VARIABLE HEAT RECOVERY IN DOUBLE BUNDLE ELECTRIC CHILLERS

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ABSTRACT

In programs such as BLAST and DOE–2, the Double Bundle Electric Chiller model uses fixed input values for determining the recoverable heat component. The drawback of this approach is no dependence on system demands, plant, and cooling tower loads. Determining the availability or gradation (quality of heat) of the recoverable heat, is a subjective user input, and independent of the flow rates and temperatures. In a program like EnergyPlus, the plant and heat recovery equipment is now connected with loops having mass flow rates and temperatures, allowing for a more sophisticated simulation. Execution speed still restricts the chiller simulation to empirical models that give the total condenser heat as an output for the cooling tower and heat recovery loops. A new algorithm that bases the recoverable heat fraction on the flow rates and inlet temperatures has been developed. This algorithm uses relatively simple inputs to determine the fraction of the heat recovered and the heat rejected by the cooling tower. The variations in the mass flow rates and temperatures in the simulation are now used to obtain more realistic heat transfer rates of each component.

This paper presents an analysis of the new algorithm for determining the heat recovery factor, and presents examples showing its performance and advantages of this model over the simple model. The electric chiller in EnergyPlus now has the option of having its condenser hooked up to a heat recovery loop, or what is commonly known as a double bundled chiller.

INTRODUCTION

With the development of high discharge pressure, temperature, compressors, recovering heat from the chiller's condenser has improved significantly. This recovered heat can be used for domestic hot water systems, air-handling unit preheating, heating, or reheating coils, etc. Since there is no reason to heat air with high temperature water during summer, a heat recovery chiller can be used in providing warm water to the reheat coils during that time. Recovered heat can be used when hot water and chilled water are used simultaneously in the building, or it can be stored in a hot water storage tank and used later.

Not all buildings are suitable for chiller heat recovery, but facilities with sufficient internal loads and a simultaneous heat or reheat demand, or buildings that use a large amount of domestic water throughout the year can be considered for heat recovery. Buildings that eliminate boiler operation in the summer can use heat recovery as an option to have reheat available for comfort.

The Heat Recovery chiller in EnergyPlus is simulated using an empirical model for a standard vapor compression refrigeration cycle, then simulates the double bundled condenser. A double bundle condenser involves two separate flow loops through the condenser; one loop can be a standard cooling tower, the other loop is for heat recovery. This chiller is used as a heat recovery machine when condenser heat is rejected at a temperature high enough to be used for space heating or other uses. The water flow rate in the tower and heat recovery loops can be modified by the user to maintain a high temperature for the heat recovery loop. Excess heat not recovered is rejected to the cooling tower loop. Therefore the performance of the double bundle chiller is mainly dependent on the load entering the condenser from the compressor, and the temperature and mass flow rates from the connected loops.

ELECTRIC CHILLER HEAT RECOVERY ALGORITHM DEVELOPMENT

Model Assumptions and Constraints:

An empirical chiller model is used to simulate the vapor compression refrigeration cycle in EnergyPlus. This empirical model does not provide condenser temperatures or mass flow rates, just a condenser heat transfer rate, Qcond, that needs to be rejected. The evaporator load and chiller electric consumption make up the condenser load. This constrains the condenser to reject all of the heat from the refrigeration cycle.

The mass flow rates from the cooling tower loop and heat recovery loop are determined by system operation before they enter the condenser.

The algorithm development assumes the UA as constant for both heat exchangers in the double bundled condenser.

In a real system performance could be improved if the hot gas inlet from the compressor would flow through the heat recovery heat exchanger first and then cooling tower heat exchanger. In this algorithm development we are assuming symmetry.

ALGORITHM DEVELOPMENT

The objective for this model was to maintain simple user inputs while allowing temperature and flow dependence in the condenser of the chiller. The user would like to describe the heat recovery parameters with simple inputs to estimate the amount of the heat that is recovered and the amount of heat rejected by the cooling tower. The simple user inputs in this model are the flow rates of the cooling tower and heat recovery loops. The heat balance for the chiller in Equation 1 describes the total heat rejected and the quantities that need to be determined, the cooling tower and heat recovery heat transfer.

Equation 1 describes the four main contributors to the heat balance of the chiller.

$$Q_{Cond} = Q_{Evap} + Q_{Elec} = Q_{CTow} + Q_{Heat\,Rec} \quad (1)$$

Equation 2 describes the total condenser heat transfer in terms of the heat recovered and heat rejected.

$$Q_{Cond} = \dot{m}_{CTow} * Cp_{CTow} * (T_{CTowOut} - T_{CTowIn}) + \dot{m}_{Heat\,Rec} * Cp_{Heat\,Rec} * (T_{Heat\,RecOut} - T_{Heat\,RecIn}) \quad (2)$$

Keeping the total condenser heat transfer constant and approximating the heat recovered and heat rejected with average temperatures in and out, since the values of the outlet temperatures are not known. This is shown in Equation 3.

$$Q_{Cond} = (\dot{m}_{CTow} * Cp_{CTow} + \dot{m}_{Heat\,Rec} * Cp_{Heat\,Rec}) * (T_{AvgOut} - T_{AvgIn}) \quad (3)$$

Then the inlet temperature can be flow ratio averaged to determine its conditions using Equation 4.

$$T_{AvgIn} = \frac{(\dot{m}_{CTow} * Cp_{CTow} * T_{CTowOut} + \dot{m}_{Heat\,Rec} * Cp_{Heat\,Rec} * T_{Heat\,RecIn})}{\dot{m}_{CTow} * Cp_{CTow} + \dot{m}_{Heat\,Rec} * Cp_{Heat\,Rec}} \quad (4)$$

Subsequently the average outlet temperature can be determined from Equation 5.

$$T_{AvgOut} = T_{AvgIn} + \frac{Q_{Cond}}{\dot{m}_{CTow} * Cp_{CTow} + \dot{m}_{Heat\,Rec} * Cp_{Heat\,Rec}} \quad (5)$$

The total heat can be approximated as the fractional split between heat recovered and rejection through the tower with Equation 6.

$$\frac{Q_{Heat\,Rec}}{Q_{Cond}} = Frac_{Heat\,Rec} = \frac{\dot{m}_{Heat\,Rec} * Cp_{Heat\,Rec} * (T_{AvgOut} - T_{AvgIn})}{\dot{m}_{CTow} * Cp_{CTow} * (T_{AvgOut} - T_{AvgIn})} \quad (6)$$

The heat rejected by the cooling tower and by heat recovery can be calculated by Equations 7 and 8.

$$Q_{CTower} = (1 - Frac_{Heat\,Rec}) * Q_{Cond} \quad (7)$$

$$Q_{Heat\,Rec} = (Frac_{Heat\,Rec}) * Q_{Cond} \quad (8)$$

Equation (7) and (8) now provide an approximate split of the heat recovered with relationship to the mass flow rates and the inlet temperatures. The earlier alternative to variable heat recovered was the user having to pre-determine the heat recovery split with no dependence on the actual simulation conditions.

Knowledge of temperatures at the inlet and exit of the loop eliminates the problem of determining the availability or grading the recoverable heat for usage in the building systems a priori. For example, when the temperature returning from the heat recovery loop is greater than the calculated temperature entering the condenser, the fraction of heat transferred to heat recovery loop tends to zero. The next section shows how this algorithm performs in an energy analysis of a building with an electric chiller with heat recovery.

SIMULATION RESULTS

The electric chiller in this simulation has heat rejected to the condenser with a cooling tower loop, and heat recovery loop attached to a water heat storage tank, defined as perimeter with an electric heating element, as shown in Figure 1.

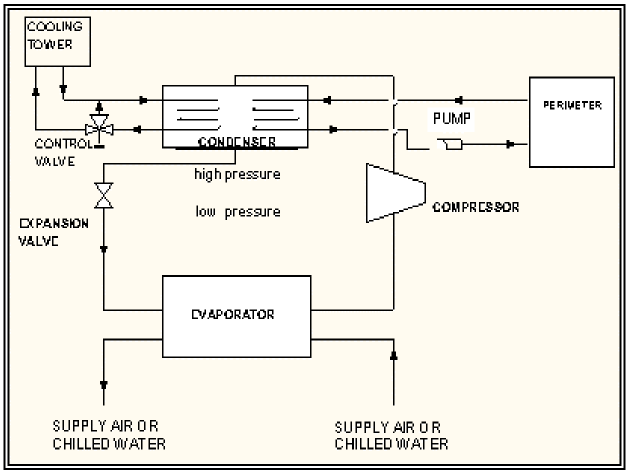

Figure1: Diagram of General Electric Chiller with Heat Recovery.

The hot water storage tank, used for perimeter heating, allows for storage of the recovered heat at other times. The reheat coils are attached to a hot water loop, which in turn is attached to the hot water tank. For the base case the electric heating element is scheduled to operate from October to the end of March. From April to the end of September the heat recovered from the double bundle chiller provides all of the heat for the reheat coils to maintain zone comfort. The water tank has a loss term and both the heat recovery pump and the hot water pump contribute to the simulation.

Weekly Simulation Results

Figures 2 through 7 show hourly results for an annual simulation for the last week of June with the first two days being a weekend.

Figure 2 shows cooling tower heat transfer rate and the heat recovery rate plotted hourly. The algorithms described in the previous sections determine the fraction of heat recovered. Figure 2 show variable heat recovery and based on the simulation conditions. The effect of this heat recovery is evident on the cooling tower load, as the chiller load increases during the peak-cooling load for the day. The two curves shows how the total condenser load from the chiller is being distributed between heat recovered and the cooling tower.

Figure 3 shows the evaporator load, or cooling coil load and the dynamic response of the hot water loop, heat recovery loop, and tank water capacitance. It shows the Total Reheat Load, Heat Recovery Used Rate, and the Evaporator Load. The Big Water Heater Heat Recovery Rate supplies the Total Reheat Loads, and it can be seen that the Heat Recovery Rate tries to match the Total Reheat Load. The water tank has a loss term and the amount of heat recovered includes the tank loss.

Figure 4 shows the temperature variation of the hot water tank, and the inlet and outlet temperature to the hot water loop attached to the reheat coils and the water tank. The graph shows the heat loss during the night in the hot water tank, and over the weekend the tank equilibrates with the zone temperature. The hot water loop only operates during the day and is shut off at night. The loops do not have a heat loss term therefore their temperature is constant from the last operating condition. Otherwise the temperature in the hot water loop is nearly the water tank temperature. The outlet from the reheat coil fluctuates with the cooling coil conditions.

Figure 5 shows the heat recovery inlet and the outlet temperatures. When the outlet temperature is higher than the inlet temperature this provides a heat recovery energy source and when both temperatures are the same the system is off.

Figure 6 shows the cooling tower water loop inlet and outlet temperatures. This shows that the majority of the heat is being rejected through the cooling tower. The comparison of the inlet temperatures from the cooling tower loop and the heat recovery loop reveals that the cooling tower loop inlet temperatures are lower overall. Since the inlet temperatures for the heat recovery loop are not as low, there is greater heat rejected to cooling tower. Figures 5 and 6 illustrate how the simulation conditions affect the fraction of heat recovered.

Figure 7 shows that the outlet temperatures from the heat recovery loop and the cooling tower loop are nearly the same. This is from the average temperature out assumption and then using that answer to determine the fraction of heat recovered. After the heat rejected to the cooling tower and heat recovery loop are calculated, the actual outlet conditions for each loop are calculated from the flow rates and inlet temperatures. This can result in slightly different outlet temperatures where in an ideal model they would be the same.

This new algorithm allows the next level of realism in simulation of variable heat recovery. The dynamic response of the system is accounted for in this new algorithm and is achieved in a simple manner without using a complex simulation model requiring large number of user inputs and greater processor time.

Annual Simulation Results

The annual simulation results help to determine the overall performance of algorithm of the component models. Figure 8 shows the performance and interactions of the cooling load; reheat load, heat recovery, and water tank electric heating element. The water heater heat recovery rate supplies the total requirement of the reheat coil during the summer months and is higher than the total reheat coil rate. This difference accounts for the recoverable heat lost to the environment due to thermal losses in the water storage tank. Figure 8 shows that the water heater electric consumption rate is zero in the summer, but with the reheat load being met this avoids what would have been occupant thermal discomfort. This recovered heat would have been waste heat and rejected to the atmosphere, instead is being utilized for reheat for the added cost of operating the heat recovery pump. This can be seen in Figures 8 between April and September when heat recovery is maximized. During the winter the reheat loads are met by the electric heating element on the water tank.

In Figure 9 there are 3 different cases that have been studied:
Case 1 No heat Recovery and No Reheat, with Heat Recovery and Hot Water pumps turned off.
Case 2 Heat Recovery operating, this is the base case.
Case 3 No Heat Recovery with Water Tank Electric element being operational.

Some energy standards do not allow buildings to reheat air that has just been cooled. This standard of operation does save the most energy, but occupant comfort is sacrificed if a system is not perfectly balanced. As expected, Figure 9 does show the monthly electric consumption with no summer reheat coil operations to have the lowest energy consumption of the three cases. But with a small, additional energy expense of operating the heat recovery pump, occupant comfort can still be achieved. If the electric water-heating element were used to meet the reheat demands, the electric consumption increases significantly as shown in Figure 9.

CONCLUSION

The use of heat recovery chillers is an old energy conservation method, but the development of digital control, along with high-pressure compressors (screw or scroll chillers) has opened a renewed interest in this energy conservation method.

The algorithm developed in this paper allows for the next level of realism without changing the empirical chiller model or burdening the user with many new inputs. This algorithm utilizes the information that is being simulated by the water loops to provide the interactions and inputs necessary to improve the simulation.

This paper shows how the chiller model and heat recovery fraction can interact with the loop inlet temperatures and mass flow rates. Currently simulation controls for the mass flow rates are constant for the entire simulation. Additional controls can be developed that can monitor the temperature at the inlet and outlets of the cooling tower and heat recovery loops to control the mass flow rates to further optimize the performance of the heat recovery.

NOMENCLATURE

The variables used in many cases are formed by combination of various other variables/abbreviations as shown in the following example:
THeatRecIn=Temperature of Heat Recovery at Inlet

Q:	Heat Transfer Rate
CTow:	CoolingTower
Evap:	Evaporator
Elec:	Electric
Cond:	Condenser
HeatRec:	Heat Recovery
M	Mass flow rate of water
T:	Temperature
RecOut:	Recovery Outside
RecIn:	Recovery In
Cp:	Specific Heat Capacity of fluid.
AvgIn:	Average Inside
AvgOut:	Average Outside
Frac:	Fraction

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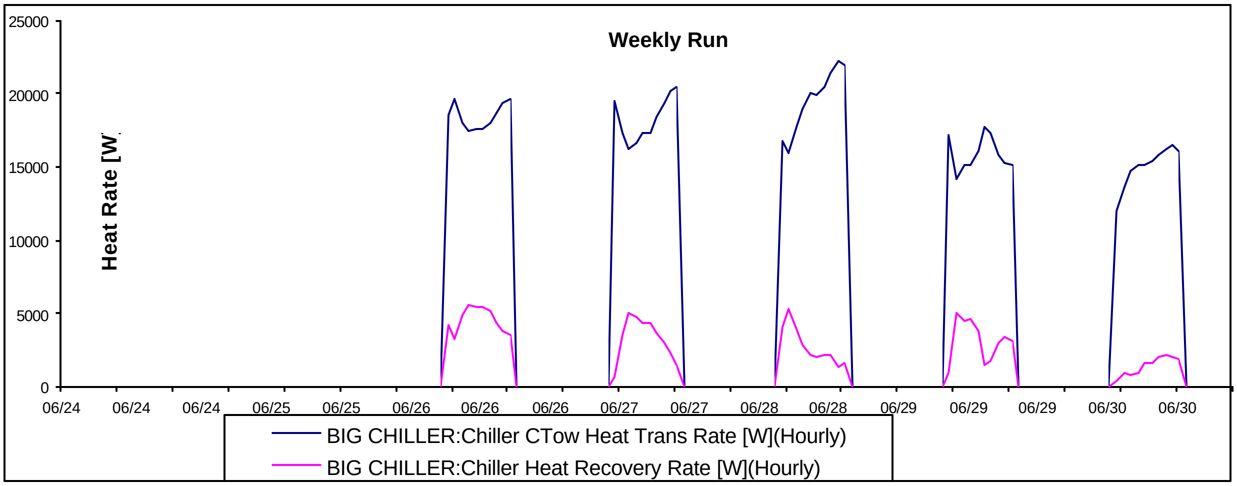

Figure 2: Cooling Tower Heat Transfer Rate and Heat Recovery Rate

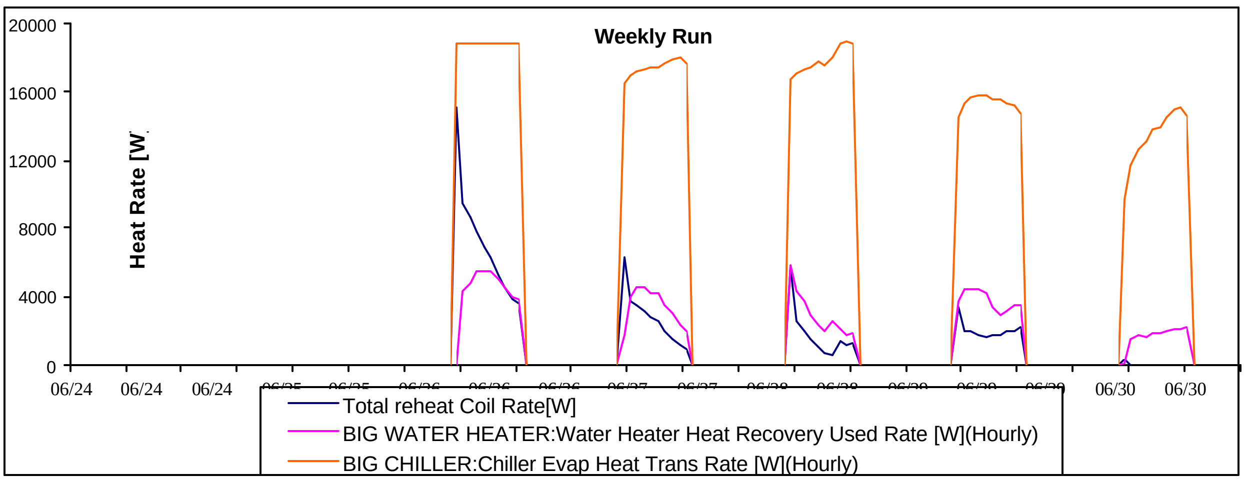

Figure 3: Evaporator Load on system

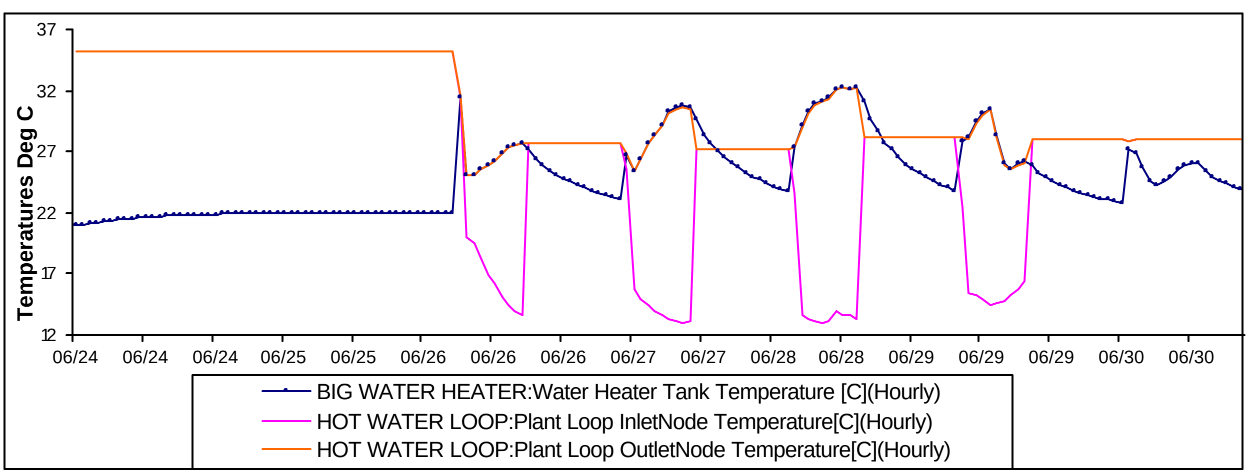

Figure 4; Temperature Variation of Hot Water Tank and Loops

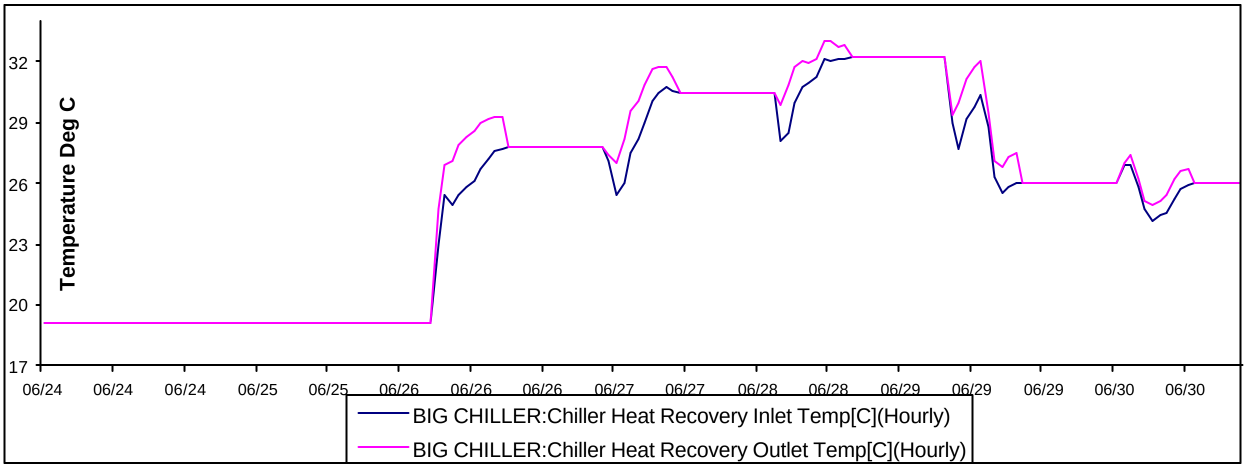

Figure 5: Heat Recovery Inlet and Outlet Temperatures

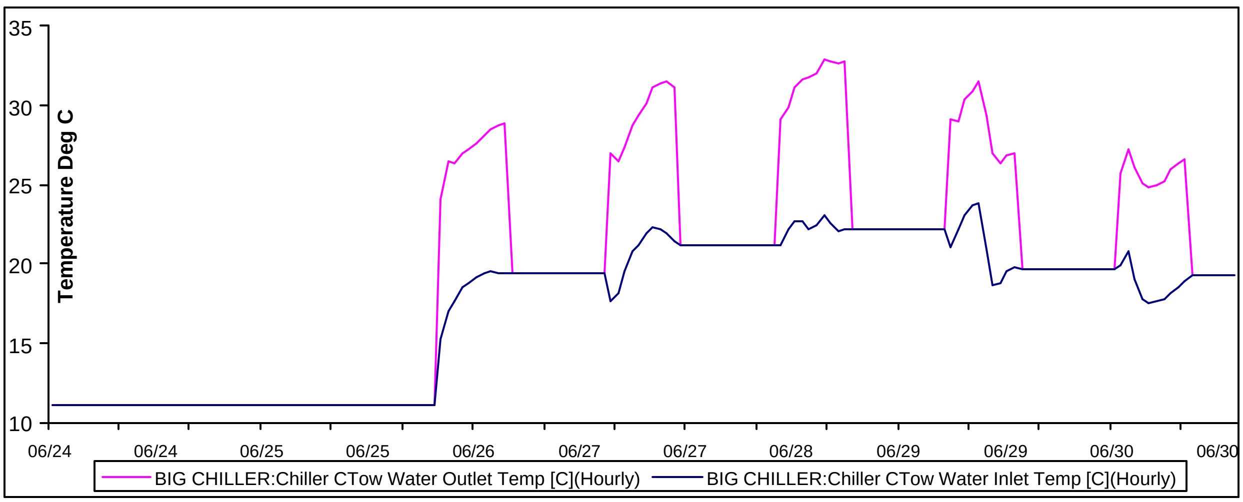

Figure 6: Cooling Tower Water Loop Temperatures

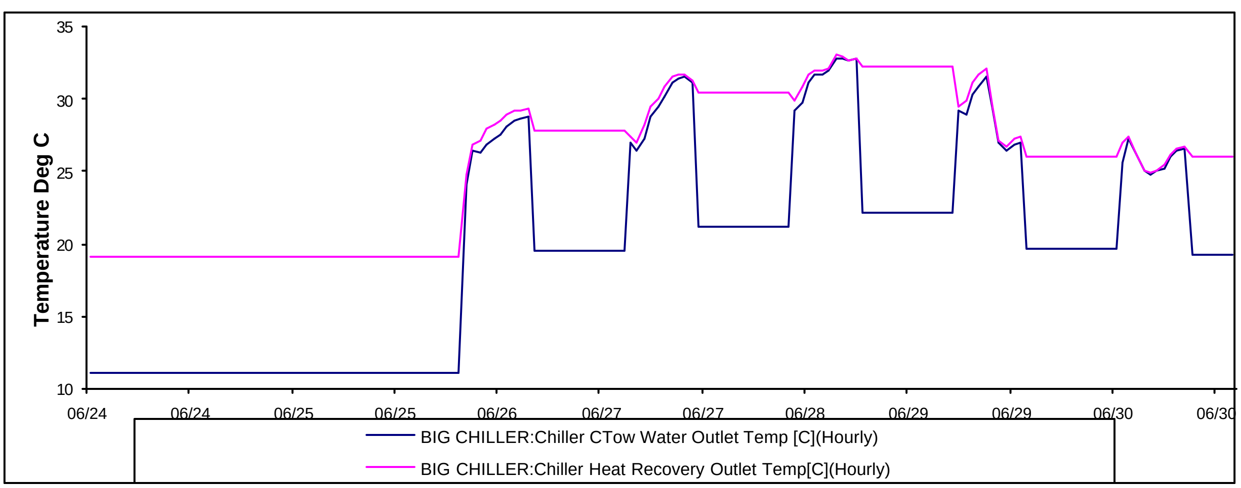

Figure 7: Outlet Heat Recovery & Outlet Chiller Condenser Temperature

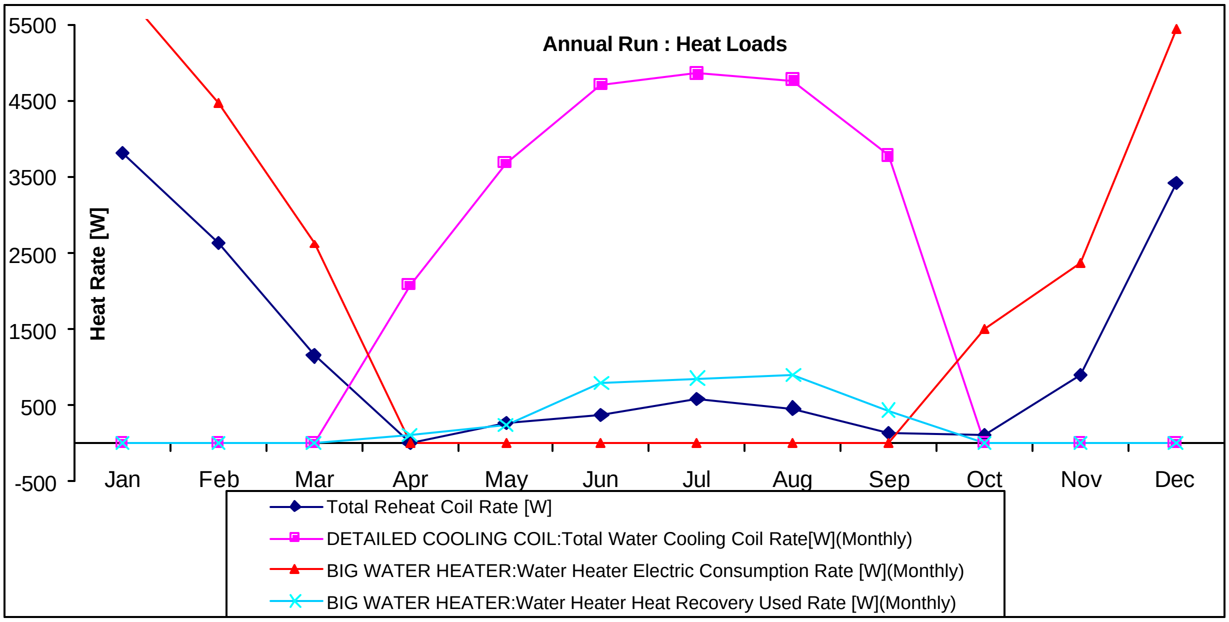

Figure 8: Load Comparison & Performances

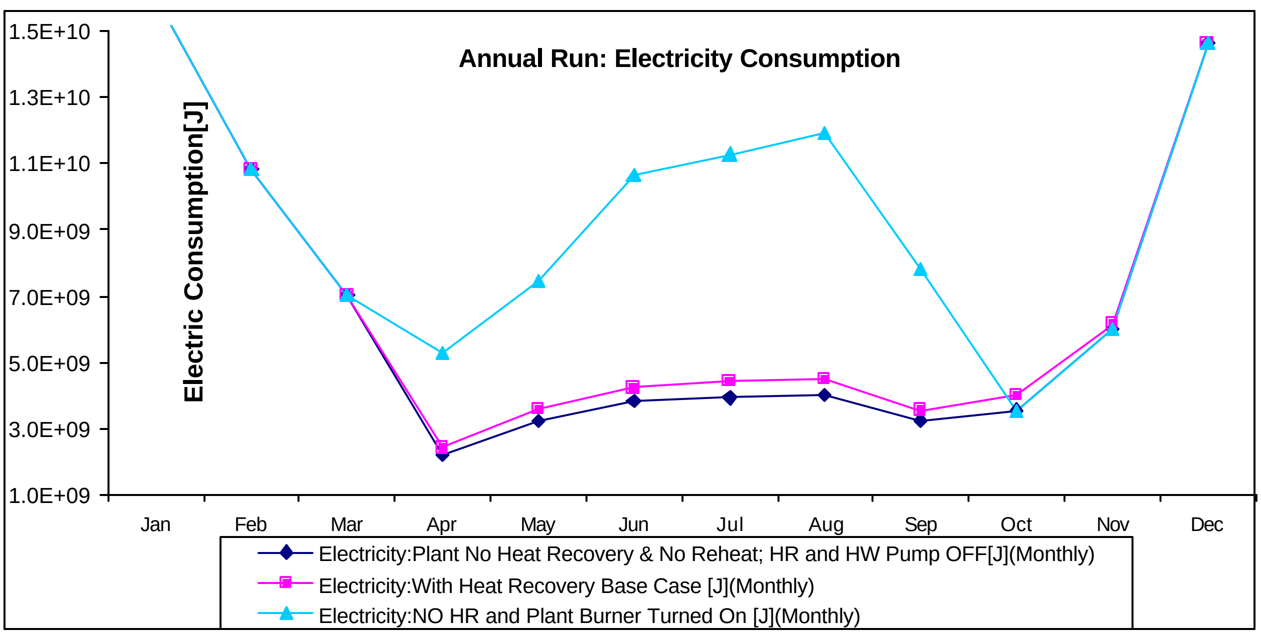

Figure 9: Heat Recovery & Non Recovery Cases