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Modeling of radiative free cooling for data centers

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Abstract: Demand for data centers with high-performance computing is growing rapidly. However, large energy consumption in data centers (DC) is increasingly becoming a major challenge. As cooling systems are a key part of data centers accounting for a substantial fraction of energy consumption, improving their energy efficiency remains an important goal. Here, we demonstrate cooling energy saving in a data center with a radiative free cooling system that operates as part of the DC chiller system. Using physics-based models of the radiative free cooling and chiller systems, we simulate chiller energy consumption with and without free cooling. We specifically study the effects of DC outlet air temperature, free cooling system size, cooling tower water flow rate, free cooling system flow rate, relative humidity and ambient temperature on the system performance such as coefficient of performance, power consumption, and energy and water savings. Through a series of sensitivity analyses, we identify operation parameters of the integrated cooling system that must be optimized to achieve the best energy-saving state. Energy and water savings are positively corelated with cooling power and size of the free cooling system, cooling tower flow rate and relative humidity. We show that 7.5% cooling energy and 7.6% water consumption can be saved for the annual average weather conditions of Singapore.

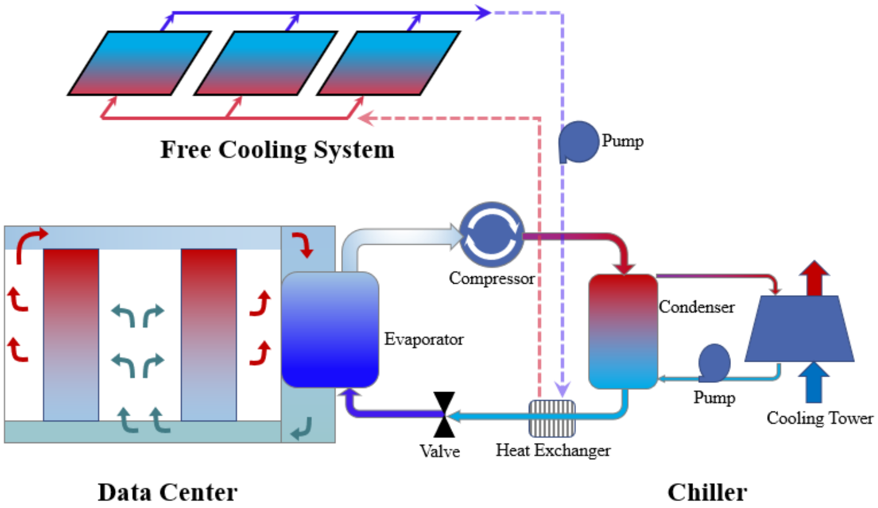

Figure 1. Schematics of a data center along with an integrated cooling system consisting of a water-cooled chiller and a radiative free cooling system

Keywords: *Data center, free cooling, energy saving, water saving*

NOMENCLATURE

A_{val}	Flow area of valve, m^2
C_{val}	Valve orifice coefficient
COP	Coefficient of performance
d	Diameter of tube, m
f	Single phase friction factor
L	Length, m
m	Mass flow rate, kg/s
NTU	Number of transfer unit
p	Pressure, Pa
P	Power, W/m^2
T	Temperature, ℃
ε	Spectral emissivity
x	Quality
ρ	Density, kg/m^3
α	Heat transfer coefficient, $W/(m^2 \cdot K)$
Φ^2	Two phase friction factor

Subscript

amb	Ambient
atm	atmosphere
conv	Convection
cool	Cooling
l	Liquid
i	Inlet
o	Outlet
r	Refrigerant
s	Surface of radiative-cooling film
sat	Saturated
v	Vapor

1. INTRODUCTION

With growing numbers of data centers (DC) around the globe, data centers are facing increasing demand for power and water. Their high energy consumption for computation and cooling has become a major concern partly because of associated carbon emissions. Large demands for power and water occasionally hinder uninterrupted operation of data centers, especially during major droughts (Diana Olick, 2022). Information technology (IT) equipment and air conditioning systems are the main energy consumption components in data centers (Wang et al., 2022). The energy consumption of cooling equipment sometimes accounts for as high as 40% of the DC total energy consumption (Shehabi et al., 2016). Therefore, reducing data center cooling energy consumption is critical to saving energy and reducing carbon emissions. Currently, data center cooling systems mainly include air-cooled chillers, water-cooled chillers, and free cooling with or without chillers (Zhang et al., 2021). The main advantages of air-cooled chillers are simple maintenance and acceptable operation cost (Habibi et al., 2017). However, water-cooled chillers save more energy than air-cooled chillers because of much better heat transfer performance of water than air. Free cooling systems can reduce both power and water consumptions in data center because free cooling takes advantage of natural cooling sources such as cold ambient air or radiative cooling. Free cooling can be used in combination with other cooling and energy techniques. For instance, Malkamäki et al. evaluated the solar energy and data center free cooling potential in Europe (Malkamäki et al., 2012). Recently developed radiative sky cooling can be also considered as a kind of free cooling for air conditioning. A study showed that in the hot dry weather of a Los Angeles summer, when a radiative free cooling system is integrated into the condenser side of a central air conditioning system, the cooling system power consumption can be reduced by 21% (Goldstein et al., 2017). For power plants, a hybrid evaporative and radiative free cooling system yields annual water savings of 30–60% in the hot dry United States (Aili et al., 2021).

In this paper, we model a radiative free cooling system for a data center. Radiative free cooling is used as natural supplemental free cooling to further reduce the temperature of refrigerant after a chiller condenser, thereby reducing the amount of refrigerant used and increasing the coefficient of performance (COP) of the chiller. The methodologies of the chiller and free cooling systems are described in Section 2. Section 3 discusses the influence of DC outlet temperature, free cooling system size, free cooling working fluid flow rate, cooling tower working fluid flow rate, relative humidity (RH), and ambient temperature on the overall system performance.

2. METHODOLOGY

As illustrated in Figure 1, the integrated cooling system of a data center consists of a water-cooled chiller system (evaporator, compressor, condenser, valve, cooling tower) and a radiative free cooling system. The free cooling system with recirculating water flow exchanges heat with refrigerant from the chiller through a crossflow heat exchanger. For every component of the cooling system, we calculate heat exchange rate and power consumption. We assume that DC outlet air is evenly mixed, and its temperature is constant. With the DC inlet air temperature set as the target temperature, the system reaches a balanced state by adjusting the refrigerant flow rate. Working fluids between chiller and free cooling system and between condenser and cooling tower are water. Chiller refrigerant is R134a. Fluid properties and wet bulb temperature are calculated with opensource tool CoolProp6.4 (Bell et al., 2014). The heat transfer rates between fluids in heat exchangers are computed using the number of transfer unit (NTU) method.

2.1. Chiller

The chiller is composed of an expansion valve, evaporator, compressor, condenser, cooling tower, etc. Refrigerant flowing through the expansion valve is an isenthalpic process. Expansion converts a high-temperature, high-pressure liquid into a low-temperature, low-pressure liquid. The refrigerant flow rate is controlled by the cross-sectional area of the valve and calculated by (He et al., 1998)

$$m_{ref} = C_{val} A_{val} \sqrt{\rho_i (p_i - p_o)}. \tag{1}$$

where ρ is refrigerant density calculated with CoolProp6.4 (Bell et al., 2014).

In the evaporator, the refrigerant removes heat from air inside the DC through phase change. Heat transfer coefficient of vaporization between heat exchanger wall and refrigerant can be obtained by (Gungor et al., 1986)

$$\alpha_r = E\alpha_{cb} + S\alpha_{nb}. \tag{2}$$

where α_{nb} and α_{cb} are boiling heat transfer coefficients of the nucleate and convective liquid flow, respectively; E (>1) is the enhancement factor which reflects the higher velocities in the thinner boundary layer; S is the suppression factor. The pressure drop of refrigerant in two-phase region is calculated by (Chisholm, 1985; Huo et al., 2007)

$$\Delta p = 1 \times 10^5 \emptyset^2 f \frac{L}{d_i} \frac{m^2}{2\rho_l} \left[1 + x\left(\frac{\rho_l}{\rho_v} - 1\right)\right]. \tag{3}$$

The compressor compresses low-pressure and low-temperature refrigerant into high-temperature and high-pressure gas, which is an isentropic adiabatic process. Its outlet temperature is calculated by

$$T_o + 273.15 = (T_i + 273.15)\left(\frac{p_o}{p_i}\right)^{\frac{n-1}{n}}. \tag{4}$$

where n is the polytropic coefficient. Compressor is the main equipment of power consumption, accounting for at least 90%.

The refrigerant is liquefied by the condenser. The heat transfer coefficient is calculated by (Incropera et al., 1996)

$$\alpha_r = 51104 + 2044T_{sat}. \tag{5}$$

2.2. Free cooling system

The radiative free cooling system is simulated with a radiative sky cooling model developed in our previous work (Aili et al., 2019). This model is used to determine the net cooling power density of a radiative cooling module. The following power densities are calculated by considering cooler surface properties and weather conditions: upward thermal emission from the cooler surface, atmospheric downward radiation absorbed the cooler surface, solar irradiance absorbed by the cooler surface and convective power density over the cooler surface. The net cooling power is then given as

$$P_{cool} = P_{up}(T_s, \varepsilon_s) - P_{down}(T_{atm}, \varepsilon_{atm}, \varepsilon_s) - P_{conv}(T_s, T_{amb}, h_{air}). \tag{6}$$

2.3. Performance metrics

Coefficient of performance (COP) is a measure of the efficiency of a heat pump or refrigeration system, defined as the ratio of heat load to energy consumption. The higher the COP, the more efficient the system is at transferring heat, which can result in lower energy consumption and operating costs.

3. RESULTS AND DISCUSSION

We explore the influence of DC outlet temperature, size and water flow rate of the free cooling system, cooling tower flow rate, relative humidity, and ambient temperature on the cooling system performance such as coefficient of performance, power consumption, and energy and water savings. In modelling, the DC hall floor size is 72 m^2, and the DC heat rejection rate (heat load on the cooling system) is 352kW. DC inlet temperature is the target temperature, which remains constant at 26°C except when we investigate DC outlet temperature effect on cooling system performance. The system reaches a steady state when the target and modelled temperature difference is below 0.01°C. Due to many factors affecting the system performance, we set the evaporation temperature at 6°C and the condensation temperature at 50°C (Goldstein et al., 2017). We adopt the control variable method to carry out sensitivity analyses. Weather conditions (relative humidity and ambient temperature) are constant, except when we investigate their effects on the cooling system performance. Constant weather conditions are based on the annual average values of Singapore. Case 1 is the baseline cooling system with only a chiller (without a free cooling system). Case 2 is an integrated cooling system with a water-cooled chiller and a radiative free cooling system (see Figure 1).

3.1. Effect of the DC outlet air temperature

The DC outlet temperature influences CPU performance and power consumption. To keep heat load constant, target temperature increases with outlet temperature while the air flow rate remains constant at 21 m^3/s. As DC outlet air temperature increases, heat transfer in the evaporator is enhanced and refrigerant flow rate decreases. However, refrigerant temperature at the evaporator outlet goes up. Eventually, compressor power consumption goes up and COP goes down, as shown in Figure 2. Free cooling power (in W/m^2) and free cooling capacity (in W), energy and water savings (in %) decrease slightly as refrigerant mass flow rate goes down.

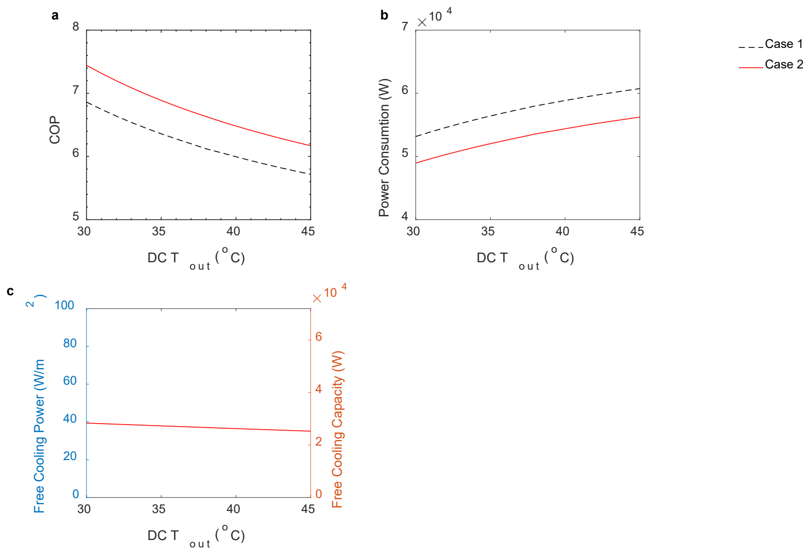

Figure 2. Effect of DC outlet temperature on the cooling system performance. Case 1 is the baseline cooling system with only a chiller (without a free cooling system). Case 2 is the integrated cooling system with a water-cooled chiller and a radiative free cooling system.

3.2. Effect of the radiative free cooling system size

The free cooling system size (normalized by the DC floor area) influences the cooling power of the radiative free cooling system and thus the COP of the whole cooling system. As shown in Figure 3, as the area ratio increases, the free cooling capacity (in W) goes up for case 2, whereas free power density (in W/m^2) goes down. As the free cooling system takes up more heat from refrigerant, the refrigerant flow rate goes down. Therefore, COP as well as energy and water savings go up. However, the rate of growth in these parameters gradually decreases as the unit-area effectiveness of the free cooling system decreases with increasing size, i.e., Law of Diminishing Returns. For following parametric studies below, the area ratio is set as 10.

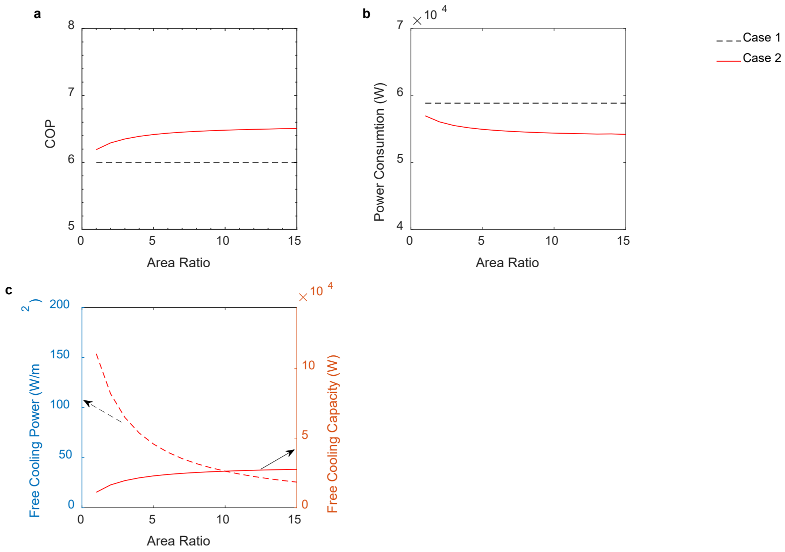

Figure 3. Effect of the radiative free cooling system size on the cooling system performance. Here, area ratio refers to the radiative free cooling system area normalized by the DC floor area

3.3. Effect of the cooling tower water flow rate

The cooling tower mass flow rate directly affects heat exchange in condenser. For Case 1 (baseline), as cooling tower flow rate increases, the condenser outlet refrigerant temperature and flow rate both decrease. Therefore, compressor power consumption goes down and COP goes up, as shown in Figure 4. For Case 2, however, the heat exchanger between the free cooling system and the chiller also function as a condenser and thus further reduces the refrigerant temperature. Therefore, power consumption and COP in Case 2 changes only slightly, from 55kW to 54kW and 6.4 to 6.5, respectively. As the cooling tower flow rate increases, the free cooling power density (in W/m^2) and cooling capacity (in W) both decrease, because refrigerant temperature after condenser goes down. Energy saving goes down from 14.6% to 6.2%. Meanwhile, water saving goes down from 13.3% to 6.4%.

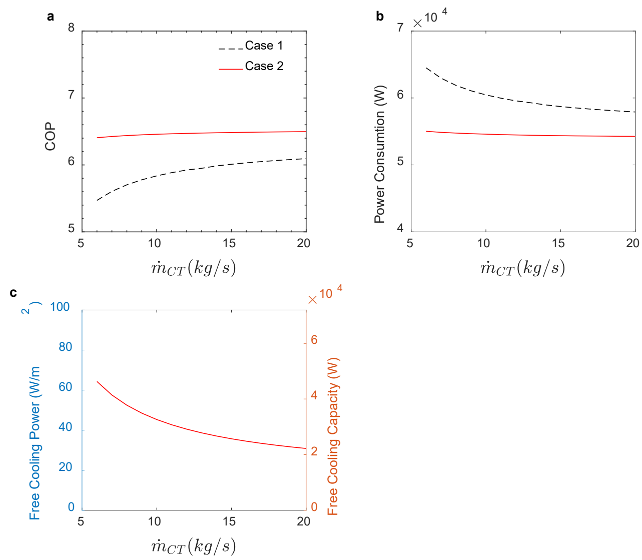

Figure 4. Effect of cooling tower water flow rate on the cooling system performance

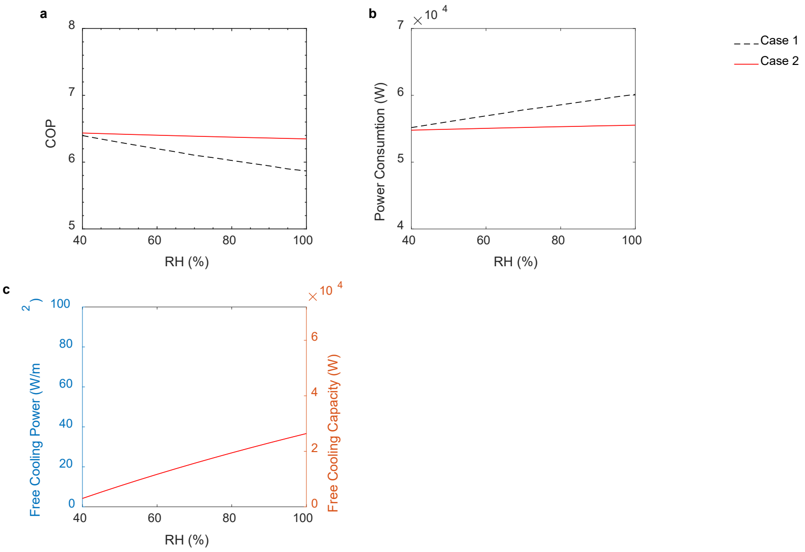

Figure 5. Effect of relative humidity on cooling system performance

3.4. Effect of relative humidity

Relative humidity (RH) influences both radiative free cooling and wet bulb temperature (evaporation in cooling tower). Cooling tower water outlet temperature is set 5°C higher than the wet bulb temperature (i.e., cooling tower approach temperature is 5°C). For baseline case 1, as RH increases, refrigerant flow rate and power consumption both go up while COP goes down as expected (Figure 5). For case 2 with radiative free cooling, free cooling power and cooling capacity both increase, because condenser refrigerant outlet temperature goes up as RH increases. As a result, this increase in the free cooling capacity offsets the negative impact from the increase in cooling tower outlet water temperature. As a result, power consumption and COP are both maintained. COP remains constant at about 6.5. Energy and water savings both go up, from 2.3% to 9.2% and from 0.9% to 7.6%, respectively.

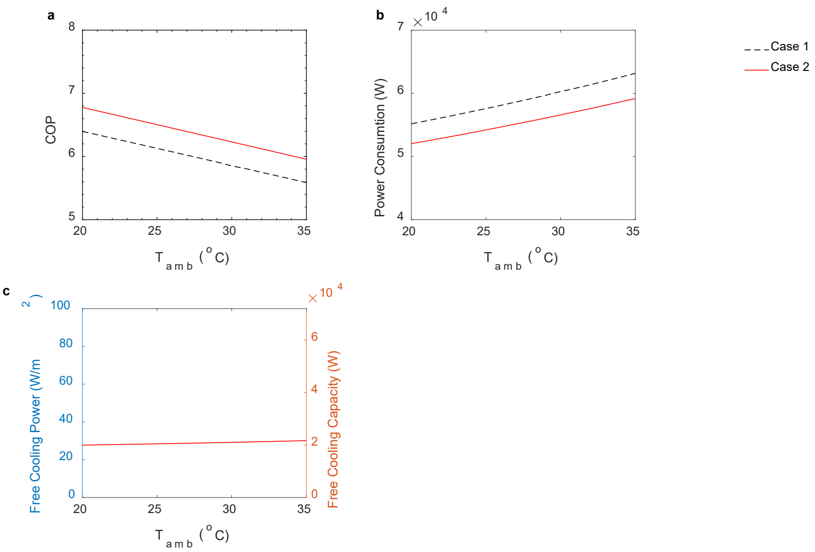

Figure 6. Effect of ambient temperature on cooling system performance

3.5. Effect of ambient temperature

Ambient temperature influences both free cooling power and cooling tower outlet water temperature. The higher the ambient temperature, the more refrigerant the chiller system needs. With increasing ambient temperature, power consumption of case 2 goes up and COP goes down from 6.8 to 6.2, as shown in Figure 6.

As ambient temperature increases, on the free cooling system, radiative cooling power goes up whereas convective power goes down. As a result, net free cooling power and cooling capacity nearly remain constant. Energy and water savings also remain constant at around 5.0%.

Based on the series of sensitivity analyses above, COP and power consumption in case 2, are less sensitive to cooling tower water flow rate and ambient relative humidity thanks contribution by the free cooling system. The cooling system COP goes up as free cooling system size increases. Free cooling system capacity influences refrigerant flow rate and thus heat rejection taken away by the cooling tower. Energy and water saving are positively corelated with the free cooling system capacity. Under the average weather conditions of Singapore (ambient temperature 27.5°C, relative humidity 83.6%, and solar radiation 209W/m^2), modeling shows that 7.5% cooling energy and 7.6% water consumption can be saved. These trends offer important benchmarks for designing free cooling systems for data centers in the tropics and around the world.

4. CONCLUSIONS

This paper proposes a new energy-saving solution for data center cooling. Radiative free cooling is used to further reduce the temperature of refrigerant after the condenser of a data center chiller system. We studied the effects of cooling system parameters (DC outlet temperature, free cooling system size and water flow rate, and cooling tower water flow rate) and environmental factors (relative humidity and ambient temperature) on the overall system performance including COP, power consumption, free cooling power and capacity, as well as energy and water savings. To achieve more energy and water savings, we propose increasing free cooling system area and decreasing cooling tower mass flow rate. We show that 7.5% cooling energy and 7.6% water consumption can be saved under annual average weather conditions of Singapore. In addition to data centers, radiative free cooling can also be applied to other buildings such as supermarkets, office buildings, and airports to reduce energy and water consumptions by cooling systems around the world.

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