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Energy Conversion and Management 44 (2003) 1333–1342

ENERGY CONVERSION & MANAGEMENT

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Predictive control of intermittently operated radiant floor heating systems

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Received 14 January 2002; accepted 18 May 2002

Abstract

A predictive control strategy as a means of improving the energy efficiency of intermittently heated radiant floor heating systems is explored. Both computer simulations and experiments are conducted to assess and compare the energy performance of the predictive control strategy with an existing conventional control strategy. The results show that use of the predictive control strategy could save between 10% and 12% energy during the cold winter months. The energy savings are somewhat higher during mild weather conditions.

Keywords: Space heating; Radiant floor heating systems; Predictive control; Energy efficiency

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1. Introduction

In general, the continuous mode of room temperature regulation is the most common method of operation of radiant floor heating (RFH) systems. In the continuous mode, the heat flux delivered by the floor slab is regulated to maintain the room temperature within chosen limits, as in on–off control or close to a setpoint as in proportional plus integral (PI) control. Several authors have studied the operation, control and comfort issues of continuously operated RFH systems [1–5]. For example, McCluer [3] investigated the RFH system performance using a proportional flux modulation strategy. Outdoor air temperature as a variable in resetting the hot water temperature

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PII: S0196-8904(02)00116-4

is found to be an effective control technique by Ref. [3]. A two parameter on–off control [6] strategy is shown to be effective in improving the room temperature regulation properties of RFH systems. The common denominator in these control strategies is the continuous mode of operation of the boiler and the radiant floor control loop using either PI control or on–off control.

While the continuous control strategies are expected to give better room temperature regulation, it is known that room air temperature based on–off control and/or poorly tuned PI controls could give rise to large fluctuations in the room air temperature, causing thermally uncomfortable conditions in houses heated with RFH systems. As opposed to the continuous mode of control, the notion of operating the RFH systems intermittently only at a certain number of prescribed hours during the day is very appealing. It is known that the intermittent control strategy can be designed to utilize effectively the thermal storage characteristics of the floor slab and the building, thereby improving the energy efficiency in buildings. For these reasons, an intermittent control strategy is widely used in multiple unit apartment buildings in Korea. In the intermittent mode of operation, the RFH system practically runs in an open loop mode. In other words, no feedback control, either PI or on–off, is used at the zone level. Since heat is supplied to the floor slab at some prescribed hours during the day, the intermittent control strategy eliminates the cost of the thermostat and the associated control hardware.

2. The conventional control strategy

The current practice of intermittent heating is based on past operating experience. For example, when the forecast daily outdoor temperature is between −5 and 0 °C, then as recommended in Table 1, the heat is supplied to the floor slab three times a day during the hours between 03:00 and 05:30; 10:00 and 11:30; and 17:30 and 20:00 for a total of 6.5 h/day. As the outdoor temperature becomes warmer, the number of heat supply cycles, as well as the total length of heat supply time, decreases and vice versa, as shown in Table 1. It can also be noted that a small change in outdoor temperature from the range defined in Table 1 could lead to a significant increase or decrease in the heat supply hours. For example, if the outdoor air temperature is forecast to be −5.1 °C, then the recommended heat supply hours (Table 1) could increase from 6.5 to 8.0 h. This strategy, which is currently practiced in many buildings, is generally well received. However, it is

Table 1
Heating schedule according to outdoor air temperature

Minimum outdoor air temperature	Operating time	Total (h)
$T \leqslant -10$ °C	3:00–7:00, 10:00–12:00, 17:30–21:30	10.0
$-10 < T \leqslant -5$ °C	3:00–6:00, 10:00–12:00, 17:30–20:30	8.0
$-5 < T \leqslant 0$ °C	3:00–5:30, 10:00–11:30, 17:30–20:00	6.5
$0 < T \leqslant 5$ °C	3:00–5:30, 17:30–20:00	5.0
$5 < T \leqslant 10$ °C	3:00–5:00, 17:30–19:00	3.5
$10 < T \leqslant 15$ °C	3:00–5:00	2.0
$T > 15$ °C	–	–

found to be more on the conservative side in its recommendations on the total number of heat supply hours. Consequently, it leads to higher energy consumption. In order to improve the existing intermittent control technique, a predictive control strategy is proposed here, which is expected to yield the optimal number of heating hours per day. As such, significant energy savings are expected without compromising on thermal regulation compared to the conventional scheme.

Thus, in the predictive control scheme, as in the conventional control strategy, there is no zone thermostat to regulate the zone temperature. However, by choosing the optimal length of heating hours, both energy efficiency and temperature regulation can be improved. Therefore, in this study, we propose to compare the performance of the predictive control strategy with an existing conventional control scheme using both computer simulations and measurements made in an experimental test facility.

3. The predictive control strategy

In order to implement the predictive control strategy, a forecast of outdoor air temperature must be available. Lacking this, a forecasting model must be used. To this end, a model based on the Fourier series method given in Ref. [7] is adapted in this study.

3.1. Prediction of outdoor air temperature

The following model equations can be used to predict hour-by-hour values of outdoor air temperatures. The inputs to the model are the expected maximum (T_h) and minimum (T_l) temperatures and their time-of-day occurrence (t_h, t_l) respectively.

$t \leqslant t_l$

$$T = T_v - T_d \cos\left[\left(\frac{\pi}{24-(t_h-t_l)}\right)(t-t_l)\right] \tag{1}$$

$t_l < t \leqslant t_h$

$$T = T_v - T_d \cos\left[\left(\frac{\pi}{(t_h-t_l)}\right)(t-t_l)\right] \tag{2}$$

$t_h \leqslant t$

$$T = T_v - T_d \cos\left[\left(\frac{\pi}{24-(t_h-t_l)}\right)(t-t_h)\right] \tag{3}$$

where

$$T_d = (T_h - T_l)/2$$

and

$$T_v = (T_h + T_l)/2$$

3.2. Predictive control methodology

In the predictive control strategy for heating, there are two important variables that one must determine. First, the total length of time in hours per day that the heat must be supplied and, second, determine how these heating hours have to be distributed over the day. In other words, one could choose a small number of relatively long on-time heat supply hours or vice versa. Of course, the sum of all heat supply on-times per day should not exceed the predicted length of heat supply hours per day. Obviously, there could be several heat distribution cycles that could be deemed as acceptable solutions. In the conventional control method (Table 1), the number of on-cycles per day as chosen based on operating experience, and it is generally agreed that the number of cycles as proposed in Table 1 and their prescribed start or stop times give acceptable temperature conditions in buildings. However, one area where the conventional control scheme needs improvement is in determining the length of on-time for each cycle. This is where we believe the predictive control strategy offers an optimal solution. The predictive control technique consists of the following four steps:

1. From the forecast of daily high and low temperatures obtained from the meteorological services, predict the hour-by-hour magnitudes of the outdoor temperatures using Eqs. (1)–(3).
2. Estimate the rate of boiler heat output from

   $$q_{\text{boiler}} = \eta \times \text{Capacity} \tag{4}$$

   $$\text{Capacity} = mC_p(T_{\max} - T_{\min})$$

   where $T_{\max}$ and $T_{\min}$ are the maximum and minimum boiler water temperatures.
3. Choose the heat distribution pattern (number of heat supply cycles and the start-time of each heat supply cycle) from Table 1.
4. Calculate the heat supply on-time as follows:
   For the first heat supply cycle

   $$\tau_{\text{on1}} = \int_0^{t1} q_{\text{bldg}}(t)\,\mathrm{d}t / q_{\text{boiler}} \tag{5}$$

   Repeat the calculations to determine $\tau_{\text{on2}}, \tau_{\text{on3}}, \ldots$ as needed. The building load q_{bldg} was determined using an existing buildings loads simulation program [8] and the weather data as predicted in step 1.

Fig. 1 shows the building load as a function of average outdoor air temperature. Several simulation runs were made with different weather conditions to extract this relationship. The results presented in Fig. 1 show that a linear relationship between q_{bldg} and T_{o} may lead to errors, especially during mild weather conditions. Therefore, a fifth order polynomial was used to fit the simulation data. The polynomial equation is given by

$$q_{\text{bldg}}(t) = -0.0008X^5 - 0.0084X^4 + 0.109X^3 - 26.17X + 972.6 \text{ kcal/h} \tag{6}$$

Note that Eq. (6) is specific to each building geometry and thermal design data. For the building used in this study, the heating loads were computed using Eq. (6).

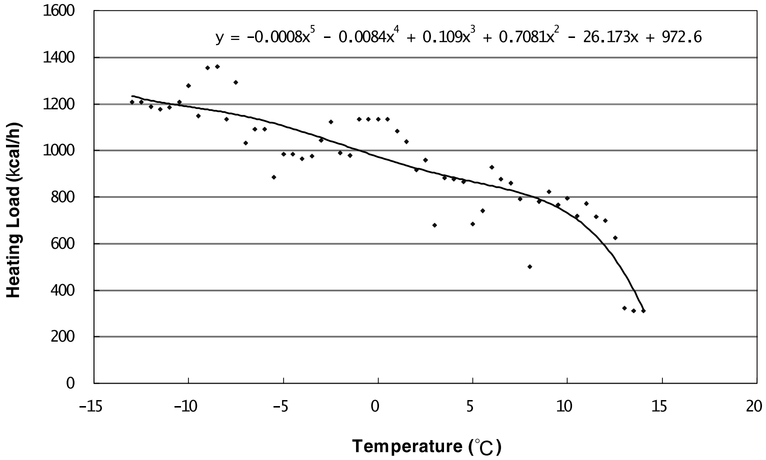

Fig. 1. Heating load profile for model building.

4. Simulation results

The performance of the predictive control strategy was compared with the conventional control scheme by using computer simulations. In the TRNSYS computer program [8], an RFH system model was incorporated, and the control strategies were defined. Using this computer model, simulation runs were made. In the following, the simulation results are presented.

Shown in Fig. 2a and b are the typical daily responses (slab temperature, room air temperature, outdoor air temperature and heat flux) of the RFH system under conventional control (Fig. 2a) and predictive control (Fig. 2b).

From the results, we note that in the predictive control strategy, the heat flux delivered to the floor slab is lower than that in conventional control scheme. The difference in heat fluxes is about 20% in favor of the predictive control method. This means that less energy is utilized in predictive control compared to conventional control. Furthermore, the room temperature variations are much smaller (19–22 °C) compared to the conventional scheme (19–23.5 °C).

The energy efficiency characteristics of both control schemes were evaluated under three typical winter heating days, such as a cold day, a mild day and a warm day. The outdoor daily average conditions corresponding to these three days were, respectively, −10.4, −0.4 and 9.59 °C. The simulation results are depicted in Fig. 3.

Note that as the outdoor temperature increases, the heat fluxes delivered to the floor slab decrease in both control schemes. However, the energy savings are larger with the predictive control strategy compared to the conventional control strategy. On an average, the predictive control scheme reduces energy consumption by about 20%.

Even though the heat flux delivered by the slab is decreased by 20%, the drop in room temperature is not significant. Besides, the room temperature fluctuations are within the thermal comfort range of the occupants. This is in spite of the fact that no temperature control or thermostat is used in the zone.

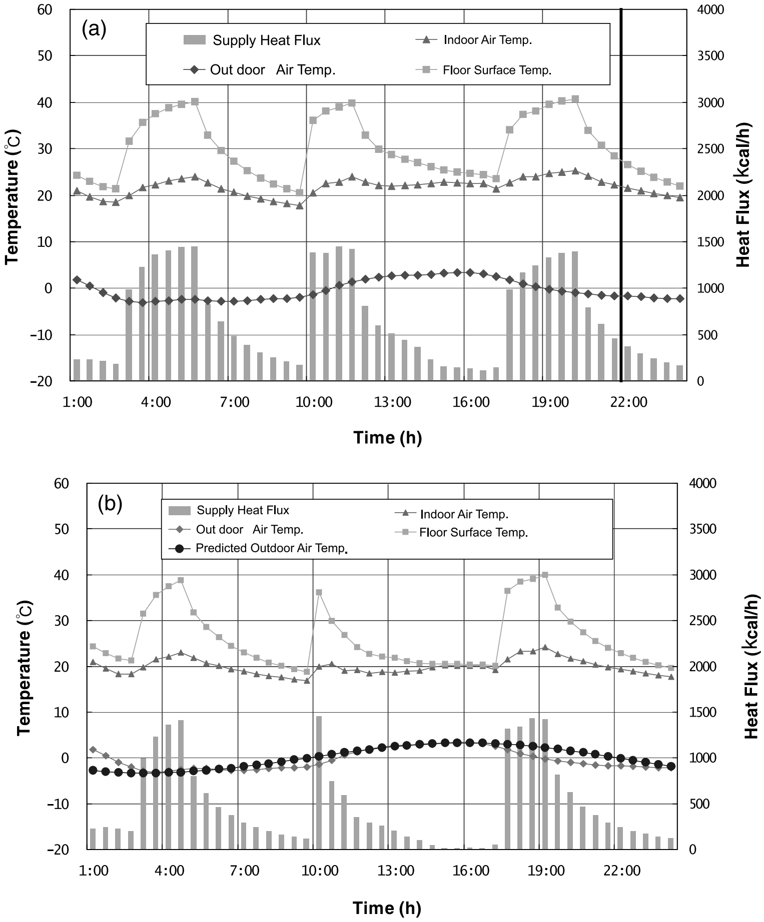

Fig. 2. Comparison of control strategies: (a) conventional control strategy, (b) predictive control strategy.

5. Experimental results

5.1. Experimental facility

The experimental facility consists of two rooms constructed side-by-side with a common wall. Each room measures 3 × 4.4 × 3.8 m^3. The rooms are facing approximately due South, and each room has two windows (1.5 × 1.5 m^2), one in the South wall and the other in the North wall. To eliminate the unequal effects of direct solar radiation incident on the East and West walls, sun screens were installed. A 7 kW air conditioning unit is installed in each room to create identical initial conditions (within ±0.5 °C) in the test rooms as fast as possible. Besides saving time between tests, this arrangement was found to be quite useful in eliminating unequal storage effects associated with unequal initial conditions in the rooms.

The embedded-piping floor consisted of 15 mm diameter copper tubes installed on 200 mm centres. Two identical heating systems were installed, one for each room. The central objective

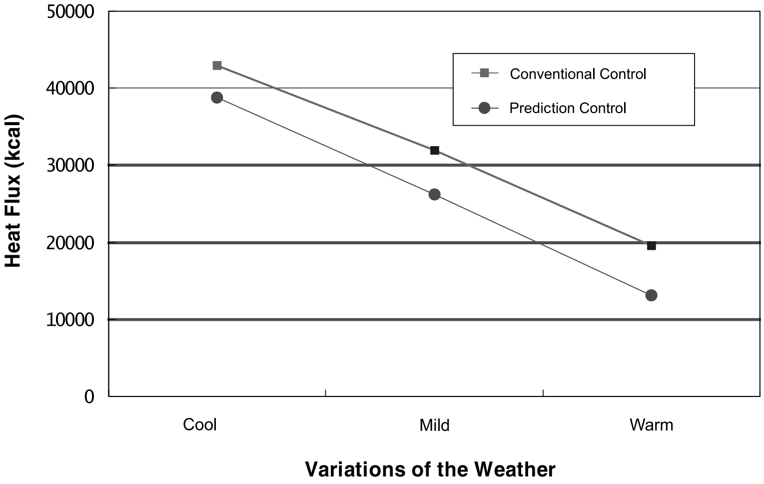

Fig. 3. Heat flux as a function of outdoor air temperature.

was to evaluate the performance of two different control strategies simultaneously under similar environmental conditions.

5.2. Data acquisition and monitoring system

A total of 56 temperature points (28 points per room) were monitored by a multi-channel data acquisition and control system. Separate channels were dedicated to measure room temperatures, water temperatures, pressures and flow measurements. Two output channels were used for control. The data acquisition system was connected to a 486 PC via RS 232C. A user-friendly program was written for implementation of the control strategies. The program works in the Window environment and displays the system schematic and monitoring status. The sampling interval of data acquisition can be changed. For the experiments conducted, the data was gathered every 30 s. Note that a single data acquisition system was used for gathering the data and control of the individual heating systems.

6. Results and discussion

Fig. 4a and b show the experimental results in which the room air temperature, outdoor air temperature and heat fluxes are plotted. Tests were conducted on two different days: the first day identified as Case-1 (outdoor temperature range −5 to 8 °C, Fig. 4a) and a second day referred to as Case-2 (outdoor temperature range −3 to 6 °C, Fig. 4b). We note that the average temperature on both days is somewhat similar, but the temperature distribution is different.

From Fig. 4a (Case-1), we note that the air temperatures in room 2 using the predictive control strategy are lower than those in room 1 that was operated using the conventional control strategy. This pattern remains similar for the second day (Case-2) as well (Fig. 4b). Also, we note that

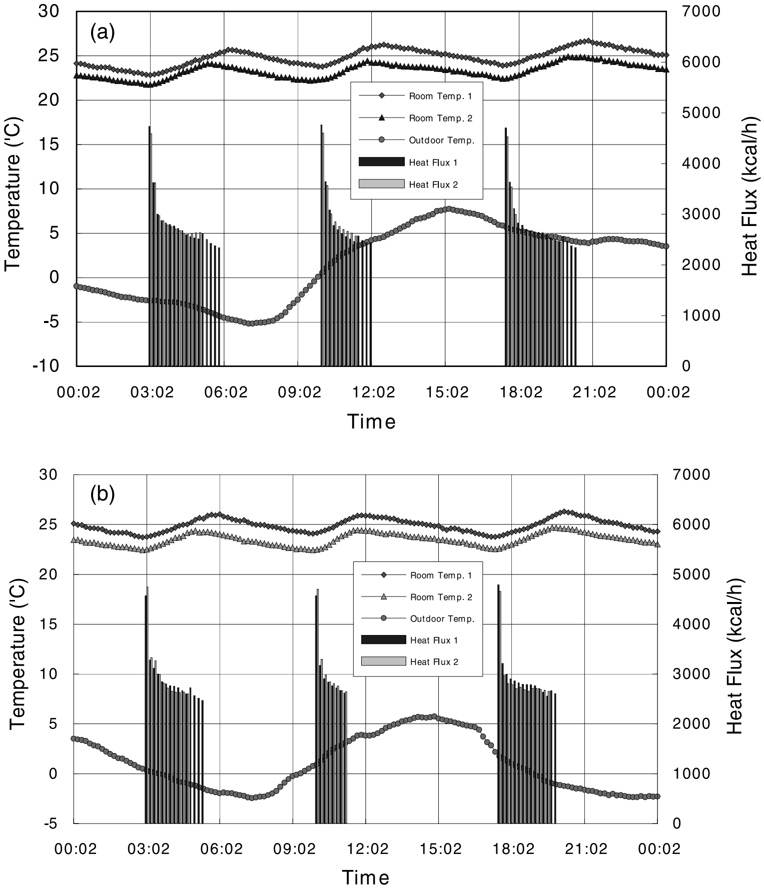

Fig. 4. Comparison of conventional and predictive control method for intermittent heating: (a) typical daily responses (case-1), (b) typical daily responses (case-2).

under predictive control the variations in room 2 air temperatures are smaller (22–25 °C) than those in room 1 using the conventional control (23–27 °C).

A comparison of energy consumption between the two cases shows that the predictive control scheme saves about 24% energy (Case-1) on the first day and saves about 13% energy on the second day (Case-2) compared to the conventional control scheme. Also, the difference in the energy consumption between the conventional strategies is 20% and that between the predictive strategies is 9%. In other words, the conventional strategy gives rise to significant changes in energy consumption even though the average outdoor temperatures on both days were about the same. The predictive control scheme avoids this problem and gives a more reasonable and smooth transition due to changes in outdoor temperatures, as reflected in the 9% change in energy consumption between the two cases.

A summary of the energy consumption obtained with both control schemes on three typical winter days is given in Table 2. It is apparent that the use of predictive control results in significant energy savings compared to conventional control. For example, the energy savings achieved with

Table 2
Experimental results for various outdoor air temperatures

Outdoor air temperature	Predicted outdoor air temperature (°C)	Measured outdoor air temperature (°C)	Existing control strategy			Predictive control strategy		
			Indoor air temperature (°C)	Heating time (h)	Energy consumption (kcal/day)	Indoor air temperature (°C)	Heating time (h)	Energy consumption (kcal/day)
Low	Min: −4 Max: 6	Min: −2.45 Max: 5.74 Avg: 0.93	Start: 25.10 Stop: 24.31 Avg: 24.90	6:30	18,600	Start: 23.48 Stop: 23.04 Avg: 23.48	5:20	15,870
Medium	Min: 1 Max: 9	Min: −0.46 Max: 14.12 Avg: 5.03	Start: 23.37 Stop: 22.73 Avg: 22.58	5:00	15,290	Start: 20.83 Stop: 20.95 Avg: 21.27	3:50	11,600
High	Min: 6 Max: 18	Min: 3.66 Max: 19.87 Avg: 12.35	Start: 23.26 Stop: 25.33 Avg: 24.64	3:30	11,750	Start: 22.75 Stop: 24.19 Avg: 23.67	2:20	7590

predictive control compared to the convention control are 14.6% on a cold day, 24.13% on a mild day and 35.4% on a warm day. What is consistent is that the predictive control strategy results in lower energy consumption than the conventional control strategy. This is also quite obvious if we compare the total number of heat supply hours per day for both control strategies as shown in Table 2.

7. Conclusions

In intermittently heated buildings using RFH systems, the predictive control strategy has been shown to be more energy efficient compared to the conventional control strategy. One reason for the higher energy efficiency is that the heat supply hours per day in the predictive control strategy is determined based on a forecast of hourly outdoor temperatures. On the other hand, the heat supply hours per day in the conventional control strategy were estimated based on the daily minimum outdoor temperature. In other words, the conventional control strategy uses a more conservative approach. Another advantage of the predictive control is that it eliminates the drastic changes in heat supply hours when the outdoor air temperatures fall slightly beyond the range defined in Table 1. The results show that between 10% and 20% energy savings could be achieved by using the predictive control technique compared to the existing conventional control scheme.

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