Improved operation scheme for a radiant floor heating system to reduce overheating

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Abstract. This study aims to evaluate an optimal operation control scheme for a radiant floor heating system in a residential building to maintain a desired room temperature. Radiant floor heating systems frequently cause overheating—exceeding the set temperature—due to the heat capacity of the flooring material. To mitigate this problem, an optimal operation control scheme is proposed to determine the optimal set temperature for each room. To evaluate the suggested optimal operation scheme, experiments were conducted on a living test bed—two bedrooms. In Bedroom 1, three operation periods with the suggested operation control were implemented and in Bedroom 2, three operation periods with the optimal operation control were implemented, reducing overheating from 4.0 °C to 0.0 °C and 4.5 °C to 0.5 °C, respectively.

1. Introduction
Radiant floor heating is a heating system that achieves indoor climate control for indoor thermal comfort through the use of hot water circulating in a concrete slab. Radiant floor heating systems are an efficient way to achieve occupant thermal comfort in buildings with a low energy demand [1]. However, one problem with the system is that the room temperature may exceed the set temperature, causing overheating. This occurs because there is a time lag in the heat transfer from the boiler to room air, along with the thermal insulation capacity of the building. Also, internal loads from occupants, lighting, and direct sunlight can contribute to overheating of the room temperature [2]. To resolve this problem, Ahn and Song [3] proposed operational strategies that involved controlling the supply water temperature. The temperature of the supply water is controlled through environmental variables including the outdoor, indoor, and supply water temperatures, and water flow rate. Yang [4] suggested a predictive control method with proportional feedback to resolve the overheating problem with constant flow heating. From this model, it was found that the most influential factor is the outdoor temperature, and the model was useful for improving indoor thermal comfort. Lee et al. [5] suggested a predictive control model using an artificial neural network (ANN). In that study, control parameters including the outdoor and room temperatures, and variation in indoor temperature, and variation in outdoor temperature were selected as input parameters to construct an ANN model. The result showed that the predictive control model reduced the incidence of overheating and total heating time. Kang et al. [6] proposed an advanced on-off control method based on fuzzy logic to improve thermal comfort with a hydronic radiant floor heating system. The proposed model was applied to resolve overheating by overcoming the limitation of the on-off controller, which has a fixed operating range. Simulations were conducted to evaluate this model, and the results demonstrated better performance than the conventional on-off control method.
However, the results of these studies are difficult to commercialize because they require complicated techniques, additional sensors, and measuring devices. Thus, to overcome this limitation, an optimal operation control method that consists of a relatively simple formula without the need for additional sensors and devices is proposed and evaluated in this study.

2. Methods

An operation control algorithm is proposed for a radiant floor heating to resolve the problem of overheating. As shown in Figure 1, the suggested operation control algorithm is based on comparisons between the desired temperature of the room, set temperature of the boiler, and maximum temperature of the room, which reflects the occurrence of overheating.

- **Step 1**
  In the first operation period, the boiler is started with the set temperature equal to the desired temperature of the room.

- **Step 2**
  After the boiler stops upon reaching the set temperature, the room temperature is checked to determine whether it is equal to the desired room temperature.

- **Step 3**
  If the maximum temperature is equal to the desired room temperature, the boiler is operated at the same set temperature during the next operation period. In contrast, if the maximum temperature exceeds the desired room temperature, the set temperature is lowered by an amount equal to the difference between the desired room temperature and maximum temperature for the next operation period. Finally, if the maximum temperature is lower than the desired room temperature, the set temperature is increased by an amount equal to the difference between the desired room temperature and maximum temperature for the next operation period.

- **Step 4**
  Steps 1–3 are repeated to determine an appropriate set temperature that can maintain indoor thermal comfort considering the thermal characteristics, performance of the floor heating system in the room, and outdoor conditions.

To evaluate the suggested operation scheme for a radiant floor heating system, experiments were conducted in a living test bed. The living test bed is an enclosed chamber that consists of one living room and two bedrooms with a boiler installed for the floor heating system, variable refrigerant flow (VRF) system for cooling, heat recovery ventilator, humidifier, dehumidifier, dimming system, and automatic blinds. The living test bed also includes household appliances including a television, washing machine, refrigerator, microwave, gas stove, vacuum cleaner, and sink to simulate an actual residential environment. Indoor and outdoor environmental data such as the temperature, relative humidity, CO₂ concentration, acoustic level, occupant movement, illumination, and concentration of fine dust are collected and saved to a server once per minute. To control and collect data from the appliances and environmental control devices, they are connected using Modbus/TCP and a Building Automation and Control Network (BACnet). Modbus/TCP is a standard communication protocol commonly used for connecting electric devices [7], and BACnet is an ASHRAE, ANSI, and ISO 16484-5 standard protocol for building automation and control systems [8].
3. Results
Experiments were conducted in the living test bed to evaluate the proposed operation algorithm. The desired room temperature was 24.0 °C, and the set temperature was varied according to the algorithm to reduce overheating. All experiments were conducted for 8 h. The data presented in Table 1 and the figures below was collected via remote control with 0.5 °C accuracy once per minute.

| Table 1. Experimental results for optimal control of radiant floor heating |
|-----------------|-----------------|-----------------|
|                  | First operation | Second operation | Third operation |
| Bedroom 1        |                 |                 |                 |
| Desired room temperature (°C) | 24.0            |                 |                 |
| Set temperature (°C)         | 24.0            | 19.5            | 18.0            |
| Maximum temperature (°C)     | 28.5            | 25.5            | 24.5            |
| Overheating (°C)             | 4.5             | 1.5             | 0.5             |
| Total operating time (min)   | 312             | 187             | 148             |
| Bedroom 2        |                 |                 |                 |
| Desired room temperature (°C) | 24.0            |                 |                 |
| Set temperature (°C)         | 24.0            | 20.0            | 19.0            |
| Maximum temperature (°C)     | 28.0            | 25.0            | 24.0            |
| Overheating (°C)             | 4.0             | 1.0             | 0               |
| Total operating time (min)   | 338             | 222             | 189             |

Figure 1. Flow chart of the suggested operation control method for radiant floor heating
First operation

Before the first operation period, the temperature in each bedroom was 4.5 ℃, and the outdoor temperature was -4.0 ℃. The floor heating system was operated by coding the suggested scheme in the control server. As shown in Figure 2, the boiler stopped running when the indoor air temperature reached the set temperature of 24 ℃. The total operating time required to reach the set temperature in Bedroom 1 was 312 min, while Bedroom 2 required 338 min. Although the boiler had stopped, the indoor air temperature in Bedroom 1 continued to increase to 28.5 ℃. This represents 4.5 ℃ of overheating. In addition, the temperature in Bedroom 2 reached 28.0 ℃, representing 4.0 ℃ of overheating.

Second operation

For the second operation period, the set temperatures were adjusted to 19.5 ℃ (Bedroom 1) and 20.0 ℃ (Bedroom 2) to reflect the degree of overheating during the first operation. The starting temperature in
each bedroom was 6.5 °C, and the outdoor temperature was -4.0 °C. As shown in Figure 3, the boiler stopped operation when the indoor temperature reached set temperatures of 19.5 °C (Bedroom 1) and 20.0 °C (Bedroom 2). The total operating time to reach the set temperature of Bedroom 1 was 187 min, while Bedroom 2 required 222 min. After the boiler stopped, the temperature in Bedroom 1 increased continuously to 25.5 °C. This represents an overheating of 1.5 °C in Bedroom 1. Similarly, the temperature in Bedroom 2 reached 25.0 °C, representing overheating of 1.0 °C. In the second operation period, the total operating time was reduced by 125 min in Bedroom 1 and 116 min in Bedroom 2. The overheating was decreased by 3.0 °C in each bedroom.

Third operation

For the third operation period, the set temperatures were adjusted to 18.0 °C in Bedroom 1 and 19.0 °C in Bedroom 2 to reflect the degree of overheating that occurred during the second operation. The starting temperature in each bedroom was 4.5 °C, and the outdoor temperature was -4.0 °C. As shown in Figure 4, the boiler stopped operation when the indoor temperature reached set temperatures of 18.0 °C (Bedroom 1) and 19.0 °C (Bedroom 2). The total operating time to reach the set temperature in Bedroom 1 was 148 min, while Bedroom 2 required 189 min. After the boiler stopped operation, the temperature in Bedroom 1 reached 24.5 °C as the indoor temperature continued to increase. This shows that Bedroom 1 still experienced overheating of 0.5 °C. In contrast, the temperature in Bedroom 2 reached 24.0 °C as the indoor temperature continued to increase. This result demonstrates that the temperature of Bedroom 2 could be maintained at the desired room temperature without overheating using the suggested operating algorithm. In the third operation period, the total operating time was reduced by 164 min (Bedroom 1) and 149 min (Bedroom 2), and overheating was decreased by 4.0 °C in each bedroom compared with the first operation period.

4. Discussion
This research aimed to mitigate overheating without the need for additional sensors or complicated methods. Many factors can affect the occurrence of overheating, such as the outdoor temperature, internal loads, and thermal characteristics of the room and building. However, these factors cannot be easily measured with simple sensors. The approach in this study only considers the indoor air temperature of the room during each boiler operation period. When this operation scheme was repeated for each boiler on/off cycle, the room temperature could be maintained without overheating. To improve
the proposed approach, future studies will conduct experiments with varying outdoor temperatures, number of people, daylight illuminance, operation time of home appliances, etc. Various machine learning models will be further developed and evaluated to consider all related parameters and interactions.

5. Conclusion
In this study, an operation scheme to maintain the indoor air temperature of a room was proposed to reduce overheating. Experiments were conducted to evaluate the method with a radiant floor heating system in a living test bed. After three operation periods, overheating could be reduced from 4.5 ℃ to 0.5 ℃ in Bedroom 1, and from 4.0 ℃ to 0.0 ℃ in Bedroom 2. In the future, the model will be further improved to consider additional influential factors and evaluated in the living test bed.

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