Simulational Analysis of Adaptive Outdoor Reset Control based on a Fuzzy Target Temperature Gap for a Hydronic Radiant Floor Heating System

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Abstract
This paper proposes an adaptive outdoor reset control based on a fuzzy target temperature gap for a hydronic radiant floor heating system. A hydronic radiant floor heating system has nonlinear characteristics, such as the effect of time delay and temperature inertia. In hydronic radiant floor heating systems, a heating source system, such as a boiler, has a target temperature gap determined by nonlinear characteristics. An unadjusted target temperature gap causes the indoor temperature to fail at tracking the desired level, and results in many wide swings in room temperature. For these reasons, the hydronic radiant heating system has lower energy efficiency than is desired. To solve these problems, a fuzzy system is employed to find the dynamic target temperature gap of the hydronic radiant floor heating system under both indoor and outdoor temperatures. The fuzzy target gap temperature can determine calorie supply time and On-Off time. The obtained control system shows effectiveness compared with a classical On-Off controller. Simulational results are provided to illustrate the control performance.

Keywords: hydronic radiant floor heating system; outdoor reset control; fuzzy control; target temperature gap; adaptive control

1. Introduction
Among several functions in a building, the ability to control a room's environment is a very important factor. In cold weather, the types of heating systems used to provide a comfortable indoor environment are divided into convective air types and radiant floor heating types. An air convection method is used in heating, ventilating, air conditioning systems, and variable air volume systems, etc.1-3) In a radiant floor heating method, electric heat wires, hot-water pipes or firewood are used.

Since the 1980s, when hydronic radiant floor heating systems were introduced in Europe and North America, they have provided users with a way to improve the comfort and hygiene of their environments. Nowadays, several types of buildings employ this type of heating system. The hydronic radiant floor heating system is generally used in high-rise apartments. Hydronic radiant floor heating systems that are installed in a concrete floor have tremendous mass, compared to the mass of other types of heating systems4). At the floor surface, heat is radiated to warm up the air temperature, and consequently, to keep the inhabitants warm.

The American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE), prescribes rules for various heating methods. In the case of radiant floor heating systems, such rules are employed to control the surface temperature of the floor. In addition, heating efficiency was improved by altering the heating floor structure, the material of floor ash, the structure of the building, etc., in several studies5).

The main objective of a floor heating system control is to supply a rate of heat equal to that which is lost through the facade of a building during continuously changing outdoor conditions, in order to maintain stable and comfortable indoor temperatures.

In research related to the control of radiant floor heating, bottom panel heating, which uses warm water, was developed from the 1940's steadily until the latter half of the 1980's. Among the many advancements resulting from such research were the use of new piping materials and the development of a control technique6).

In accordance with the development of the electronics technique, digital control systems have appeared in the radiant floor heating control and the outdoor reset control has been the main control field. Leigh proposed an outdoor reset controller...
which regulates the temperature of the hot water supply in inverse proportion to outdoor temperatures for circulating hot water\(^7\). Adelman showed that a thermostat was ineffective in the case of calorie control in the room\(^8\).

In this paper, the authors propose an adaptive outdoor reset control based on a fuzzy target temperature gap for hydronic radiant floor heating systems. The adaptive fuzzy logic for the system is developed to approximate a dynamic target temperature gap between a set-point and an On-Off time under the indoor and outdoor temperatures. The dynamic target temperature gap is used to set the hot-water supply time. The proposed controller can be used to set the room temperature of the hydronic radiant floor heating systems. The hydronic radiant floor heating system maintains the system to track the set-point through the proposed controller.

The remainder of this paper will be organized as follows. Section 2 will introduce the configuration of hydronic radiant floor heating systems. An adaptive outdoor reset control based on a fuzzy target temperature gap will be proposed for the hydronic radiant floor heating systems in section 3. The design of a fuzzy system will be briefly introduced in this section. In section 4, simulational results of the proposed control will be presented. Finally, some concluding remarks will be given in section 5.

2. Hydronic Radiant Floor Heating Systems

Compositions of radiant floor heating systems consist of the bottom structural body, the heat source, and the control system. Hydronic radiant floor heating systems are a category of radiant floor heating systems in which water is used as the heat-transfer medium. One type of hydronic radiant floor heating system uses warm water in a pipe which is laid in the structural body of a concrete bottom. Concrete gathers and holds heat from radiant floor heating systems\(^4\). Hydronic radiant floor heating systems control the surface temperature of the bottom by circulating water that has been warmed by the heat source.

The caloric value of the surface temperature of a hydronic radiant floor heating system is determined by water flux and hot water temperature as

\[ Q = M \Delta T C_p \] (1)

where \( M \) is the flux of hot water, \( \Delta T \) is the difference between the supply water temperature and the return water temperature, and \( C_p \) is the specific heat. A hydronic radiant floor heating system uses a method which controls the quantity of radiant heat on the surface structure by controlling the temperature of supplemental hot water\(^9\).

In (1), when considering the heat transfer characteristics of floor materials, the hydronic radiant floor heating system controls both the flow rate of the required supply water and its temperature. Because

the calorific value of the floor structure and the flow of warm water demonstrate nonlinear change, precise flow control is difficult under 50% of the maximum heat generation. Therefore, On-Off control is adopted instead of variable flow control, as shown in Fig.1.

On-Off control has a fixed target temperature gap. A valve of a hot water diver is turned on under the following condition:

\[
\text{Indoor Temp.} < \text{Desired Temp.} - \text{fixed target temp. gap} \quad (2)
\]

Hot water is supplied to the thermal zone using an On-Off operation. Off operates to close valves under the following condition:

\[
\text{Indoor Temp.} > \text{Desired Temp.} + \text{fixed target temp. gap} \quad (3)
\]

In simple On-Off control, derivation of the On operation and the Off operation is not equal because of the affect of outdoor air, wall materials and floor materials. This affect occurs during an operational interval on a large scale. The unnecessary energy is consumed by strong swings in room temperatures.

3. Adaptive Outdoor Reset Control based on Fuzzy Target Temperature Gap

A classical hydronic radiant floor heating system has a fixed target gap in simple On-Off control under indoor temperature conditions only. The hydronic radiant floor heating system using the simple On-Off control has more swings than set-points in maintaining comfortable temperature because of the fixed target temperature gap.

Outdoor reset controls are extremely effective in controlling stable heat temperatures. This type of control reacts to outdoor temperatures. When outdoor temperatures become colder, the outdoor reset control increases the temperature of the water being supplied to a heating system. In contrast, as the outdoor temperature rises, the temperature of the supply water is lowered. This process produces very constant heat
The authors briefly explain the approximation property of the plane in order to meet the desired performance by using fuzzy logic systems. Fuzzy systems are based on the foundation of fuzzy mathematics. These are considered to be expert, knowledge-based, or rule-based systems. The knowledge base consists of the so-called fuzzy IF-THEN rules. The basic configuration of fuzzy logic systems consists of some fuzzy IF-THEN rules and a fuzzy inference engine. The fuzzy inference engines are used to combine the fuzzy IF-THEN rules in the fuzzy rule base into a mapping from an input linguistic vector to an output linguistic variable.

First, the authors design the following fuzzy system based on the input-output pairs using the table lookup scheme\(^{14}\).

**Step 1.** Define fuzzy sets to cover indoor temperature and outdoor temperature spaces \((x_1, x_2; B^{\text{type}})\).

**Step 2.** Generate one rule from each indoor-outdoor temperature pair.

**Step 3.** Assign a degree to each rule generated in Step 2.

**Step 4.** Create the fuzzy rule base.

The fuzzy IF-THEN rules are defined as:

\[
R^l : \text{if } x_1 \text{ is } A^l_1 \text{ and } x_2 \text{ is } A^l_2 \text{ then } f(x_1, x_2) \text{ is near } B^{\text{type}},
\]

\(l = 1, \ldots, 16, \quad i, j = 1, 2, \quad \text{type} = 1, \ldots, 4\)

where \(x_1\) is the outdoor temperature, \(x_2\) is the indoor temperature, \(f(x_1, x_2)\) is the target temperature gap and \(B^{\text{type}}\) equals the constant gap values. The fuzzy rule base consists of only linguistic rules from human knowledge such as "extremely cold", "somewhat cold", "cold", "comfortable", "warm" and "hot".

**Step 5.** Construct the fuzzy system based on the fuzzy rule base.

The authors may choose the fuzzy system with a singleton fuzzifier, product inference and center-average defuzzifier, as follows:

\[
f(x_1, x_2) = \frac{\sum_{i=1}^{M} B^{\text{type}} \left( \prod_{i=1}^{2} u_{A_i^l}(x_i) \right)}{\sum_{i=1}^{M} \prod_{i=1}^{2} u_{A_i^l}(x_i) } \quad (5)
\]

where \(M\) is the number of the fuzzy \(u_{A_i^l}\) rules and is the fuzzy membership function.

When the proposed fuzzy system is applied to Eqs. (2) and (3), valves of a hot water diver are turned on under the following new condition:

**Indoor Temp. < Desired Temp.** – \(f(x_1, x_2)\) \quad (6)

Off operates to close valves under the following new condition:

**Indoor Temp. > Desired Temp.** + \(f(x_1, x_2)\) \quad (7)

Equation (6) depends on the time delay effect and Eq. (7) depends on the effect of temperature inertia. \(f(x_1, x_2)\) can be changed drastically by indoor and outdoor temperatures. The scheme of the adaptive outdoor reset control based on a fuzzy target temperature gap for a hydronic radiant floor heating system is shown in Fig.2.

### 4. Simulational Results

The authors consider a single ONDOL zone of the building with the following conditions and Table 1. for application of the proposed controller. The circular pump of the heating source has these characteristics: a supply water temperature of 55°C, return water temperature of 45°C, and a water flux of 1.65lpm. The heating source has these characteristics: 1.5m of pipeline with 5 bends, and temperature variations of 15°C. The pipe used to send and return water is 20m long with 6 bends. A water pipe in a single zone is 82m long with 64 bends. In the initial temperature conditions, floor temperature is 25°C and indoor temperature is 23°C. The desired indoor temperature is
The fuzzy system considers both outdoor and indoor temperatures in order to set a dynamic target temperature. Table 2. shows the rules and their target temperature gaps generated by the corresponding inputs. The constant temperature gap value $B^{ope}$ is set as $0.2^\circ C$, $0.3^\circ C$, $0.4^\circ C$ and $0.5^\circ C$ each temperature period.

The membership functions $A_i^1$ and $A_i^2$ are defined as:

$$
\mu_{A_i^1}(x_i) = \frac{1}{1 + e^{-(x_i-2)^2/2(0.6)^2}}
$$

$$
\mu_{A_i^2}(x_i) = \mu_{A_i^3}(x_i) = \mu_{A_i^4}(x_i) = e^{-\frac{(x_i-1)^2}{2(0.8)^2}}
$$

Table 2. Fuzzy IF-THEN Rules for the Target Temperature Gap

| Outdoor Temp ($x_i$) | Extremely Cold | Somewhat Cold | Cold | Comfortable |
|----------------------|----------------|---------------|------|-------------|
| -5°C                 | 0.5°C          | 0.5°C         | 0.4°C| 0.3°C       |
| -5-0°C               | 0.5°C          | 0.5°C         | 0.4°C| 0.3°C       |
| 0-5°C                | 0.5°C          | 0.5°C         | 0.4°C| 0.3°C       |
| 5°C                  |                |               |      |             |



where $\mu_{A_i^1}$, $\mu_{A_i^2}$, $\mu_{A_i^3}$ and $\mu_{A_i^4}$ are gaussian
functions and $\mu_{A_1}, \mu_{A_2}$ and $\mu_{A_3}$ are sigmoid functions. In Step 5, using Eq. (5), the authors obtain the following fuzzy system for the dynamic target gap:

$$ f(x_1, x_2) = \sum_{i=1}^{16} \mu_{A_i}^2 \prod_{j=1}^{2} u_{ij}(x_j) $$

(9)

For a simulation, the authors use Labview ver.8.6 for applying the proposed controller to a hydronic radiant floor heating system. The GUI part is shown in Fig.3. This is developed and upgraded to be convenient for fine-tuning. The GUI part watches the states of the system. In Fig.4, 24 hours of winter outdoor temperature data is considered. The GUI has a simple On-Off control mode and the proposed control mode. After running for 24 hours, temperature response results can be shown on the GUI panel. In addition, the fuzzy system is implemented by Matlab ver.7.0.4.

Fig.5 shows the indoor temperature response and the floor temperature in simple On-Off control mode with only a single target temperature gap of 0.5°C and 0.35°C. The indoor temperature is overheated or underheated from the desired temperature. The On-Off control signal is shown in Fig.6. The indoor temperature response in the proposed control mode is shown in Fig.7. The proposed controller minimizes strong swings in room temperatures.

Fig.8 shows the proposed control signal. On-Off intervals vary according to outdoor temperature variations. On a cold night, On-Off intervals are long.

| Temperature gap | On-Off Control | Proposed Control |
|-----------------|----------------|------------------|
| 0.5°C           | 349            | 332              |
| 0.35°C          | 323            |                  |

Table 3. Heat Calories and Flux

These intervals are usually shorter during the daytime. In Fig.9, the fuzzy target temperature gap is shown. The authors know that the target temperature gap continuously changes in relationship to the indoor and outdoor temperatures. On a cold night, tuning of the fuzzy target temperature gap is frequently generated. However, the fuzzy target temperature gap is nearly regular during the day.

The simulational results are also shown in Table 3. In the proposed control approach, the heating operation is lower than for the classical On-Off control. Energy consumption over a period of time is also reduced with smaller overheating and underheating than the classical On-Off control.

5. Conclusions

This paper proposed an adaptive outdoor reset control based on a fuzzy target temperature gap for a hydronic radiant floor heating system. The proposed controller employed a fuzzy system to find the dynamic target temperature gap of the hydronic radiant floor heating system.

The fuzzy target gap temperature was adjusted by IF-THEN rules according to the indoor and outdoor
temperatures. The IF-THEN rules depended on the lookup table related to the indoor and outdoor temperatures. The fuzzy target temperature gap determined On-Off time under the desired set-point.

In simulation, the adaptive outdoor reset controller based on the fuzzy target temperature gap was applied to the hydronic radiant floor heating system for a single zone in a building for one day in the Korean winter. The proposed controller was more effective than the classical On-Off controller. The results of the simulational analysis showed that the proposed system may be used to reduce energy consumption and regulate indoor temperatures.

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