A Strategy to Determine a Heating Curve for Outdoor Temperature Reset Control of a Radiant Floor Heating System

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SUMMARY

In many countries, a radiant heating system is gaining much popularity due to its high comfort level, energy efficiency, improved IAQ and so on. A lot of studies have suggested that the supply water temperature of a radiant heating system be modulated by a heating curve, which is a linear function of outdoor temperature. The heating curve, however, has been determined by an operator's experience or a tedious trial and error approach. This study aims at deriving a heating curve to determine supply water temperature based on heat loss of a building and a heat flow model of the floor structure. To evaluate the derived heating curve, TRNSYS simulation and a mock-up experiment were conducted. The results show that the developed heating curve provides optimum water temperature enough to keep the indoor environment comfortable. This study would be able to provide an algorithm for the outdoor reset controller of a radiant floor heating system.

INTRODUCTION

The goal of a radiant heating system is to supply heat at the same rate at which the building loses heat, thereby keeping the indoor environment stable and comfortable. To achieve this purpose, outdoor temperature reset control is widely applied to the radiant heating system. The main principle of the control strategy is to modulate the supply water temperature according to the heating curve or reset ratio, which means the relation between supply water and outdoor air temperature. Although a lot of studies have been conducted to evaluate and improve the performance of outdoor temperature reset control, there has been little research on the determination of heating curve or reset ratio.

Adelman proposed a heating curve based on supply water design temperature and supply water starting temperature, which corresponds to the coldest and mildest outdoor condition, respectively [1]. But he did not explain how water design temperature and water starting temperature should be calculated.

MacCluer used a reset ratio determined by U-value of the wall, thermal resistance of the slab and heat transfer coefficient of floor surface [2]. But the detailed floor structure was not considered in the calculation of a reset ratio. Leigh conducted several experiments on the outdoor temperature reset control and other control methods of a radiant floor heating system. In the experiment, a reset ratio was estimated based on design conditions and thermal characteristics of the building. But the reset ratio was adjusted by performing several pre-tests before the experiments [3].

Gibbs recommended that auxiliary control strategies be combined with outdoor reset control for the multi-zone control [4]. In the research, a reset ratio was set constant but the method to calculate the reset ratio was not described specifically.
Liao et al compared the energy consumption and control performance of the heating system with different heating curves. It was pointed out that the performance declines significantly if a heating curve is not determined properly [5]. The method of determining a heating curve, however, was not explained definitely. Zhang argued that outdoor reset control requires a good relation between zone load, outdoor temperature and supply water temperature. And it was emphasized that the absence of accurate knowledge of such a relation could result in either overcorrection or poor control [6].

In most residential buildings, however, a heating curve is determined by an operator's experience or time-consuming trial and error procedure. This makes supply water temperature determined incorrectly, with heating load, thermal characteristics of a building and heat flow from the radiant heating floor ignored.

The objective of this study is to derive a method to determine a heating curve which considers heating load of the building and heat flow from radiant heating floor. The result of this study could help to determine optimum supply water temperature for the enhancement of indoor thermal environment.

FACTORS OF A HEATING CURVE

Heating load is the first factor to influence the heating curve of a building. As it is general that the building is under steady-state when heating system is operated continuously, heating load can be expressed as follow:

$$Q_{load} = \sum_{exterior} U_i A_i (T_{set} - T_{out}) + \sum_{interior} U_j A_j (T_{set} - T_{ad,j}) + V_{air} (T_{set} - T_{out}) \quad \text{(W)}, \qquad (1)$$

where first two terms in the right side of the equation are heat loss through exterior walls and interior walls respectively. And the last term is heat loss by infiltration or ventilation. Solar gains and internal heat sources were not included so that the gains could act as a safety factor.

The second factor of a heating curve is heat flow from the radiant heating floor. Heat flow is determined by various parameters of floor structure such as pipe spacing, thermal conductivity and thickness of the screed, thermal resistance of surface covering and so on. According to EN 1264, heat flow between embedded pipes and the space is calculated by the general equation as follows [7]:

$$Q_{panel} = A_f B \prod_i (a_i^{m_i}) \Delta\theta_H \quad \text{(W)}, \qquad (2)$$

where A_f is an area of heating surface, and B is a system coefficient dependent on system type and the heat exchange coefficient (for floor heating, B=6.5W/m^{2}K). $\prod_i (a_i^{m_i})$ is the power product which links the parameters of the floor structure (surface covering, pipe spacing, pipe diameter and pipe covering) . $\Delta\theta_H$ is heating medium differential temperature determined by following equation.

$$\Delta\theta_H = \frac{T_{sup} - T_{ret}}{\ln \frac{T_{sup} - T_{set}}{T_{ret} - T_{set}}} \quad \text{(K)}, \qquad (3)$$

where T_{set}, T_{sup} and T_{ret} are room air temperature, supply water temperature and return water temperature, respectively.
In other words, heat flow from the radiant heating floor is proportional to $\Delta\theta_H$ and $B\prod_i (a_i^{m_i})$ can be considered as a heat transfer coefficient for the surface of a radiant heating floor. Figure 1. shows the factors influencing the heating curve of a building.

DERIVATION OF A HEATING CURVE

If a building is maintained steady-state with continuous heating, heat output from the floor is equivalent to heating load. And if downward heat flow is restricted with insulation and the lower space is heated, as in a multi-family house, heat output from the floor is also equivalent to heat discharged by hot water in the embedded pipe, which is calculated as follows:

$$Q_{water} = m_w \cdot c_{p,w} \cdot (T_{sup} - T_{ret}) = m_w \cdot c_{p,w} \cdot \Delta T \quad \text{(W)}, \qquad (4)$$

where m_w is a mass flow rate of hot water (kg/s), $c_{p,w}$ is a specific heat capacity of hot water (J/kgK), ΔT is a temperature drop of hot water (K).
Combining equation (2), (3) and (4), supply water temperature T_{sup} can be calculated as

$$T_{sup} = T_{set} + \alpha \Delta T \quad \text{(K)}, \qquad (5)$$

where α is a coefficient dependent on the geometry and thermal property of the radiant floor, expressed as following equation.

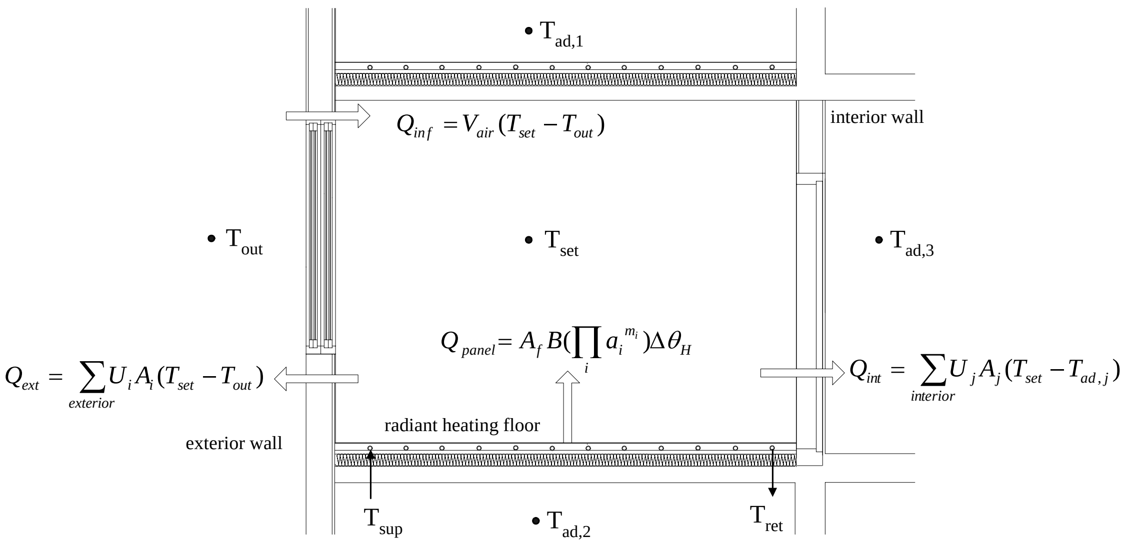


Figure 1. The factors related with the heating curve of a building

$$\alpha = \frac{1}{1 - \exp\left(- \frac{A_f B \prod_i (a_i^{m_i})}{m_w \cdot c_{p,w}} \right)} \qquad (6)$$

On the other hand, ΔT in equation (5) can be obtained by combining equation (1) and (4). Thus ΔT can be replaced with following equation (7).

$$\Delta T = \frac{(\sum_{exterior} U_i A_i + V_{air})(T_{set} - T_{out}) + \sum_{interior} U_j A_j (T_{set} - T_{ad,j})}{m_w \cdot c_{p,w}} \text{(K)} \qquad (7)$$

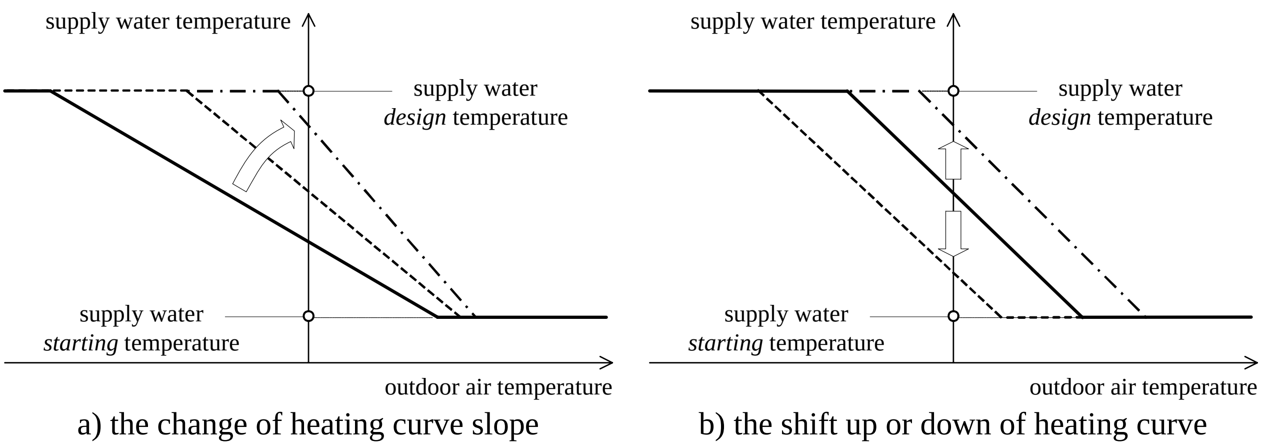
Putting equation (7) into equation (5) and arranging the equation with regard to T_{out} gives a final result, that is, a heating curve expressed as a linear function of outdoor air temperature.

$$T_{sup} = -\left(\frac{\alpha(\sum_{exterior} U_i A_i + V_{air})}{m_w c_{p,w}} \right) T_{out} + \left(1 + \frac{\alpha(\sum_{all} U_i A_i + V_{air})}{m_w c_{p,w}} \right) T_{set} - \frac{\alpha}{m_w c_{p,w}} \sum_{interior} U_j A_j T_{ad,j} \quad (8)$$

According to equation (8), the slope of heating curve gets steeper as the heat loss of a building becomes larger as described in Figure 2. a). On the other hand, the change of set temperature and adjacent room temperature tends to shift up or down without changing the slope of the heating curve, as illustrated in Figure 2. b).

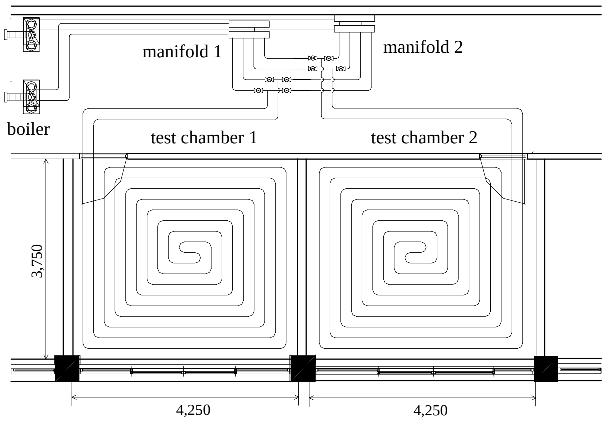
EVALUATION OF THE DERIVED HEATING CURVE

In order to examine whether the derived heating curve can assure optimum supply water temperature, a simulation and a mock-up experiment were conducted. The analyzed building, located in the vicinity of Seoul, Korea, consists of two test chambers equipped with radiant floor heating system as illustrated in Figure 3. A radiant floor structure conforms to Type A in EN 1264, which has pipes inside the screed.

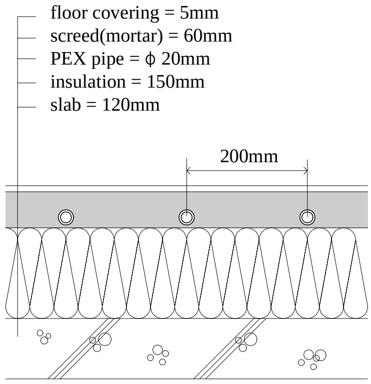


a) the change of heating curve slope b) the shift up or down of heating curve

Figure 2. The characteristics of a heating curve



a) The plan of test chambers



b) floor structure

Figure 3. Test chambers for the mock-up experiments

Simulation Analysis

Based on the thermal properties and design condition of the chambers, heating curve was estimated as T_{sup} = -0.887T_{out}+43. In order to analyze the performance of the chamber with the estimated heating curve, a TRNSYS type which can modulate supply water temperature according to a heating curve was developed. The type receives an outdoor air temperature, calculates water temperature with the heating curve and transfers water temperature to the active layers of the analyzed thermal zone. But it does not receive the feedback from the room because outdoor temperature reset control is basically open-loop control algorithm.

The simulation was performed for the whole winter season using standard weather data of Seoul. The effect of internal heat sources was not taken account into the simulation. Figure 4 and Figure 5 describe the simulation result for the whole season and coldest 3 days, respectively. Although the heating system did not receive a feedback from the room, room air temperature was kept at set temperature, 23℃, by just modulating supply water temperature according to outdoor air temperature. Figure 5 shows the performance of the heating system more clearly. Room air temperature is maintained stable without much fluctuation, as in a conventional on/off control heating system. Thus it can be said that the derived heating curve can assure the optimum supply water temperature to keep the heated space comfortable.

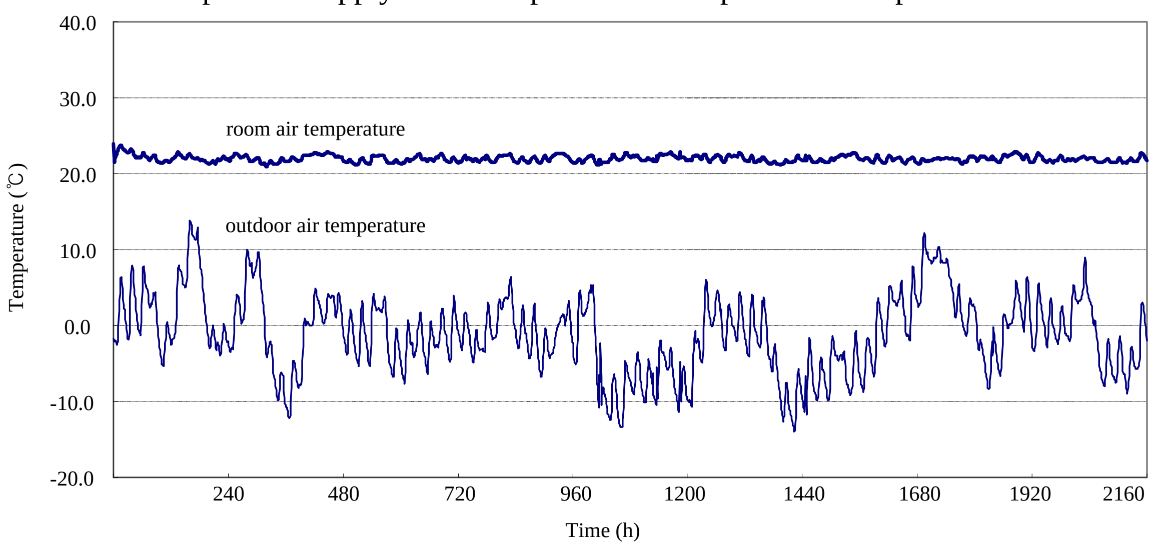


Figure 4. Simulation result for the whole winter season

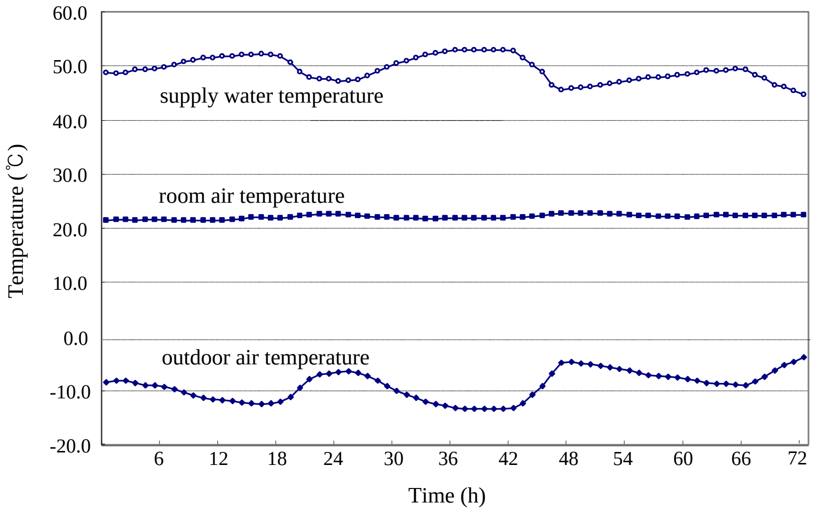


Figure 5. Simulation result for the coldest 3 days

Mock-up Experiment

For the purpose of more accurate evaluation, a mock-up experiment was performed. The derived heating curve was applied to the aforementioned test chambers. The chamber, water distribution system and control instruments used in the experiment are presented in Figure 6. As it is the main purpose to analyze the relation between outdoor air temperature and supply water temperature, a sun shade device was installed on the windows of a chamber.

a) a test chamber b) gas-fired boiler c) distribution system d) control devices

Figure 6. Equipments for the mock-up experiments

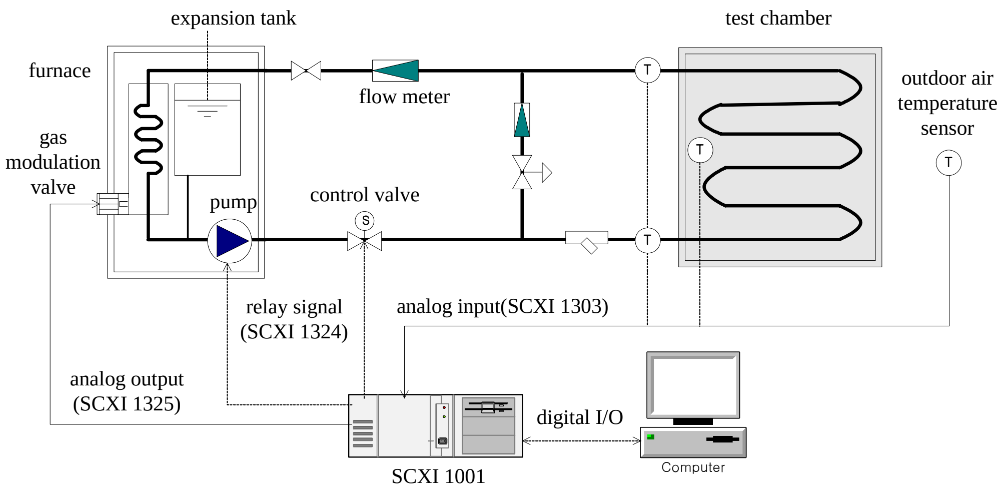


Figure 7. The schematic diagram of the instruments

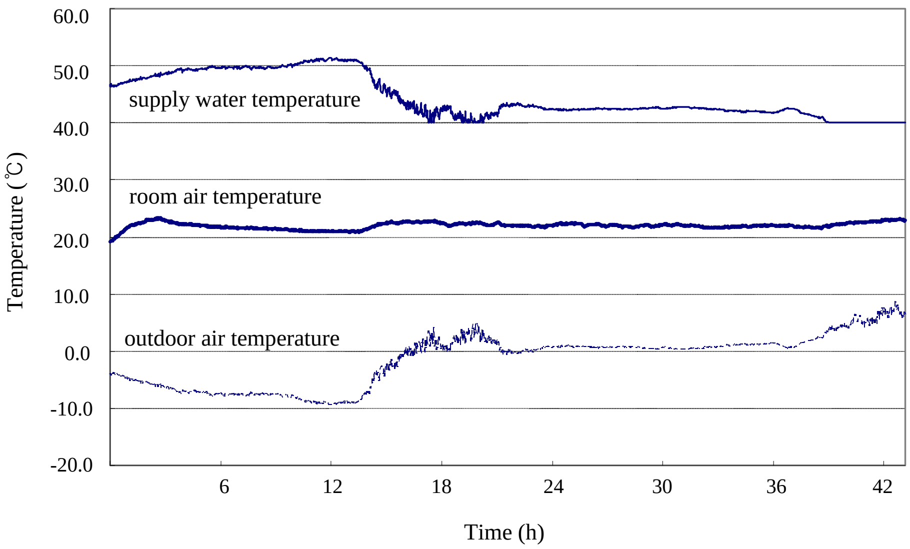


Figure 8. The result of a mock-up experiment

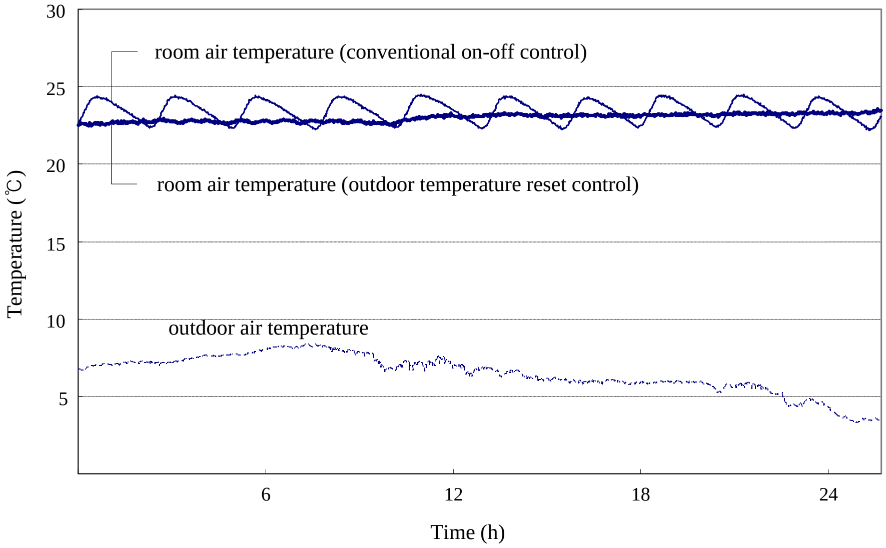


Figure 9. The comparison with a conventional on-off control

To modulate the supply water temperature, the firing rate of a gas-fired boiler was proportionally modulated with the analog input and output devices (NI SCXI-1001). Figure 7 describes the schematic of the equipments for the mock-up experiment. Supply water temperature was calculated by a heating curve, but maximum and minimum temperature were constrained to 80℃and 40℃ respectively for the purpose of preventing an overheating or flue gas condensation in a boiler.

Figure 8 shows the results of the experiment to examine whether the derived heating curve results in a good control of room air temperature. With the modulation of supply water temperature, room air temperature was maintained at averagely 23.1℃, with slight difference with set temperature, 23℃. Moreover, overshoot and/or undershoot, which occur frequently in conventional on/off control, were not observed in the experiment as shown in Figure 9. In conclusion, the derived heating curve can assure the optimum supply water temperature which can supply heat at the same rate at which the building loses heat.

CONCLUSIONS

In this study, a method to determine heating curve of a radiant heating system was proposed and evaluated. The heating curve could be expressed as a linear function of outdoor air temperature. It was also found that the slope of a heating curve varies with the heat loss of exterior walls and air change rate of the room. And set temperature of the room and adjacent room temperature would shift up or down of a heating curve.

The results of a simulation and a mock-up experiment show that the derived heating curve yields an optimum supply water temperature enough to keep the room stable and comfortable. The room air temperature was maintained closely at designed set temperature, without any feedback from the room. It can be said that the modulation of water temperature according to the derived heating curve provides as much heat as the building loses.

This study, however, assumes no solar gain and internal heat source. Those gains might result in slight increase of the room air temperature because they provide additional heat to the room. Thus it is proper to use outdoor reset control in combination with an auxiliary control to prevent additional heat supply. Outdoor temperature reset plus on-off control can be a good alternative. In addition, this study assumes that the heating system operates continuously and the room is under steady-state. Thus a heating curve should be modified so that it can cope with the dynamic condition such as an initial boost-up operation, a recovery from deep setback and so on.

Despite of those limitations, this study can be said to be significant because it provides a basic strategy to determine optimum supply water temperature, which considers heating load and the floor structure of a building. The results can be applied to the outdoor reset control algorithm of a heat exchanger or a boiler for a radiant heating system.

ACKNOWLEDGEMENT

This research (03 R&D C103A1040001-03A0204-00310) was financially supported by the Ministry of Construction & Transportation of South Korea and the Korea Institute of Construction and Transportation Technology Evaluation and Planning, and the authors wish to thank the these governmental organizations for their support in this work.

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