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Assessment of Simulation Models when Considering Energy Efficiency in a Real-World District Cooling System Condenser Loop

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Abstract

In the past, researchers have published many studies investigating the usefulness of reducing condenser loop flow in chiller systems. Some authors broadly recommended reducing condenser loop flow rate to save system power, while others claimed that reducing condenser loop flow rate was not always advisable. This study aims to compare results from two widely used chiller model calibration methods. A model of a real system was built and validated in Modelica, and test simulations were performed as part of a case study. Presented results for several 24-hour test periods indicate that in this particular system reduced condenser loop flow generally causes an increase in system power, and even when condenser loop flow is optimized, savings compared to a baseline are 1.5% or lower.

Introduction

Optimal control sequences are an integral part of efficient district energy system operation. In large energy intensive campus systems utilizing district energy, a properly designed control sequence can result in significant energy savings. In a typical district cooling system, energy is consumed by the chiller, cooling tower, and distribution pumps for the condenser-cooling tower loop and the evaporator chilled water loop. One aspect of district cooling system control that has been studied by various authors in the past without producing consistent results is that of varying condenser-cooling tower loop flow. If this condenser loop flow ($\dot{\boldsymbol{V}}$) is reduced by variable speed pumps, it will save pump power by following the pump power law ($P\sim\dot{\boldsymbol{V}}^{3}$). However, the reduction in flow will cause larger condenser inlet-outlet temperature differences which may result in higher average condenser water temperatures; this increases the work done by the compressor, thereby increasing the chiller's electricity consumption. Some past studies have claimed that the savings in pump power was greater than the cost of increased chiller electricity consumption and favoured reducing condenser loop flow below established 3.0 GPM/Ton industry guidelines (Kirsner, 1996). Several of these studies recommending reduced condenser loop flow were summarized by Kirsner in his own study (Kirsner, 1996). Trane engineers performed a study and found that reduced condenser loop flow was beneficial at all conditions they examined, and savings ranged from 4.6% of total system power at 90% load to 27% of total system power at 30% load (Schwedler, 2012). Other studies have claimed that the unique attributes of each individual cooling system make it difficult to draw conclusions applicable to all, and presented results where reduced flow either decreased or increased power consumption depending on specific design conditions (Kirsner, 1996; Wang et al., 2020; Zhang & Liu, 2012).

To build upon these past studies this paper will take advantage of equation-based object-oriented modelling using the Modelica language and further investigate how operation conditions and modelling methods impact the calculated savings. Modelica features an open source buildings library developed at Lawrence Berkeley National Laboratory that allows users to build custom system models from connecting different building components such as pumps, cooling towers, chillers, and many other HVAC components not used in this paper (Wetter et al., 2014). The library enables fast and accurate simulation of integrated building energy systems while minimizing manual coding. Users can provide component performance characteristics and input data to produce validated models for further testing. Recent studies have shown that Modelica is extremely useful for simulating building HVAC systems and components while also optimizing control schemes and setpoints (Anbarasu et al., 2022; Fan et al., 2021; Fu et al., 2019; Hinkelman et al., 2021; Hinkelman et al., 2022).

The cooling system modelled in Modelica for this study is located at the University of Texas (UT) at Austin. UT Austin utilizes a district energy cooling plant comprising six chilling stations that can produce 60,000 tons of cooling while serving 160 campus buildings. The cooling system is closely monitored and provides high frequency data from all major components enabling accurate system validation. For the purposes of this study, components from the campus' highly efficient chilling station 6 (which utilizes variable speed chillers, pumps, and cooling tower fans) were modelled and validated with real time operating data. The coupled model produced results for chiller power, overall system power, and entering and leaving water temperatures. Results related to the condenser loop flow effect on power were compared to the previously described studies. The combination of a well-defined Modelica district cooling system model, and the expansive availability of campus operating data allowed this study to provide a unique analysis of the effect of condenser loop flow rate on system power consumption and to investigate the usefulness of two different chiller models integrated in the Modelica library for such studies.

Methodology

To construct a simulation model for this study in Modelica, equipment characteristics had to be identified and input into Modelica blocks. Then necessary system connections were made linking components together, and the system was validated with measured data. Finally, differing condenser flow operating points could be tested and compared. For the model construction process, system component performance data was collected from existing construction drawings, specifications, equipment nameplates, and designed sequence of operation. A schematic of the UT Austin chiller station 6 is shown in Figure 1.

In Figure 1 there are three 5,000 ton chillers, three 15,000 gallon per minute cooling towers, four condenser water pumps, and four chilled water pumps. The chilled water side of the modelled system was used as input data for the chiller cooling load. This included chilled water flow rate, supply temperature, and return temperature. On the condenser side, one of the four pumps was only used as a standby. In this chilling station, the sequence of operation requires that one condenser pump and one cooling tower operate with each chiller; depending on the cooling load additional chillers are added to the loop. When more than one chiller is operating, each chiller runs at the same part load, as does its corresponding tower and condenser pump. Therefore, modelling of the chilling station with this sequence of operation simplified the modelling procedure where only one chiller, one condenser pump, and one cooling tower needed to be simulated. The total cooling load of the chilling station was divided by the number of active chillers and the chiller plant could be modelled by a single chiller.

Component models were created in Modelica using existing blocks from the Modelica Buildings Library (MBL) for chillers, cooling towers, and pumps (Wetter et al., 2014). Within the MBL this model utilized two available chiller models: (1) the *Buildings.Fluid.Chillers.ElectricEIR* block, and (2) the *Buildings.Fluid.Chillers.ReformulatedElectricEIR* block. For the cooling tower and pumps the *Buildings.Fluid.HeatExchangers.CoolingTowers.Merkel* block, and the *Buildings.Fluid.Movers.FlowControlled_m_flow* block were used, respectively. Specifically, this study used the two different chiller modelling calibration methods described by Hydeman et al. to investigate applicability of these models with varying condenser flow rates and corresponding entering and leaving condenser water temperatures. The first model (*EIR*) predicts chiller power based on entering condenser water temperature, and the second (*ReformulatedEIR*) predicts chiller power from leaving condenser water temperature (Hydeman, Jr, et al., 2002; Hydeman, Webb, et al., 2002). Because the variable condenser water flow in the cooling tower-condenser loop impacts both entering and leaving condenser water temperatures, the two models produce different power consumption for differing condenser flow. The application of both with the wide range of flow rates in the high-fidelity models and the corresponding result analysis assessed whether either was useful. Specifically, Hydeman et al. (2002) stated that one motivation for creating the reformulated electric chiller calibration method was due to the original not accurately predicting power in systems with variable condenser flow; therefore, usefulness of results from the first method (*EIR*) must be analysed carefully. The cooling tower block is based on Merkel's theory of cooling tower heat transfer (Wetter et al., 2014), and the 'fluid mover' block models the performance of the variable speed condenser pump. The Modelica schematic of the system is shown in Figure 2.

In Figure 2 the condenser side of the chiller, cooling tower, and condenser pump were connected in a loop. The evaporator side of the chiller was provided with a flow source set equal to the corresponding entering chiller water flow and temperature. The outlet of the chiller evaporator was set to the system's chilled water setpoint. Thermometers on either side of the chiller condenser measured the entering and exiting temperature, and these signals were connected to a PI block that controlled the mass flow of the condenser pump. The ΔT of the condenser loop was used to control the pump's mass flow, and the effect of mass flow on system power was evaluated for different ΔT, or flowrate. The UT Austin chilling station 6 system was designed on an industry standard 3.0 GPM/Ton condenser loop flow rate, or approximately 5°C ΔT for the condenser loop. Performance

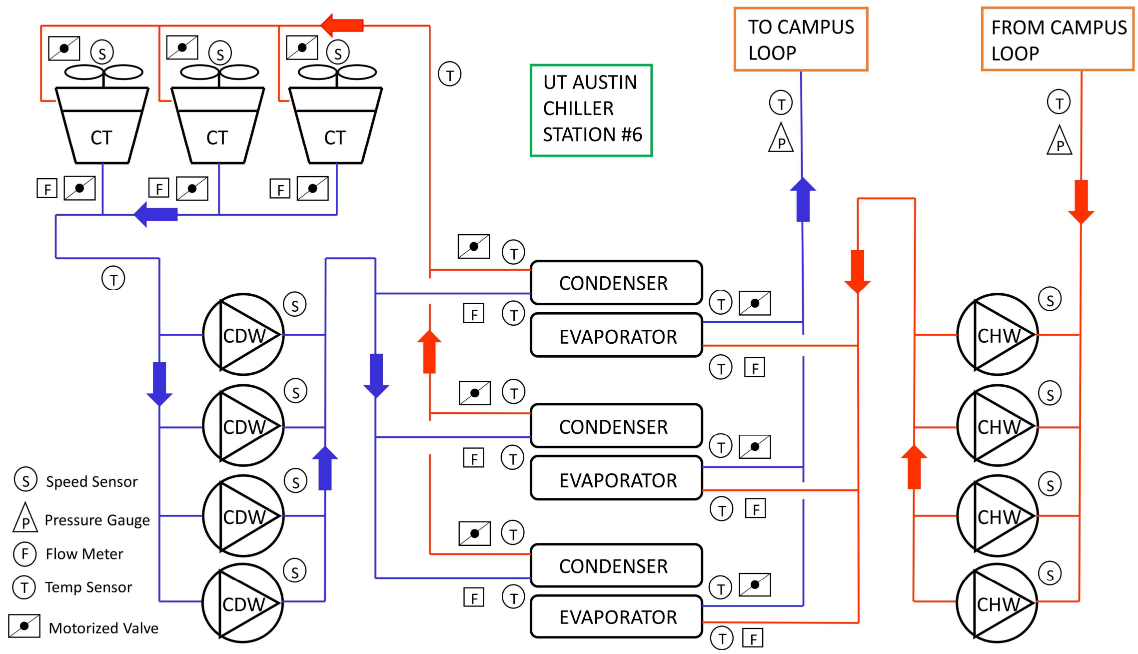

Figure 1: A schematic of the UT Austin chiller station 6 displaying cooling towers (CT), condenser water pumps (CDW), chilled water pumps (CHW), chillers, and system data points.

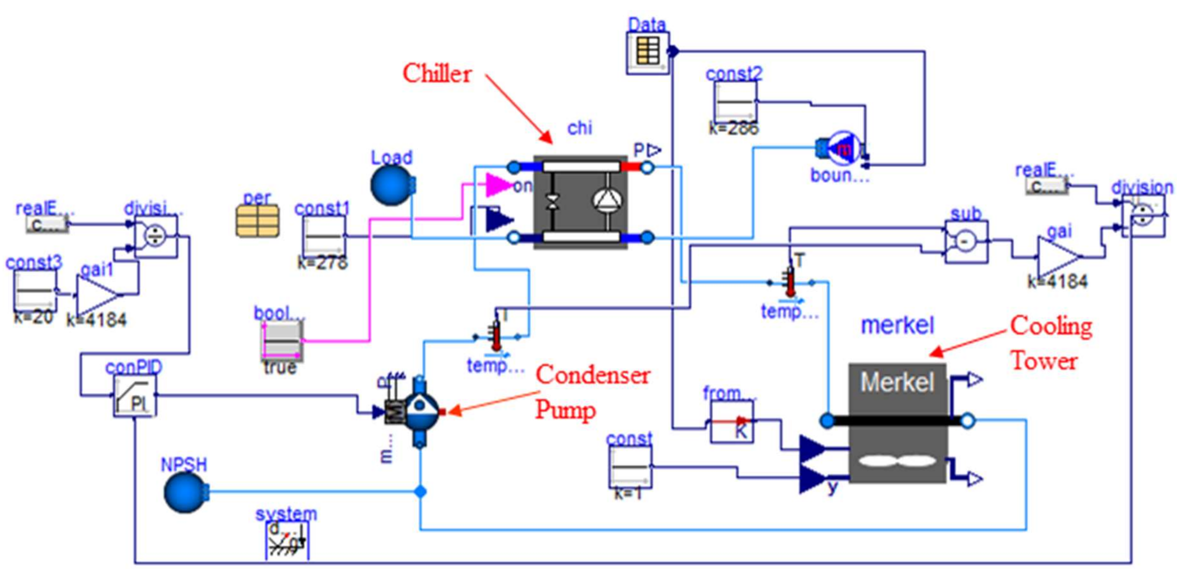

Figure 2: The Modelica system schematic of the cooling system including chiller (chi), cooling tower (merkel), and condenser pump.

characteristics of each component were defined within each block.

After the model was constructed, it was necessary to additionally adjust regression model coefficients for the chiller and cooling tower block based on measured data; further comparison of results generated by adjusted models validated the model for the given set of operation conditions. Specifically, to calibrate and validate system models, measured data was gathered and used to compare to predicted performance results. Certain parameters that define nominal chiller efficiency with variable speed were adjusted as needed to ensure error was within acceptable modelling standards as defined by ASHRAE (ASHRAE, 2014). ASHRAE defines a calibrated model as having mean bias error (MBE) less than 10% and coefficient of the variation of the root mean square error (CVRMSE) less than 30%. Validation testing was performed for a 72-hour test period and the results for each component are presented in Table 1.

Table 1 Cooling System Component Validation

Error Metric	**Chiller (EIR)**	**Chiller (Reformulated EIR)**	**Cooling Tower (Merkel)**	**Condenser Pump**
CVRMSE	3.7%	4.5%	2.6%	3.4%
MBE	2.7%	2.2%	1.1%	-0.7%

The results in Table 1 were within the acceptable range as defined by ASHRAE, and the model was considered calibrated. Having been calibrated, the model was then ready for testing different condenser flow rates controlled by ΔT, and the results are presented in the next section.

Results

This section will present results of the Modelica cooling system model tested with different condenser loop flow rates controlled by altering loop ΔT. The effect of loop ΔT on both (i) the overall chilling station and component power consumption and (ii) output cooling were compared for the two different chiller models (*EIR* and *ReformulatedEIR*) in a coupled Modelica simulation. Also, these results were compared to the results reported in previous studies on condenser loop flow.

In the following graphs, results displayed are from tests where the condenser loop ΔT was increased due to the proportional reduction in the condenser-cooling tower loop flow from the nominal/design flow. In these tests the cooling tower fan speed was kept constant and this reduced the leaving cooling tower water which entered the condenser. The UT station 6 system was nominally designed for condenser loop flow of about 3.0 GPM/Ton or approximately a 5°C ΔT. These values are used as a baseline for comparison. In each plot, ΔT is referred to as “R”.

The first results shown in Figure 3 were from a 24-hour test period (July 2023) using the *EIR* model with entering condenser water temperature. The results present the calculated chiller power from an increasing ΔT or (R) in the condenser loop. With the water flow reduced to 50%, 30% and 25% of the nominal flow this ΔT increased to 10, 15, and 20°C respectively, and the *EIR* chiller model results showed significantly lower electric power consumption by the chiller. This result did not seem reasonable, as it is known that a lower condenser flow rate will increase the temperature of the water leaving the condenser, thereby increasing chiller power. After further investigation it was found that because this particular method is dependent on entering condenser water, it will continue to output reduced chiller electrical consumption until the leaving condenser water reaches boiling point and the model crashes. This is because a decrease in condenser loop flow along with the cooling tower fan remaining at the same speed between tests produced a lower entering condenser water temperature. However, as the ΔT increased, the leaving condenser water temperature increased, and this negated the positive effect of lower entering water temperature with reduced flow. Depending on the operating condition, the evaporation temperature of refrigerant in the condenser will more or less increase (or in the best case stay the same) resulting in the higher (or same) power consumption, which should produce higher power consumption of the chiller. Obviously, the results in Figure 3 show that the *EIR* chiller does not capture this effect as it is designed to capture dependency only on entering condenser water temperature and not all of ΔT.

The continuous decrease of chiller power consumption with the lowering flow rate in Figure 3 demonstrated that the *Buildings.Fluid.Chillers.ElectricEIR* was not suitable for modelling impacts that variable condenser flow has on chiller and overall chilling station energy performance. This confirmed statements of Hydeman et. al (2002) that the original *EIR* model was in fact inaccurate in predicting the power usage of chillers with variable condenser flow.

The next set of tests investigated how the *Buildings.Fluid.Chillers.ReformulatedElectricEIR* block (which uses leaving condenser temperature to model the impact of varying refrigerant condensation temperature) captured the impact of reduced condenser-cooling tower water flow. It should be noted that in these simulations the condenser fan was kept constant, like in the simulations for the *EIR* model presented in Figure 3.

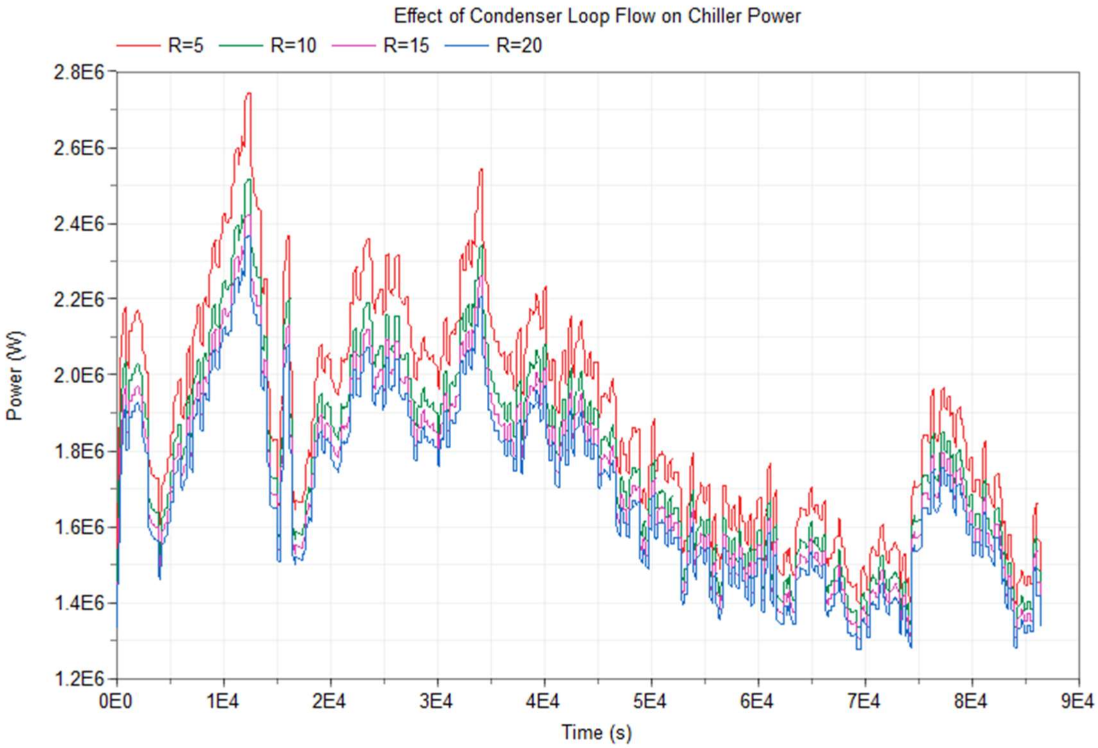

Figure 3: Test results displaying the effect of condenser loop flow on chiller power for various ΔT with Buildings.Fluid.Chillers.ElectricEIR chiller model. At the lowest R value of 5 (red), power is highest. As R is increased, power continues to decrease, and produces the lowest values at R=20 (blue).

Results testing the chiller power consumption with varying ΔT using the *ReformulatedEIR* block for the same 24-hour period (in July 2023) are displayed in Figure 4.

Results in Figure 4 show power consumption in line with expectations. As the loop ΔT was increased, and flow was reduced, the leaving condenser water temperature rose and resulted in more power consumed by the chiller. The highest ΔT of 8 produced the highest power value (blue curve). The lowest ΔT of 4 produced the least power consumption (purple curve at bottom). Note this is opposite of Figure 3. However, the range of ΔT tested here is notably smaller than that in Figure 3. The results show that when using the *Buildings.Fluid.Chillers.ReformulatedElectricEIR* during this test, power continued to increase as long as the chiller had enough capacity to meet the load. Beyond a ΔT of 8 for this particular test day, the rising condenser temperature reached a point where the chiller could no longer maintain the setpoint leaving evaporator temperature of 5°C. With this *ReformulatedEIR* block, once the temperature of the leaving condenser water was so high that the capacity of cooling was automatically reduced, the model continued to output results but with lower overall cooling capacity and higher leaving evaporator temperature. For this specific example the power consumption began to decrease when the condenser loop ΔT went above 8, but this was because of the higher leaving evaporator temperature (higher than 5°C). The system provided less and less cooling, and even though it was less efficient, the model output less overall power. These results were discarded and were not useful for analysis.

Figure 5 displays how the cooling load delivered by the system using the *ReformulatedEIR* block was reduced by higher values of ΔT above 8. When using the *ReformulatedEIR* block for condenser flow testing it is important to verify that the cooling produced and leaving evaporator temperature remain constant between trials or power results will not be accurate. Figure 5 shows the decrease in the chiller compressor's energy consumption due to the change in condenser entering and leaving water temperature.

Having shown that the results for this test day up to a ΔT of 8 were valid, it is now useful to display some of the other outputs from the model from this test day. As mentioned earlier, when the loop flow was reduced, but cooling tower fan speed was kept constant, the entering

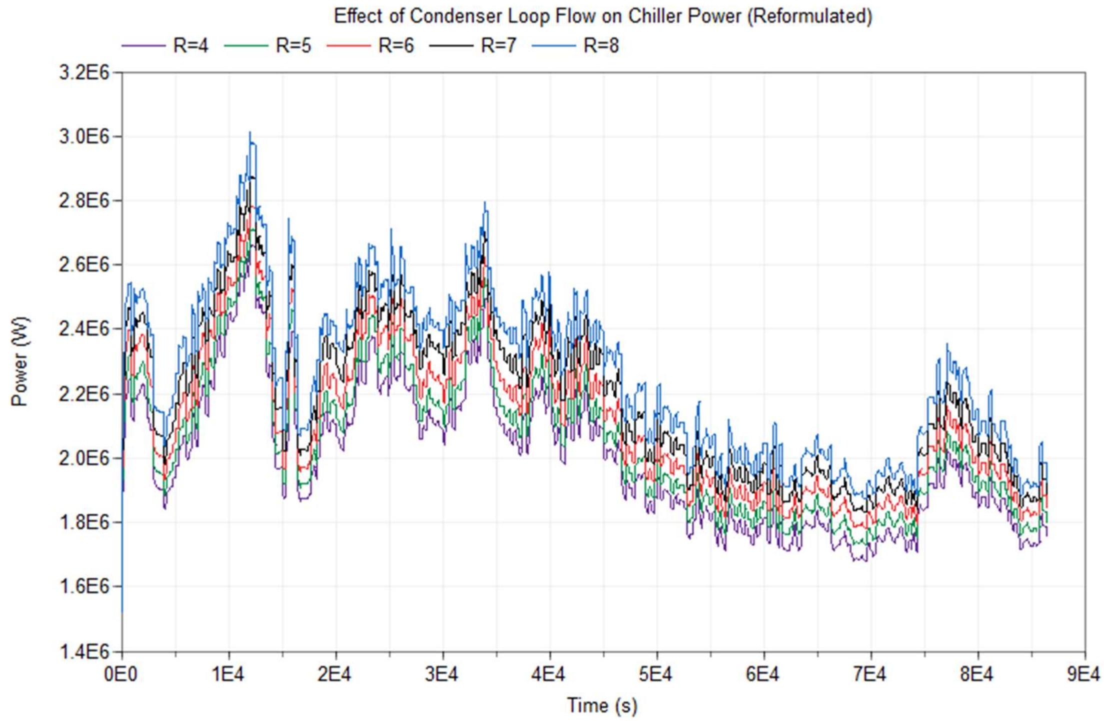

Figure 4: Test results displaying the effect of condenser loop flow on chiller power for various ΔT using Hydeman's reformulated model (model that uses Buildings.Fluid.Chillers.ReformulatedElectricEIR block).

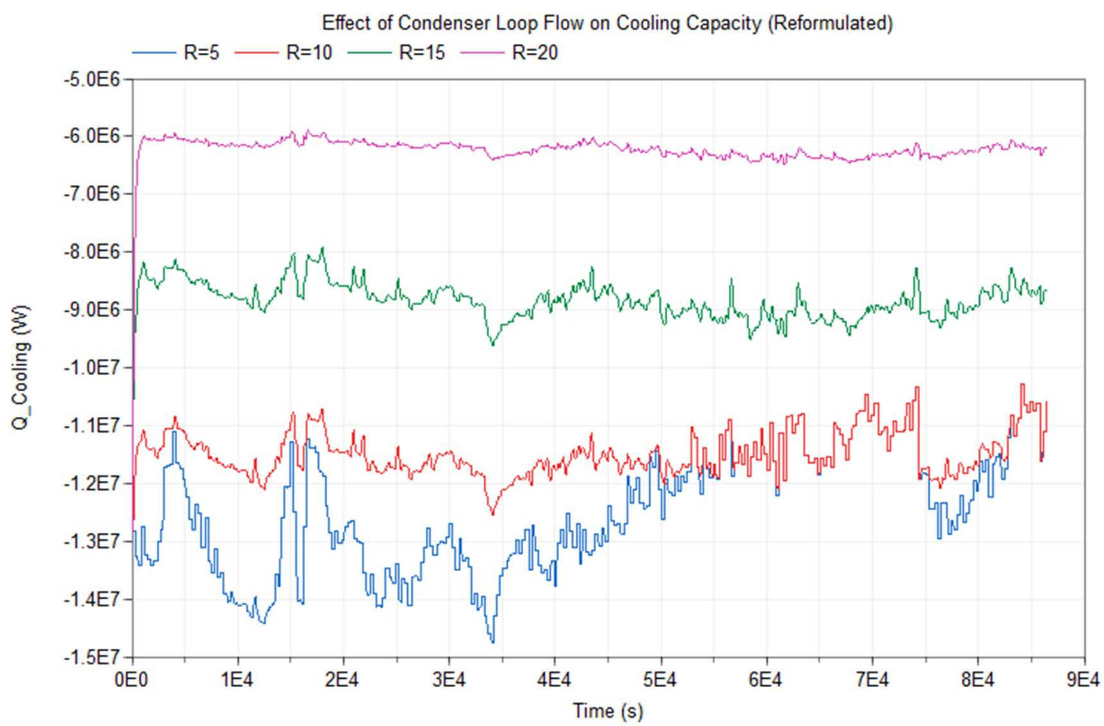

Figure 5: Results from the reformulated model displaying the reduction in chiller capacity caused by reduced condenser loop flow and increasing leaving condenser temperature.

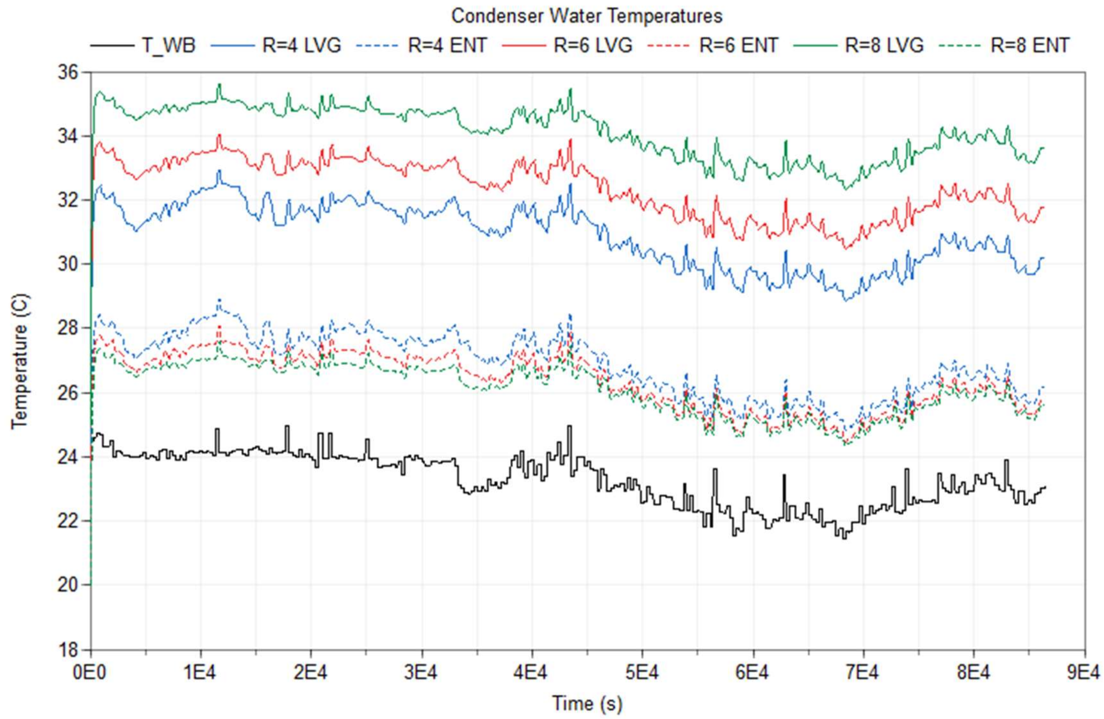

Figure 6: Entering and leaving condenser water temperatures for different condenser loop ΔT.

condenser water temperature was slightly lower due to the higher efficiency of the tower, but as seen from inspection in Figure 6, most of the increasing ΔT was on the leaving condenser side. Figure 6 displays the entering and leaving condenser water temperatures using the reformulated model. Here, the slightly lower entering condenser temperature would benefit heat transfer in the chiller, but it was overcome by the cost of the higher leaving condenser temperature, and higher overall average condenser temperature. This slight reduction in entering condenser temperature was responsible for the power decrease shown in Figure 3 using *Buildings.Fluid.Chillers.ElectricEIR*. There was no offsetting cost in that model to account for the higher leaving condenser water temperature resulting in the power error.

Up until this point of the study we have only been concerned with producing accurate chiller power as affected by condenser loop flow. However, the overall question as to the effectiveness of reduced condenser flow to reduce system power also involves the condenser water pump itself. From the presented results it was seen that reducing condenser loop flow increased chiller power consumption, and to reduce overall plant electrical consumption, the benefit of reduced pumping power must overcome the cost of increased chiller consumption. Using the validated model incorporating the *ReformulatedEIR* block overall cooling system power results were calculated for three separate testing days providing unique weather and loading conditions. Results for a hot July day, a moderate October day, and a cooler lower load February day are presented in Table 2. Figure 7 displays the load distribution over the 24-hour (1440 minutes) period of testing for each day. On the hotter July day, the campus experienced some of its highest loads, but this particular chiller produced fewer overall tons of cooling than it did on the moderate October day because the hotter July condenser water reduced the chiller's capacity. Similarly, the October day had cooler condenser water increasing the ton capacity.

Table 2 Cooling System Power Results by ΔT

	7/22/23	*10/17/23*	*2/3/23*
ΔT (°C)	**Daily Power (MWh)**	**Daily Power (MWh)**	**Daily Power (MWh)**
4	59.3	52.9	25.7
5	58.5	52.5	26.1
6	59.1	51.8	27.3
7	60.2	53.4	28.8
8	61.7	54.1	29.4

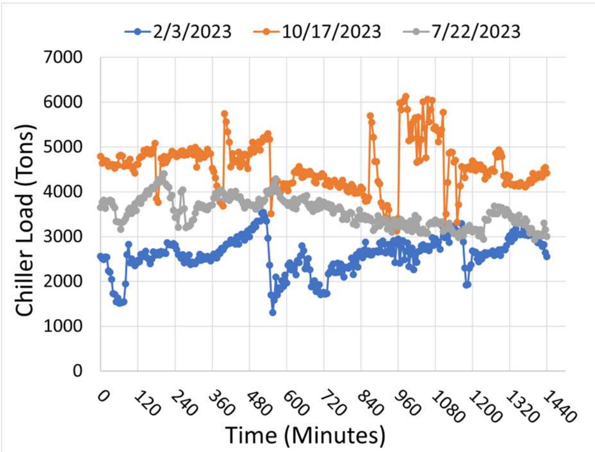

Figure 7: Load profile in tons of the three test days.

Reviewing the results of the cooling system testing indicates that reducing condenser loop flow with increased ΔT did not generally reduce overall system power. It is noted again that the UT system nominally runs at 3.0 GPM/Ton of condenser loop flow, or a 5°C ΔT. During the July 22 test day, the lowest overall system power took place at 5°C ΔT nominal conditions. A reduction in ΔT to 4°C or an increase in ΔT to 6°C both resulted in approximately 1% daily power increases. As the ΔT rose higher, power consumption increased at a faster rate. In this test day it is apparent that the cost of running the chiller with a higher leaving condenser temperature was greater than the benefit of reduced pump power. Table 3 presents a detailed breakdown of the power results from July 22 and displays the tradeoff that occurred between condenser pump power and chiller power.

Table 3 7/22/23 Power Breakdown by Component for Chiller, Condenser Water Pump (CDW) and Cooling Tower Fan + Chilled Water Pump (CT+CHW)

	Chiller	*CDW*	*CT+CHW*
ΔT (°C)	**Daily Power (MWh)**	**Daily Power (MWh)**	**Daily Power (MWh)**
4	48.0	4.4	6.9
5	49.4	2.2	6.9
6	50.8	1.4	6.9
7	52.6	0.7	6.9
8	54.5	0.3	6.9

On October 17, increasing the condenser loop ΔT from 5°C to 6°C did result in a 1.3% decrease in overall system power, but this trend did not continue when the ΔT was raised further. Last, in the February 3 test day, the minimum system power occurred at a ΔT of 4°C which was an increase in condenser loop flow rate. Increasing ΔT above 4 resulted in higher and higher power consumption.

From the results of the simulation, it appears that generally for this system power consumption increased when condenser loop flow was reduced. Further, it appears that if loop flow was optimized on an ongoing basis, the benefits would be small, and generally no more than 1.5%. It is notable that the station 6 system at UT Austin is the lead chilling station for the campus, and it is rare for the chillers to run at a low load where some past researchers have found that reduced condenser loop flow was more suitable. Due to a lack of operation data at low loads, we were unable to test whether the reduced condenser loop flow would benefit this system in that operation region. While this study was limited by the relatively low number of test periods, and the constraints of the chiller and cooling tower regression models, it does indicate that it should not be taken as a general rule that reduced condenser flow will save power in most existing systems.

Conclusion

The results of this study are in line with past works recommending that the optimizing of condenser loop flow rates should be performed on a case by case basis because the outcome is dependent on specific design conditions, and that under certain circumstances, a reduced condenser loop flow rate can result in either increases or decreases in overall power consumption (Kirsner, 1996; Wang et al., 2020; Zhang & Liu, 2012). For this particular system the sequence of control for the condenser pump was not as important as originally thought. Further study of this system can be conducted over a longer period to produce more thorough results.

Acknowledgment

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