Optimizing Chilled Water Design in High-Rises in Hot, Humid Climates

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Chilled water cooling systems consume nearly 50% of building energy required to meet cooling loads, especially in hot, humid climates.[1] Chiller COP can be improved with the optimal chilled water supply temperature, and significant amounts of system energy can be reduced. Similarly, chilled water distribution pumps designed with high temperature delta *T* will have less annual energy consumption compared to low delta *T* chilled water system design. The optimal chilled water supply temperature needs to be determined based on space dehumidification factor, since a high chilled water supply temperature leads to a decrease in the cooling coil latent load capacity and a potential increase in the size of cooling coils. This study examined the impact of chilled water (CHW) supply temperature on the chiller's efficiency, the effects of CHW temperature differentials on pump energy consumption and the most suitable CHW supply temperature for space dehumidification.

Methodology

We consider a hypothetical office building model as a case study for optimizing the performance of the chilled water system in a high-rise 40 floor office building in Abu Dhabi (ASHRAE Climate Zone 1A,1B). The conditioned area of the office building is 58,000 m^2 (624,306.8 ft^2) with a mechanical floor on the 20th floor. Office space occupancy density is based on 1 person per 20 m^2 (215 ft^2) per ASHRAE Standard 62.1-2022.[2] The chilled water system is designed to meet the cooling load of the occupied spaces. Software was used to build a 3D geometry (*Online Figure 1*) for a hypothetical office

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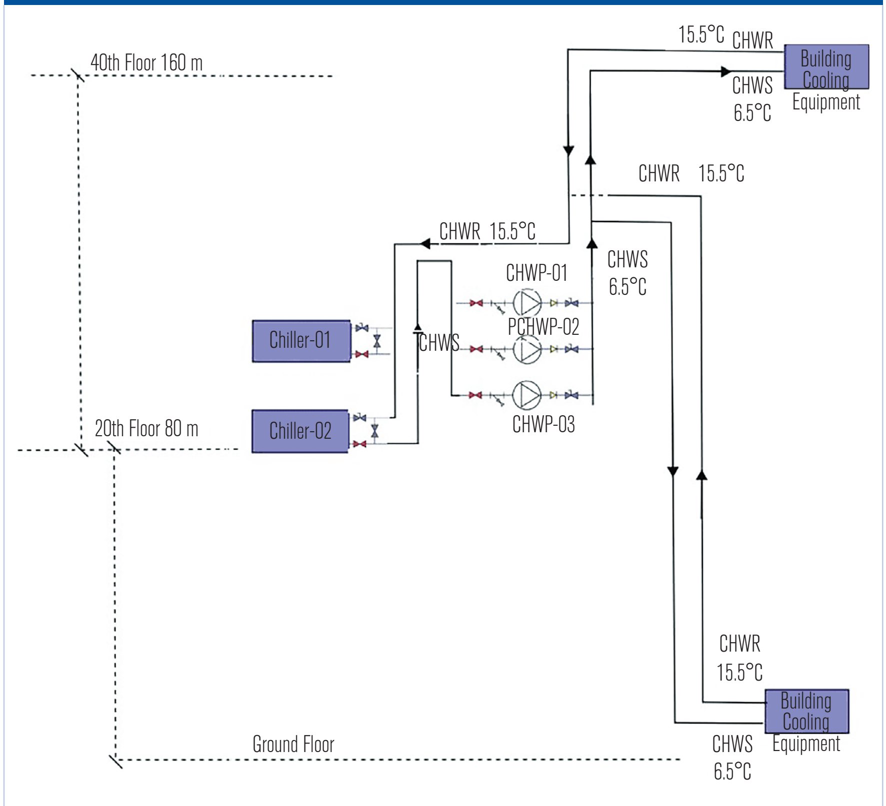
building and also used to run a thermal load and energy simulation.

A chilled water (CHW) distribution system consists of two water-cooled centrifugal chillers, each with a 50% design capacity of 2838 kW (807 tons). A variable primary flow design uses three variable chilled water pumps (two working + one standby) to circulate the chilled water from chillers to cooling equipment through two CHW risers. The CHW riser circulates water from water cooled chillers located on the mechanical floor (20th floor) to the ground floor, while a second riser distributes water from chillers (mechanical floor) to the 40th floor.

Fan coil units (FCU) and air-handling units (AHU) are designed to meet the cooling load for the office spaces in the hypothetical building model. Water-cooled centrifugal chillers are located on 20th floor, and two cooling towers with counterflow, induced draft axial fans are located on the roof. FCU and AHU cooling coils, valves and fittings from the roof to the 7th floor are designed for pressure rating PN16. Cooling equipment coils, valves and fittings from the 6th floor to the ground floor are designed for pressure rating PN20 due to the hydrostatic pressure of the building (*Figure 1*)

FIGURE 1 Chilled water schematic.



Analysis

As the supply chilled water temperature increases, the efficiency of the water-cooled centrifugal chillers increase. Energy simulations have been performed to evaluate the chillers' annual energy consumption based on different CHW supply temperatures such as 5.5°C (42°F), 6°C (43°F), 6.5°C (44°F). The analysis shows that the chillers' annual electrical energy consumption decreased from 8,627,093 kWh (2.9 × 10^{10} Btu) to 8,322,910 kWh (2.8 × 10^{10} Btu), with the CHW supply temperature increasing from 5.5°C (42°F) to 6.5°C (44°F) (*Table 1*). If the average cost per kWh of electricity is $0.10, the annual operating cost difference would be $30,418. Over the course of 10 years, the building will save $304,183 in electricity costs. A higher chilled water supply temperature will improve the chillers efficiency, but space-designed relative humidity levels need to be considered as the latent load capacity for the FCU coil decreases. The amount of carbon embodied in chillers will decrease at a high chilled water supply temperature.

Using an FCU unit to maintain 23°C (73°F) dry-bulb (DB)/53% relative humidity (RH) in the occupied

TABLE 1 Water-cooled centrifugal chiller energy consumption.

DESCRIPTION	COOLING CAPACITY, kW	CHWS TEMPERATURE, °C	CHWR TEMPERATURE, °C	ELECTRICAL POWER, kW	COP	QUANTITY	ELECTRICAL CONSUMPTION, kWh	ANNUAL OPERATION COST, $
Water-Cooled Centrifugal Chiller	2,838	5.5	14.5	499.6	5.68	2	862,7093	862,709
Water-Cooled Centrifugal Chiller	2,838	6	15	490.1	5.79	2	8,473,437	847,343
Wate- Cooled Centrifugal Chiller	2,838	6.5	15.5	481.9	5.89	2	8,322,910	832,291

TABLE 2 FCU schedule.

DESCRIPTION	CAPACITY, kW	SENSIBLE CAPACITY, kW	LATENT CAPACITY, kW	AIRFLOW RATE, m^3/s	CHW INLET TEMP °C	CHW OUTLET TEMP °C	ON COIL AIR TEMPERATURE, °C		OFF COIL AIR TEMPERATURE, °C PER DESIGN		OFF COIL AIR TEMPERATURE, °C PER SELECTION		MOISTURE CONDENSED OUT
							DB	WB	DB	WB	DB	WB	GR/KG
FCU	6	5.2	0.78	0.4	5.5	14.5	23	16.6	12.5	12	12.2	11.7	0.9
FCU	6	5.2	0.78	0.4	6	15	23	16.6	12.5	12	12.5	12	0.7
FCU	6	5.2	0.78	0.4	6.5	15.5	23	16.6	12.5	12	12.9	12.4	0.5
FCU	6	5.2	0.78	0.4	7	16	23	16.6	12.5	12	13.5	12.9	0.3

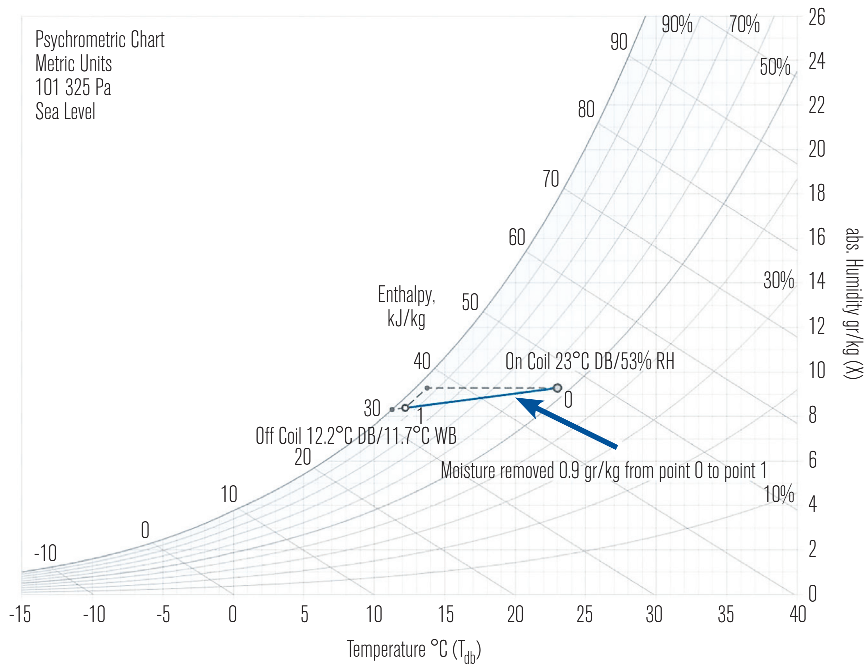
space, a sensible load of 5.2 kW (1.5 ton), a latent load of 0.8 kW (0.2 ton) and an airflow rate of 0.4 m^3/s (848 cfm), a cooling coil supply air temperature of 12.5°C (55°F) DB/12°C (54°F) WB is considered to maintain design conditions in the occupied office space.

As the inlet CHW temperature rises from 5.5°C (44°F) to 7°C (45°F), the FCU meets the sensible load, but the latent load capacity decreases. As a result, the higher the supply air temperature from the FCU cooling coil, the less moisture condenses out from the indoor air. Based on the FCU schedule in *Table 2* and the psychrometric charts in *Figures 2* and *3*, as well as *Online Figures 2* and *3* at https://tinyurl.com/JournalExtras, moisture condensed out from indoor air decreases from 0.9 gr/kg (0.4 gr/lb) to 0.3 gr/kg (0.1 gr/lb) with an increase in the inlet CHW temperature from 5.5°C (42°F) to 7°C (45°F).

A CHW supply temperature at 6.5°C (44°F) condensed out moisture of 0.5 gr/kg (0.2 gr/lb), and the latent load will decrease slightly. The relative humidity of the space increases; however, it will remain below 60% RH at a 6.5°C (44°F) inlet CHW temperature, within the acceptable limits per Standard 62.1-2022.

Considering the office space dehumidification from the FCU cooling coil and chillers' efficiency (*Table 1*

FIGURE 2 FCU selection. CHWT inlet 5.5°C (42°F) for on coil 23°C DB/16.6°C WB (73°F DB/62°F WB); off coil 12.2°C DB/11.7°C WB (54°F DB/53°F WB).



and *Table 2*), the optimum chilled water supply temperature from the chillers is 6.5°C (44°F) for the cooling equipment serving from the 20th floor to the ground floor and from the 20th floor to the 40th floor cooling equipment in the proposed chilled water system.

A higher chilled water temperature differential between the leaving and entering water temperature (delta *T*) can have significant impact on pump energy consumption. In the case of low delta *T*, there will be higher flow, higher energy consumption rate and a higher capital cost for pumps, pipes and valves.[3] An energy simulation was performed by varying the CHW temperature differential from 7°C to 9°C (13°F

FIGURE 3 FCU selection. Inlet CHWT 7°C (45°F) for on coil 23°C DB/16.6°C WB (73°F DB/62°F WB) off coil 13.5°C DB/12.9°C WB (56°F DB/55°F WB).

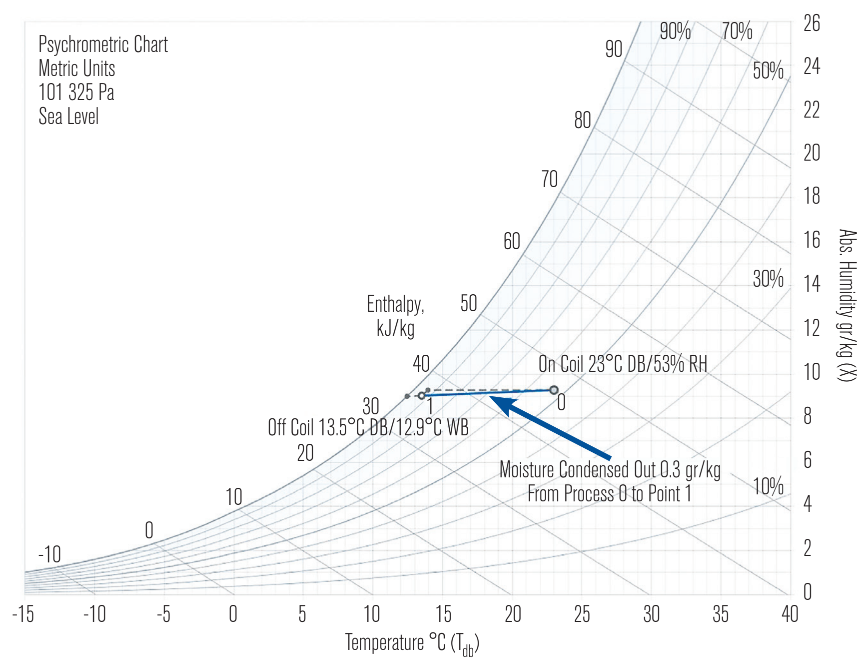
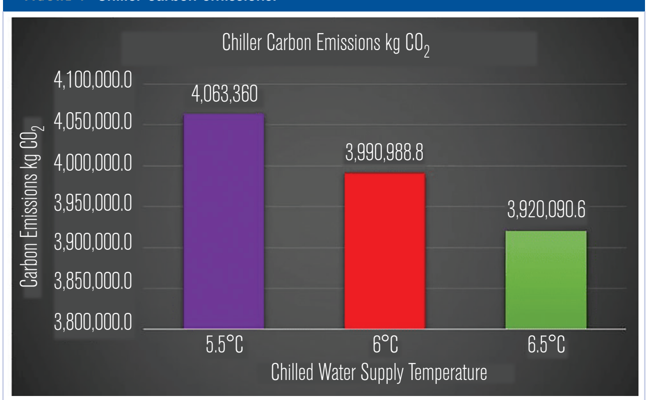


TABLE 3 CHW pump energy consumption.

DESCRIPTION	COOLING CAPACITY, kW	FLOW RATE, L/s	PUMP, kW	PUMP HEAD, kPa	DELTA *T*, °C	NUMBER OF PUMPS	TOTAL PUMPS ENERGY, kWh	ANNUAL PUMP ENERGY COST, $
Chilled Water Pump	2,838	96.99	25	198.2	7	2	149,324	14,932
Chilled Water Pump	2,838	84.86	22	198.2	8	2	131,231	13,123
Chilled Water Pump	2,838	75.43	19	198.2	9	2	116,632	11,663

FIGURE 4 Chiller carbon emissions.



to 16°F) to evaluate the annual energy consumption of CHW pumps. In this study, chilled water pumps used 116,632 kWh (3.9 × 10^8 Btu), which is a reduction of 149,324 kWh (5.1 × 10^8 Btu) on an annual basis (*Table 3*). If the average cost per kWh of electricity is $0.10, the annual operating cost difference would be $3,269 for the pumps. Over the course operation (10 years), the building will save $32,692 in electricity costs. This is the simple cost for accurate economic analysis discount factor to be applied for future cost to present. However, higher delta *T* increases the FCUs' cooling coils rows, and the pressure drop across the coils. Online *Table 1* shows that fan energy consumption will increase from 543,490 kWh (1.8 × 10^9 Btu) to 571,655 kWh (1.9 × 10^9 Btu), but pump energy savings equivalent to 32,692 kWh (1.1 × 10^8 Btu) will be higher than the fan energy. The amount of carbon embodied in pumps will decrease, whereas carbon embodied in FCUs and AHUs will rise due to bigger cooling coils.

For compliance with ASHRAE/IES Standard 90.1-2016, the chilled water temperature differential must be a minimum of 8.3°C (15°F) or higher.[4,5] Therefore, the CHW temperature differential of 9°C (16°F) complies with Standard 90.1-2016 requirements, and significant energy savings can be achieved throughout the project's life cycle.

Carbon Emissions

Each kWh saved will have an economic impact, reduce carbon emissions, and limit global warming. Based on a hypothetical office building model with a higher chilled water supply temperature of 6.5°C (44°F), the chiller annual energy consumption is reduced compared to a low supply chilled water temperature of 5.5°C (42°F). As a result, carbon emissions could be reduced to 143,270 kg CO_2 annually (*Figure 4*).[6] Similarly chilled water pumps' energy consumption is reduced with a higher temperature differential of 9°C (16°F) compared to a temperature differential of 7°C (13°F).[6] As a result, operational energy carbon emissions could be reduced to

38,764 kg CO_2 annually (*Online Figure 4*). Optimizing chiller COP and using a higher temperature differential could reduce 182,034 kg CO_2 through annual operational energy. This strategy could mitigate 1,820.3 metric tons of CO_2 from the atmosphere over the period of 10 years of operation. The amount of carbon embodied in chillers and pumps will be reduced whereas FCUs and AHUs' embodied carbon will increase due to an increase in cooling coil size.

Conclusion

An increase in chilled water supply temperature of 1°C (1.8°F) can achieve 3.5% savings in chiller annual energy consumption. The optimal chilled water supply temperature for a high-rise building is to be evaluated for every project based on the space-designed humidity levels and building static height. This will help achieve the designed relative humidity levels and comfortable indoor environment for occupants. The chilled water temperature differential delta T = 9°C (16°F) or higher can significantly reduce pump energy cost and comply with Standard 90.1-2016 standard requirements. Proposed chilled water design energy efficiency measures implemented on new building designs at the community level will develop climate resilient cities. Energy efficient system design will help meet the building decarbonization target by 2050.

References

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