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# Possibility of coupling outdoor air cooling and radiant floor cooling under hot and humid climate conditions

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ABSTRACT

Existing radiant floor cooling systems introduce minimum outdoor air to provide ventilation and to prevent condensation on the floor surface. Conventional radiant floor cooling systems save energy relative to conventional air conditioning systems; these savings arise from the use of higher set-point temperatures and the minimization of outdoor air.

In this work, the possibility was analyzed of coupling outdoor air cooling with radiant floor cooling in a hot and humid climate. A radiant floor cooling system using a dehumidified ventilation system with an outdoor air cooling mode was analyzed by a simulation method. Moreover, the behavior of the indoor thermal environment, the system's operation and its energy consumption were reviewed. Simulation modeling to analyze the possibility of using the coupled system was validated against experimental results. Simulations showed that the proposed system can provide cooling energy savings of more than 20% compared to the existing radiant floor cooling system in the hot and humid climate of Seoul, Korea; these savings arise primarily from a reduced operation rate of the radiant floor cooling loop and from reduced energy consumption by the chiller realized through proper operation of the outdoor air cooling strategy. The outdoor air cooling reduced the chiller's electricity use by about 24%. Two outdoor air cooling modes were tested: a temperature-based outdoor air cooling mode was more energy-efficient than an enthalpy-based mode even during the hot and humid season in Korea.



## 1. Introduction

Radiant cooling methods save energy relative to conventional air systems through greater chilled water temperature cooling and lower transport energy consumption [1–7]. Based on their research on industrial buildings, Feustel and Stetiu [7] reported that using a radiant cooling system can save up to approximately 40% of electrical energy compared to existing HVAC systems.

Typically, radiant cooling systems are implemented in hot, humid climates to reduce air conditioning loads, but cannot be used alone because water vapor in the humid air will condense on the cold radiant surface. As such, radiant cooling systems must always be coupled with some form of air handling unit to ensure that the interior air is dry enough to prevent condensation [8]. Consequently, when radiant cooling is used in hot, humid climates, indoor moisture levels need to be carefully controlled, not only for the purpose of thermal comfort but also to avoid condensation. Zhang and Niu [9] investigated indoor humidity behaviors associated with various air dehumidification and ventilation strategies for a chilled-ceiling system in Hong Kong. They determined that 1 h of dehumidification/ventilation in advance of occupancy during summer could completely eliminate the condensation problems. Song and Kato [10] proposed a dehumidifying radiant panel cooling system with natural ventilation in Japan and analyzed the thermal comfort and energy savings through a computational fluid dynamics simulation. In their study, the performance of the radiant panel cooling system with natural ventilation was compared with than of an under-floor air cooling system, showing that the radiant panel cooling system was more energy-efficient than an under-floor air cooling system when wind-driven cross ventilation was introduced. Leigh and Song [11,12] proposed a radiant floor cooling system integrated with dehumidified ventilation in Korea and reviewed the effects of the system control features on temperature and humidity using experiments and simulations, showing that the radiant floor cooling system with dehumidified ventilation resulted in approximately 67% electrical energy savings compared to the all-air cooling system in the summer season in Korea.

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**Nomenclature**

| | |
|---|---|
| $C_p$ | specific heat of air [kJ/(kg °C)] |
| $\rho$ | density of air [kg/m$^3$] |
| $E_{in}$ | enthalpy of indoor air [kJ/kg] |
| $E_{out}$ | enthalpy of outdoor air [kJ/kg] |
| $OT_{iset}$ | indoor set point operative temperature [°C] |
| $Q$ | ventilation airflow [m$^3$/h] |
| $Q_{max}$ | ventilation airflow for outdoor air cooling [m$^3$/h] |
| $q_{sc}$ | sensible cooling load [kJ/h] |
| $T_d$ | calculated optimized supply air temperature for cooling [°C] |
| $T_{dp}$ | dew point temperature [°C] |
| $T_g$ | globe temperature [°C] |
| $T_{in}$ | indoor air temperature [°C] |
| $T_{iset}$ | indoor set-point temperature [°C] |
| $T_{mrt}$ | mean radiant temperature [°C] |
| $T_{out}$ | outdoor air temperature [°C] |
| $T_{surf}$ | floor surface temperature [°C] |
| $v$ | air velocity [m/s] |
| $\Delta t$ | temperature difference between indoors and outdoors [°C] |

As another approach to control indoor humidity under radiant cooling, a liquid desiccant system was developed rapidly in China; discussion of its main principle and performance analysis can be found in the literature [13,14].

However, there still remains the possibility of coupling outdoor air cooling with radiant floor cooling in hot and humid climate zones, because annual temperature and humidity fluctuates according to the season in some regions. Also, cooling residences by opening windows and doors during mild weather is a familiar strategy that is indigenous to practically all climates [15]. Although some theoretical studies have been conducted on radiant ceiling panels integrated with outdoor air systems [16,17], and some field measurements have been made [18], radiant floor cooling coupled with outdoor air cooling has seldom been reported.

In this work, a numerical simulation method was used to investigate the possibility of using a coupled system of outdoor air cooling and radiant floor cooling. A radiant floor cooling system using a dehumidified ventilation system with economizer control was analyzed. Herein, we review the behavior of the indoor thermal environment, the system's operation and its energy consumption features. Our results can be used to improve the energy savings of radiant floor cooling systems in actual applications.

## 2. Description of the coupled cooling system

The system discussed herein is composed of a radiant floor cooling system and a ventilator capable of dedicated ventilation, dehumidification and outdoor air-cooling. Radiant floor cooling can be achieved using the existing radiant floor heating system fixtures that are commonly installed in residential buildings in Korea [12]. A radiant floor cooling system removes indoor sensible heat by lowering the surface temperature of the floor; this is achieved by running chilled water through an existing piping system installed in a concrete floor (Fig. 1). The main features of the ventilator used in the proposed system are minimum OA ventilation, dehumidification of indoor air to prevent surface condensation, and outdoor air cooling (Fig. 2). When conditions outdoors are favorable, outdoor air is introduced indoors for air cooling and ventilation. However, when the outdoor air is unfavorable for controlling the indoor environment, it is used for ventilation at the minimum OA level only (0.7 ACH [19]) and the room is cooled mainly by radiant floor cooling.

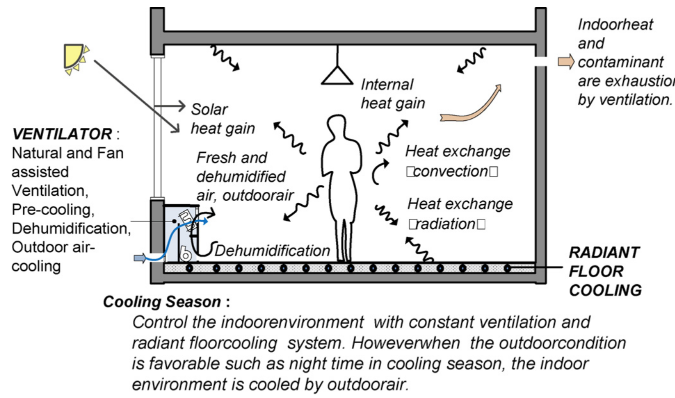


**Fig. 1.** Concept of radiant floor cooling system with ventilation system.

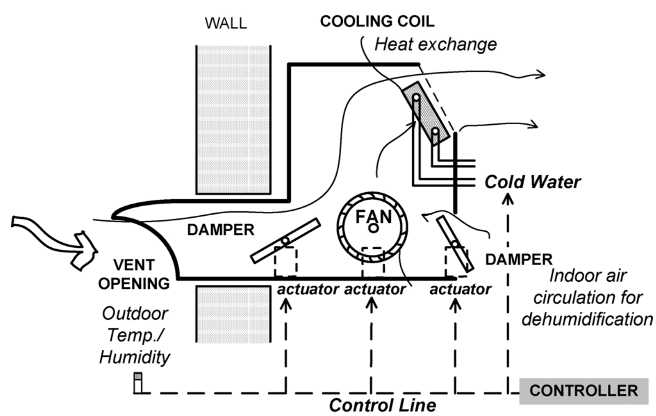


**Fig. 2.** Ventilator with minimum OA, outdoor air cooling, dehumidification and secondary cooling.

Moreover, if the indoor air temperature near the floor surface falls close to the dew-point temperature, the dehumidification control in the ventilator is activated, acting to recirculate the indoor air and remove moisture. While the dehumidification control operates, chilled water is supplied to the cooling coil in the ventilator.

Fig. 3 shows the control strategies used in the proposed system. The operative temperature is used as a measure for indoor thermal environment control. The operative temperature is set at the set-point of 26.7 ± 0.2 °C according to ASHRAE Standard 55 [20]. If the indoor operative temperature ($OT_{in}$) is higher than the set-point ($OT_{iset}$), the cooling mode will be started and the optimized supply air temperature ($T_d$) for cooling will be calculated using Eq. (1).

$$T_d = T_{iset} - \frac{q_{sc}}{C_p \cdot Q_{max}} \tag{1}$$

$T_d$ is used as the switchover temperature to determine whether outdoor air cooling is possible.

Outdoor air cooling can be classified into two modes: one is enthalpy-based and the other is based on the dry-bulb temperature. If the outdoor air temperature ($T_{out}$) is lower than $T_d$, the indoor environment will be controlled by the temperature-based outdoor air cooling mode. When the outdoor air is hotter than $T_d$, it is still introduced at the minimum OA requirement. Meanwhile, the indoor air can be sufficiently cooled by radiant floor cooling. In enthalpy-based outdoor air cooling, outdoor air is introduced for cooling when the enthalpy of the outdoor air is lower than that of the indoor air (i.e., $E_{in} > E_{out}$). When the outdoor temperature is below 18 °C, outdoor air is introduced at the minimum OA level to avoid cold drafts. When the system operates in outdoor cooling