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Application of the control methods for radiant floor cooling system in residential buildings

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Abstract

In applying radiant floor cooling, its control system must prevent the floor surface condensation in hot and humid weather conditions. With no additional dehumidification system, only the radiant floor cooling system prevents floor condensation. In this case, the effects of the control of the cooling system on the indoor conditions can be changed because of the thermal inertia of the systems. Also different types of control system can be composed according to the control methods, which can affect the construction cost in the design stage. Therefore, the control methods for the radiant cooling system with respect to floor surface condensation must be studied. Furthermore, because Korean people's lifestyle involves sitting on the floor, it is necessary to evaluate if a floor cooling system will influence the thermal comfort of the occupants. This study intends to clarify the control methods of the radiant floor cooling system and to analyze the control performance and applicability of each control method with regard to the floor surface condensation and comfort by computer simulations and experiments on the control methods of the radiant floor cooling system. The results of computer simulations and experiments show that water temperature control is better than water flow control with respect to temperature fluctuations in controlling room air temperature. To prevent floor surface condensation, the supply water temperature could be manipulated according to the dew point temperature in the most humid room, and in individual rooms, the water flow rate (on/off control) can be controlled. Also, the results of radiant cooling experiments show that the floor surface temperature remained above 21 °C, the temperature difference among surfaces remained below 6 °C, and the vertical air temperature difference remained below 1.9 °C, conforming well to comfort standards.

Keywords: Radiant floor cooling system (RFCS); Control methods; Condensation; Comfort; Water temperature control; Water flow control

1. Introduction

Korean residential buildings, in general, are furnished with Ondol—the Korean traditional radiant floor heating system, and this system has been widely used as a heating method by flowing hot water into tubes embedded in the floor [1]. But residential buildings were not installed with cooling systems because of economical problems, and poor living standard. Now, with industrial growth and GNP increase, residents have become interested in convenience and comforts of living. Therefore, the demand for cooling systems and installations of packaged air-conditioner (PAC) are increasing [2]. Unfortunately, the use of PAC in residential buildings has been found to have negative effects on the environment by using the CFCs (chlorofluorocarbon), and apparently causes the problem of day-time peak of electric power demand in summer [3]. Moreover, some of the problems of conventional cooling system with PAC include draft, local discomfort and temperature differences between rooms. Therefore, a cooling system that can reduce the problems caused by the use of PAC is needed. One of the alternatives that attracted

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attention in comfort and energy issue is the radiant floor cooling system, in which case one would have to consider effective heating-cooling transformation of the floor, conservation of resources and the environment. In radiant floor cooling, heat is exchanged with cooled surfaces, so the probability of condensation is great at the cooled surface in hot and humid climate such as that of Korea. Furthermore, because the lifestyle of the Korean people is based on the culture of sitting on the floor, to apply radiant floor cooling to residential buildings, floor cooling system must be evaluated to determine if it will influence the thermal comfort of occupants from the viewpoint of floor temperature.

Several studies on radiant floor and ceiling system for cooling have been conducted about comfort, cooling capacity, and energy savings in US, Japan, China, Korea, and many European countries. In US, Corina [4] reported that a building equipped with radiant cooling system can be operated in any US climate with low risk of condensation, and can save on average 30% of the energy consumption and 27% of the peak demand due to space conditioning by employing radiant cooling system instead of the traditional all-air system. And Mumma [5,6] discussed the major concerns given in the US about the radiant cooling system, such as condensation concerns, cooling capacity concerns, and initial cost concerns compared to conventional systems. In these studies, they concluded that condensation can easily be controlled by using DOAS (dedicated outdoor air system), and radiant cooling can meet its capacity duty and only use about 50% of the ceiling in most cases. As for economic concerns, their system holds great potential not only for construction cost and operating cost advantages but also for improved IAQ and thermal comfort. Also, Jeong et al. [7] showed that the cooling capacity of the radiant panel can be enhanced in mixed convection situations by 5–35% under normal operating panel surface temperature. In Japan, Imanari et al. [8] examined that radiant ceiling panel system is capable of creating smaller vertical variation of air temperature and more comfortable environment than conventional systems, and energy consumption can be reduced by 10%. Kitagawa et al. [9] reported that small air movement with radiant cooling system could improve the comfortable sensation votes in radiant cooling. Nagano et al. [10] conducted experiments on thermal environmental design of ceiling radiant cooling for supine human subjects, and presented the conditions that gave neutral thermal sensation. In China, Niu et al. [11,12] analyzed the energy savings potential and indoor humidity behaviours of a chilled ceiling combined with desiccant cooling. In Europe, Miriel et al. [13] evaluated the performances of radiant ceiling panel in heating and cooling mode, and studied thermal comfort through model experiments. Simulation modules were developed with TRNSYS and experimental validation were performed. Antonopoulos et al. [14–16] presented theoretical investigation based on numerical and analytical solutions, and evaluated the thermal comfort and energy savings of radiant cooling system. Michel et al. [17] presented information on floor heating/ cooling systems control and system structures, such as coverings, pipe fixation, and insulating material, through research survey.

Radiant floor and ceiling for cooling must be controlled to prevent floor surface condensation in hot and humid weather conditions. For this purpose, radiant cooling systems have been generally combined with the central air system for ventilation and dehumidification [18,19]. Some probes for condensation detection have been generally used, and supply water has been adjusted according to the dew point inside the room [17]. With no additional dehumidification system, floor condensation can be prevented by controlling the radiant cooling system. In this case, the effects of the control on the indoor conditions can be changed because of the thermal inertia of the systems. Furthermore, different types of control systems can be composed according to the control methods, which can affect the construction cost in design stage. Therefore, control methods of radiant cooling system must be studied with regard to floor surface condensation. However, no practical studies on control methods of radiant cooling system have been conducted. In this study, we clarify the control methods of radiant floor heating and cooling system, and develop the simulation program to analyze of the thermal environment. Also by simulations and experiments on the control methods of the radiant floor cooling system, the control performance and applicability of each control method were analyzed with regard to floor surface condensation and comfort.

2. Control methods of radiant floor cooling system

To apply the existing radiant floor heating system for efficient cooling, first, various control methods of radiant floor cooling system that have been suggested or applied until now must be clarified. The control methods can be systematically classified according to control parameters. In a control system, the control parameters are divided into input variables, controlled variables, and manipulated variables. The input variables such as room air temperature, operative temperature, outdoor air temperature, floor surface temperature, and room air humidity could be measured by temperature and humidity sensor. Because air temperature is the most commonly controlled condition in radiant floor heating and cooling system, room air temperature or operative temperature are determined as the controlled variable. The manipulated variable, which causes the necessary changes in controlled variables, could be the water flow rate or water temperature because controlled variables can be regulated by adjusting these variables as shown in Eq. (1).

$$q_{\mathrm{panel}} = M_{\mathrm{flow}} C_{\mathrm{pw}} \Delta T, \tag{1}$$

where q_{panel} is the heat supply rate for the radiant panel (W); M_{flow} the flow rate of supply water (kg/s); C_{pw} the specific heat of water (J/kg °C); ΔT the temperature difference between supply water and return water (°C).

Various control methods for heating based on these two parameters have been presented in previous practices and researches [20,21]. In this study, the control methods for radiant floor heating and cooling system are basically classified according to the manipulated variables, such as water flow rate and water temperature. Two types of control methods are used to manipulate water flow rate. One is the on/off bang-bang control, so called on/off control, which can supply water by fully opening or shutting down the valve, and the other is the variable flow control, which can adjust the flow rate of supply water continuously. A variable flow control system can be used for minimizing pump energy while maintaining design conditions, but this system is more complicated and difficult for controlling flow rate precisely in the range of low-flow rates [22]. To manipulate supply water temperature, two types of control methods are generally used. One widely applied approach is the outdoor reset control, which is an open loop approach where the temperature of the water sent to the slab is proportional to the outdoor temperature. Common intuition holds that for any existing heating system, there is a hot water temperature that corresponds linearly to a given outside air temperature. But this open loop control responds ineffectively to disturbances in indoor temperature. The other control method is the outdoor reset with indoor temperature feedback control, which controls supply water temperature by sensing both the outdoor temperature and indoor temperature. In radiant floor cooling, internal load elements, such as lighting and people, can badly affect increases in the indoor temperature, therefore, the supply water temperature should be not only a function of the outdoor temperature but also that of the indoor temperature. Indoor temperature feedback may be provided by an indoor temperature sensor that allows the outdoor reset control to automatically shift its reset line downward to compensate for internal heat gain or upward to compensate for internal heat loss. The reset line maintains the same slope as that of the outdoor reset control, and shift value is calculated by using the information about the change rate of the indoor air temperature with PID logic. Normally, in Korea, on/off bang-bang control system using conventional thermostats is installed in each housing unit using a gas-fired boiler, and outdoor reset control system with flow inhibition to each housing unit [20] is installed in apartment buildings via district heating. Thus, 2-way on/off valves have been used for heating because they are so easy to operate and not very expensive. In European countries, supply water temperature control is generally applied by operating a 3-way valve, and control system can vary according to the zones inside the buildings by operating a thermostatic valve [17].

In this study, in order to conduct a comparative analysis on control methods for radiant floor cooling system, we performed computer simulations and experiments in a laboratory setting on the water flow control such as on/off bang-bang control and variable flow control, and water temperature control such as outdoor reset with indoor temperature feedback control. As the first stage of application, room air temperatures are simply controlled by using a 2-way on/off valve, 2-way modulating valve, and 3-way mixing valve respectively. To analyze floor surface condensation, room air humidity and floor surface temperatures were calculated by simulation and measured in experiments.

3. Simulation program

From a thermal viewpoint, a building is modelled as a complex network of thermal resistances and capacitances linking different components and representing conductive, convective, radiative and heat storage processes. Also radiant heating and cooling systems are very complicated systems since they involve different heat transfer mechanisms—conduction within a slab, radiation between a radiant surface and its surrounding surfaces, convection between a radiant surface and the adjacent zone air, and conduction between slab and ground [23]. Furthermore, a radiant heating and cooling system has to interact with the operation of the building control system. Therefore, a simulation program has to take into account the transient characteristics of a building structure, radiant heating and cooling system, and dynamic control algorithms. And the simulation results should adequately predict the heat transfer from the radiant panel to the room space according to the control action. Therefore, in this study, to compare room thermal environments according to the control methods, we developed a simulation program that could predict the thermal performance of a radiant floor heating and cooling system in residential buildings integrated with a control system.

3.1. Mathematical modelling

The simulation program consists mainly of four parts: weather data modelling, solar radiation modelling, room thermal modelling, and control system modelling. Weather data consist of the following hourly data: direct normal radiation, sky diffuse radiation, outdoor temperature, absolute humidity, cloud ratio, wind direction, and wind speed. The simulation program accepts binary type weather files (*.bin) and generates its own data structure to be used during the simulation. In solar radiation modelling, the angle of solar incidence for exterior walls and windows is calculated by using solar altitude and azimuth angles, which depend on the site longitude, latitude, local standard meridian (LSM), and solar time. The total irradiance is the sum of the ground-reflected and diffuse irradiance, and direct irradiance. The room thermal model is based on the finite difference method (FDM) for the calculation of one-dimensional unsteady-state heat conduction of building structures. The numerical solution of the finite difference method is attained by an implicit method, which can get stable results regardless of the time increment. For the solution of the implicit method, the Gauss–Seidel iteration method is utilized. For the modelling of interior surface heat transfer, radiation and convection are calculated separately. As shown in Fig. 1, the room thermal model is used to analyze radiant floor panel, walls, room air temperature, and room air humidity. The heat transfer in a panel is analyzed as one-dimensional unsteady-state heat transfer using the fin efficiency and effectiveness-NTU (number of transfer unit) in the unit section perpendicular to the pipe as shown in Eqs. (2)–(3) [24].

$$q_{\text{panel}} = \varepsilon_{\text{PNL}} M_{\text{flow}} C_{\text{pw}} (T_{\text{water}} - T_{\text{m}}), \tag{2}$$

$$\varepsilon_{\text{PNL}} = \frac{\varepsilon_{\text{px}}}{1 + (\varepsilon_{\text{px}} M_{\text{flow}} C_{\text{pw}} / A_{\text{f}} C_{\text{f}})((1/\eta_{\text{m}}) - 1)}, \tag{3}$$

where q_{panel} is the heat supply rate for the radiant panel (W); ε_{PNL} overall effectiveness of radiant panel; M_{flow} the flow rate of supply water (kg/s); C_{pw} the specific heat of water (J/kg °C); T_{water} the supply water temperature (°C); T_{m} the average temperature of heat extraction node (°C); ε_{px} the heat transfer effectiveness of pipes in panel; A_{f} the floor area (m^2); C_{f} the heat transfer rate from the upper and lower node (W/m^2 °C); η_{m} the fin efficiency of the pipe embedded layer.

In external wall surfaces, convective and radiative heat transfer, which are considered sol–air temperature, and conductive heat transfer to structure are used as shown in Eq. (4). Sol–air temperature is the equivalent outdoor temperature that causes the same rate of heat flow at the exterior surface of a wall and ceiling, considering the current outdoor temperature and solar gains on the exterior surface [25].

$$\rho C_{\text{p}} A_{\text{i}} \delta x_{\text{so}} \frac{T_{\text{so}}^{p+1} - T_{\text{so}}^{p}}{\Delta t} = h_{\text{o}} A_{\text{i}} \left(T_{\text{sol}}^{p+1} - T_{\text{so}}^{p+1} \right) + A_{\text{i}} \times \frac{T_{\text{i}}^{p+1} - T_{\text{so}}^{p+1}}{(\delta x_{\text{so}}/2k_{\text{so}}) + (\delta x_{\text{i}}/2k_{\text{i}})}, \tag{4}$$

where ρ is the density (kg/m^3); C_p the specific heat (J/kg °C); A_{i} the area of surface i (m^2); δx_{so} the distance between outer surface and adjacent node in the x direction (m); $T_{\text{so}}^{\text{p+1}}$ the outside surface temperature of

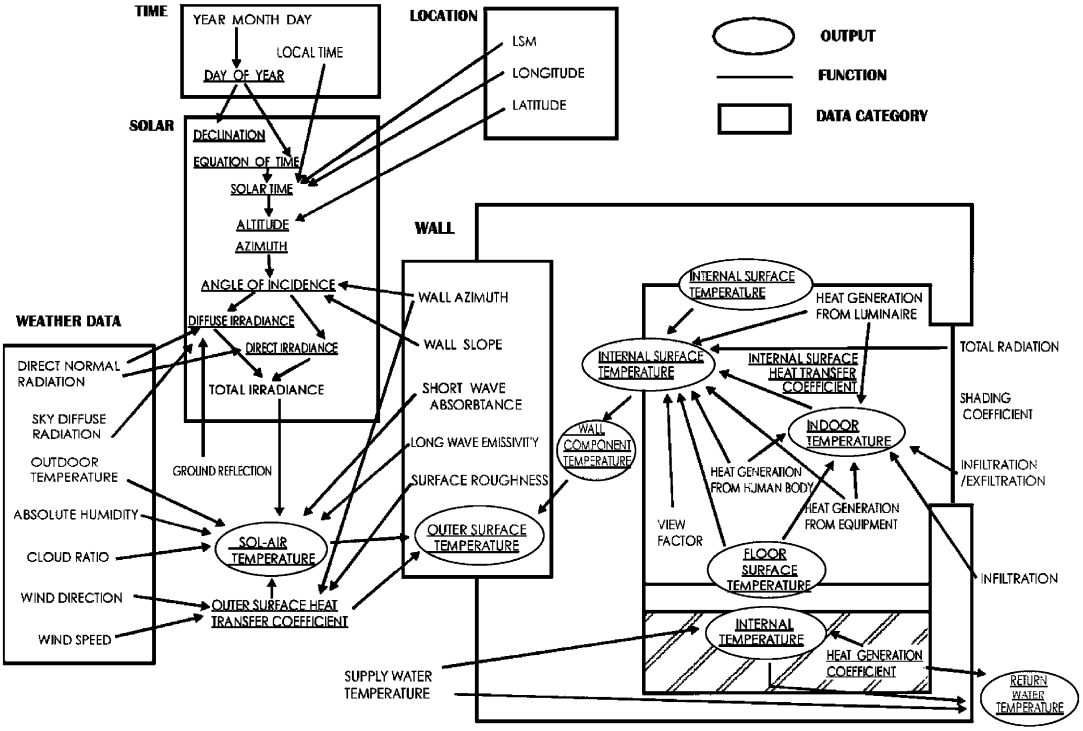

Fig. 1. Diagram of the room thermal model for simulation program.

the wall in time step $p+1$ (°C); T_{so}^{p} the outside surface temperature of the wall in time step p (°C); Δt the time interval (s); h_o the outside surface heat transfer coefficient (W/m^2 °C); T_{sol}^{p+1} the sol–air temperature in time step $p+1$ (°C); T_i^{p+1} the temperature of adjacent node in time step $p+1$ (°C); k_{so} the thermal conductivity of outside surface (W/m °C); δx_i the distance between adjacent nodes in x direction (m); k_i the thermal conductivity of adjacent node (W/m °C).

For interior wall surfaces, conductive heat transfer to a structure, convective heat transfer with room air, solar insolation through glazing, radiative heat transfer among the interior surfaces, and radiative heat transfer from lighting, people, and equipment, are considered as shown in Eq. (5). Radiative heat transfer among interior surfaces is calculated by the Modified Thermal Balance model, in which a fictitious surface is defined as having an area, emissivity and temperature giving about the same radiant heat transfer as in the real case [26].

$$\begin{aligned}\rho C_p A_i \delta x_{si} \frac{T_{si}^{p+1} - T_{si}^{p}}{\Delta t} = {} & A_i \frac{T_i^{p+1} - T_{si}^{p+1}}{(\delta x_{si}/2k_{si}) + (\delta x_i/2k_i)} \\ & + h_i A_i (T_{room}^{p+1} - T_{si}^{p+1}) + s_i q_{sol} \\ & + h_{ri} A_i (TMRT_i - T_{si}^{p+1}) + s_i q_{rl} \\ & + s_i q_{rp} + s_i q_{re}, \qquad (5)\end{aligned}$$

where δx_{si} is the distance between inner surface and adjacent node in the x direction (m); T_{si}^{p+1} the inner surface temperature of the wall in time step $p+1$ (°C); T_{si}^{p} the inner surface temperature of wall in time step p (°C); k_{si} the thermal conductivity of the inner surface (W/m °C); h_i the convective heat transfer coefficient of the inside surface (W/m^2 °C); T_{room}^{p+1} the room air temperature in time step $p+1$ (°C); s_i the area ratio of the wall i to the total area of walls in a space (0 to 1); q_{sol} the solar radiation transmitted through glazing (W); h_{ri} the radiative heat transfer coefficient of the inside surface (W/m^2 °C); $TMRT_i$ the mean radiant temperature (°C); q_{rl} the radiative heat from lighting (W); q_{rp} the radiative heat from people (W); q_{re} the radiative heat from equipment (W).

Room air temperature is determined based on the convective heat transfer at each surface, amounts of infiltration and ventilation, and convective heat transfer from people, lighting, and equipment as shown in Eq. (6).

$$\begin{aligned}& \rho_{air} C_{air} V_{room} (T_{room}^{p+1} - T_{room}^{p})/\Delta T \\ & \quad = \sum_{i=1}^{N} q_{hi} + q_{Infil} + q_{Supply} + q_{cp} + q_{cl} + q_{ce}, \qquad (6)\end{aligned}$$

where ρ_{air} is the density of air (kg/m^3); C_{air} the specific heat of air (J/kg °C); V_{room} the volume of the room (m^3); T_{room}^{p} the room air temperature in time step p (°C); q_{hi} the convective heat at surface i (W); q_{Infil} the heat gain by infiltration (W); q_{Supply} the heat gain by supply air (W); q_{cl} the convective heat from people (W); q_{cp} the convective heat from lighting (W); q_{ce} the convective heat from equipment (W).

In latent loads, outdoor air through infiltration and moisture generation by people and equipment are considered as shown in Eq. (7).

$$\rho_{air} V_{room} \frac{dx_R}{dt} = G_o (x_a - x_R) + \sum_{i=1}^{M} LH, \qquad (7)$$

where x_R is the humidity ratio of room air (kg/kg(DA)); G_o the air infiltration rate (kg/s); x_a the humidity ratio of outside air (kg/kg(DA)); LH the moisture generation rate by people and equipment (kg/s).

In control system modelling, there are three basic methods for controlling room air temperature: on-off bang-bang control system, variable flow control system, and outdoor reset with indoor temperature feedback control system. In on–off bang-bang control system, a control function that has a value of 0 or 1 is used with a set point and differential value. When the difference between the set temperature and the room temperature lies within a differential gap, the controller remains in its previous state. In variable flow control, the flow rate is controlled by adjusting the position of the valve stem with equal percentage valve characteristics because the energy emission from hydronic system has a nonlinear characteristic with respect to flow rate. So energy emission versus valve position is linear at a constant pressure drop [27,28]. In outdoor reset with indoor temperature feedback control system, the reset ratio, which determines the necessary rise in supply water temperature for every degree of outdoor temperature drop, is fixed first. According to this ratio, supply water temperatures are determined at the current outdoor temperature, and the reset ratio is parallel shifted by the indoor temperature feedback.

3.2. *Validation of the simulation program*

A simulation program that can predict the time-varying thermal behaviours of building structure subject to real weather and operating conditions was verified. For the simulations, test rooms were built with equivalent heat loss from the envelope and floor structures same as those in an existing apartment building unit. Test rooms have the same dimensions of 2.4 m × 2.4 m × 2.2 m and their façades were oriented to the south. Each floor structure was composed of floor sheet, cement mortar, ALC(Autoclaved light-weight concrete), and concrete slab, and an XL pipe (cross-linked polyethylene pipe) was embedded in the cement mortar layer with a 300 mm spacing, 37 mm deep from the floor sheet layer. The solar radiation intensities, outdoor temperature and relative humidity, wind velocity, and wind direction were obtained from a weather station located at the roof of the building. Boundary conditions, i.e. air temperatures in the adjacent spaces, were also measured and used in the simulations. In this experiment, water flow rate or water temperature was manipulated according to the control methods. As shown in Fig. 2, chilled water was controlled by a 2-way on/off valve, 2-way modulating valve, and 3-way mixing valve, respectively. The temperatures of the supply and return water were recorded and thus, could be used as the simulation input data. Thermal data such as the temperatures of indoor air, floor surface, 4-sided walls, windows, and door were also measured for comparison with the simulation results.

The simulation program was validated by comparing its results, that is, the simulation results of indoor air temperatures, floor surface temperatures, and indoor relative humidity against experimental results. As shown in Fig. 3, simulation results for air temperature and floor surface temperature show good agreement with

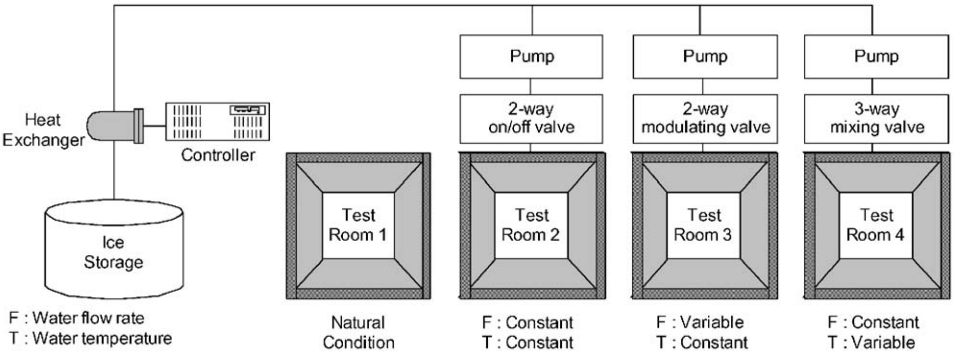

Fig. 2. Experimental devices and cooling schedule in experiment.

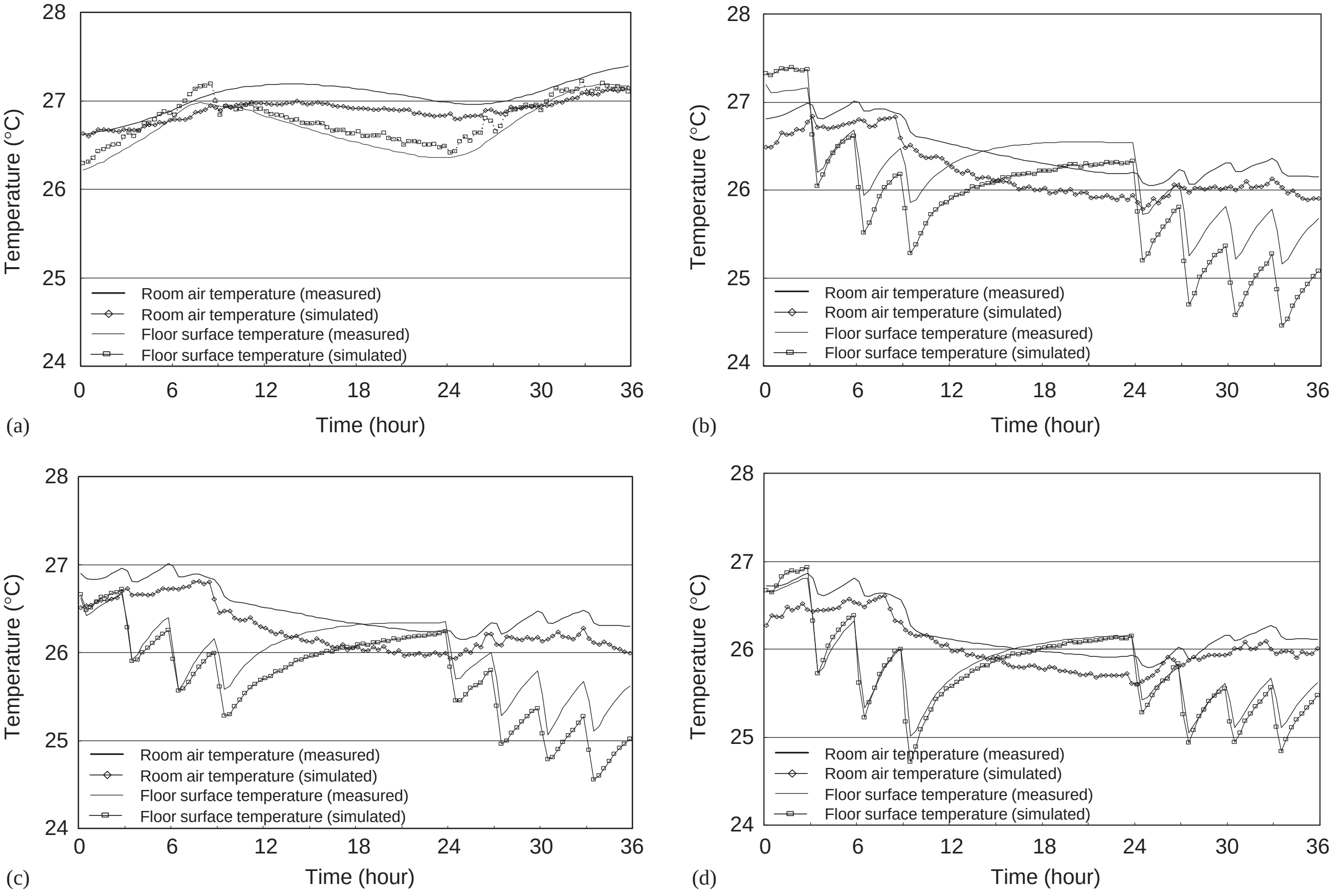

Fig. 3. Comparison of experimental and simulated results. (a) Natural condition without cooling, (b) water flow rate: constant, water temperature: constant, (c) water flow rate: variable, water temperature: constant, (d) water flow rate: constant, water temperature: variable.

measured results within 0.5 °C absolute mean errors for every case, and indoor relative humidity within 3.2% absolute mean errors. Although these small errors can be found for every case, it is considered that these will not affect the overall tendency of the room thermal environment.

4. Comparison of the control methods

4.1. Simulation conditions and methods

In simulations for comparing the control methods, a typical room in the mid-floor of an apartment building with radiant floor heating system is selected as a model case. In this room, one wall is facing south and the other walls, ceiling, and floor are in contact with rooms in identical conditions. The structure of the radiant floor is the same as the commonly used radiant floor structure used for heating in Korea. The structure consists of a 135 mm concrete slab, 55 mm ALC, 20 mm cement mortar embedded with a 230 mm-spaced XL pipe, and 25 mm cement mortar as a finishing layer. Simulations are performed for the summer season according to the standard meteorological data of Seoul [29]. Infiltration rates are fixed on 1 ACH under average conditions in residences referred to in previous researches [30,31]. Internal loads are composed of sedentary people with light work, fluorescent lighting, and equipment. The input data for the simulations are summarized as shown in Table 1.

To determine the lowest temperature of supply water, outdoor reset control is first applied for the week of the highest outdoor temperature, and the reset ratio is determined. And the minimum temperature of the supply water is applied to on/off bang-bang control and variable flow control. In on/off bang-bang control, the differential value of the set point temperature is fixed to ±1 °C, which is the same value in the commonly used thermostat in Korea. In variable flow control, the flow rate is controlled by adjusting the position of the valve stem with equal percentage valve characteristics. In outdoor reset with indoor temperature feedback control, the reset ratio is parallel shifted by the indoor temperature feedback control.

4.2. Analysis of the floor surface condensation

Korea is located in the mid-latitudes of the northern hemisphere and the temperate zone with four distinct seasons. Geographically, it lies on the east coast of the Eurasian continent adjacent to the west Pacific. Summer from June to August is hot and humid with heavy rainfalls. So the monthly mean temperature ranges from 20 to 26 °C and maximum 34 °C, and humidity reaches about 70% nationwide in meteorological data. Therefore, an important issue is the prevention of floor surface condensation when radiant floor cooling system is used in residential units.

In radiant floor cooling, floor surface condensation occurs with the changes of floor surface temperature, room air temperature, and room air humidity. Therefore, when the frequency of condensation occurrence is analyzed, simulation results of room air temperatures, floor surface temperatures, and dew point temperatures are reviewed. Over the entire cooling period, the frequency of condensation occurrence with outdoor reset with indoor temperature control is lower than those with the other control methods as shown in Table 2. Shorter times of condensation occurrence are given in the order of outdoor reset with indoor temperature feedback control, variable flow control,

Table 1
Summary of assumptions for the simulations to compare the performance of control methods

Category				Input data
Geographical location				37.5°N, 127.0°E
Weather conditions				Standard meteorological data of Seoul
Infiltration rates				1 ACH, constant rate
Internal loads	People	Sensible heat	Convective	21.3 W/person
			Radiative	49.7 W/person
		Latent heat		45.0 W/person
		Number of occupants		2 persons
	Lighting	Sensible heat	Convective	11.8 W/m^2
			Radiative	9.2 W/m^2
	Equipment	Sensible heat	Convective	8.3 W/m^2
			Radiative	8.3 W/m^2
Settings for radiant floor cooling	Water mass flow rate (volume flow rate)			0.0367 kg/s (= 2.2 lpm)
	Set point of room air temperature			26 °C

Table 2
Comparison of on/off bang-bang control, variable flow control, and outdoor reset with indoor temperature feedback control during the entire cooling period

Category		On/off bang-bang control		Variable flow control		Outdoor reset with indoor temperature feedback control
		Fully open	Fully closed	Open	Fully closed	
Total sum of condensation occurrence (hr)		284.6	59.5	314.9	19.0	
		344.0		333.9		287.3
Room air temperature (°C)	Average	25.7		25.7		25.9
	Standard deviation	0.7		0.7		0.5
	Maximum	27.5		27.2		27.4
	Minimum	24.3		24.1		24.3
Floor surface temperature (°C)	Average	24.3		24.2		24.6
	Standard deviation	1.0		0.8		0.6
	Maximum	26.0		25.6		25.5
	Minimum	22.5		22.6		22.5

Total cooling period : about 1270 (h)

and on/off bang-bang control. A difference in condensation occurrence is due to the fluctuation of floor surface temperature. In the week of the highest outdoor temperatures, when room dew point temperatures are about 23 °C and outdoor dew point temperatures are about 24 °C, room air temperatures are maintained to a set temperature (26 °C) ± 1 °C for all three control methods. However, in the cases of on/off bang-bang control and variable flow control, fluctuation of floor surface temperature is larger than that by outdoor reset with indoor temperature feedback control. Because of this problem, it is inferred that floor surface condensation appears more frequently with on/off bang-bang control and variable flow control. With 70% indoor relative humidity, condensation occurs at about 20 °C floor surface temperature and at about 17 °C at 60% indoor relative humidity. To prevent floor surface condensation, radiant floor cooling system should be stopped or some type of dehumidification system should be integrated into the system to keep the relative humidity below 70% during this period. A dehumidification system in a room would decrease the dew-point temperature and increase the cooling capacity of a radiant floor cooling system. In particular, since condensation may occur even when chilled water is not supplied in the case of on/off bang-bang control, a countermeasure is required in real application. It can be considered that chilled water remaining in the embedded pipes cools the floor structure, even though the water supply is stopped.

Floor surface temperatures are mainly affected by supply water temperatures. In outdoor reset with indoor temperature feedback control, the lowest temperature of the supply water is about 16 °C at the highest outdoor temperature in Seoul (34 °C). At this time, the floor surface temperatures are about 23 °C and fluctuate within the range of about 1 °C. And the lowest floor surface temperature does not always occur at the highest outdoor temperature, because the cooling load in the room is affected not only by outdoor temperature but also by internal load, solar radiation, and the thermal storage effect of the slab. In on/off bang-bang control and variable flow control, as shown in Fig. 4, the floor surface temperature fluctuated slightly when higher water temperature was supplied with continuous cooling. Therefore, we can conclude that the condensation occurrence can be reduced by raising the supply water temperature and increasing total supply time, considering the temperature fluctuation of the floor surface when weather conditions show a high percentage of humidity.

4.3. Analysis of the overall thermal comfort

According to existing standards, comfort criteria are given as a range for operative temperatures (OT), PMV, and PPD [32,33]. It may be too costly to keep the temperature levels in buildings always within specified comfort ranges, so there should be some allowance for a limited time to exceed the specified range. And to compare alternative design methods, there is a need to quantify with some index for the long-term comfort conditions. For this purpose, 'weighted time (WT)' is used in comparing the performance of each control, which is calculated by multiplying the number of hours by the deviation from the comfort level. That is to say, the time during which the actual PMV exceeds the comfort boundaries is weighted with a factor that is a function of the PPD. And the summation of the product 'weighting factor x time' is called 'weighted time (WT)'

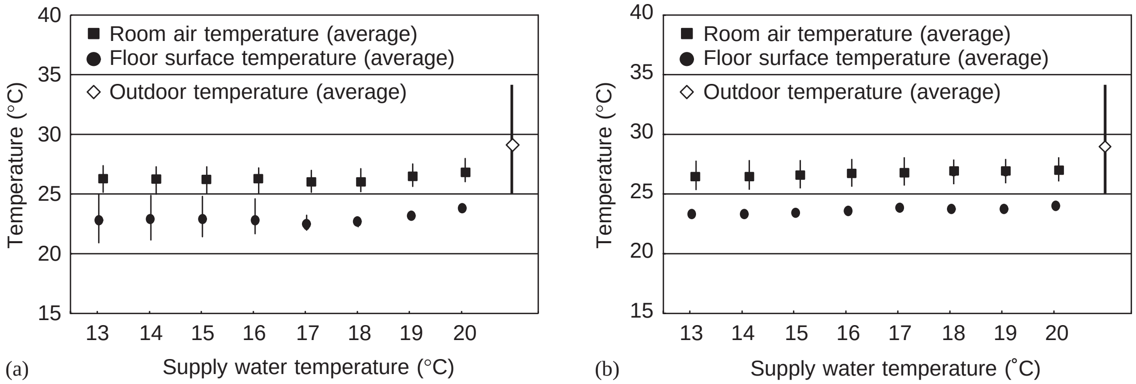

Fig. 4. Average, maximum, and minimum temperatures of room air and floor surface according to the supply water temperature. (a) The case of on/off bang-bang control, (b) the case of variable flow control.

in hour. The values may be used for the evaluation of long-term comfort conditions, which can be expressed as shown in Eqs. (8)–(10) [34,35].

$$wf = \frac{PPD_{\text{Actual}}}{PPD_{\text{Limit}}}, \tag{8}$$

where wf is the weighting factor considering the hours exceeded with the PMV limit; PPD_{Actual} the instantaneous value in which the PPD exceeds the limit; PPD_{Limit} the comfort limit in PPD.

This single weighting factor is then multiplied by the time step in which the thermal environment is obtained from simulation. The total value of the factors calculated this way is defined as the weighted time (WT) which can be calculated by Eqs. (9) and (10).

$$WT_{\text{warm}} = \sum wf\,\text{TimeStep} \quad \text{for } PPD > PPD_{\text{Limit}}, \tag{9}$$

$$WT_{\text{cold}} = \sum wf\,\text{TimeStep} \quad \text{for } PPD < PPD_{\text{Limit}}, \tag{10}$$

where WT_{Warm} is the weighted time of warm side(h); WT_{Cold} is the weighted time of cold side(h); TimeStep the time step(h).

The overall thermal environment among the control methods can be analyzed by comparing operative temperature, PMV, and weighted time (WT). The simulated results of room air temperature, mean radiant temperature, and air humidity were used and metabolic rates of 1.2 met (i.e. 70 W/m^2, mainly sedentary activity), clothing of 0.5 clo (i.e. 0.08 m^2 °C/W, light summer clothing), and air velocity of 0.2 m/s (air speed limit for the summer comfort zone at 26 °C) were assumed. In the results, operative temperatures were about 25.6 °C for all three control methods, which shows little differences among the control methods. As shown in Table 3, PMV indices are within the range of -0.5 and $+1.0$, and the average is $+0.3$, values which satisfy the recommended comfort requirements [33]. Also this value can be close to 0 (neutral condition), considering that physical activity in residential building is very small, mostly sitting or reclining on the floor. Furthermore, if a dehumidification system is integrated with condensation control, room conditions can be more comfortable due to lower humidity. The hours corresponding to allowable PMV ranges ($-0.5 < \text{PMV} < 0.5$ i.e. $\text{PPD} \leqslant 10\%$) during the cooling period show that more values of PMV with outdoor reset with indoor temperature control are in the comfort range than those with on/off control and variable flow control. The weighted time on the warm side (WT_{warm}) are 146.5, 11.2, 7.8 h, respectively for the control methods. Over-shooting of room air temperature in on/off bang-bang control has made little warm condition.

5. Application of each control method

After the comparison of the performances of the control methods through simulations, experiments were performed to analyze the applicability of each method during cooling season. To compare the control methods with each other, deviations in room air and floor surface temperatures were first analyzed. On/off time, flow rate of the supply water, and supply water temperature were examined for the on/off bang-bang control, variable flow control, and outdoor reset with indoor temperature feedback control. Local discomfort levels were analyzed with respect to the floor surface temperature, vertical air temperature difference, and radiant asymmetry, of which results were compared to the ISO 7730, ASHRAE standard, and other experimental results.

5.1. *Experimental settings and methods*

Test rooms were the same with those of the validation experiments. And the experimental equipments were divided into cooling plant, measurement devices, and control devices. The cooling source devices included the

Table 3
OT, frequency of PMV value, and the weightend time on the warm side according to each control method

Category		On/off bang-bang control	Variable flow control	Outdoor reset with indoor temperature feedback control
OT (°C)	Average	25.6	25.6	25.6
	Standard deviation	0.5	0.5	0.4
	Maximum	26.9	26.9	26.9
	Minimum	24.6	24.2	24.8
Frequency of PMV value (h)	$-0.5\sim-0.1$	54.8	223.6	0.6
	$-0.1\sim+0.1$	311.2	361.2	252.2
	$+0.1\sim+0.3$	344.9	367.8	471.4
	$+0.3\sim+0.5$	280.4	143.9	373.9
	$+0.5\sim+0.8$	112.7	8.6	6.0
WT_{warm}		146.5	11.2	7.8

Total cooling period:about 1270 (h)

cooling source, pump, and distribution devices. The measurement devices included temperature and humidity sensors in the space, water temperature sensors, a water flow meter, and weather station. The control devices included analogue input and output devices and a computer with an algorithm for controlling these devices. The measured data were stored in computers using an analogue input device and a data logging system. To realize the various cooling modes, input and output boards for the sensor and valve interfaces were integrated with the computer, which contains algorithms to control these devices. Water was cooled by an ice storage system and readjusted by a heat exchanger to meet the set temperature. In on/off bang-bang control and variable flow control, this water was supplied to the cell, and in outdoor reset with indoor temperature feedback control, the water was supplied to the cell after the water temperature was manipulated using a 3-way mixing valve.

After calculating the cooling loads of the test cell, the flow rate was determined to be 1.2 lpm, which was close to the design flow rate for heating in apartment buildings. The room air temperatures in each cell were measured at the height of 1.1 m and the set point was fixed at 26 °C. As shown in the simulations, supply water temperature was first determined by the outdoor reset control. After setting the water temperatures in on/off bang-bang control and variable flow control, water flow rate was controlled by room air temperature feedback in each control method. Internal loads were modelled by installing several light bulbs inside the test room and controlled by switching on and off. To model the loads due to random occupant behaviour, the following occupancy pattern was used: normally about 15W/m^2 (a total of 60W) and about 30 W/m^2 (a total of 120 W) from 7 to 8 a.m. and 6 to 7 p.m.

5.2. Analysis of the applicability of each control method

As shown in Fig. 5, room air temperatures were lowered by nearly 3 °C compared with those in non-cooling condition. In the beginning (the first day), on/off bang-bang control was a little more accurate than the other control methods. However, as time went on (the second day and the third day), the deviation from the set-point temperature was slightly greater in on/off bang-bang control than in the outdoor reset with indoor temperature feedback control. When the average deviation was compared, it was 0.6 °C for on/off bang-bang control and 0.5 °C for outdoor reset with indoor temperature feedback control. However, because large variation of the floor surface temperature makes it more difficult to prevent condensation, a more sensitive control method was required in on/off bang-bang control by adopting surface temperature as a control parameter. Wave-like spikes in the room air temperature from 7 to 8 a.m. and 6 to 7 p.m. in Fig. 5 was caused by internal loads according to the residential occupancy pattern, which was modelled by the operation of light bulbs.

In on/off bang-bang control, the 2-way on/off valve generally opens for nearly 6 h a day. The opening begins at about 1 p.m., which means that it cools down the structure at the hottest time of the day and its effect lasts overnight. And the supply water circulates through the distribution system for about 35% of the total experiment period. If the supply water temperature can be changed according to the cooling load, the circulation period can be extended and the deviation of the floor surface temperature can be decreased in this method.

In variable flow control, the flow characteristics of 2-way modulating valve can be changed according to the flow coefficient, rangeability, and valve authority

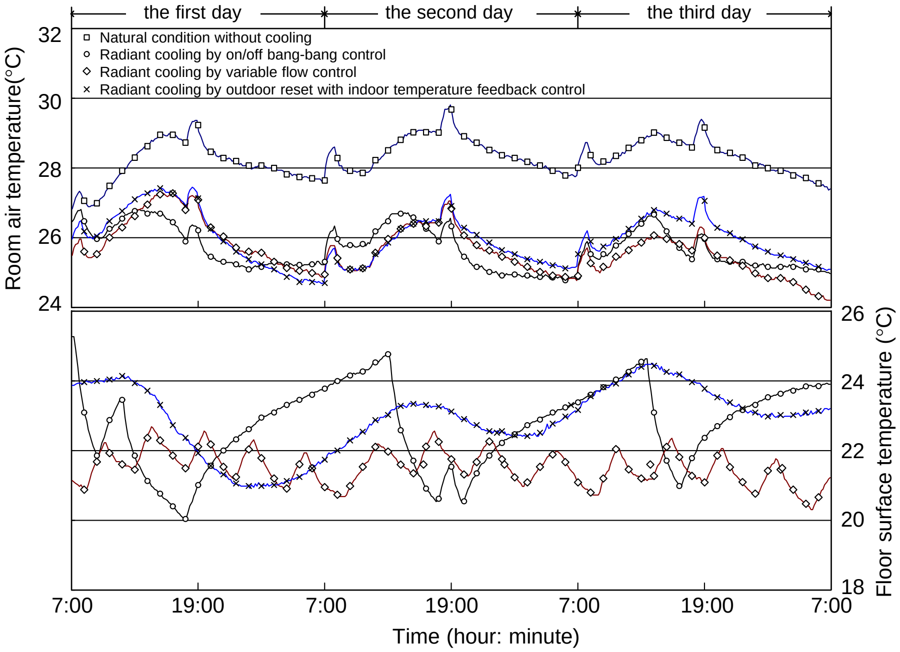

Fig. 5. Profiles of room air and floor surface temperatures.

[28,29]. Flow coefficient is the number of US gallons per minute of water (GPM) that will pass through a given flow restriction with a pressure drop of 1 psi. This is a capacity index upon which is normally determined through the experiment and the engineer can rapidly estimate the required size in any fluid system by using this. Rangeability is the ratio between the maximum controllable flow and the minimum controllable flow, between which the characteristics of the valve (linear, equal percentage, quick opening) will be maintained. With most control valves, at some point before the fully closed position is reached, there is no longer a defined control over flow in accordance with the valve characteristics. Valve authority of the control valve is the ratio of the valve pressure drop to the system loop pressure drop. If an undersized valve was installed in a system, a pump would use a large amount of energy simply to pass sufficient water through the valve, but control would be accurate because even small increments of valve movement would result in change in flow rate. If an oversized valve was installed in a system, the energy required from the pump would be reduced with little pressure drop across the valve in the fully open position, but erratic control with poor stability and accuracy was induced by small effect of valve travel on the flow rate to the system. Therefore, by calculating the valve authority relative to the system in which it is installed, control performance against the energy consumption should be evaluated with the valve selection.

In the experiment of variable flow control, the valve stem moved frequently to maintain the set temperature. Due to this control action, the floor surface temperature of variable flow control fluctuated more frequently than those of other control methods. Also, with regard to the flow rate, the system was operated under conditions of low flow rate (from 0 to 0.3 lpm) during 45% of the overall experimental period. If the 2-way modulating valve operates with low-flow rate, the control valve's throttling plug should be provided with suitable rangeability. To apply variable flow control where low-flow rate is needed for cooling, it is important to select the 2-way modulating valve in accordance with the valve authority and valve rangeability of the system. As shown in Fig. 6, because the valve authority is very small

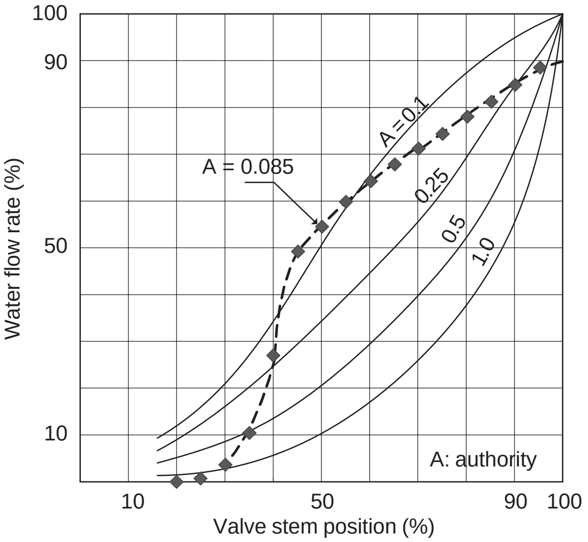

Fig. 6. The relation between valve stem position and water flow rate.

for the current design condition of radiant heating system, the equal percentage valve characteristics distorts nearly linearly. To provide as much valve authority as feasible to maintain the equal percentage curve shape, it is very important to select a control valve with a pressure drop at least 25% to 50% of the system loop pressure drop. In a real application, smaller valve sizes with high authority would increase the initial cost when it is custom-made and not ready-made.

In outdoor reset with indoor temperature feedback control, overshooting normally occurs at the first day due to its slow response to cooling load. However, the temperature fluctuation decreases with time. This is why the supply water of low temperature is required to cool the slab in the early start-up period, while the temperature fluctuation of supply water decreases over time with the stabilization of the room air temperature. In continuous cooling, water is circulating at a constant rate so that heat extraction is even. If the room air temperature and floor surface temperature become stabilized, the supply water temperature could rise up to about 20 °C. Considering condensation prevention, it can be concluded that the supply water temperature could be manipulated according to the dew point temperature of the most humid room, and that in individual rooms can be controlled by the water flow rate (on/off control).

5.3. Analysis of the local thermal discomfort

A person may feel thermally neutral as a whole, but still feel uncomfortable if one or more parts of the body are too warm or too cool. To evaluate the local discomfort of a person, the distribution of the floor surface temperature, surface temperature difference with the wall and window (radiant asymmetry), and vertical distribution of the room air temperature are analyzed. Most importantly, the effect of floor surface temperatures on comfort has been major issue in previous studies [36–41]. In ISO 7730 standard, acceptable floor temperatures range from 19 °C to 29 °C for sedentary activity to 10% dissatisfied condition (PPD = 10). However, because Koreans are used to sitting or lying down on the floor, the thermal characteristics of the materials for floor structure are very important factors affecting thermal comfort. Fanger [36] reported that the optimal surface temperature is 24–35 °C for a linoleum rubber and 22–35 °C for oak tree. And Song et al. [37,38] showed that the comfortable floor surface temperature is 18–30 °C for the pine tree material, and 18–23 °C for urethane rubber floor when a person is lying down or sitting on the floor. Also Lee et al. [39] concluded that the parts of the body affected by the floor temperature vary with posture; thus a person has different skin temperatures. Comfort level is rated as more comfortable when the globe temperature is 29 °C

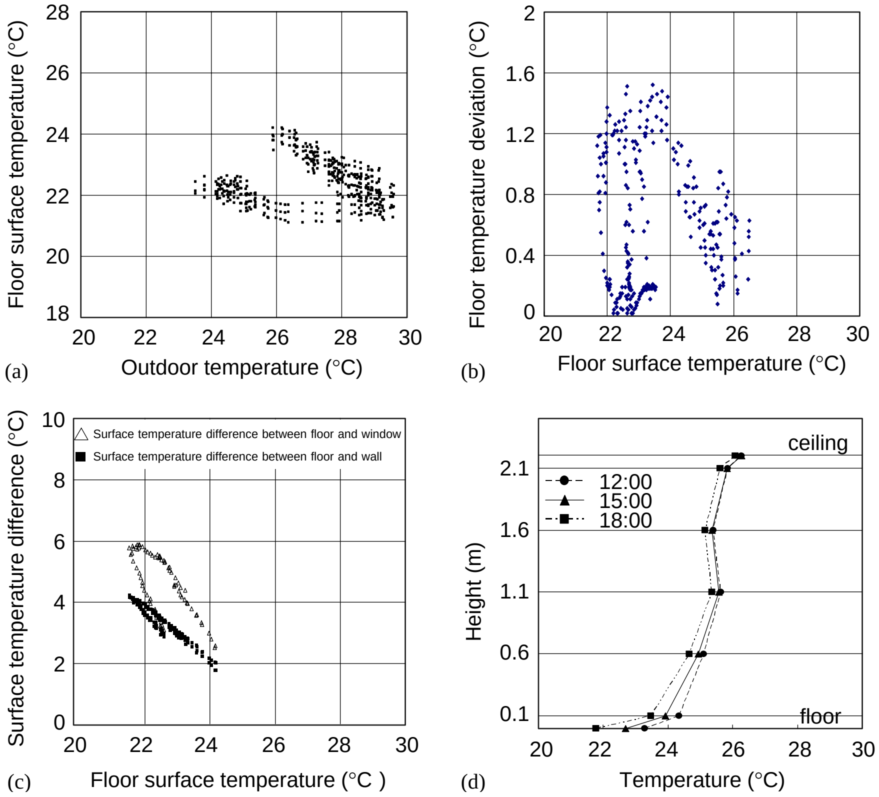

Fig. 7. Profiles of surface temperatures of floor and wall, and vertical air temperature.

when a person is sitting on the floor and sitting on a chair. As shown in Fig. 7(a), the floor surface temperature is above 21 °C during most of the cooling period and is higher than the standard for the minimum floor surface temperature for comfort in ISO (19 °C). And considering that vinyl and linoleum sheet or wood goods are most common floor covering for radiant floor heating in Korea, the local discomfort experienced by a person due to floor surface temperature drop may not be a problem. However, to avoid the overcooling of floor by sudden increasing of cooling loads, it is necessary to include the floor surface temperature as a control parameter. In Fig. 7(b), it is seen that the floor surface temperature difference between the point right above a pipe and that in the middle of a pitch is less than 2 °C, and any local discomfort is not significant compared to the current design guidelines for radiant heating system in Korea. In radiant asymmetry, Olesen presented the guide for the optimal surface temperature differences in the range of 5 to 10 °C [40]. Because the temperature difference among the surfaces in a space is less than 6°C (see Fig. 7(c)), it may be inferred that the radiant floor will not cause discomfort. With respect to the vertical distribution of the room air temperature, Fig. 7(d) shows that the results fall within the recommended maximum temperature difference of comfort, which is 3 °C between the height of the ankle (0.1 m) and the head (1.1 m) of a seated person [33,41]. Consequently, the results of the model experiments show that radiant floor cooling systems conform well to comfort standards.

6. Conclusions

In radiant floor cooling system, floor surface condensation and comfort are major concerns for field application. According to the control methods, the effects on the condensation are different from each other, and it can affect the construction cost in the design stage. This study intended to clarify the control methods of radiant floor cooling system and to analyze control performance and applicability of each control method with regard to the floor surface condensation and comfort by simulations and experiments on the control methods of the radiant floor cooling system.

The results of computer simulations and experiments show that in controlling the room air temperature, the water temperature control (outdoor reset with indoor temperature feedback control) is better than the flow control (on/off control and variable flow control) with respect to the temperature fluctuation. In the early start-up period, overshooting normally occurs in the water temperature control (outdoor reset with indoor temperature feedback control) due to its slow response to cooling load. However, the temperature fluctuation decreases with time because the temperature fluctuation of supply water decreases over time with the stabilization of room air temperature. As for room air temperature control and condensation prevention, it can be concluded that supply water temperature should be manipulated according to the dew point temperature of the most humid room, and by the water flow control (on/off control) for individual rooms. Also, the results of the model experiments applying radiant cooling show that the floor surface temperature remained above 21 °C, the temperature difference among surfaces remained below 6 °C, and the vertical temperature difference remained below 1.9 °C, conforming well to comfort standards.

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