Predictive Control of the Radiant Floor Heating System in Apartment Buildings

Jin-Young Lee¹, Myoung-Souk Yeo² and Kwang-Woo Kim ³

¹Research Engineer, Hanil Mechanical & Electrical Consultants
173, Hangang-ro 2-ga, Yongsan-gu, Seoul, 140-012, Korea (jinyoung.lee@himec.co.kr)

²Assistant Professor, Dept. of Architecture, School of Architecture, Landscape Architecture and Civil Eng., Sungkyunkwan University, 300, Chunchun-dong, Jangan-gu, Suwon, Kyunggi-do, 440-746, Korea (msyeo@yurim.skku.ac.kr)

³Professor, Department of Architecture, College of Engineering, Seoul National University (snukkw@snu.ac.kr)

Abstract

The objective of this study is to improve the control performance of the radiant floor heating system in apartment buildings. For this, predictive control, which is simple and also compatible with the existing system, is suggested, and its performance is evaluated. The control system of radiant floor heating should be easily adapted to thermal mass characteristics and building load variations without complication in real application. In this study, predictive control using the ANN (Artificial Neural Network) model is proposed and the possibility of this predictive control is investigated through experimental research. The results show that the performance of this predictive control is better than that of the current 2-position on/off control. Through the dynamic simulation analysis of the thermal mass model using a computer for the multi zones of a real apartment building, the adaptability of the predictive control to several load variations and thermal characteristics is evaluated.

Keywords: Radiant floor heating; Predictive control; Artificial Neural Network; Apartment buildings

1. Introduction

The radiant floor heating system is a domestic heating method that has been used in the majority of houses in Korea. In particular, this system is adopted in all of the current apartment buildings, which is the prevailing housing style to satisfy the demand for new housing in cities with high population density. Owing to the remarkable progress in construction and engineering techniques, the current radiant floor heating system is applied with the use of hot water running through embedded tubes to heat the floor and a boiler as a heat producing equipment.

Two types of heating production and supply systems are generally used in the current radiant floor heating of apartment buildings. One is the central heating system that supplies hot water from a central boiler or a district heating plant covering multiple blocks of apartment buildings. The other is the individual heating system using a gas-fired boiler for each housing unit.

Some years ago, the only control method of these two heating systems for zone control, was intermittent heating control by the firing boiler or closing/opening the manually operated zone valve. However, it was recognized that due to the high pick-up load when initiating boilers in the early morning, intermittent heating control demands large system capacity, and consequently the room temperature variation range is so wide that it causes thermal discomfort between the periods with and without heat supply.

The next alternative control method was 2-position on/off control. While intermittent heating control is the method in which hot water of a fixed flow rate and temperature is supplied intermittently according to a prescheduled time schedule, 2-position on/off control is one where hot water of a constant flow rate is supplied using on/off acting valves or boiler on/off controllers according to each zone’s set temperature. However, this basic 2-position on/off control also yields thermal discomfort and energy waste problems of over-heating and under-heating caused by the time lag, because most of the apartment buildings in Korea are constructed of high thermal mass concrete.

The continuous control (outdoor reset with indoor temperature feedback control) of the supply water temperature reset proposed as an alternative method is good for maintaining room temperature, but the complicated system with mixing valves that require more installation space and high initial cost, prevents it from being used as a control method for domestic housing. In the case of an apartment building with numerous multi zones to control, the economical demerit is increased.

In order to prevent over-heating, it is considered...
that the control method should be able to determine the proper on/off position in advance to keep the room temperature within the set temperature range. Also, to reduce the extra cost, piping and equipment should not be complicated compared to those of the current system. So, a simple system is needed which can be used with the existing systems and which is also applicable to the central heating system with multi zones.

In this study, a predictive control that determines the proper hot water supply on/off time by learning the thermal characteristics of a room is proposed considering the thermal characteristics of apartment buildings and the availability of control parameters. In the learning process, the Artificial Neural Network (ANN) model is used. To evaluate the applicability of the proposed control method, model experiments are performed. Through the dynamic simulation analysis of the thermal mass model using a computer, the adaptability of the predictive control to several load variations and thermal characteristics are also evaluated.

2. Concept of predictive control

2.1 Radiant heating and its control parameters

In order to obtain a desirable solution using the ANN, proper input and output parameters should be chosen. In the case of radiant heating, the control parameters can generally be split into three components: the manipulated variable, the input variable and the controlled variable. The input variable is a measured value needed to output target values. The controlled variable is a set value to keep the controlled room comfortable. The manipulated variable is the quantity or condition regulated by the control system to keep controlled variables within a set value range.

For the predictive control of radiant heating, the room temperature is selected as a controlled variable, as in the current 2-position on/off control. Other variables (floor surface temperature, supply water temperature, MRT, heat flux, etc.) are difficult to measure, require expensive equipment, or are unavailable for central heating systems.

In general, the factors affecting room temperature are as follows: convection and radiation at each surrounding surface, internal heat generations, and infiltration.

Inner surface temperature is primarily affected by outdoor temperature through the wall layers. Making allowance for the time lag, variations in temperature for a period of time should also be considered. Thermal characteristics of constructed materials are the factors that can be learned by the ANN. In conclusion, room temperature, outdoor temperature, variation in room temperature and variation in outdoor temperature with time are selected as input variables for the network model.

Manipulated variables are to prevent over-heating.

To prevent over-heating and to keep the room temperature within its set temperature range, the on/off action should be performed before the room temperature reaches one of the two limits of the differential. So, the neural network used in this study is constructed to predict the peak value of room temperature increase when the valve is open (on position) and the peak value of room temperature decrease when the valve is closed (off position). Accordingly, the control algorithm is made to change the position of the control valve if the predicted value reaches the differential limits. Fig. 1 shows the concept of predictive control compared to the current 2-position on/off control.

Two network models are constructed for the on and off terms. Figure 2 shows the ANN models constructed with their selected input and output variables.
program using this algorithm is implemented (see Fig. 3). In this study, an ANN emulator module is coded using the back-propagation method (Rumelhart and McClelland 1986). The control system is based on 2-position on/off control to make the system simple.

In this study, an ANN emulator module is coded using the back-propagation method (Rumelhart and McClelland 1986). The control system is based on 2-position on/off control to make the system simple.

3. Experiment for predictive control

3.1 Experimental setup and conditions

As basic research for the predictive control of the radiant floor heating system, the suggested control method is verified through experiments.

With two identical test chambers each having one external wall facing south, the performance of predictive control (A model) and 2-position on/off control (B model) are evaluated under the same conditions. Two constant temperature baths are used to supply water of a constant temperature to each test chamber (see Fig. 4). Pumps and the solenoid valve’s on/off action operated by the control apparatus circulate hot water. The control apparatus is composed of analogue input/output modules, solid-state relays and a PC with the control program (see Fig. 5).

The setpoint and its differential for the room temperature are fixed at 21°C±1.0°C for both models. The supply water temperature and flow rate are 50°C and 6lpm, which are derived from the heating load of test chambers and the capacity of the constant temperature bath. Measurement items and their locations are shown in Table 1.

3.2 Experimental method

First, to obtain the training data set for the initialized ANN, the A model is heated with the current 2-position on/off control for five days. Then, the

Table 1. Measurement items and their locations

| Measurement items                  | Measurement locations                                      |
|------------------------------------|-----------------------------------------------------------|
| Room temperature                   | The point 1.5m high from the floor surface                 |
| Floor surface temperature          | 4 points (Over pipe), 4 points (Over 1/2 pitch), 4 points (Over 1/4 pitch) |
| Supply/return water temperature    | In the supply/return pipe to/from the radiant floor panel  |
| Outdoor temperature                | Northern outdoor area                                      |

Fig. 4. Plan of the thermal test chamber (unit:mm)

Fig. 5. Control apparatus
obtained data is trained to the ANN. All training data used in the experiments are normalized to the range of 0 to 1 for some specific data so as not to govern the whole of the ANN training process. Using this early-trained ANN, one chamber (A model) is heated with predictive control and the other chamber (B model) is heated with 2-position on/off control at the same time.

3.3 Analysis of experiment

Fig. 6 shows the room temperature variations with outdoor temperature during the experimental period. As shown in Fig. 6, the room temperature of model A to which predictive control is adopted, is maintained within the differential, although the outdoor temperature varies over a wide temperature range of -3.3°C~15.5°C. Meanwhile, the over-heating condition occurs by 0.5°C~1°C in model B with the current 2-position on/off control.

Table 2 shows the errors between the peak values of the measured room temperature and the limits of the differential at each heating cycle (a heating cycle is the cycle from the first on to the next off position, and vice versa). A comparison of these errors for the cases of predictive control and the 2-position on/off control is expressed in Table 2.

Fig. 7 shows the heating status and the floor surface temperature variations of each chamber. The maximum floor surface temperature is 28.1°C in model A with predictive control and 29.3°C in model B with 2-position on/off control, and the minimum is 21.9°C in model A and 21.7°C in model B. From this result, it is known that the temperature range of the floor surface in model A is less than that in model B. As shown in table 3, the total heating time during the experimental period is less in model A than that in model B. Also, from Fig. 6 and Table 3, the results show that unnecessary heat is supplied to model B.

From the experimental results, it can be concluded that the predictive control effectively learns the thermal characteristics of a radiant floor heating space.

| Errors of low limit | Errors of high limit |
|---------------------|---------------------|
| Model A | Model B | Model A | Model B |
| -0.12 | -0.2 | 0.16 | 0.94 |
| 0.3 | -0.07 | -0.04 | 1.08 |
| -0.07 | -0.11 | -0.04 | 0.96 |
| -0.03 | -0.17 | 0.01 | 0.67 |
| -0.08 | -0.09 | 0.03 | 0.92 |
| 0.03 | -0.13 | -0.03 | 0.59 |
| 0.06 | - | 0.15 | - |
| -0.12 | - | -0.03 | - |
| 0.07 | - | -0.14 | - |

Table 3. Total heating time during the experimental period

| Control method | Total heating time |
|----------------|-------------------|
| Predictive control (Model A) | 806 min |
| 2-position on/off control (Model B) | 931 min |

This control also determines the proper on/off time of the hot water supply using the ANN.

The performance of the predictive control proposed in this study is better than that of the current 2-position on/off control in terms of maintenance of room temperature and energy consumption. So, in an actual application, it may be possible for the predictive control to be easily applied to existing electronic thermostats as the current 2-position on/off control.

4. Simulation with an apartment house model

4.1 Simulation program

The computer simulation is aimed at checking the applicability to real scale apartment houses and the adaptability to apartments with multi zones, while the purpose of the experiment is to find the adaptability to real thermal mass characteristics and the system lag for a single-zone (space). To determine whether or not,
the ANN can be adapted to real scale apartment houses, dynamic thermal analysis is performed. For the accuracy of the results, an unsteady heat balance analysis model using the finite difference method (Park, S.S. et al., 1993 and Yeo, M.S. et al., 1999) is adopted to calculate the temperatures of all of the nodes in the wall layer.

The effectiveness-NTU (Number of Transfer Units) method (M. Udagawa, 1993) is adopted to calculate the heat flow from the floor panel. For indoor spaces, radiant heat transfer as well as convection heat transfer is calculated. The surface heat transfer coefficients are calculated according to the heat flow’s directions from all surfaces (Yeo, M.S. and Kim, K.W., 1997). The whole structure of the heat balance analysis model is shown in Fig. 8. From the experiment, the set data for training can be obtained. Based on the obtained set data of the experiment, the simulation program starts the training of the initialized network.

4.2 Simulation considerations

The unit rooms of an apartment building in Korea are selected as the simulation model. To compare the performance of predictive control with 2-position on/off control under identical conditions, three rooms are selected, facing north with little effects of direct solar radiation and located in the mid-floor of the building. These three rooms (room A and room C for the bedroom, and room B for the kitchen) are different in their dimensions and openings. Under the same external and internal load conditions, predictive control and 2-position on/off control are simulated using a week's weather data of Seoul. Before this, the current 2-position on/off control is simulated for pre-training of the ANN using another week’s weather data.

The simulation conditions are determined from the actual operating conditions of Korean apartment buildings. The setpoint and its differential of the room temperature are fixed at 21°C±1.0 for the three rooms of the two control methods. The supply water temperature and flow rate are 60°C and 3lpm, which are derived from the design calculation sheet of the model apartment house.

4.3 Results of simulation

Room temperature variations with predictive control and with 2-position on/off control of the three selected rooms are shown in Figs. 9, 10 and 11. With the 2-position on/off control, the over-heating after the off points occurred irregularly by 0.2°C~0.7°C, but with the proposed predictive control, the room temperature of each room is kept within the differential range.

Fig. 8. Structure of the heat balance analysis model
Fig. 9. Simulation Result: Comparison of Room Temperature (Room A)

Fig. 10. Simulation Result: Comparison of Room Temperature (Room B)

Fig. 11. Simulation Result: Comparison of Room Temperature (Room C)
Room B (used for the kitchen) is open to the living room facing south. So, the effects of solar radiation on the living room are partially expressed.

Although the three rooms are different in their physical characteristics, the ANN used in this simulation is adapted to each room.

Table 4. Total heat supply during winter time (from Nov. to Feb.)

| Control method                | Total heat supply |
|-------------------------------|-------------------|
| Predictive control (Room A)  | 2,035,594 kWh     |
| 2-position on/off control (Room B) | 1,944,375 kWh |

To compare the total energy consumption during the entire winter period with a room facing north (Room A), the total heating energy supply is calculated. As shown in Table 4, the total heat supply from November to February is less in model A than in model B.

The ANN model is trained in real time. With more training, better performance will be expressed in its solutions. Therefore, as the ANN will have more time for training in real applications, the room temperature will be more precisely kept. Also, the operator does not need to adjust control parameters even if other design conditions such as external load, internal load, floor material, etc., are changed.

5. Experiment for revised predictive control

Beside indoor and outdoor temperature, there are some factors that affect the building load conditions such as solar radiance and internal heat sources. Under heating conditions, these factors are not considered, but in the case of predicted control with the ANN, if these factors affect the room temperature variation patterns and it is taught to the ANN, the ANN’s performance may become poor. Therefore, the ANN should not be trained based on such data when solar radiance or internal heat gain is induced and the room temperature is unusually increased.

To make this action real, if the room temperature is increased over a specific threshold temperature, the ANN must not be allowed to learn such data, but if this specific threshold temperature is set too low, the ANN may lose several training opportunities that do reflect real circumstances.

From the results of the former experiment, the minimum degree of over-heating was 0.6°C in model B with the current 2-position on/off control. Therefore, the control algorithm is revised so that the ANN does not learn when the overheating exceeds 0.6°C. Of course, this specific threshold temperature is determined with empirical methods and should be reconsidered in real applications.

To evaluate the modified ANN’s performance, experiments are conducted with two identical test chambers (predictive control (model A) and 2-position on/off control (model B)) under the same conditions and allowing solar radiation to be induced through windows.

Fig. 12 shows the room temperature variations with outdoor temperature during the experimental period. In the daytime, it shows that solar radiation affects the room temperature variation, but in the night-time, the room temperature of model A, to which modified predictive control is adopted, is maintained within the differential. Meanwhile, the over-heating condition occurs by 0.7°C~1°C in model B with the current 2-position on/off control.

6. Conclusions

For the best performance of the current radiant panel heating method in Korea, a predictive control using the ANN is suggested. To evaluate the performance of the presented predictive control, the experiments are performed to check the adaptability to real thermal mass characteristics, system lag, and solar radiations. The computer simulation is continuously run to verify the applicability to real scale apartment houses and the adaptability to apartments with multi-zones. The results of this study are summarized as follows.

1) Considering the thermal characteristics of buildings and the availability of control parameters, room temperature, outdoor temperature, room temperature variation rate, and outdoor temperature variation rate are selected as input parameters for predictive control. The control algorithm is based on 2-position on/off control to make the system simple.

2) The experimental results show that the performance of the proposed predictive control is better than that of the current 2-position on/off control in terms of maintenance of room set temperature and energy consumption.
3) The dynamic analysis using a computer shows that the neural network used in predictive control is adapted to each zone (room) of apartment building whose load variation and thermal characteristics are different from the others.

4) The modified ANN considering solar radiation is proven to maintain the prediction performance with regard to room temperature variations.

5) The evaluation of the experiments and the computer simulation prove that this predictive control system of radiant floor heating is simple in real application and can easily be adapted to building load variations and different thermal mass characteristics.

This simple predictive control system can utilize existing control system equipment (on/off valves and electronic controller) so that no more initial cost will be added than the existing on/off 2-position control system. Also, there will be no need to adjust the control parameters in minor changes of the space condition, because the ANN has automatic adaptability in real time.

References
1) ASHRAE (1997), ASHRAE Handbook: Fundamentals, ASHRAE.
2) ASHRAE (1992), ASHRAE Standard 55-1992: Thermal Environmental Conditions for Human Occupancy, ASHRAE.
3) Brown, Martin, Harris Chris (1994), Neurofuzzy Adaptive Modeling and Control, Prentice Hall.
4) Curtiss, Peter S., Gideon Shavit, Jan F. Kreider (1996), Neural Networks Applied to Buildings-A Tutorial and Case Studies in Prediction and Adaptive Control, ASHRAE Transactions, Vol. 102, No. 1, 1996, pp. 1141-1146.
5) Fausett, Laurene V. (1994), Fundamentals of Neural Networks: architectures, algorithms, and applications, Prentice Hall, New Jersey.
6) Haines, Roger W. (1987), Control System for Heating, Ventilating and Air Conditioning, 4th ed., Van Nostrand Reinhold, New York.
7) Incropera, Frank P., David P. Dewitt (1996), Introduction to Heat Transfer, 3rd ed., John Wiley & Sons, New York.
8) Kawashima, Minoru, Charles E. Dorgan, John W. Mitchell (1995), Hourly Thermal Load Prediction for the Next 24 Hours by ARIMA, EWMA, LR, and an Artificial Neural Network, ASHRAE Transactions, Vol. 101, No. 1, pp. 186-200.
9) Kreider, J. F., D. E. Claridge, P. Curtiss, R. Dodier, J. S. Haberl, and M. Krarti (1995), Building Energy Use Prediction and System Identification Using Recurrent Neural Network, Transactions of ASME: Journal of Solar Energy Engineering, Vol. 117, No. 3, pp. 161-166.
10) Larkin, D. J. (1988), Engineering Manual of Automatic Control, Honeywell, Minnesota.
11) M. Udagwa (1993), Simulation of Panel Cooling Systems with Linear Subsystem Model, ASHRAE Transactions DE93-3-2.
12) MacCleave, C. R., M. Milkavcic, Y. Chait (1989), The Temperature Stability of a Radiant Slab-on-grade*, ASHRAE Transactions, Vol. 95, No. 1, pp. 1001-1009.
13) Park, S.S. and Yeo, M.S. and Kim, K.W. (1993), A Study on the Development of the Thermal Environment Prediction Method for the Hot Water Ondol Heated Space, Proceedings of the AIK (Architectural Institute of Korea) Spring annual conference, 13 (2), pp. 301-306.
14) Rumelhart, D.E., J.L. McClelland (1986), Parallel Distributed Processing: Explorations in the Microstructure of Cognition, Vol. 1, MIT Press, Cambridge.
15) Schalkoff, Robert J. (1997), Artificial Neural Networks, McGraw-Hill, New York.
16) Tekmar (1992), Tekmar-Essay, E001.
17) Yeo, M.S. and Kim, K.W. (1999), A Study on the Control Methods of Hydronic Radiant Floor Heating System in Apartment Buildings, Journal of the AIK(Architectural Institute of Korea), 15 (3), pp. 119-127.
18) Yeo, M.S and Kim, K.W. (1997), A Study on the Thermal Performance Simulation to Evaluate the Prefabricated Radiant Floor Heating Panels, Proceedings of the 5th International IBPSA Conference, Vol. 2, pp. 103-110.