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RESEARCH

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Feasibility of a Radiant Floor Cooling System for Residential Buildings with Massive Concrete Slab in a Hot and Humid Climate

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Abstract

In Korea, radiant floor heating systems are commonly used in residential buildings, even high-rise houses. If these existing radiant floor heating panels could be used for cooling as well, additional benefits beyond the basic advantages of radiant heating and cooling systems in terms of energy efficiency and comfort level could be conferred upon the homeowner, such as avoiding redundant investments for both heating and cooling equipment, and reducing the area occupied by the equipment. However, the comfort requirement of floor surface temperature has to be satisfied, because the human body comes in direct contact with the floor surface. In addition, dehumidification equipment is required to remove the latent load and to prevent surface condensation. It may be particularly difficult to apply such a system in high-rise residential buildings with massive concrete slabs as compared to light-weight buildings, because of the complexity of the system configuration and the thermal capacity of the building structure. In this study, the feasibility of radiant floor cooling systems (RFCS) for residential buildings with massive concrete slabs was evaluated. The strategy for the configuration and arrangement of an RFCS was based on the current configuration of the heating and cooling system as well as the cooling load. Then, through field testing, the performance of this system for cooling and condensation prevention was evaluated along with the occupants' characteristics for adjusting parameters related to thermal comfort. As a result, an RFCS combined with supplementary equipment for dehumidification and cooling would satisfy the requirements for cooling and condensation prevention in a residential house with multi-zones.

Keywords: radiant floor cooling system, residential building, surface condensation, dehumidification, concrete slab

1 Introduction

Radiant heating and cooling systems (RHCSs) have attracted increasing interest, due to their high comfort level and high energy efficiency. An RHCS is a system in which 50% or more of the design heat transfer on its surface takes place by thermal radiation (Handbook American Society of Heating, Refrigerating and Air-Conditioning Engineers 2012), and in which thermal radiation and convection are used by the radiant panel to heat and cool the space. Many studies (Imanari et al. 1999; Nagano and Mochida 2004; Wang et al. 2008; Tian and Love 2009) have reported that RHCS is more advantageous than convective heating and cooling systems in terms of both energy saving and comfort. Thus, the adoption of RHCSs has increased mainly for commercial buildings (Stetiu 1999; Niu et al. 1995), and these systems are being gradually applied to large residential buildings as well.

In Korea, packaged air-conditioners (PACs) have mainly been used as cooling systems for residential buildings, and their use has tended to increase. However, the increased application of PACs can lead to issues of discomfort in convective cooling systems, and can also increase the cooling energy consumption of an individual residential house, as well as its peak electric power demand during the cooling season. Therefore, as an alternative to PACs, radiant cooling systems (RCSs), which

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are comfortable and energy-efficient, can be applied to residential buildings in Korea.

For radiant cooling, using the ceiling as a thermal radiation surface, as compared to the floor or walls, is more advantageous in terms of thermal performance. Hence, there have been research reports (Sui et al. 2013) evaluating the thermal performances of radiant ceiling cooling systems for residential buildings. Radiant floor heating systems (RFHSs) using hot water are used as heating systems for most residential buildings in Korea, as this is the traditional heating system that has been used in Korea for residential buildings for a long time. Therefore, if an existing radiant floor heating panel is used for space cooling, improvements in comfort and energy saving due to the basic characteristics of the RHCS can be expected. In addition, additional advantages include avoiding redundant investments in both heating and cooling installations, improving the disadvantage of system utilization (RFHS only during the winter season, and PAC only during the summer season), and the area occupied by the system can be reduced, because one terminal unit can deal with both space heating and cooling.

Further, when a radiant floor cooling system (RFCS) is adopted for a residential building, the floor surface temperature comfort requirement must be satisfied, because the human body is in direct contact with the radiant floor cooling panel. This issue is of particular importance in countries with a sedentary or barefoot lifestyle, such as Korea. In Korea, where radiant floor heating has been used for a long time, it is an even more important issue, because Koreans are conventionally familiar with a warm floor surface temperature.

In addition, because an RCS can remove only the sensible load, a dehumidification system is required to remove the latent load. This is particularly important when RCS is applied in humid summer climate regions such as Korea, where a dehumidification system for the prevention of surface condensation is necessary. In addition, measures to prevent surface condensation are more important, because of the various and irregular latent loads in residential buildings. Additionally, if surface condensation occurs, the occupants may face safety issues, because the floor surface that is used as the radiant cooling panel is in direct contact with the human body.

Additionally, a supplemental cooling system may be required, depending on the space cooling load, because of limitations of cooling capacity imposed by the requirement for surface temperature comfort, the risk of surface condensation, and the limitation of the radiant panel installation area.

The application and maintenance of the RHCS are relatively straightforward for residential buildings that use centralized heating and cooling, as compared to those that use individual heating and cooling. However, individual decentralized boilers are used relatively often for residential buildings in Korea. Therefore, the whole system needs to be simplified in terms of the initial cost, system control, and maintenance. This is even more necessary for small residential buildings.

In this study, a strategy for the configuration and arrangement of an RFCS using an individual cooling source was derived for application to residential buildings in hot and humid summer climate regions, such as Korea. Then, the feasibility of this system for a residential building was verified through the field test, by evaluating the performance of space cooling and surface condensation prevention.

In order to accomplish this, the cooling load, system requirement, and configuration of the existing heating and cooling system were investigated. From these results, a strategy for the configuration of the whole RCS for application to residential buildings using individual heat production units was derived. Then, through the field test with uncontrolled occupants' behaviors, the performances of the cooling and surface condensation of the RHCS were evaluated, and the operational characteristics of the whole system were analyzed.

2 Alternative of RCS for Residential House

2.1 Analysis of Cooling Load and System Requirements

In order to derive an alternative configuration of the whole RCS for residential buildings using individual heat production units, previous research (Jeong et al. 2007) that analyzed the cooling loads for typical Korean residential buildings was investigated. In this research, the cooling load based on a design indoor temperature of 26 °C and design relative humidity of 50% was estimated through EnergyPlus simulation; the simulation result is shown in Table 1. This research also reported that the sensible load during the cooling period (May 1st to September 30th; 3672 h) exceeded 50 W/m^2 for about 90 h.

RCS can remove only the sensible load. Therefore, a dehumidification system is additionally required to remove the latent load for the prevention of surface condensation.

The comfort requirements of the floor surface temperature also have to be satisfied, because when the existing

Table 1 Result of cooling load simulation.

	Sensible load (W/m^2)	Latent load (W/m^2)	Total load (W/m^2)
Maximum total load day	48	9	57
Maximum latent load day	45	11	56

radiant floor heating panel is used for cooling, the floor surface used as the radiant cooling panel is in direct contact with the human body. Some studies and standards (Handbook American Society of Heating, Refrigerating and Air-Conditioning Engineers 2009; Olesen 2008; Standard American Society of Heating, Refrigerating, and Air Conditioning Engineers 2004; International Organization for Standardization 2012; Babiak et al. 2009; International Organization for Standardization 2005; Zhang et al. 2001) suggest the lower limit for an acceptable floor surface temperature to be around 17–21 °C. The REHVA guidebook (Babiak et al. 2009) provides an acceptable minimum surface temperature (19 °C) as well as a method of calculating the cooling capacity for each panel type. The cooling capacity of a Radiant Floor Panel (RFP) calculated based on this method may be insufficient for space cooling when considering the simulation result for cooling load in the above research (Jeong et al. 2007), the acceptable minimum floor surface temperature, and the effective installation area of the RFP. Thus, it can be inferred that supplementary cooling equipment is required in addition to the RFP.

From the above investigation, applying the RCSs to residential houses in hot and humid summer climate regions requires dehumidification equipment, to remove the latent load and to prevent surface condensation; and supplementary cooling equipment, to remove the sensible load beyond the cooling capacity of the radiant panel.

However, the respective installations of all of these systems in a house increases the burden in terms of the initial cost, area occupied by the equipment, control of the whole system, and maintenance. Thus, the system configuration needs to be simplified.

The application of cooling-based dehumidification, which can perform both dehumidification and cooling, can be considered. Supplementary cooling equipment with dehumidification can also be considered, which uses the same heat transfer medium, in order to avoid an increase in the number and kinds of heat sources. Therefore, the Fan Coil Unit (FCU) was selected as the additional system for dehumidification and supplementary cooling, because the FCU is typical equipment that uses water as the heat transfer medium, as does the radiant panel, and adopts the cooling-based dehumidification.

2.2 Configuration of Heating and Cooling System in Korea

In order to establish a strategy for the configuration and arrangement of the whole RCS, the configuration of the heating and cooling system for a residential house in Korea was analyzed through corresponding statistical data (Korean Statistical Information Service). According to this data, for heating, RFHSs using hot water have been adopted in 99% of total residential houses, and the percentage of houses employing individual heating was 85% in 2010. For cooling, PACs had been adopted in 55% of total residential houses in 2011, with this proportion tending to increase. It was also found that indoor package air-conditioner units tend to be installed only in the living room, or in the living room and only one bedroom (1.1 indoor unit per each household, in 2011).

2.3 Strategy of Configuration and Arrangement for the Whole RFCS

Based on the analysis results of the requirement for applying RCSs in residential buildings with individual heat sources, and the configuration of existing heating and cooling systems for residential buildings with massive concrete slab, it has been determined that the whole cooling system should consist of RFCS and supplementary cooling equipment combined with dehumidification, and should be installed in a similar manner to the existing radiant heating system and PAC systems.

Because the existing radiant floor heating panel can be used as the radiant cooling panel, it has been determined that a radiant floor cooling panel for space cooling should be adopted for every thermal zone (each room). For the supplementary cooling equipment with dehumidification, installation in every room may lead to sufficient dehumidification and supplementary cooling, but this may be unreasonable in terms of cost, system control, maintenance, and required area, because of the multi-zone space. In Korea, most occupants' activities are mainly carried out in the living room, and the doors of rooms connected to the living room are often left open. In addition, while bedrooms are mainly used during bedtime and have a relatively low latent load, a living room may have substantial latent load, because of the direct influence of cooking, laundry, and drying, as well as its proximity to the bathroom. Thus, it has been determined that supplementary cooling equipment with dehumidification should be installed in a representative room, such as a living room, rather than being installed in every room. This strategy is similar to the existing arrangement, in which the indoor unit of the PAC is installed in one or two representative rooms, such as the living room and/or the bedroom.

3 Field Test for an RFCS in a Residential House with a Massive Concrete Slab

The performance evaluation of a heating and cooling system is generally conducted under a specific condition that represents the operation environment for the system. However, various conditions that arise during the real operation of a system may not be reflected in these evaluations. In particular, this is more apparent for residential houses with irregular load profiles. Therefore, in this study, in order to assess the feasibility of RFCSs for residential houses under real operation environments, the field test was conducted over one month in August, when it is hottest in Korea.

3.1 The House for Evaluation and the Configuration of the Whole RFCS

A dormitory house with four thermal zones located at Seoul National University in Korea was selected for the field test. This house has a living room, a bathroom, three bedrooms, and a balcony on the north side of the living room (Fig. 1). Two bedrooms are equipped with a bed and one bedroom is equipped with a mattress, so as to reflect the traditional Korean sleeping style. A total of 16 persons participated in the field test during the whole test period, with four persons each day, which is similar to the number of occupants of a typical residential house in Korea.

The chiller was placed in the balcony space, and produced chilled water at 7 °C. The chilled water from the chiller made high temperature chilled water of 16 °C by a fixed plate heat exchanger, and this high temperature chilled water was supplied to each RFP through a distribution manifold. The existing RFP based on the heating load was used for cooling, but the design water flow rate for cooling was calculated and supplied. In addition, a control valve was installed at each room circuit for individual room control, and was controlled to be either on/off depending on the temperature of each room.

The FCU, as the supplementary equipment for dehumidification and additional cooling, was installed on the window side of the ceiling of the living room. If dehumidification or/and supplementary cooling was required for any room, the FCU was turned on. Based on sensor-measured values in each room, if the difference between the radiant floor surface temperature and the indoor dew point temperature was less than 1 K, the FCU was turned on for dehumidification. In contrast, if the difference between room temperature and set room temperature was more than 0.5 K continuously for 20 min, the FCU was turned on for supplementary cooling.

Table 2 shows detailed information related to the field test, and Fig. 2a and b show a schematic diagram of the whole installed RFCS and a sectional geometry of the installed radiant floor panel, respectively.

3.2 Evaluation Process

The field test was performed under conditions without any artificial restrictions on the activities of participants. Participants slept, ate, washed, and dried their clothes

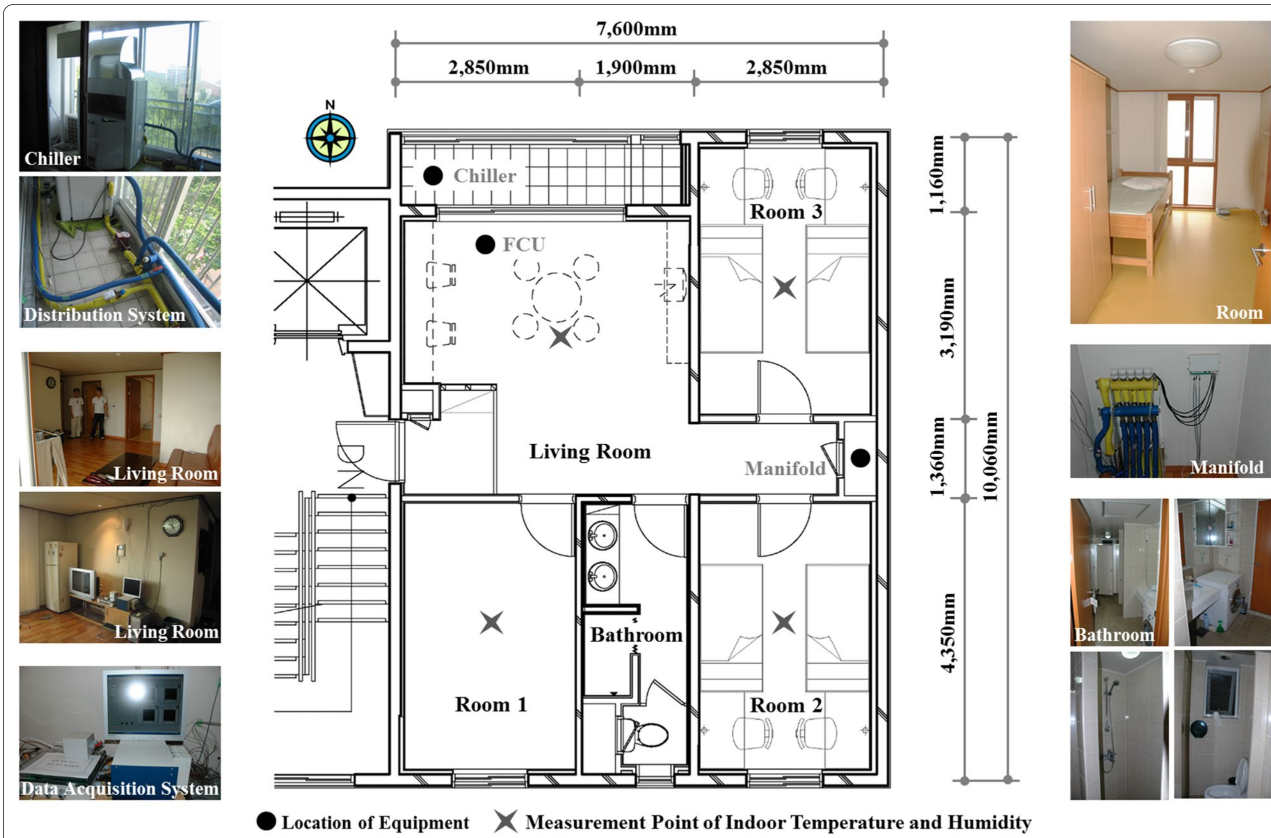

Fig. 1 Plan and equipment arrangement of the selected residential building for the field test.

Table 2 Description of selected residential building and field test.

Parameter	Description
House	
Location	Seoul, South Korea
Orientation	Rooms 1 and 2: South Room 3 and living room: North
Area	76.5 m^2
Occupancy	Total of 16 persons (M: 8, W: 8) 4 persons/day Ages 25–35
Air-tightness	7.4 ACH at ΔP=10 Pa
Radiant floor cooling system	
Heat source	Chiller (2 USRT)
Radiant floor panel	Supply water temperature 16 °C Pipe diameter 16 mm Pipe space 230 mm
Control	Individual room control (on/off)
Supplementary equipment	
Fan coil unit	4 way type Supply water temperature 7–10 °C
Control	On/off control
Measurement	
Room temperature	T-type thermocouple Center of room (height 1.2 m)
Relative humidity	Center of room (height 1.2 m)
Floor surface temperature	5 locations for each room
Equipment	NI SCXI with LabVIEW 8.0
Adjustable variables	Set room temperature Set minimum floor surface temperature
Field test period	1 month (August)

freely, just like real occupants would in a residential house. In other words, they were living freely, without any constraints. This ensured that the real feasibility of the system was evaluated under various situations that can occur in a real residential house.

The ASHRAE Handbook (2009) proposes the comfortable operative temperature of approximately 24 ~ 27 °C under the relative humidity of 40 ~ 60% and clothing insulation of 0.5clo during the cooling season. Generally, the indoor dry-bulb set-point temperature is set at 26 °C for simulation or experimental evaluation. However, the occupants' real indoor dry-bulb set-point temperatures may be changed, because of thermal radiation heat transfer, in the case of the RFCS operation. The occupants set the target room temperature that they wanted to be maintained for thermal comfort through the system operation. Thus, the cooling performance of the system was evaluated in terms of maintaining the target room temperature set by occupants. Consequently, the performance of the RFCS can be evaluated by whether occupants' various requirements related to thermal comfort were met.

Therefore, in this study, the performance of cooling and condensation prevention of RFCSs for residential buildings with massive concrete slab was evaluated through a field test in which the occupants freely set the indoor set-point temperature and acceptable minimum floor surface temperature for thermal comfort.

The cooling performance of the RFCS was analyzed in terms of whether the indoor set-point temperature set by the participants was met. The condensation prevention performance was analyzed based on whether the floor surface temperature was kept higher than the room dew point temperature. In particular, because the supplementary equipment for dehumidification and additional cooling (FCU) was installed only in a representative room (the living room), the condensation prevention performance was analyzed for the living room, as well as for each room. The participants could modulate the set-point temperature to 0.5 K intervals.

The indoor set-point temperature, room temperature, indoor relative humidity (dew point temperature), and floor surface temperature were measured and recorded in order to evaluate the performance, and a post occupancy evaluation was conducted.

4 Feasibility of RFCS Through the Field Measurement

4.1 Setting Characteristics of Room Temperature and Minimum Floor Surface Temperature and Cooling Performance

4.1.1 Setting Characteristic of the Room Temperature by Occupants

Part of the recorded data of the indoor air temperature set by the occupants of Room 1, where occupants set the most varied cases of the set value during the field measurement, is shown together with the corresponding outdoor air temperature in Fig. 3. As shown in Fig. 3, it was found that the indoor air temperature set by occupants was not related to the outdoor air temperature.

According to the frequency analysis during the whole test period (Fig. 4), it was shown that the percentage of time in which the indoor set-point temperature was at 27 °C or more was 67 ~ 84%, depending on the room. The indoor set-point temperature at 30 °C was also presented 6 ~ 12% of the time for each room, which is the case (non-occupancy mode) that occupants set during the unoccupied period. Consequently, during the occupied period, the percentage of indoor set-point temperature at 27 °C or more was 64 ~ 69% for the room equipped with a bed (Room 2 and 3), and 82% for the room equipped with a blanket (Room 1).

According to the survey result during this field test, while 18% of participants answered that they felt comfortable but slightly cold under the indoor temperature of

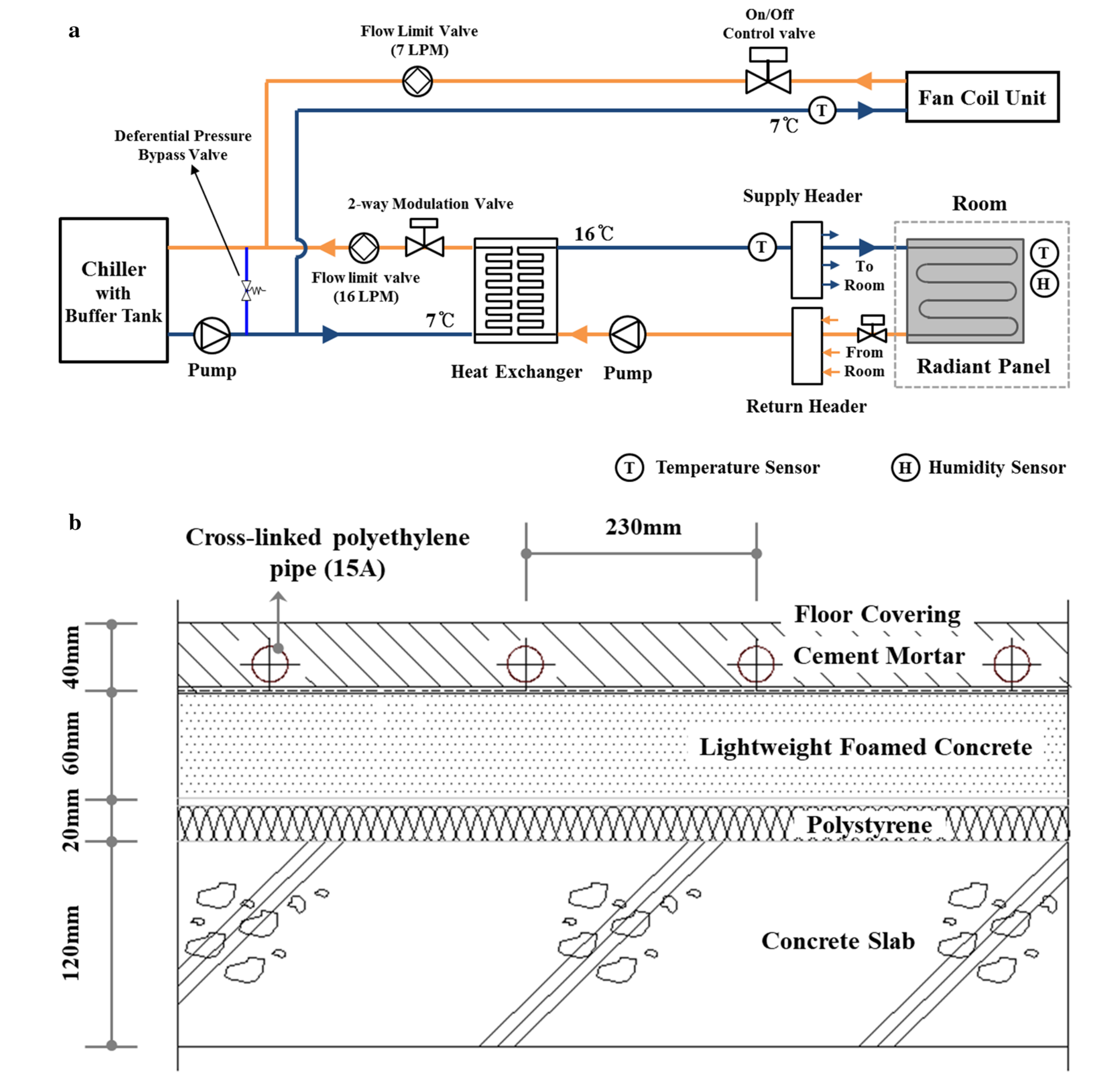

Fig. 2 **a** Schematic diagram of the whole installed RFCS. **b** Sectional geometry of the installed RFP.

26 °C, most participants answered that they felt comfortable under the indoor temperature of 27 °C. These can be considered to be the result of thermal radiation transfer by the RFCS. For this reason, the same thermal comfort level is expected even if the indoor temperature is set approximately 1 K higher, as compared to a conventional air system. Further, considering that the participants are 25 ~ 35 years old, it is expected that the indoor temperature can be set much higher for room in which occupants with a relatively low metabolic rate (children, the elderly, etc.) live. In particular, most participants felt a little cold under the indoor temperature of 26 °C while sleeping, so they tended to set the temperature to 27 °C or higher.

4.1.2 Setting Characteristic of the Minimum Floor Surface Temperature by Occupants

Occupants could set the acceptable minimum floor surface temperature so as to avoid discomfort by the floor surface temperature. According to the frequency analysis of the setting value for the occupied period (Fig. 5), it was shown that the percentage of time in which the floor surface temperature was set at 22 °C was 49 ~ 80%,

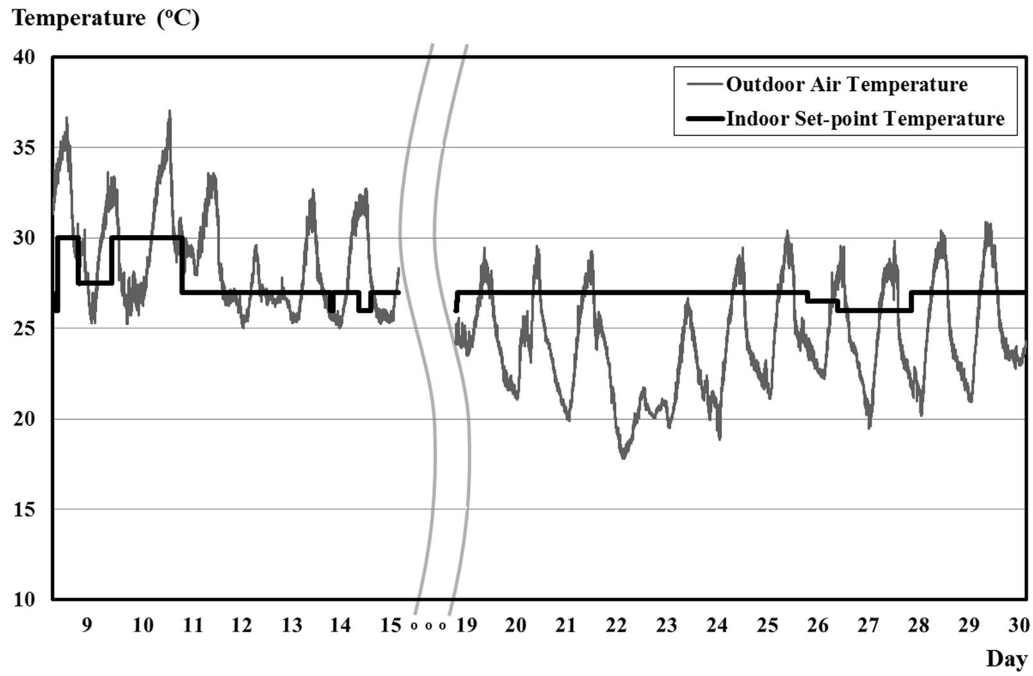

Fig. 3 The indoor set-point temperature of Room 1, and the outdoor air temperature.

depending on the room. Occupants set the minimum floor surface temperature to 20 ~ 22 °C in all rooms, except for the living room (19 °C, only 2% of the total case). Because the human body comes in direct contact with the RFP due to the sedentary Korean lifestyle, it can be inferred that the set value for the minimum floor surface temperature is higher than international standards. These set values are relatively lower for the living room than for the bedroom, which is thought to be the result of the kind and level of activity in each zone.

After the occupancy experience, a prominent trend was revealed in which the occupants set the minimum floor surface temperature to 22 °C. The indoor temperature was also satisfactory with the set value under the minimum floor surface temperature of 22 °C, according to the survey result during this field test, which revealed that issues of discomfort did not occur.

4.1.3 Cooling Performance of the RFCS

During the field measurement, the outdoor air temperature ranged from 18 ~ 37 °C, and the outdoor air relative humidity ranged from 40–97%. The room air temperature for the month ranged from 24 ~ 27 °C, except for during the period with a set value of 30 °C (non-occupancy mode). In addition, the room air temperature remained within the set value (differential of temperature = ± 1 K). The room temperature, floor surface temperature, and indoor dew point temperature for 7 days (8^{th} ~ 14^{th} Aug.), based on the day with the highest outdoor air temperature during this period, are shown in Fig. 6 for the case of the Living Room.

The participants could set the minimum floor surface temperature according to their comfort. At this point, the room air temperature should also meet the set value for cooling. The control algorithm used in this research could meet the set value for room temperature regardless of the floor surface temperature.

Because the embedded water-based surface heating and cooling type [particularly with a massive concrete slab (Newell and Goggins 2018)] of the RHCS exhibits a relatively slow response as compared to the air system, issues might be raised in terms of the pick-up time following a long-term shut-down of the system. Therefore, there are concerns that occupants might feel hot and uncomfortable when returning after a long-term unoccupied period. During this field test, occupants set the room temperature to 30 °C for their absence (non-occupancy mode), so the operation of the RFCP was stopped during this period. Then, when occupants returned after being gone for 18 h, the room temperature had remained in the range of 26.8 ~ 27.5 °C, and the occupants did not claim discomfort from this room temperature. Based on these results, there were no significant issues of thermal discomfort by the slow response of the RFCS with thermal mass such as a massive concrete slab, due to the effects of thermal storage and time-lag by the thermal mass.

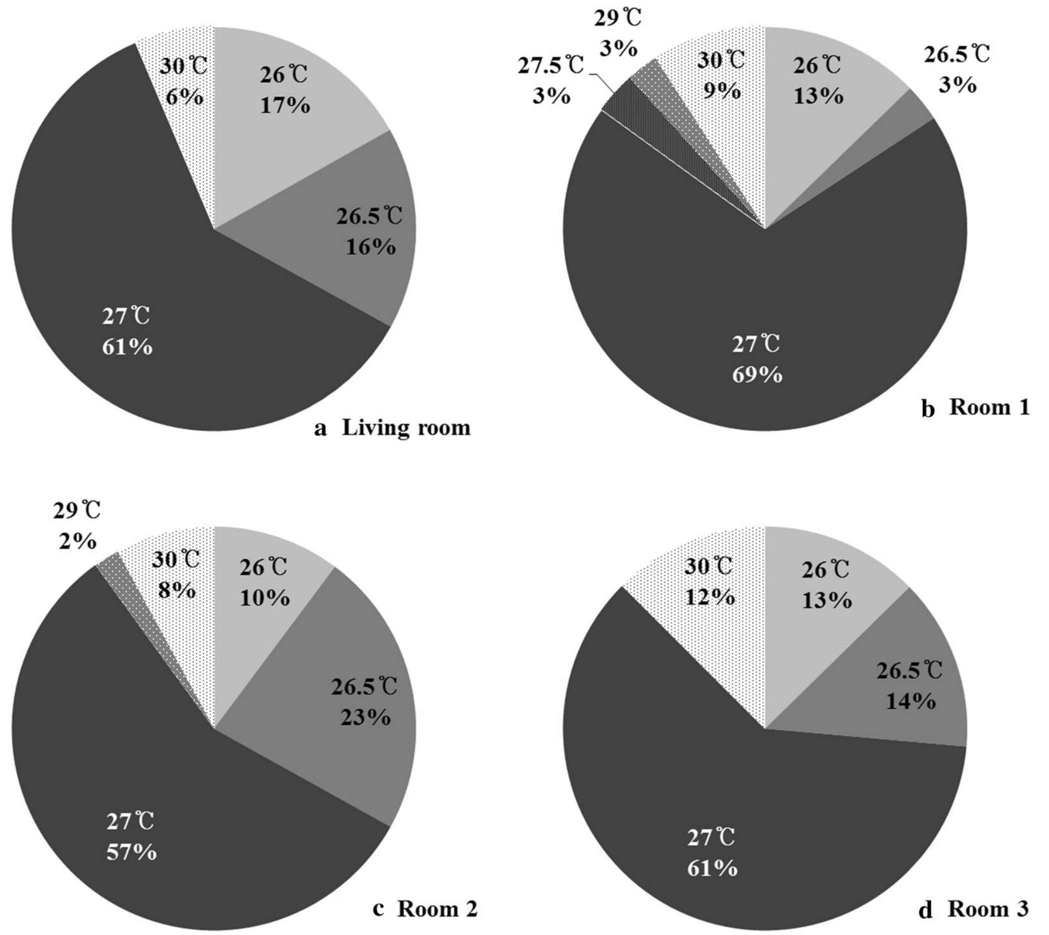

Fig. 4 Frequency of the indoor set-point temperature in each room.

4.2 Performance of Condensation Prevention for Individual Room

4.2.1 Performance of Condensation Prevention in the Living Room

As might be expected, surface condensation did not occur in the living room with the FCU for supplementary cooling and dehumidification. As shown in segments A, B, and D of Fig. 7, the dew point temperature for the living room was lowered by operating the FCU, and ended up being lower than the floor surface temperature that has been lowered by operating the RFCP. Consequently, surface condensation was avoided.

When the living room did not require cooling but the FCU was being operated due to the requirements of other rooms, the air temperature of the living room was 0.5 K lower than the set value, as shown in segment C of Fig. 7, and it was found that the living room air temperature could reach a maximum of 2.6 K lower than the set value. Because the door of the room where dehumidification was required was closed, the humidity could not be satisfied in this room, so dehumidification was still required, and the living room was consequently over-cooled. Therefore, if a door is closed because of sleeping, leading to the airflow being limited, the representative room not requiring cooling might become over-cooled, while other rooms that need dehumidification might not be dehumidified; considerations of these conditions are necessary for system design.

4.2.2 Performance of Condensation Prevention in the Bedrooms

Surface condensation did not occur in Rooms 1 and 3. As shown in Fig. 8a and c, the dew point temperatures for each room were lowered by operating the FCU, and were ultimately lower than the floor surface temperatures that were lowered by operating the RFCP. A similar pattern was also shown in all periods in which dehumidification and supplementary cooling were required. Therefore, it was found that the FCU installed in the living room (representative room) could meet the requirement of condensation prevention for Rooms 1 and 3. In particular,

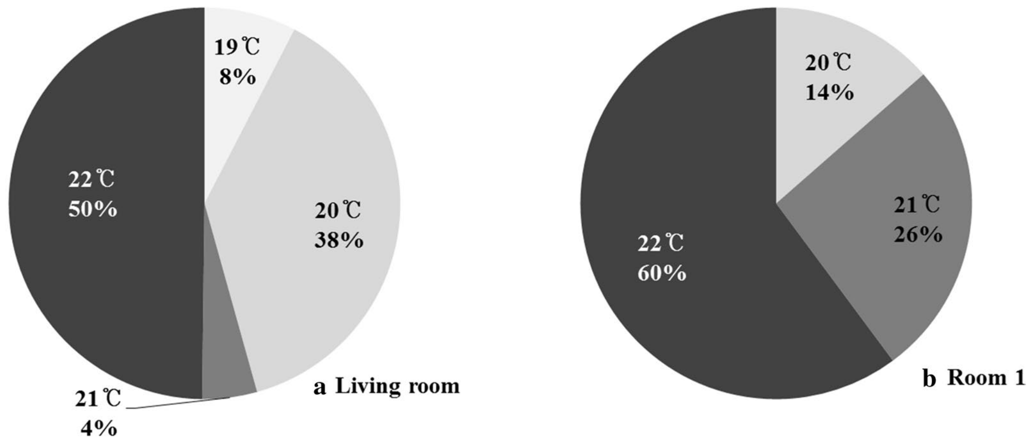

Fig. 5 Frequency of the minimum floor surface set temperature in each room.

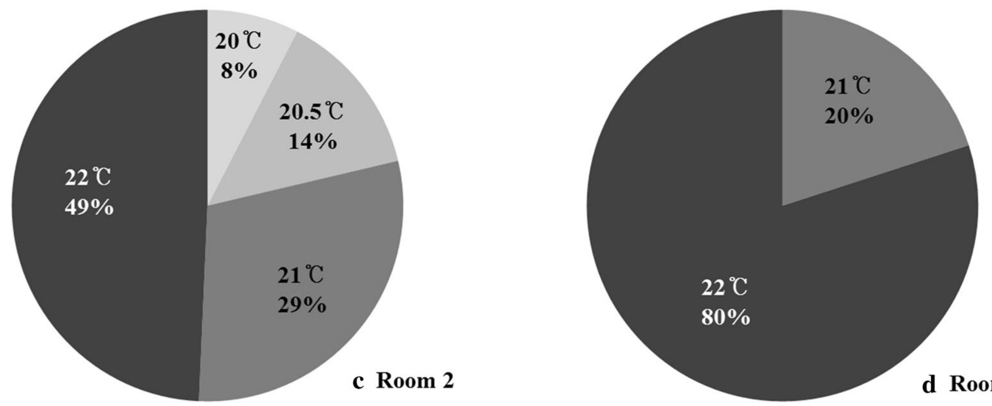

Fig. 6 Profile of the indoor air temperature, floor surface temperature, and dew-point temperature in the living room.

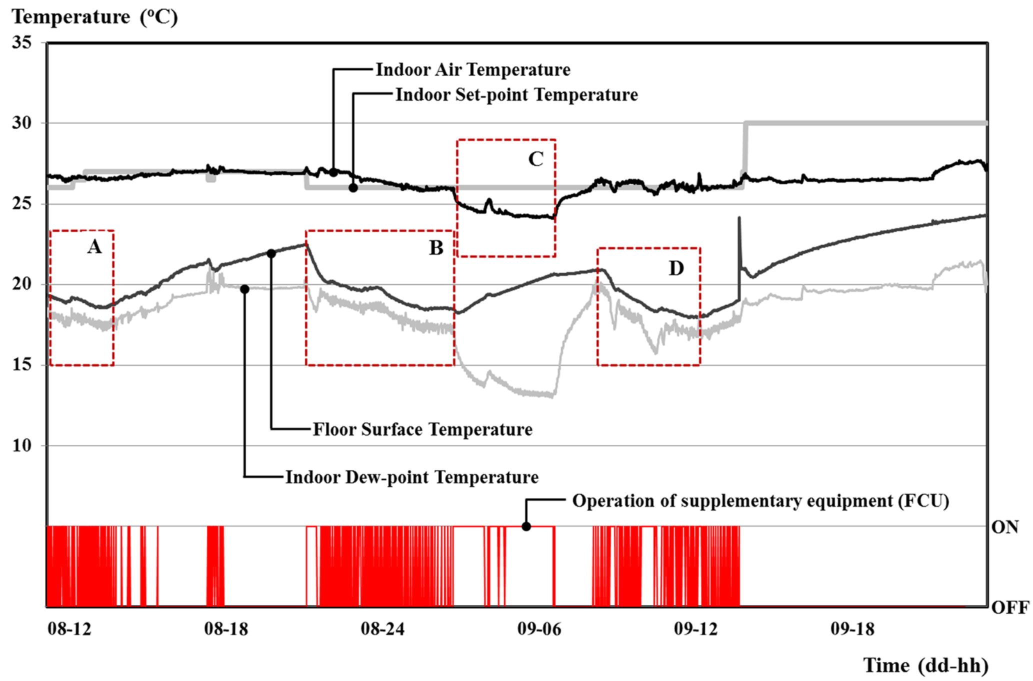

Fig. 7 Performance of condensation prevention in the living room.

because Room 1 can be affected directly by the FCU, and because airflow between each space is facilitated if the door is open, the room temperature was similar to that of the living room, as shown in Fig. 9.

On the other hand, surface condensation was found for a relatively large amount of time in Room 2. During the whole test period, the floor surface temperature in Room 2 was lower than the room dew point temperature for 551 min. This means that surface condensation occurred. Although dehumidification for Room 2 was required and the FCU installed in the living room was being operated, the dew point temperature in Room 2 showed no change, regardless of the operation of the FCU, or even rose, as shown in Fig. 8b. However, in some periods, the room temperature was similar to that of the living room, as shown in Fig. 10, from which it could be inferred that these phenomena were affected more significantly by the condition of door opening than by the distance to the FCU, according to the participants' answer that the door was often closed as well as the results in Room 3.

5 Conclusions

This study aimed to evaluate through a field test the performance in terms of cooling and condensation prevention of RFCSs for residential buildings using individual heat sources, including supplementary equipment for dehumidification and cooling. In addition, the setting characteristics of the room temperature and minimum floor surface temperature were analyzed through a survey during this field test. For these purposes, the field test was conducted under the condition of a real system operation environment in which occupants were not limited in their activities. The main results of this study can be summarized as follows.

1. The room temperature remained at the indoor set-point temperature during most of the measurement period, and the floor surface temperature was higher than the indoor dew point temperature. As a result, an RFCS combined with supplementary equipment for dehumidification and cooling can satisfy the requirements for cooling and condensation prevention in a residential house with multi-zones.
2. When the room temperature was approximately 26 °C in the space operated by the RFCS, the occupants felt slightly cold, so they adjusted the set-point temperature to 27 °C or higher. These effects can be considered to be the results of thermal radiation transfer by the RFCS. Therefore, for the design of the RFCS, the controlled variable and its set value must be determined in consideration of the effect of thermal radiation transfer.
3. The occupants tended to mostly set the minimum floor surface temperature at 22 °C after the residential experience. This is thought to be influenced by the sedentary or barefoot lifestyle in Korea. Of course, it

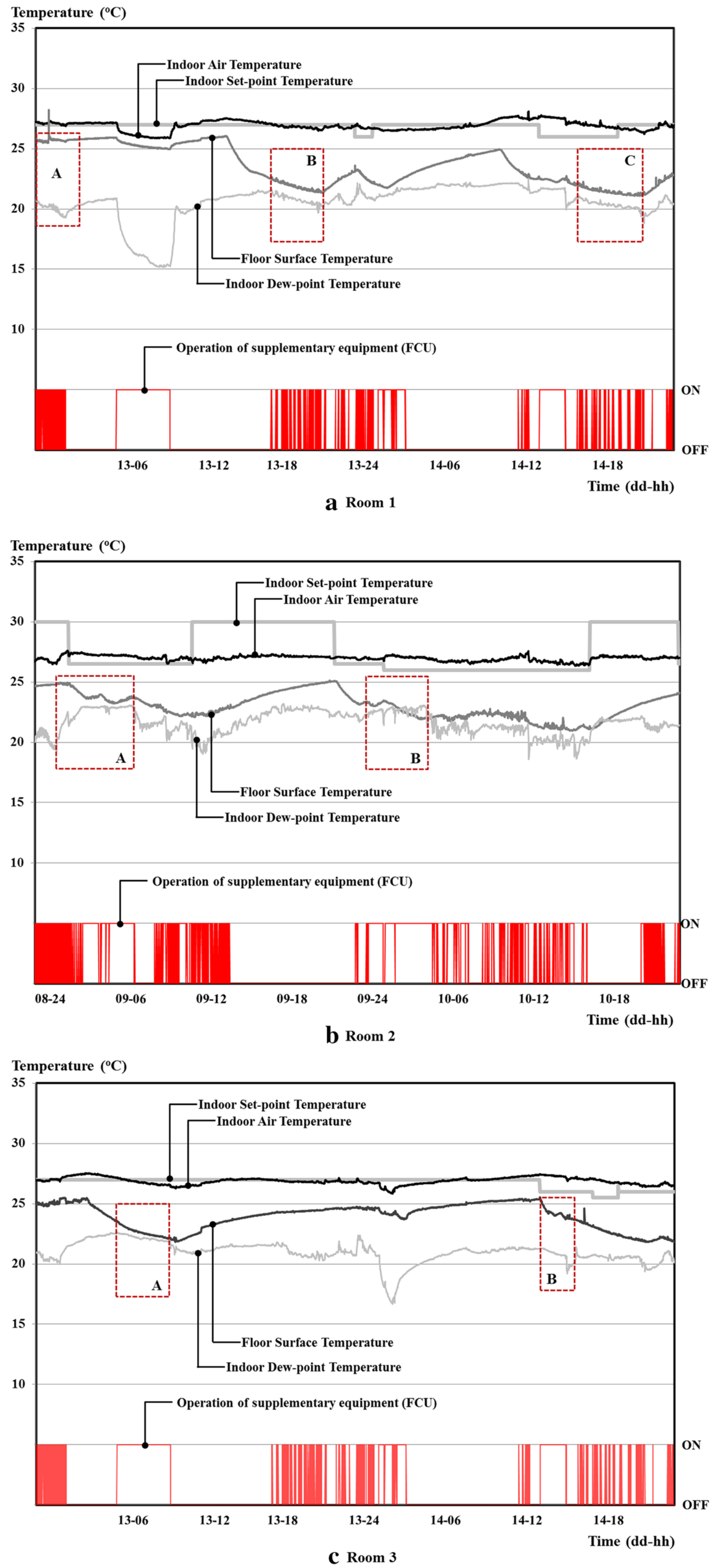

Fig. 8 Performance of condensation prevention in the bedrooms (rooms 1, 2, and 3).

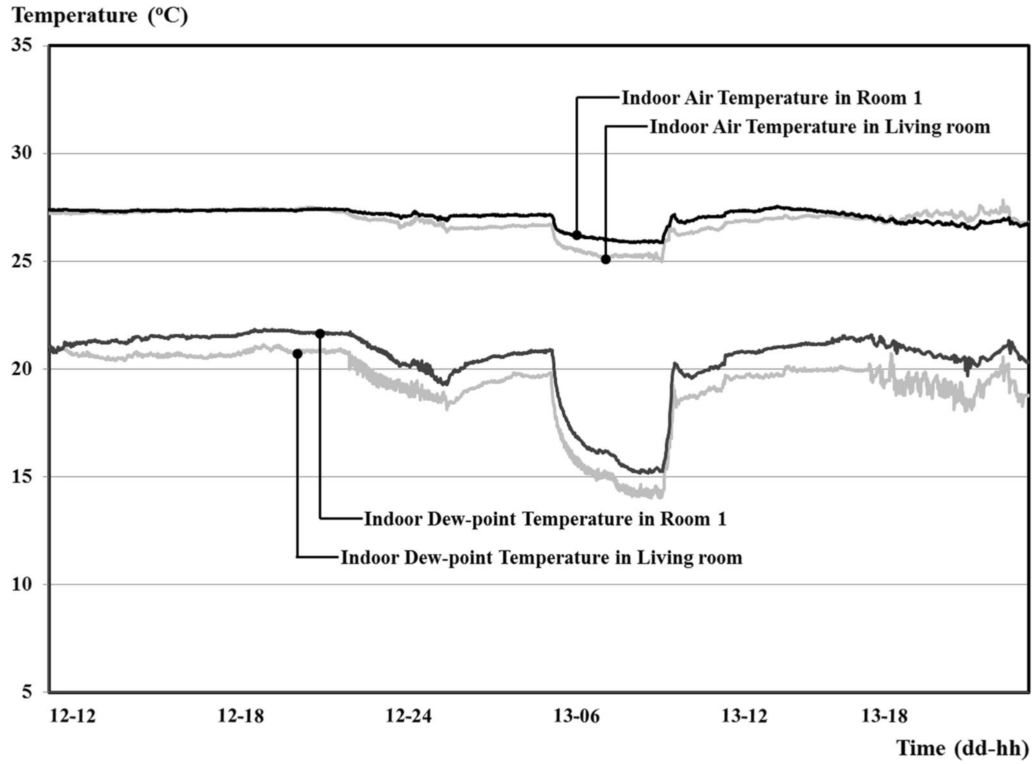

Fig. 9 Temperature profiles in the living room and room 1.

was revealed that the room temperature was able to meet the set value for this situation. This setting characteristic of the minimum floor surface temperature could be used to determine the supply water temperature for the RFCS, and also to estimate the dehumidification load at the design stage of the RFCS.

4. Even when the RFCS was shut down, the cooling capacity of the system could last for a long time, due to the heat storage and time lag by the thermal mass such as a massive concrete slab (RFCP). Therefore, the room temperature could be kept in the range of thermal comfort, even when shut-off for extended periods of time. As a result, through the field test, the issue of thermal discomfort after a long-term absence without system operation was considered not to be a significant concern.
5. The FCU installed as the supplementary equipment for dehumidification and cooling in the representative room met the requirement of condensation prevention in most of the rooms. However, for the room where the latent load was high and the door was closed, some surface condensation occurred. The performance of the condensation prevention in each room is related to the airflow by the door being open or shut, which should be considered for the design and arrangement of the whole system.

In this study, a questionnaire survey was also administered to the occupants. The operation characteristic analysis of the radiant floor cooling system, in connection with the questionnaire survey for occupants, will be published in the future. This study was conducted to evaluate the performance of space cooling and surface condensation prevention of an RFCS applied with FCU for dehumidification and supplementary space cooling in a multi-zone house, as compared with a conventional cooling system, such as a packaged air conditioner. In Korea, cooling systems for residential buildings predominantly involve the provision of cooling for the whole house by installing a PAC in the living room or in the living room and an additional main room (statistical data addressed in Sect. 2.2). In general, occupants tend to open the doors of each room except for at bed time in residential buildings. Therefore, it was considered to install FCU for dehumidification and supplementary space cooling in the living room only in a manner similar to typical cooling

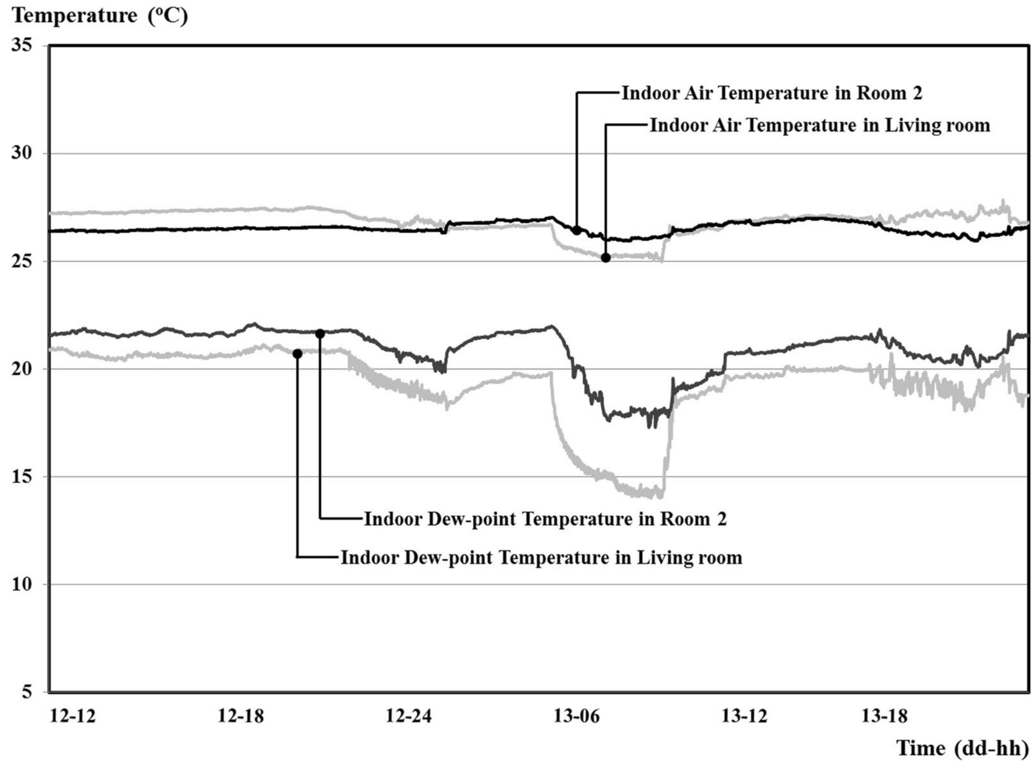

Fig. 10 Temperature profiles in the living room and room 2.

system installations. We evaluated the performance in terms of space cooling and surface condensation prevention in each room, even in cases where FCU was installed in a representative room, such as the living room. The issue of the installation of an FCU for dehumidification in each room was left for a future study.

Authors' contributions

CH made substantial contributions to perform experiment, acquisition of data, and analysis and interpretation of data, and was a major contributor in writing the manuscript. MS established research issues and designed experiment. KW involved in revision for important content. All authors read and approved the final manuscript.

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Competing interests

The authors declare that they have no competing interests.

Availability of data and materials

The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

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