to provide a 43.3°C hot water to the guestroom by mixing 60°C hot water from the boiler with the city water. The input of the DHW system model is the DHW demand for the
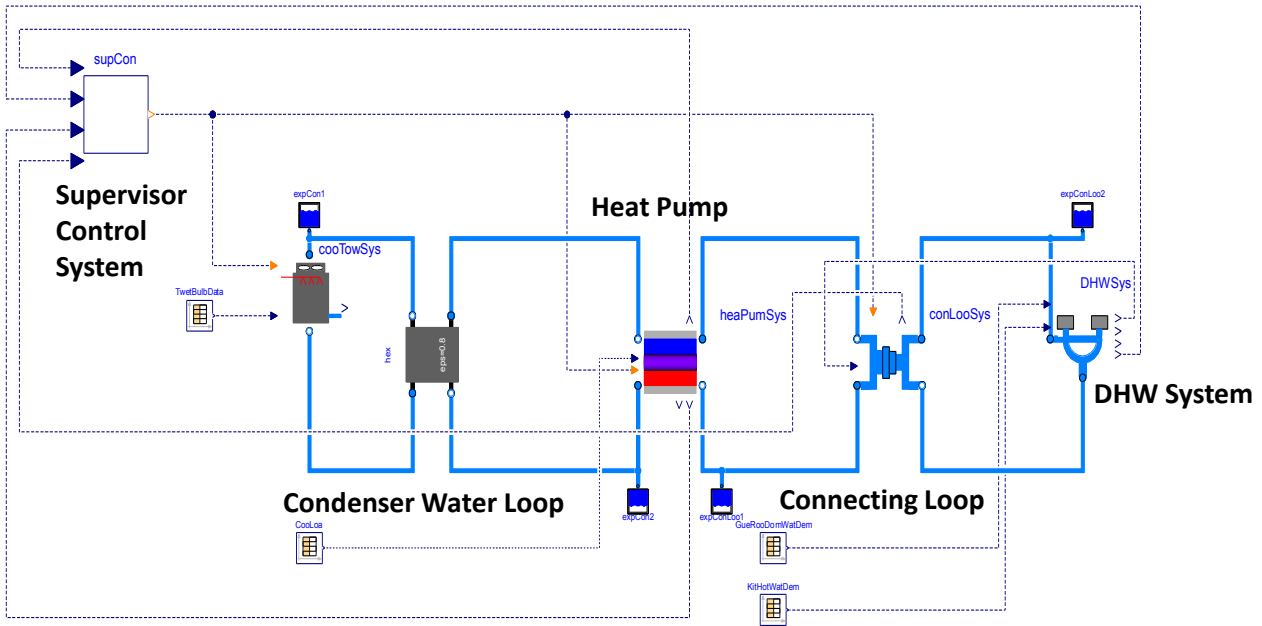
Figure 6. Diagram of the top-level model

kitchen and the guestroom while the output is the temperature of the DHW leaving Boiler-1 and the calculated recovering water flow rate as well as the energy consumption of Bolier-1 and so on.

Figure 7 shows the Modelica model for the supervisor control. The key part of this model is the state machine model, which consists of state (oval icon) and transition (bar icon) modules. The state modules were used to represent the seven states described in Figure 4. The input of the supervisor control model includes temperature of the condenser water entering and leaving the heat pump, the temperature of DHW leaving Boiler-1 and the heat recovering water flow rate. Its output is the state for the whole system.
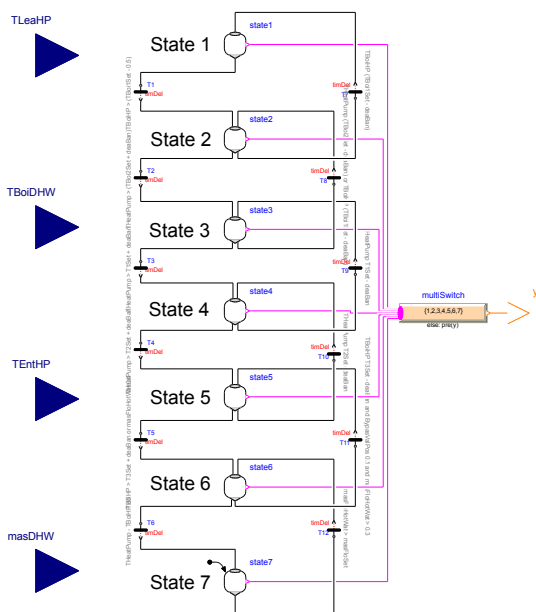

Figure 7. Diagram of the model for the supervisory control

3.2 Evaluation Setting

To evaluate the performance of the proposed heat recovery system, we simulated the system for one year period using a typical weather data. In addition, we studied the system for a typical cooling day and a special day.

For the annual simulation, there are three input variables: the weather data, the cooling load and the DHW demand. The weather data we used is the TMY (Typical Meteorological Year) file for the nearby Miami International Airport (U.S. Department of Energy). The cooling load is the heat that needs to be removed from the building. A negative sign of the cooling load means the heat is added into the building for the space heating (heating load). We used an empirical equation to calculate the cooling load according to the outdoor temperature:

$$\dot{Q} = \begin{cases} 4100\left(\dfrac{T-21}{11}+\dfrac{1}{2}\right) & 4100\left(\dfrac{T-21}{11}+\dfrac{1}{2}\right) > -145 \\ 4100\left(\dfrac{T-21}{11}+\dfrac{1}{2}\right) \le -145 & -145 \end{cases} \quad (1)$$

where $\dot{Q}$ is the cooling load (kW) and T is the outdoor air dry bulb temperature.

Furthermore, based on the engineering knowledge, we created a profile for the typical daily DHW demand in the hotel. The peak of DHW usage by the guestroom appears in the morning when guests get up and in late afternoon when guests come back from the beach. The DHW usage by the kitchen is mainly for preparing the lunch and dinner. The generated load and DHW profile is shown in Figure 8.
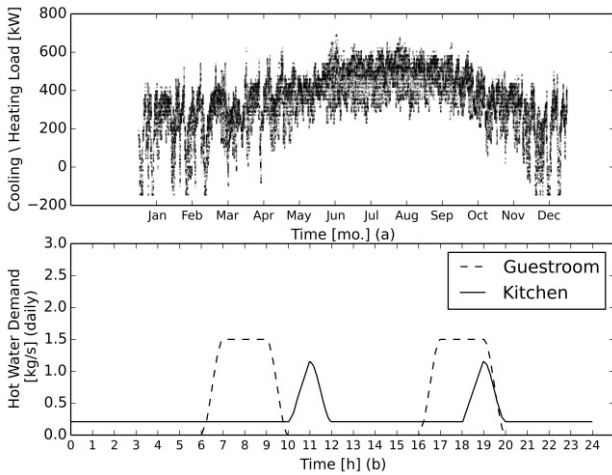
Figure 8. Cooling \ heating load and hot water usage profile for the annual simulation

For the typical cooling day, there would solely be cooling demand in the building. We used the same hourly DHW demand profile described in Figure 8 and a new hourly cooling load profile shown in Figure 9.
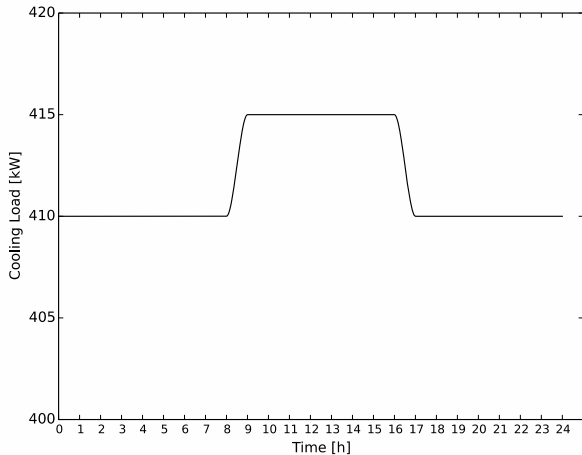

Figure 9. Cooling load for the typical cooling day simulation

For the special day (Feb 13), the heating and cooling was both needed as the day passed. We choose this day to evaluate the robustness of the supervisory control. We used the same hot water demand profile and use equation (1) to generate the load profile for cooling \ heating load data that is shown in Figure 10. According to the load, the operation mode of the space conditioning system should change from space cooling to space heating in the middle night. It then should turn back to space cooling in the morning.
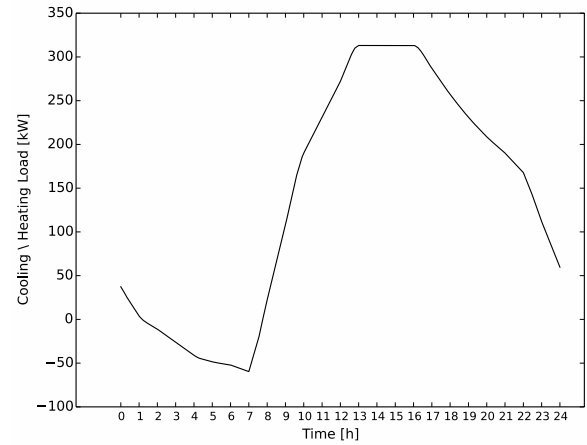

Figure 10. Cooling \ heating load for the special day simulation

3.3 Result

The result for the annual simulation is showed in Table 1 and Figure 11. The annual saving amount and saving ratio for Bolier-1 energy use is 411GJ and 19%, respectively.

Table 1. Annual simulation result

	Without heat recovery	With heat recovery
Boiler-1 annual energy consumption (GJ)	2,196	1,785
Boiler-1 annual energy saving ratio	N/A	19%

As expected, the system largely operated at State 5 to 7 and there was energy saving potential for Boiler-1 throughout the whole year (Figure 11). Most of the energy savings ranged from 20% to 30%. There were some days in the winter that the space heating was needed and the system ran at Sate 1 to 3. There are only a few hours that the system ran at State 1 when the cold weather and extreme large DHW demand happened at the same time.
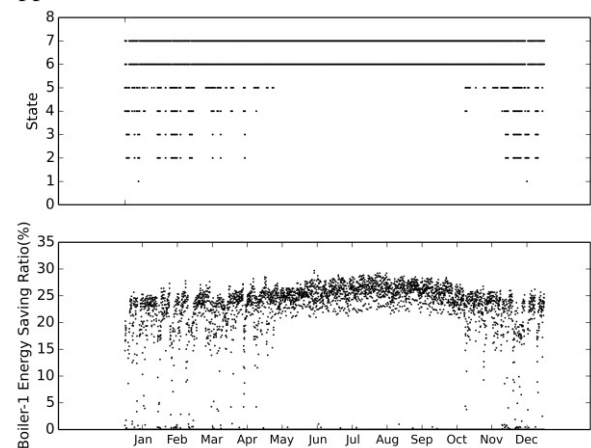

Figure 11. Annual simulation results

As shown in Figure 12 is the simulation result for the typical cooling day, the system mainly operated at States 6 and 7 depending on the DHW usage. If the DHW usage is sufficiently large, the heat recovery system ran at State 6 and saved about 25% energy for Boiler-1. Otherwise, the system ran at State 7 and there was no energy saving.
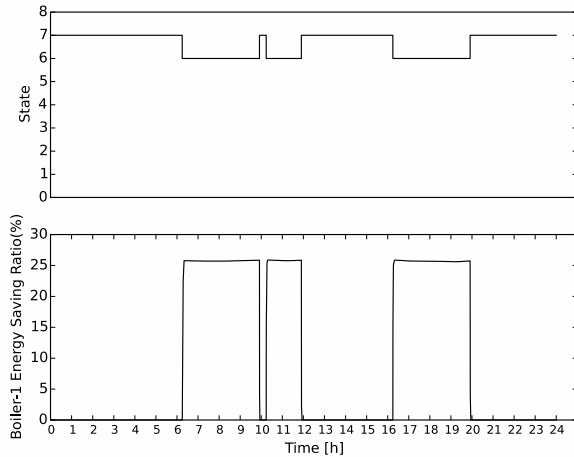

Figure 12. Simulation results for the typical cooling day

As shown in Figure 13, the system state in the special day changed from State 7 to State 2 in the early morning to switch from the space cooling to the space heating. It then switched back to the space cooling in the late morning. When the cooling load was below 200kW or there was only a little DHW demand, there was no energy savings taking place. However, when the cooling load rose above 200kW and there was DHW demand, Boiler-1 energy savings ratio spiked to just fewer than 25%. Then when the guestroom DHW demand was high between four to eight o'clock in the afternoon the boiler energy saving ratio stayed between 20% and 25%. The fall to 20% at the end of the time period could be attributed to additional DHW need for the kitchen and the lack of waste heat being transferred to warm up the 2.7kg/s of city water during the winter.
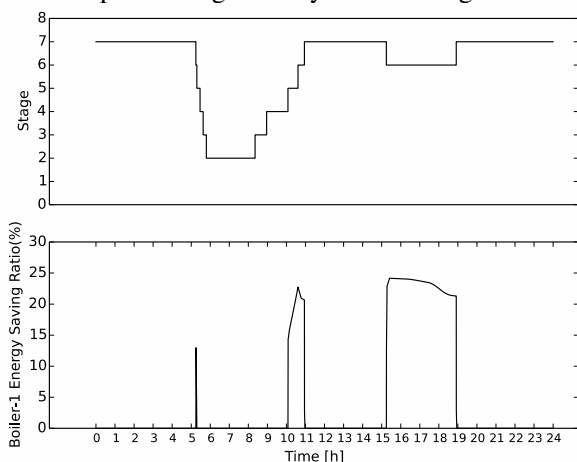

Figure 13. Simulation results for the special day

4 Conclusion

Based on the above analysis, we can find that,
1) the proposed heat recovery system can bring up to around 30% energy savings by the DHW boiler;
2) the special day simulation result showed that the proposed control system was able to regulate the relatively complicated system operation.

As we mentioned in the introduce section, the heat recovery system would affect not only the energy use of the boilers but also that of pumps and the cooling towers. However, due to the lack of the performance data, we couldn't make a quantitative analysis regarding the impact of heat recovery system on the pumps and the cooling towers energy use. Besides the energy saving, the reduction in the water usage by the cooling towers was also not considered since the water system was excluded from current simulation scope. At the next stage of this study, we will perform a more comprehensive evaluation after identifying the missing performance data for other equipment and including the water system in the system modeling. Based on those results, we may make recommendations for the design and control of heat recovery systems of hotels in tropical climate.

This study shows that there are advantages to using Modelica in the modeling of the building system. On the other hand, it still is challenging in debugging the Modelica models for the building systems using current Modelica environment, e.g. Dymola, since only limited information is provided during the simulation.

Acknowledgement

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