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Cooling Capacity and Energy Performance of Open-Type Ceiling Radiant Cooling Panel System with Air Circulators

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Abstract: Ceiling radiant cooling panel (CRCP) systems are being increasingly applied to commercial buildings due to their high thermal comfort level and energy efficiency. It is recommended that CRCP systems should be operated at a relatively high chilled water temperature to prevent condensation and save energy. However, even though a high chilled water temperature is effective for achieving condensation-free operation and high chiller efficiency, it can lead to insufficient cooling capacity. In this study, a method of enhancing the cooling capacity of CRCP systems was investigated through mock-up chamber tests. The open-type installation of CRCPs and the combination of air circulators were used to enhance the cooling capacity and energy performance of CRCP systems. Experimental results showed that compared to a conventional CRCP system, the cooling capacity of an open-type CRCP system with air circulators increased by up to 26.2%, and its cooling energy consumption decreased by up to 26.4%. Additionally, the open-type CRCP system with air circulators reduced the difference between the room air temperature and mean chilled water temperature. Thus, the proposed system can operate at a relatively high chilled water temperature, which is effective for reducing condensation risk and cooling energy consumption.

Keywords: ceiling radiant cooling panel; cooling capacity; open-type installation; air circulators; cooling energy consumption

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1. Introduction

Ceiling radiant cooling panel (CRCP) systems have been widely applied to space cooling due to their high thermal comfort level, energy-saving potential, and harmonization with architectural design [1,2]. Closed-type CRCPs are generally installed, where an entire ceiling surface is covered with CRCPs. As closed-type CRCP systems separate a plenum and an occupied space, it is difficult to utilize cooled plenum air to cool the occupied space. This separation does not lead to problems for the top-insulated panels that minimize the heat transfer at the upper surface of CRCPs [3,4]. However, metal ceiling panels without top insulation, which are commonly installed in office buildings, can absorb heat from the plenum space [5,6]. If metal ceiling panels are installed with closed-type CRCPs, the occupied space is cooled by only the lower surface of the CRCPs only. This might lead to insufficient cooling capacity and a consequent increase in cooling energy. In contrast, in open-type CRCPs, openings can be created between two adjacent CRCPs or between CRCPs and walls. Cooled plenum air can move down to the occupied space through these openings. This movement of plenum air can enhance not only the air mixture in the occupied space but also the heat transfer rate at the CRCP surface [2].

Shin et al. reported that the cooling capacity of CRCP systems can be enhanced by promoting the movement of plenum air through the openings in open-type CRCPs [7]. However, the limitation of the study was that results were obtained using only a numerical method. In the follow-up study, the numerical model of open-type CRCPs was verified against mock-up test results, and it was shown that open-type CRCPs enhanced cooling capacity by 54–80%, depending on the opening area and panel layout [2]. However, the enhancement of cooling capacity considered only the natural convection effect of the movement of the plenum air.

Another method of enhancing the cooling capacity of CRCP systems is to cause forced convection by increasing the air speed at the panel surface. Jeong and Mumma showed that CRCPs combined with mechanical ventilation could benefit from mixed (natural + forced) convection. Mixed convection was generated by air flow from a nozzle diffuser. Cooling capacity was enhanced by 5–35% compared to CRCPs with only natural convection [8]. Kim and Leibundgut proposed a CRCP system combined with an airbox convector, which could generate air flow on the panel surface. The mixed convection effect increased cooling capacity by 32% [9]. Novoselac et al. utilized a high-aspiration diffuser to create a specific air flow pattern along cooling panels to increase the convective heat transfer coefficient. Full-scale test results showed that the high-aspiration diffuser increased the heat transfer coefficient by 4–17% [10]. Karmann et al. [11] demonstrated that in a thermally activated building system (TABS), a ceiling fan increased cooling capacity by up to 22%, and small fans installed between the ceiling and acoustic clouds increased cooling capacity by up to 26%.

The abovementioned studies on the effect of forced convection on cooling capacity examined the enhancement of the cooling capacity of closed-type CRCP systems. This study aims to investigate the impact of forced convection on the cooling capacity of open-type and closed-type CRCP systems. In addition, previous studies increased the forced convection effect using heating, ventilation, and air conditioning (HVAC) systems such as nozzle diffusers [8,10], convectors [9], and ceiling fans [11]. As these systems are designed and installed for the specific purpose of generating air flow on a panel surface, additional space and cost are required to install them. In addition, it is difficult to modify the air flow direction or flow rate because HVAC systems are installed at a specific location in a room.

In this context, the present study applied air circulators to enhance the effect of forced convection on CRCP surfaces. Air circulators are becoming well known as an efficient method of increasing the overall air velocity in a conditioned space. This can contribute to the improvement of air diffusion and thermal uniformity. In addition, they reduce cooling energy consumption because the cooling set-point temperature can be decreased due to the elevated air velocity in an occupied space [12–14]. If an air circulator is configured to transport room air to CRCP surfaces, the enhancement of cooling capacity can be expected owing to the increased heat transfer rate at a panel surface. Considering that an air circulator can move air over a long distance, it was selected as an air circulation device to enhance the heat transfer even in a CRCP located far from the circulator. Based on this assumption, this study was conducted to improve cooling capacity and energy performance by utilizing the air circulator, which would be used as a low-cost and affordable auxiliary cooling system.

Previous studies on the enhancement of cooling capacity have mainly focused on the evaluation of cooling capacity. Few studies have investigated the energy consumption of open-type CRCPs combined with air circulation devices. Therefore, the present study evaluated not only the cooling capacity but also the energy performance of an open-type CRCP system with air circulators for forced convection.

For this purpose, a mock-up test chamber was constructed to analyze the cooling capacity and energy consumption depending on the CRCP installation types and the application of air circulators. The closed-type CRCP system was realized by covering an entire ceiling surface with CRCPs, and the open-type CRCP system was realized by providing an opening area between perimeter CRCPs and the chamber wall. Two air circulators were deployed to create air flow at the CRCP surfaces. Cooling capacity was evaluated based on the heat absorption by the chilled water in the CRCPs in accordance with EN 14240 [15]. Energy consumption was evaluated by adding the electricity consumed by the chiller and that consumed by the chilled water circulation pump. The outdoor air system used to handle the ventilation requirement and latent load was not included in the scope of the present study, because the outdoor air system generates a non-isothermal air flow, which makes it difficult to distinguish the impact of air velocity on the cooling capacity. As addressed in test standards such as EN 14240 [15] and ASHRAE 138 [16], internal (sensible) cooling load was only considered to investigate the impact of air circulation on cooling capacity and energy consumption.

This paper is organized as follows. Section 2 describes the development of the mock-up test chamber for the CRCP systems and performance-evaluation methods. Section 3 describes the cooling capacity and energy consumption of the CRCP systems and the application of air circulators. Section 4 discusses the implications and limitations of this study. Section 5 presents the conclusions of the study.

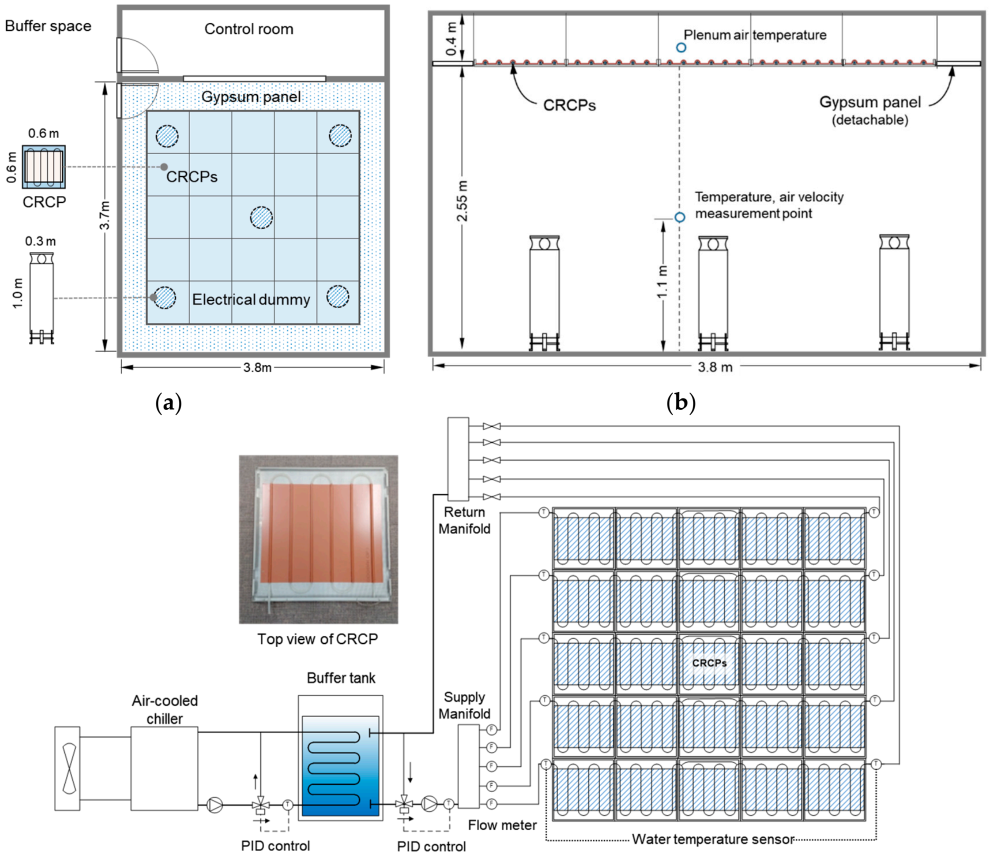
2. Research Methods

2.1. Development of Mock-Up Test Chamber

A mock-up test chamber was constructed to investigate the impact of the open-type installation on the cooling capacity and energy consumption of the CRCP system. The chamber could be equipped with open-type or closed-type CRCPs, as illustrated in Figure 1. The dimensions of the test chamber were 3.8 m (W) $\times$ 3.7 m (L) $\times$ 2.9 m (H), which represent the typical condition of an office space. The cooling load was represented by electrical dummies in accordance with EN 14240 [15]. The simulated cooling load was approximately 900 W (64.0 W/m^2), which corresponds to the internal cooling load of conventional office buildings [17]. To minimize the heat gain or loss through the test chamber, it was constructed inside an existing air-conditioned building, and its envelope was composed of metal panels with 100 mm thick insulation. In addition to the thermal insulation, an electrical heat pump system was used to control the temperature outside the test chamber to minimize the heat transfer through the test chamber envelope.

Twenty-five CRCPs were installed on the ceiling of the test chamber. The size of each CRCP was 0.6 m $\times$ 0.6 m, and it was composed of a perforated aluminum panel (thickness = 3 mm), a chilled water pipe, and a heat conduction plate. The areas of the ceiling surface and CRCP surface were 14.06 m^2 and 9.0 m^2, respectively. The ceiling surface that was not covered by CRCPs was blocked with gypsum panels when conducting experiments for the closed-type CRCP system. For the open-type CRCP system, the gypsum panels were removed to represent the opening through which plenum air can move down to the conditioned space.

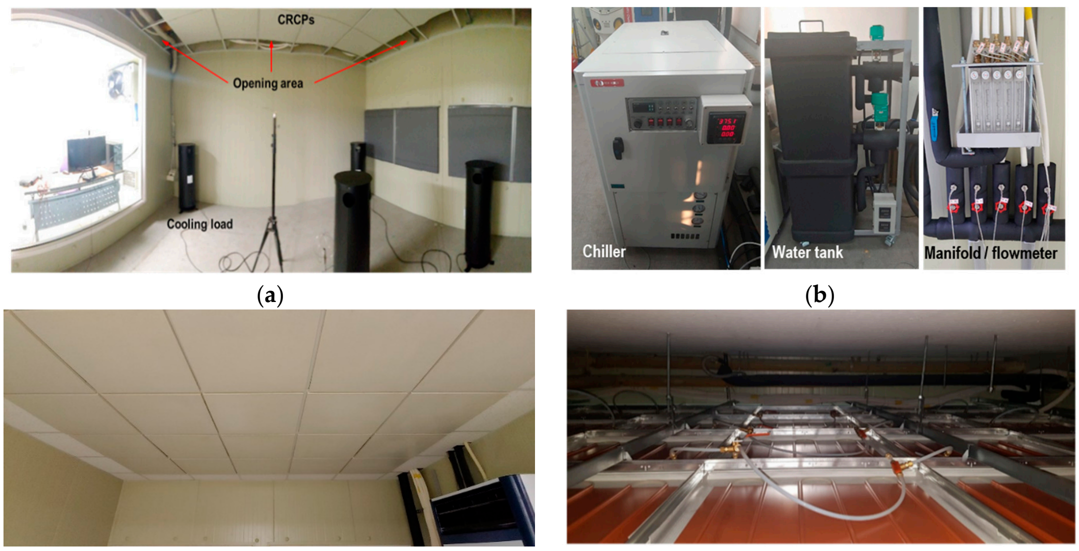
The CRCP system was designed with five hydronic subcircuits for the chilled water supply. An air-cooled chiller was used to supply chilled water. The temperature of chilled water was accurately controlled by a water storage tank and 3-way mixing loops, as shown in Figure 1c. Figure 2 shows the images of the developed test chamber. Temperature sensors for supply and return water and flow meters were installed in each subcircuit to analyze the cooling capacity of the CRCPs. Room air temperature and air velocity in the conditioned space were measured 1.1 m above the floor. The information on measurement devices is summarized in Table 1.



(**a**) (**b**)

(**c**)

Figure 1. Configuration of the mock-up test chamber for the evaluation of ceiling radiant cooling panel (CRCP) performance: (**a**) floor/ceiling plan view; (**b**) sectional view; (**c**) mechanical system.



(**a**) (**b**)

(**c**) (**d**)

Figure 2. Developed test chamber: (**a**) inside view; (**b**) mechanical system; (**c**) CRCPs; (**d**) plenum space and upper side of CRCPs.

Table 1. Specifications of measurement device.

Item	Type	Range	Accuracy
Room air temperature	NTC thermistor	−20–+70 °C	±0.2 °C
Plenum air temperature	T-type thermocouple	−250–+350 °C	±0.5 °C
Room air velocity	Hot wire	0–5 m/s	±0.03 m/s
Chilled water temperature	RTD PT100	−70–+500 °C	±0.3 °C
Chilled water flow rate	Volumetric	0.2–42 L/min	2%

2.2. Performance Evaluation Method

Four cases were considered to investigate the impact of the open-type installation and air circulators on the cooling performance of the CRCP system, as shown in Figure 3. The closed-type CRCPs without air circulators were designated as a reference case (Case 1). The closed-type CRCPs with air circulators (Case 2) were configured to investigate the impact of elevated air velocity on the cooling performance of the closed-type CRCP system. The open-type CRCPs without air circulators (Case 3) were used to investigate the impact of the open-type installation on the enhancement of the cooling capacity and energy performance of the CRCP system. The open-type CRCPs with air circulators (Case 4) were utilized to examine the further enhancement of cooling performance by applying the elevated air velocity to the open-type CRCP system.

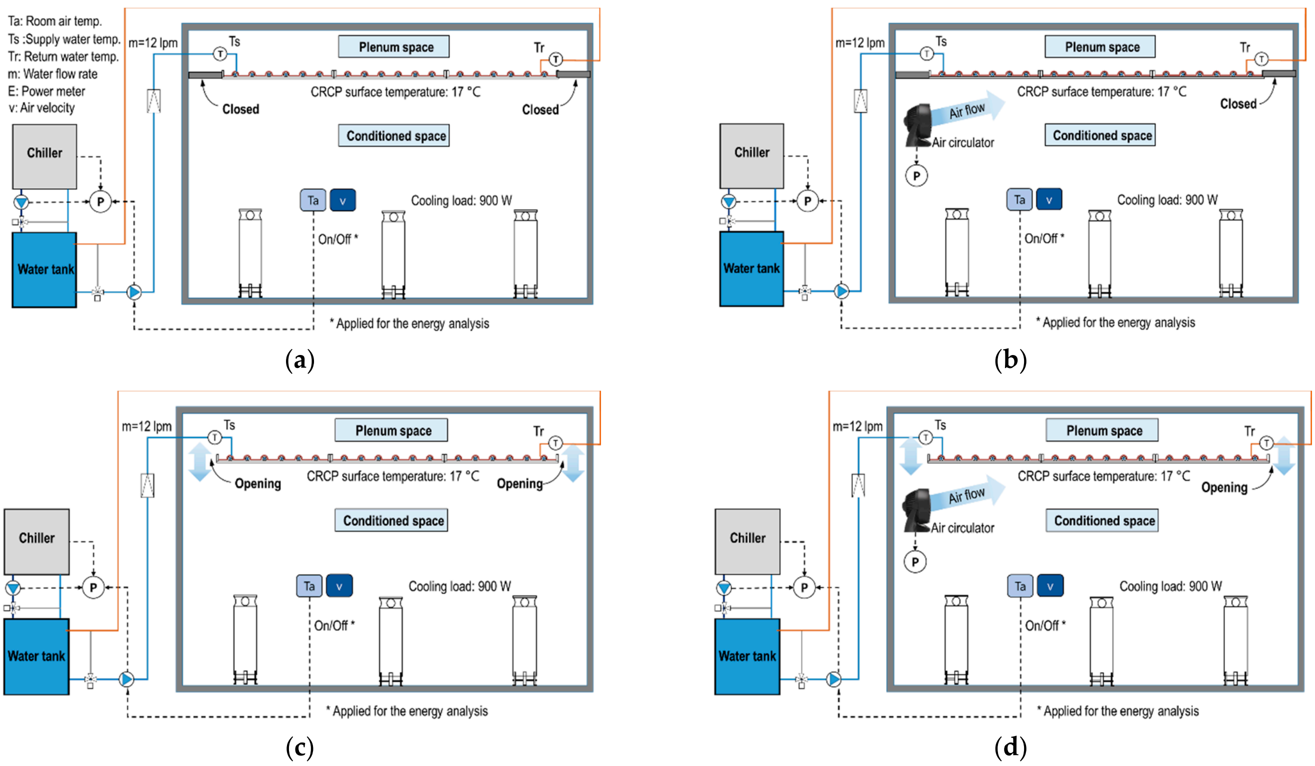


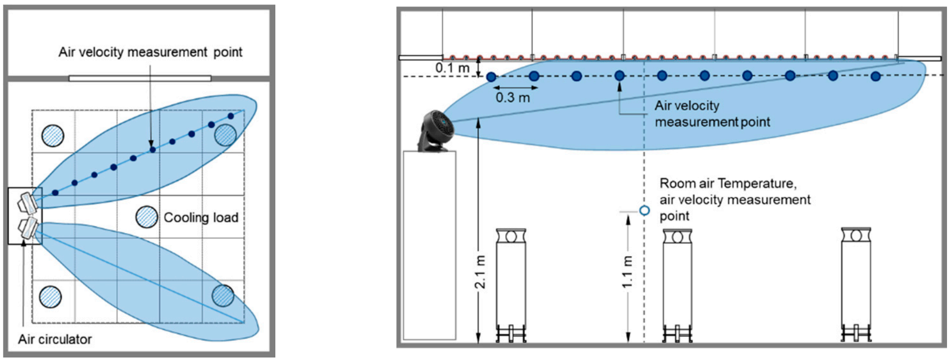
Figure 3. Evaluation cases: (**a**) closed-type CRCPs; (**b**) closed-type CRCPs with air circulators; (**c**) open-type CRCPs; (**d**) open-type CRCPs with air circulators.

For Cases 2 and 4, two air circulators were used to increase the air velocity at the CRCP surfaces. The specifications of the air circulator are summarized in Table 2. They were located at a height of 2.1 m above the floor to create air flow as close to the CRCP surface as possible, as shown in Figure 4. The air flow rate from each air circulator was approximately 284 m^3/h, which generated an air velocity of 4.5 m/s at the outlet of the circulator. A multichannel anemomaster with ten velocity probes was deployed to analyze the impact of the air circulator on the air velocity at the CRCP surface.

Table 2. Specifications of the air circulator.

Item	Performance Data			Shape
Fan step *	I	II	III	
Fan speed	1200 rpm	1700 rpm	2000 rpm	
Air flow rate	212 m^3/h	284 m^3/h	357 m^3/h	
Maximum air velocity		7.5 m/s		
Air travel range		20 m		
Area covered		20 m^2		

* Fan step II (1700 rpm and 284 m^3/h) was used in this study.



(**a**) (**b**)

Figure 4. Concept of air circulator test: (**a**) plan view; (**b**) section view.

In each case, the cooling performance of the CRCP systems was investigated in terms of cooling capacity and electricity consumption. Cooling capacity was evaluated by measuring the heat removed by the CRCPs under steady-state conditions, while a cooling load of 900 W was applied by five electrical dummies. During the test, the average surface temperature of the CRCPs was controlled at 17 °C to remove the cooling load. Cooling capacity was determined when the 60 min standard deviation of mean water temperature, wall surface temperature, and reference (room air) temperature met the steady-state criteria defined in EN 14240. Cooling capacity was calculated by dividing the total heat removed by the CRCP area, as formulated in Equations (1) and (2). The amount of heat removed was calculated based on the difference between the temperatures of the chilled water in the CRCP hydronic subcircuits.

$$Q_T = \sum_i q_i = \sum_i c_p m_i (T_{r,i} - T_{s,i}) \tag{1}$$

$$P = \frac{Q_T}{A_T} \tag{2}$$

where Q_T is the total heat removed [W], q_i is the heat removed in the i-th circuit [W], c_p is the specific heat of chilled water [J/kgK], m_i is the mass flow rate for the i-th circuit [kg/s], $T_{r,i}$ and $T_{s,i}$ are the return and supply water temperatures for the i-th circuit, respectively [°C], P is cooling capacity [W/m^2], and A_T is the total CRCP area [m^2].

Energy performance was evaluated by operating the CRCP system at a set-point temperature of 26 °C and applying a cooling load of 900 W to the test chamber. Simple on/off control was implemented to operate the CRCP system to clearly compare the operation time and energy consumption. The circulation pump was stopped when the room air temperature reached 26 °C and restarted if the room air temperature exceeded 27 °C. The electricity consumption of the chiller, circulation pump, and air circulator was measured while operating the CRCP system in each case under the abovementioned conditions for 10 h.

3. Results

3.1. Cooling Capacity Analysis

Table 3 and Figure 5 show the evaluation results of cooling capacity for the four cases. The cooling capacity of the closed-type CRCP system (Case 1) was 96.1 W/m^2, while that of the open-type CRCP system (Case 3) was 104.3 W/m^2. The open-type CRCP system reduced the room air temperature by 1.6 °C compared to the closed-type CRCP system under the same operating conditions. The open-type CRCP system also reduced the temperature difference between room air temperature and plenum air temperature, which implies that the mixture of room air and plenum air was improved compared to the closed-type CRCP system. This can be attributed to the movement of cooled plenum air, as reported in a previous study [2]. Thus, the open-type CRCPs can effectively enhance cooling capacity under the same operating conditions as those of the closed-type CRCPs.

Table 3. Evaluation results of cooling capacity.

Case	Room Air Temperature [°C]	Plenum Air Temperature [°C]	Temperature Difference * [°C]	Air Velocity [m/s]	Heat Removed [W]	Cooling Capacity [W/m^2]
Case 1	24.2	20.8	3.4	0.11	865	96.1 (Baseline)
Case 2	23.4	19.8	3.6	0.19	1013	112.5 (+17.0%)
Case 3	22.6	22.3	0.3	0.07	940	104.3 (+ 8.5%)
Case 4	22.2	21.0	1.2	0.21	1091	121.2 (+26.2%)

* Difference between room air temperature and plenum air temperature.

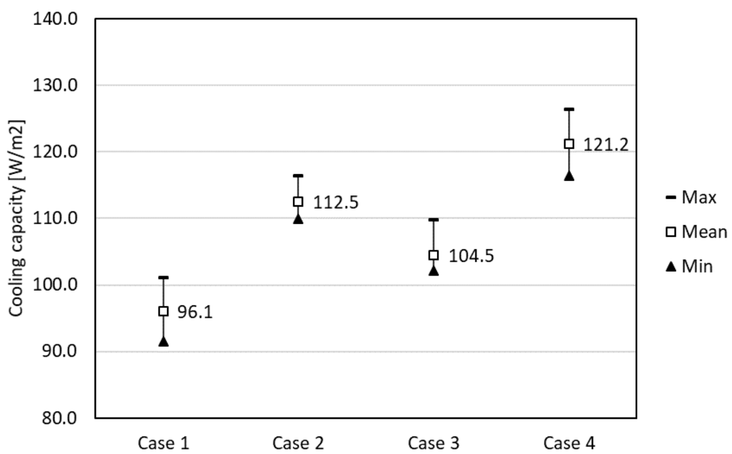


Figure 5. Measurement result of cooling capacity for different cases.

The cooling capacity of the closed-type CRCPs (Case 2) with air circulators was higher than that of the closed-type CRCPs without air circulators (Case 1) by 17.0%. Figure 6 shows the air velocity measured at the axis of air flow from the air circulator, as described in Figure 4. Although the air velocity gradually decreased, it was much higher than the typical air velocity (e.g., 0.2 m/s [14]) in the conditioned space. It was considered that the elevated air velocity at the CRCP surfaces promoted convective heat transfer between the panel surfaces and room air, which led to the increased cooling capacity and decreased room air temperature.

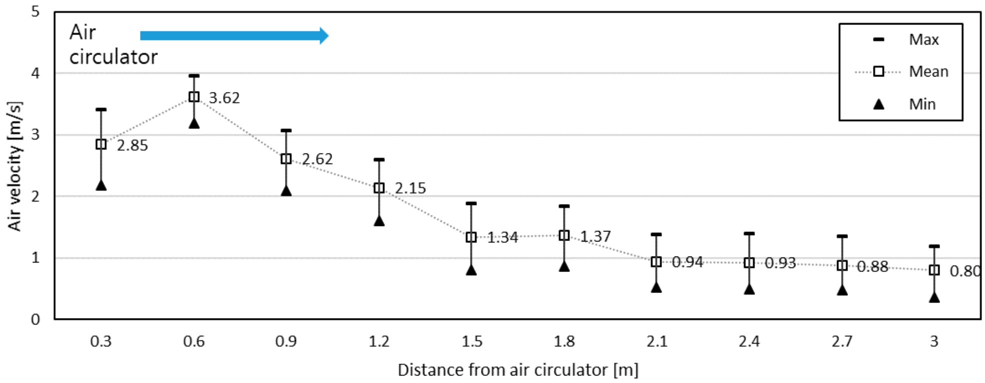


Figure 6. Air velocity measured in the direction of air flow by air circulator.

When forced air flow was generated on the surface of the open-type CRCPs using air circulators (Case 4), cooling capacity increased up to 121.2 W/m^2, which was the largest among all cases. This cooling capacity was higher than that of the closed-type CRCP system (Case 1) and the open-type CRCPs without air circulators (Case 3) by 26.2% and 16.2%, respectively. Thus, cooling performance can be further enhanced if the open-type CRCP system is operated with a supplementary air circulation device.

Regarding the surface condensation problem, it is of importance to maintain the panel surface temperature above the dew-point temperature in the conditioned space. Table 4 shows the range of panel surface temperatures (min, max and mean values), room air temperature, relative humidity and dew-point temperature in each case. It was found that condensation was prevented because the minimum surface temperature was always higher than dew-point temperature.

Table 4. Panel surface temperature and dew-point temperature.

Case	Panel Surface Temperature [°C]			Room Air Temperature [°C]	Relative Humidity [%]	Dew-Point Temperature [°C]
	Min	Max	Mean			
Case 1	16.3	19.0	17.2	24.2	42	10.5
Case 2	16.4	18.6	17.2	23.4	42	9.7
Case 3	16.0	18.6	16.9	22.6	60	14.4
Case 4	16.5	18.9	17.4	22.2	57	13.3

In addition, the use of openings or air circulators reduced the difference ($\Delta\theta$) between the mean chilled water temperature and room air temperature, which is formulated as Equation (3).

$$\Delta\theta = T_a - \frac{T_r + T_s}{2} \quad (3)$$

where T_a, T_r, and T_s denote the temperatures [°C] of room air, supply chilled water, and return chilled water, respectively. A smaller $\Delta\theta$ implies that the CRCP system can operate at a chilled water temperature that is close to the room air temperature.

Figure 7 shows the relationship between cooling capacity and temperature difference ($\Delta\theta$). In the open-type CRCP system with air circulators, a higher cooling capacity was achieved at a smaller value of $\Delta\theta$ compared to the other cases. This was because in the open-type installation, a part of the cooling load was removed by cooled plenum air and the air circulators increased the heat transfer rate between the CRCP surfaces and room air. Therefore, a high chilled water temperature that is close to the room air temperature can be used to obtain the required cooling capacity when the open-type installation and air circulators are applied. This can not only improve the energy efficiency of the chiller unit but also mitigate the condensation risk at panel surfaces.

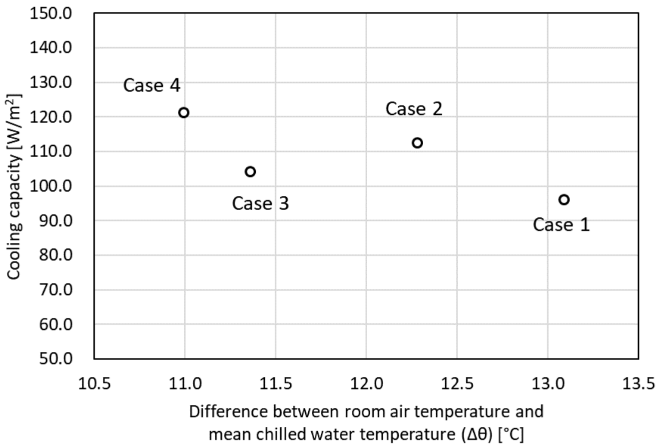


Figure 7. Relationship between Δθ and cooling capacity.

3.2. Energy Consumption Analysis

Figure 8 shows the measurement results of the room air temperature, pump operation, and chiller operation. These results were used to analyze the energy consumption for each case. As shown in Figure 8a, the room air temperature was relatively stable in Case 1 because the CRCPs removed heat at the same rate at which the cooling load was applied. The pump operated continuously during the test period because chilled water was continuously supplied to the CRCP system to maintain the steady-state condition. The chiller operated intermittently because it repeatedly performed on/off operations in order to maintain a constant chilled water temperature in the water tank.

In Case 2, the room air temperature was not stable because cooling capacity was enhanced by the air circulators, as described in Section 3.1. The enhanced cooling capacity reduced the room air temperature to less than 26 °C, causing the circulation pump to stop. Then, the room air temperature increased until the CRCP system restarted at 27 °C. Owing to this on/off operation of the CRCP system, the pump operation time in Case 2 was less than that in Case 1. This led to the energy-saving effect of the CRCP system; this is discussed in subsequent paragraphs.

The fluctuation of room air temperature was also found in Case 3, as shown in Figure 8c. However, the room air temperature decreased more rapidly compared to Case 2 because cooled plenum air contributed to the cooling of room air. For this reason, it is expected that Case 3 can provide higher energy-saving potential compared to Case 2 because of the reduced operation time of the chiller and circulation pump. In Case 4, cooling capacity was further enhanced by the air circulators. Hence, the room air temperature decreased more rapidly compared to Case 3. Thus, the on–off cycle time and pump operation time were reduced. This could lead to more energy savings for the CRCP system.

Power meter data showed that the reduced operation time could reduce the energy consumption of the overall system. Figure 9 and Table 5 show the electricity consumption of the chiller, pump, and air circulators, in addition to the operation time of the chiller and pump. In Case 2, the application of the air circulators reduced the energy consumption of the chiller and pump by 1.14 kWh and 3.19 kWh, respectively, compared to Case 1, even though the air circulators consumed 0.72 kWh. The total reduction in energy consumption in Case 2 was 3.61 kWh (10.2%) compared to Case 1.

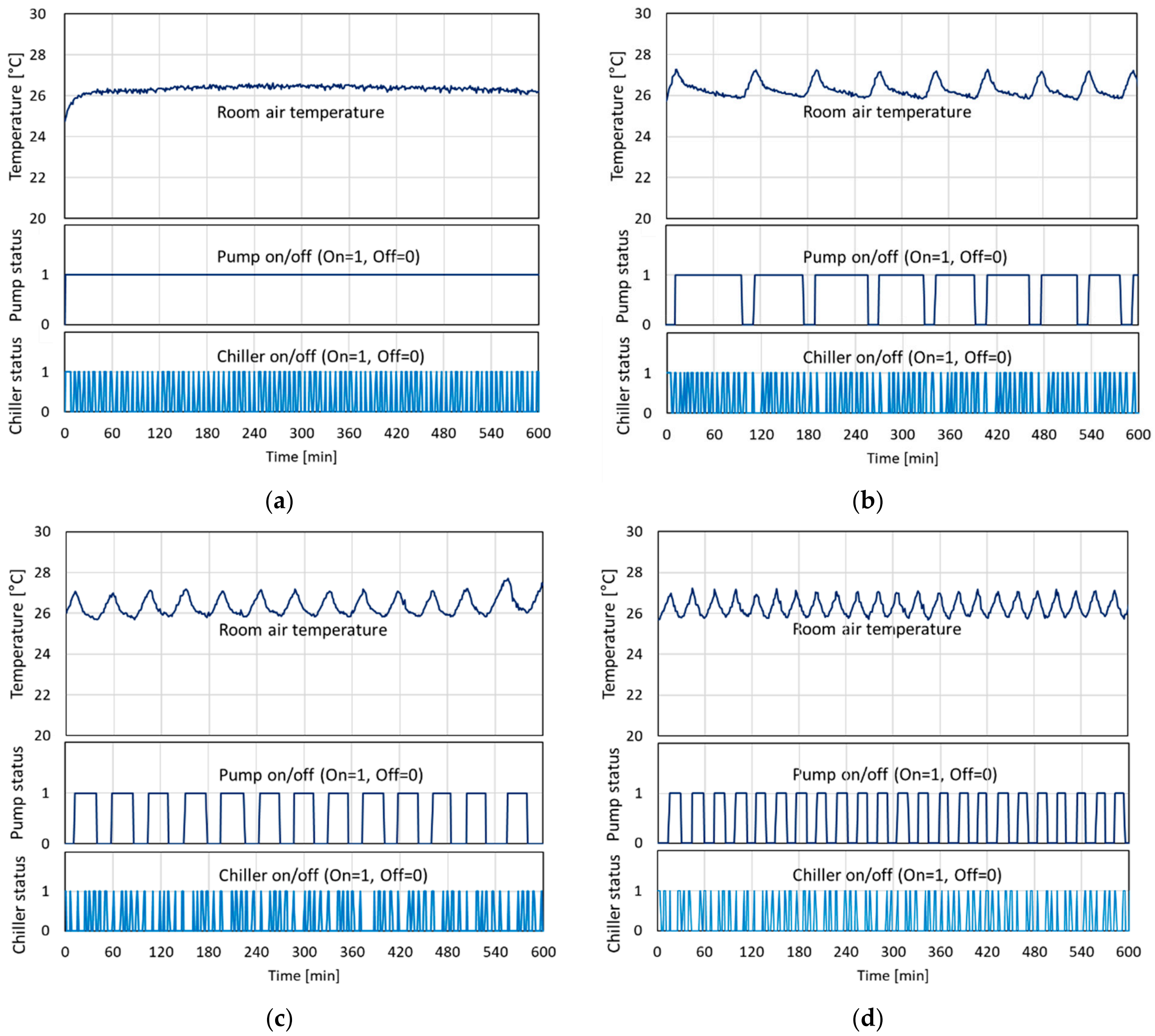


Figure 8. Measurement results of room air temperature, pump operation, and chiller operation: (**a**) Case 1; (**b**) Case 2; (**c**) Case 3; (**d**) Case 4.

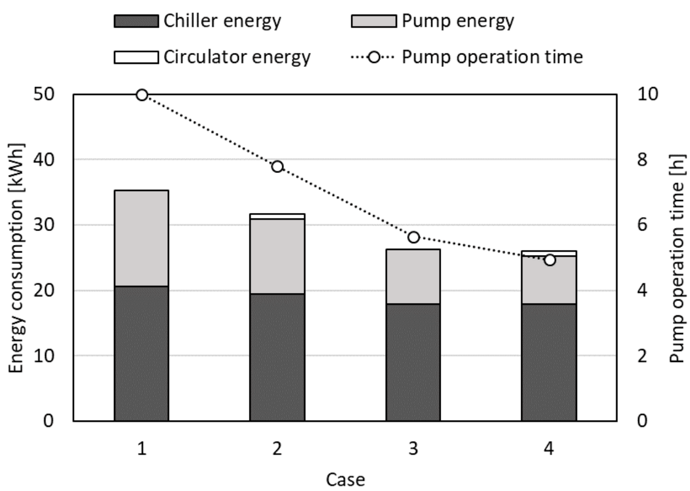


Figure 9. Comparison of energy consumption in each case.

Table 5. System operation time and electricity consumption.

Case	Operation Time [min]		Electricity Consumption [kWh]			
	Chiller	Pump	Chiller	Pump	Air Circulator	Total
Case 1	195	600	20.62	14.64	0	35.3
Case 2	178	468	19.48	11.45	0.72	31.6 (−10.2%)
Case 3	157	339	17.93	8.34	0	26.3 (−25.5%)
Case 4	157	296	17.93	7.31	0.72	26.0 (−26.4%)

In Case 3, the energy consumption of the chiller and pump was reduced by 2.69 kWh and 6.30 kWh, respectively, compared to Case 1. The total reduction in energy consumption was 8.99 kWh (25.5%). In Case 4, the energy consumption of the chiller and pump was reduced by 2.70 kWh and 7.33 kWh, respectively, compared to Case 1. As the air circulators consumed 0.72 kWh, the total reduction in energy consumption was 9.30 kWh (26.4%). Therefore, it can be concluded that the open-type installation and air circulators effectively enhance not only cooling capacity but also energy performance.

In this study, a simple on/off control was implemented to compare energy performance depending on the CRCP installation type and the application of air circulators. The reason for selecting on/off control was to investigate how the enhanced cooling capacity affects system behaviors and energy consumption. However, much fluctuation of room air temperature was observed in Cases 2–4, owing to the inherent characteristics of the on/off control. Although its impact on thermal comfort may not be significant, it can lead to the short-cycling of pump and chiller, which can deteriorate the system efficiency. To solve this problem, it needs to mitigate the room temperature fluctuation by modulating the chiller water flow rate (e.g., PID control). A further study is suggested to investigate the energy performance when the advanced control method is used for the CRCP system with air circulators.

4. Discussion

4.1. Research Implications

The experimental results presented in Section 3 show that the cooling capacity and energy performance of the CRCP systems can be enhanced by utilizing cooled plenum air for space cooling and/or applying air circulators to increase the heat transfer rate at the panel surfaces. It was found that the open-type installation increased the cooling capacity by 8.5% and air circulators increased the cooling capacity by 16.2% for the open-type CRCP and 17.1% for the closed-type CRCP system. Table 6 shows the summarized result of the increase in cooling capacity, compared with the previous studies on the cooling capacity enhancement of ceiling radiant cooling systems.

Shin et al. [2] reported that the cooling capacity can be enhanced by 54–80%, which is much higher than this study. As their study assumed a much higher cooling load (135 W/m^2) than that of this study (64 W/m^2), strong thermal plumes could be generated from the cooling load (electrical dummies), which promoted the natural convection effect in the whole space. Therefore, the difference in the cooling load condition seemed to cause the difference between the cooling capacity of the two studies. Jeong and Mumma [8] claimed that the cooling capacity could be enhanced by 5–35% when the discharge air velocity from a nozzle diffuser was 2–6 m/s. In the present study, discharge air velocity from the air circulator was 4.5 m/s, and the cooling capacity was increased by 16.2–17.1%. Thus, the increased rate of cooling capacity seems to fall within the range of the previous study. Kim and Leibundgut [9] showed that air flow by air convector increased the cooling capacity by up to 32%, which is higher than that of the present study. This is because the cooling capacity was also affected by the cooling coil in the air convector. Thus, the additional enhancement of cooling capacity can be expected if the pre-cooled (non-isothermal) air flow is distributed at CRCP surfaces. Novoselac et al. [10] reported that the isothermal jet from the high-aspiration diffuser increased the cooling capacity by 4–17% depending on the air flow rate. This result is quite similar to that of the present study, because air circulators were used to generate isothermal air flow by recirculating the room air. Karmann et al. [11] demonstrated that the cooling capacity can be increased by 22% and 26% when operating a ceiling fan and small fans, respectively. This increase in cooling capacity is slightly higher than that of the present study. This is because their study was conducted for the TABS with acoustic clouds, wherein air movement can be highly promoted in the plenum (space between ceiling surface and acoustic clouds).

Table 6. Comparison with previous studies on cooling capacity enhancement.

Literature	Method to Increase Cooling Capacity	Air Flow Characteristic	Increase in Cooling Capacity
This study	Natural convection by opening area	Isothermal	8.5% (1)
This study	Forced convection by air circulator	Isothermal	16.2–17.1% (2)
Shin et al. [2]	Natural convection by opening area	Isothermal	54–80%
Jeong and Mumma [8]	Forced convection by nozzle diffuser	Isothermal	5–35%
Kim and Leibundgut [9]	Forced convection by air convector	Non-isothermal	32%
Novoselac et al. [10]	Forced convection by nozzle diffuser	Isothermal	4–17%
Karmann et al. [11]	Forced convection by ceiling fan	Isothermal	22%
Karmann et al. [11]	Forced convection by small DC fans	Isothermal	26%

(1) 8.5% = 104.3 W/m^2 (Case 3) compared to 96.1 W/m^2 (Case 1). (2) 16.2% = 121.2 W/m^2 (Case 4) compared to 104.3 W/m^2 (Case 3), 17.1% = 112.5 W/m^2 (Case 2) compared to 96.1 W/m^2 (Case 1).

The comparison with previous studies showed that the enhancement of cooling capacity was appropriately achieved in this study. Thus, these results could be applied to develop an energy-efficient design or operation method of CRCP systems. For example, the cooling capacity of CRCP systems is frequently insufficient in hot and humid climates because the chilled water temperature should be increased to prevent condensation. If a CRCP system is used with the open-type installation or with supplementary air circulation devices, the required cooling capacity can be achieved at a high chilled water temperature.

Figure 10 shows the relationship between Δθ and energy consumption. The open-type installation and air circulators reduce not only energy consumption but also Δθ. A smaller Δθ indicates that the chilled water temperature is closer to the room air temperature. Based on this, the proposed CRCP systems (Cases 2 to 4) can operate at a higher chilled water temperature; this increases chiller efficiency [18–21]. Thus, the proposed CRCP systems can save more energy compared to the conventional CRCP system (Case 1).

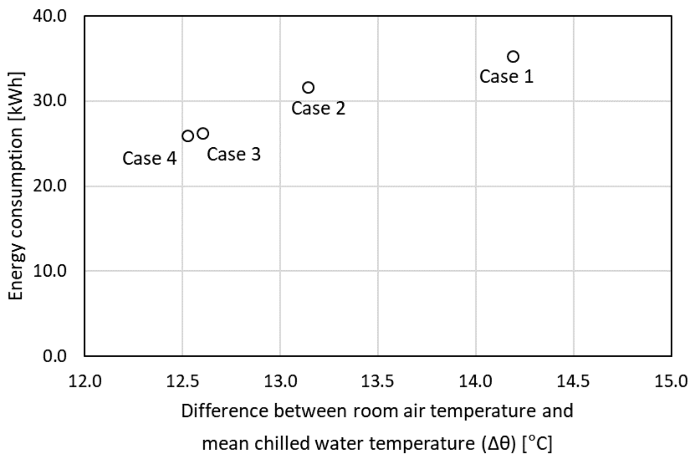


Figure 10. Relationship between Δθ and energy consumption.

Even though the open-type CRCP system effectively enhances cooling capacity, its application might be limited because of the dust migration from the plenum to the occupied space. Thus, appropriate maintenance or cleaning is necessary for utilizing cooled plenum air for space cooling. In addition, sufficient thermal insulation should be applied to the perimeter wall that surrounds plenum air (e.g., spandrel wall) because the plenum air temperature can increase, owing to the heat transmitted through the spandrel wall. This increases the cooling load and energy consumption of the open-type CRCP system. Therefore, the appropriate thermal insulation of the spandrel wall is important for successfully using the open-type CRCP system.

In the cases where it is difficult to adopt the open-type CRCP system because of the abovementioned issues, the closed-type CRCP system with air circulators can be another solution for increasing cooling capacity and energy efficiency. As the air circulators increase the air velocity, as shown in Table 3, thermal comfort can be improved while maintaining the same room air temperature as that in the conventional CRCP system.

4.2. Research Limitations

In this study, room air temperature and air velocity at a representative point (center of the test chamber) were measured to evaluate the general comfort depending on the CRCP installation type and the application of air circulators. The room air temperature at the representative point was also used as a reference value for the system control, which was necessary to analyze the cooling energy consumption. Nonetheless, air movement through the opening or the operation of air circulators may cause excessive air velocity and local discomfort (e.g., cold draught) at specific locations. To evaluate this local discomfort and thermal uniformity, air temperature and velocity need to be measured at multiple points simultaneously. Multi-point measurement with a sensor grid or CFD simulation is necessary to evaluate the thermal uniformity and local discomfort for the CRCP system with air circulators.

The thermal uniformity can also be deteriorated because the entire CRCP surfaces may not be provided with the air flow by air circulators. This is a limitation of air circulator that is designed to generate a directional air flow, not a diffusive air flow. To overcome this limitation, the cooling capacity and thermal uniformity depending on the air flow rate and arrangement of air circulators need to be investigated. The application of multiple small fans can be another solution to generate the diffusive air flow, which is effective to increase the air velocity at the entire panel surfaces while preventing excessive air velocity.

This study has the limitation that the cooling capacity of the CRCP system was investigated with regard to total cooling capacity, wherein the radiant and convective heat transfer were not separated. To quantify the impact of air circulators on the cooling capacity, convective heat transfer needs to be distinguished from the total cooling capacity. Although many studies on ceiling radiant cooling systems have suggested radiant/convective heat transfer coefficients [1,6,8,22–24], these studies focused on the ceiling radiant cooling system made of top-insulated panels. Thus, heat transfer at the upper panel surface was not considered to determine the radiant/convective heat transfer coefficients. As this study applied the ceiling panels without top-insulation, radiant/convective heat transfers also occurs at the upper panel surfaces. This makes it difficult to adopt the radiant/convective heat transfer coefficients suggested by previous studies. Therefore, a further study is proposed to determine the radiant/convective heat transfer coefficients for the CRCP system without top insulation.

In this study, the cooling capacity of the CRCP system was enhanced by recirculating room air. Outdoor air can be utilized to enhance cooling capacity if it is appropriately processed by a dedicated outdoor air system (DOAS), which is typically combined with radiant cooling systems to address ventilation and latent load. Cooling capacity can be further enhanced by utilizing an air distribution system, such as an active chilled beam, to generate widespread air flow on the CRCP surface. Thus, the cooling performance of the CRCP system combined with various air distribution systems should be further investigated.

5. Conclusions

The impact of the open-type installation and air circulators on the cooling capacity and energy performance of the CRCP system was investigated through mock-up chamber experiments. Compared to the reference case (Case 1: closed-type CRCP), cooling capacity increased by 17% when air circulators were used (Case 2: closed-type CRCP with air circulators), by 8.5% in the open-type installation (Case 3: open-type CRCP), and by 26.2% when the open-type installation and air circulators were combined (Case 4: open-type CRCP with air circulators). The experimental results showed that in the open-type CRCP system, the utilization of cooled plenum air enhanced cooling capacity. In addition, air circulators effectively increased the cooling capacity of the closed-type and open-type CRCP systems.

Regarding the energy performance, the increase in cooling capacity due to the open-type installation and air circulators reduced the operation time of the chiller and circulation pump. Compared to the reference case (Case 1), the open-type installation and/or air circulators reduced cooling energy consumption by 10.2–26.4%.

The open-type installation and air circulators also reduced the difference between the room air temperature and mean chilled water temperature. This implies that the open-type CRCP system with air circulators can operate at a relatively higher chilled water temperature, which effectively reduces the condensation risk on panel surfaces. A high chilled water temperature provides additional energy-saving potential owing to increased chiller efficiency. The detailed impact of the open-type CRCP system with air circulators on condensation risk and chiller efficiency should be further examined.

In this study, cooling capacity was enhanced by utilizing cooled plenum air or the recirculation of room air. Considering that a radiant cooling system is typically combined with a DOAS to address ventilation and latent load, the processed outdoor air from the DOAS can be utilized to enhance the cooling capacity of the CRCP system. A future study will be conducted to improve the cooling capacity and energy performance by supplying processed outdoor air through air distribution systems such as an active chilled beam system.

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