Introduction of hybrid radiant cooling system for adapting hot and humid climates

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Abstract. The main purpose of this study is to introduce a hybrid radiant cooling system which combines a conventional radiant cooling panel with an Airbox convector hydronically connected in series for adapting hot and humid climates as a novel radiant cooling strategy. This novel system can reduce moisture condensation risks on a surface of chilled ceiling panel and generates additional cooling capacity because the Airbox convector can dehumidify indoor air when indoor humidity level is increased and it enhances a mixed convection effect which combines natural convection with mechanical forced convection effect. And this system simply adjusts cooling output by the Airbox’s fan control and indoor air pollution rate because the Airbox includes an air filter, therefore, this system can be adapted to various indoor thermal conditions. This paper presents strategies to use the system effectively and to save cooling energy consumptions. And this study demonstrates systematic strategies how the hybrid radiant cooling system can minimize main challenges of using typical radiant cooling system and improve cooling and dehumidification performance in various thermal conditions.

1. Introduction
In general, cooling system in buildings is categorized into two parts: all-air system, and radiant cooling system. Compared with all-air systems, radiant cooling system is energy efficient and better indoor thermal comfort strategy because it has lower fan energy consumed, lower temperature gradient and higher cooling impact ratio, and it can minimize duct space, supply air volume amount and fan noise. The main difference of radiant cooling panel system unlike conventional all-air system, is that the radiant cooling system separates the sensible cooling provided by chilled ceiling panel and sensible and latent cooling provided by displacement air ventilation system. Many literatures describe the benefits using radiant cooling system in summer season with numerical calculation and measurement. However, conventional radiant cooling system has also limitations to use in buildings. First, radiant cooling system could not be useful in hot and humid weather condition because it has moisture condensation risk on the surface of radiant cooling panel when indoor space gains high moisture. Second, radiant cooling panel system coupled with displacement ventilation system to reduce air ventilation rate has much lower air movement, therefore, when indoor air quality is bad, it is limited to reduce indoor air pollutants. Third, compared with all-air system, radiant cooling system has longer reaction time delays in the start-up. Last, radiant cooling system has difficulty to adjust cooling output as indoor space zoning when a room is exposed to sudden cooling energy load.

Recently, a new hybrid radiant cooling system which combines an Airbox convector unit hydronically connected in series is proposed by Kim and Leibundgut [1-4]. The thermal performance of the system is presented in the references. The Airbox convector [5-8] consists of compact thermal heat exchangers, air fans, water drainer and air filters. This hybrid radiant cooling system has advantages compared with conventional radiant cooling system and all-air system. This system has around 9-10 % of higher performance to save energy and simply adjusts 32 % of additional cooling output without cooling sources added, compared with conventional radiant cooling system. This system can simply
dehumidify indoor air using the Airbox convector and reduce time delay to activate the system. And air filters in the Airbox convector can reduce indoor air pollutants. This study presents the hybrid radiant cooling system performance compared with the typical radiant cooling system. In this research, cooling capacity of hybrid radiant cooling system using estimated radiant heat flux is investigated.

2. Methods
2.1. Overview of hybrid radiant cooling system

Figure 1 and 2 show schematics of conventional radiant cooling system and hybrid radiant cooling system with a displacement ventilation system. Compared with all-air system, conventional radiant cooling system has higher energy efficient performance because it delivers minimum air volume and higher cooling impact ratios. However, it has moisture condensation risk on the surface of radiant cooling panel when the room is exposed higher moisture infiltration rate or indoor humidity gains. In order to minimize moisture condensation risk on the surface radiant cooling panel, the system requires that the supply air condition is dehumidified to reach 8 g/kg and supply water temperature is designed to 18 °C.

![Figure 1. Schematic of conventional radiant cooling system with underfloor ventilation system.](image1)

![Figure 2. Schematic of hybrid radiant cooling system with underfloor ventilation system.](image2)

The hybrid radiant cooling system shown in figure 2 is newly designed and suggested by Kim and Leibundgut [1-3]. The novel system can minimize moisture condensation risk by using an Airbox convector which dehumidifies indoor air when the indoor air is exposed to high moisture gain and increase supply water temperature due to heat transfer in compact heat exchangers in the Airbox unit since radiant ceiling panel is connected to the Airbox convector hydronically in series. And the Airbox unit can simply adjust air flow rate and reduce indoor air pollutants by air filters. Thus, this system effectively adjusts cooling output for indoor space zoning. When the convector fans are off, the hybrid
cooling system is same as conventional radiant cooling system. However, if occupants feel too warm or humid, the convector fans are on and indoor air is chilled down and dehumidified by the convector. The air flow rate and directivity is controlled by fans, and occupants can simply and effectively adjust cooling output. And the radiant cooling energy performance is enhanced by mixed convection effect which combine natural convection with mechanical forced convection [1-4, 8]. It means that higher temperature cooling contribute to a low exergy technology and energy saving in buildings.

2.2. Natural and mixed convection coefficient
In general, ASHRAE (American Society Heating Refrigerating and Air-Conditioning Engineers) Fundamental [9] defines Natural convection heat transfer coefficients. Some literatures [10-14] also uses the heat transfer coefficient as test results, equation (1).

\[ h_c = 2.13 \left( T_a - T_{pm} \right)^{0.31} \]  

Where \( h_c \) is convective heat transfer coefficient (W/m\(^2\) K), \( T_a \) is space temperature, (°C), and \( T_{pm} \) is panel mean temperature, (°C)

Mixed convection coefficient is also defined by many experimental results and literatures [10, 13-18] which are presented in equations (2) and (3).

\[ h_c = 0.49 \ \text{ACH}^{0.8} \]  

\[ h_c = (h_{cn}^{3.2} + h_{cf}^{3.2})^{1/3.2} \]  

\[ h_{cn} = \frac{2.175} {D_e^{0.575}} \left( T_a + T_{pm} \right)^{0.308} \]  

\[ h_{cf} = 4.25 \ W^{0.575} W^{0.557} \]  

Where ACH is air exchanges per hour, \( c_n \) is natural convection, \( c_f \) is forced convection, \( D_e \) is characteristic diameter of room surface (=4Ae/P) (m) and \( W \) is width of nozzle diffuser, (m)

2.3. Radiant heat transfer coefficient
Literatures [13, 14, 19-21] also show methodologies to define the radiant heat transfer coefficient which is determined by equation (4) as well.

\[ h_r = 5 \times 10^{-8} \left[ (AUST + 273)^2 + (T_{pm} + 273)^2 \right] \left[ (AUST + 273) + (T_{pm} + 273) \right] \]  

where \( h_r \) is radiant heat transfer coefficient (W/m\(^2\) K), AUST is area-weighted average temperature, (°C).

And total heat flux (\( q_t \)), (W/m\(^2\)) combines the convection heat flux (\( q_c \)) with the radiant heat flux, (\( q_r \)). It is shown in equation (5-7).

\[ q_t = q_c + q_r \]  

\[ q_c = h_c \left( T_a - T_{pm} \right) \]  

\[ q_r = h_r \left( AUST - T_{pm} \right) \]

2.4. Hybrid radiant cooling capacity
In order to define hybrid radiant cooling capacity, we used the experimental results by Kim and Leibundgut [1-3, 6]. The minimum and maximum cooling capacities of Airbox convector are 175.22-
752.85 W respectively at an airflow rate of 85 m³/h and a water flow rate of 3.1 L/min and 161.3 – 694 W at an airflow rate 85 m³/h and a water flow rate of 1.7 L/min [1-3]. In this study, we combine cooling capacity of conventional radiant cooling system with the Airbox convector.

3. Results

![Figure 3](image1.png)

**Figure 3.** The different cooling capacity models of conventional and hybrid radiant cooling system for a steel panel.

![Figure 4](image2.png)

**Figure 4.** The different cooling capacity models of conventional and hybrid radiant cooling system for an aluminium panel.
Actual cooling capacity of radiant cooling panel is performed by not only natural convection effect but also mixed convection effect which combines natural convection with mechanical forced convection with varied air volume generated by the Airbox convector. Köchendorfer showed that air diffusers can affect the increase of the cooling panel output by 10-15 % and Jeong and Mumma described that the cooling output can be improved by 10-30 %. This study presents comparisons of predicted cooling capacity for the natural and mixed convection effects with the models, Jeong and Mumma, ASHRAE Equation, TSI (Turkish Standard Institute) [22] and Manufacture model [14] combining with Kim and Leibundgut’s Airbox convector [1-3]. This study show the increase of cooling capacity of steel and aluminum panels which is enhanced by Airbox convector’s cooling output and air movement rise in a room. The results are assumed that supply water temperature lift in the Airbox convector is 1-2 °C, air velocity released by Airbox convector is 1 m/s and supply water flow rate is 2.0 L/min. The results are shown in Figure 3 and 4.

Hybrid radiant cooling panel capacity is higher than conventional radiant cooling system as illustrated in Figure 3 and 4. In general, conventional radiant cooling system has a limitation to increase cooling output because lower supply water temperature has a higher moisture condensation risk. However, the hybrid radiant cooling system simply adjust cooling output with variable air volume control depending on the Airbox fan speed without supply water temperature changed. Figure 3 and 4 present that Aluminum panel cooling output is overall higher than those of steel panel. And the hybrid radiant cooling capacity is increased to 12-15% by Airbox convector’s performance. High temperature cooling can minimize temperature difference between evaporator and condenser temperature in heat pump system and therefore it can contribute to maximize co-efficient of performance (COP) as a low exergy technology.

4. Conclusion
This study introduces a novel hybrid radiant cooling system adapting hot and humid climate. Compared with conventional radiant cooling system, hybrid radiant cooling system has higher cooling capacity and less moisture condensation risk and also simply adjust cooling output of radiant cooling system due to Airbox convector’s fan control. And the system can simply control indoor space zoning because Airbox convector can reduce time delay to start up the system. High temperature cooling can minimize temperature difference and therefore it can contribute to maximize co-efficient of performance (COP) as a low exergy technology.

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