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Performance evaluation of a radiant floor cooling system integrated with dehumidified ventilation

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Abstract

The radiant floor cooling system can be used as an alternative to all-air cooling systems, using the existing Ondol system (a radiant floor heating system) in Korea to save energy and maintain indoor thermal comfort. Unfortunately, a radiant floor cooling system may cause condensation on the floor surface under hot and humid conditions during the cooling season. In addition, the radiant floor system does not respond quickly to internal load changes due to the thermal storage effect of the concrete mass, which is usually present in radiant floor cooling systems.

This study proposes a radiant floor cooling system integrated with dehumidified ventilation, which cools and dehumidifies the outdoor air entering through the cooling coil in the ventilator by lowering the dew-point temperature to prevent condensation on the floor surface. Furthermore, outdoor reset control was used to modulate the temperature of chilled water supplied to the radiant floor, and indoor temperature feedback control was then used to respond to the internal load changes.

To evaluate the performance of the radiant floor cooling system integrated with dehumidified ventilation, both a physical experiment in a laboratory setting and TRNSYS simulation for an apartment in Korea have been conducted. As a result, it was found that the proposed system was not only able to solve the problem of condensation on a floor surface but also to control the indoor thermal environment within the acceptable range of comfort. Furthermore, the proposed system improved the responsiveness to internal load changes.

Keywords: Radiant floor cooling; Dehumidified ventilation; Performance evaluation; Indoor thermal comfort

1. Introduction

In many countries hydronic radiant floor heating systems are widely used, and the same floor system could also be used for cooling because the occupants are close to the heat source and its high radiant heat output [1].

A lot of radiant cooling systems have been used in northern Europe where the outside air humidity is relatively low during the summer season. A hybrid system of ceiling radiant cooling and natural ventilation has been proposed and is currently being used in Europe. Whereas in Korea or Japan where the humidity level is much higher than that in northern Europe, it is essential to have a device to control indoor humidity. In Japan, several buildings were designed with the panel-air combination method, which induces the controlled air with low humidity into the interior of the building, while cooling is provided by the ceiling and wall panels [2]. Song and Kato [3] proposed a radiant cooling system with natural ventilation where the outdoor air enters into the building and cools with the cooling panels installed inside the building as a partition. The radiant cooling system holds a feature in which the

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Nomenclature

$\Phi_{s,i}$	convective heat flow from the internal surfaces [W]
Φ_{inf}	infiltration heat gain [W]
$\Phi_{v,i}$	ventilation heat gain [W]
$\Phi_{g,c,i}$	internal convective heat gains [W]
$\Sigma\Phi_{cplg,j-i}$	gains due to airflow from adjacent zones j to zone i [W]
C_i	thermal capacity of zone i [kJ/kg °C]
$q_{s,i,m}$	conduction heat flux from the wall at the internal surface [W/m^2]
$S_{s,m}$	radiative heat gains absorbed at the internal surface m [W/m^2]
WG_m	user-defined energy flow to the inside wall surface [W/m^2]
$q_{c,s,m}$	convective heat flux from the internal wall m to the zone air [W/m^2]
$q_{r,s,m}$	net radiant heat flux from surface m to all other surfaces in the room [W/m^2]
$R_{equ,m}$	equivalent resistance between the surface temp. and the star temp. [°C/W]
R_{star}	star resistance [°C/W]
$R_{c,m-i}$	convective resistance between surface m and the air [°C/W]
$R_{r,m-k}$	radiant resistance between the internal surface m and k [°C/W]
U_1, U_2	heat transfer coefficient at zone 1 and zone 2 [W/m^2 °C]
h_1, h_2	heat transfer at zone 1 and zone 2 [W/m^2 °C]
d_1, d_2	insertion depth from pipe to surface of zone1 and zone 2 [m]
d_r	thickness of pipe [m]
$d_{x,l}$	distance between pipes [m]
δ	pipe diameter [m]
T_{a1}, T_{a2}	air temperature of zone 1 and zone 2 [°C]
T_{s1}, T_{s2}	surface temperature of zone 1 and zone 2 [°C]
Q_{gain}	heat gain [W]
Q_{ondol}	heat emitted from radiant floor system [W]
U_{Abldg}	overall building heat transfer coefficient [W/°C]
k	constant for radiant floor system [W/°C]
λ	thermal conductivity [W/m °C]
T_{out}	outdoor temperature [°C]
T_{in}	indoor temperature [°C]
T_{water}	supply water temperature [°C]
U_{Aaux}	overall loss coefficient [kJ/h °C]
η_{aux}	efficiency of auxiliary cooler ($0 \leqslant \eta_{aux} \leqslant 1$)
m	flow rate of cool water [kg/h]
C_a	specific heat of air [kJ/kg °C]
T_{set}	setpoint temperature [°C]
T_{inlet}	temperature at inlet of coil [°C]
T_{outlet}	temperature at outlet of coil [°C]
T_{env}	temperature of cooling device surroundings for loss calculations [°C]
C_{pm}	specific heat for humidity [kJ/h °C]
C_{pw}	specific heat for water [kJ/h °C]

cooling panels actively lower the surface temperature to a point below the dew-point temperature as well as raise the cooling efficiency [4,5]. Niu and Kooi investigated thermal comfort and energy saving possibilities using a chilled-ceiling system [6] and proposed a chilled-ceiling system combined with desiccant cooling system [7]. Zhang and Niu [8] investigated indoor humidity behaviors associated with various air dehumidification and ventilation strategies for the chilled-ceiling system.

In Korea, radiant cooling is rarely used, although radiant floor heating systems are installed in most residential buildings. The radiant floor cooling can be used with the existing Ondols (radiant floor heating systems) by simply substituting the hot water with chilled water circulation for radiant cooling. "Ondol" is a unique radiant floor heating method used in Korea. Until 1960, a method of creating a "Gorae" air tunnel under the "Goodle," which served as heat storage and was covered with loess, was used. The air heated with fuel would pass through the Gorae to radiate heat to the Goodle. In the past, woods or charcoal were used as fuel. The heat that had been saved in the Goodle would be passed indoors via conduction and radiation of heat. Today, water pipes are laid out in the radiant floor to perform this task.

The radiant floor cooling system using existing Ondols does not require separate equipment for cooling, so installation costs can be reduced. In addition, previous research results had shown that the radiant cooling method or separately operating cooling and ventilation leads to more energy savings than the all-air cooling method. Feustel and Stetiu [9] reported that using a radiant cooling system can save up to approximately 40% of electrical energy compared to the existing HVAC system based on his research of industrial buildings. Thus, it has very high potential in future applications. However, the radiant floor cooling system may cause condensation on the floor surface under hot and humid conditions in the Korean summer season. Furthermore, radiant cooling systems have slow response to internal load changes due to the thermal storage effect of the radiant floor mass. To solve these problems, a radiant floor cooling system that is integrated with dehumidified ventilation and uses the existing Ondol system is proposed in this study.

In this paper, the concept of radiant floor cooling integrated with controlled ventilation will be described. Moreover, the thermal performance and effectiveness of the proposed system are also described through a physical experiment in a laboratory setting and computer simulation for a housing unit of an apartment in Korea.