A Comparative Study on the Control of the Radiant Floor Cooling System

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ABSTRACT

Several items such as surface condensation control, floor temperature, vertical room air temperature difference should be evaluated when the heating panel system is also used for cooling in such a climate as that of Korea, where it is hot and humid during the summer. In particular, achieving a precise control method is very important in preventing surface condensation. Therefore, this study aims at finding the problems that may occur with the cooling panel system and determining the appropriate control method that has a rapid response and temperature stability.
In this study, on/off bang-bang control, variable flow control as a water flow control, and outdoor reset with indoor temperature feedback control as a water temperature control are tested through computer simulation and experimentation in the laboratory.
The results show that the water temperature control is better than the flow control with respect to room temperature stability and response to prevent surface condensation and to coping with instantaneous load changes, and that the floor temperature distribution and the vertical air temperature difference will not cause any discomfort.

1. INTRODUCTION

The radiant floor heating system, Ondol – a Korean traditional heating system, has been used as the one heating system for apartment buildings in Korea. In the past, cooling systems were not taken into account due to technical and economical shortcomings, but recently, packaged air-conditioners have come to be used. With the growth of industry and the increase of the national income, the demand for cooling and for installations of packaged air-conditioners have also increased. Subsequently, several problems such as higher peak power demand have appeared, and it has become necessary to develop a cooling system which can reduce the peak power demand.

In developing the cooling system, it is more advantageous to utilize the existing floor heating system than to append a separate system in terms of effective floor area, conservation of resources, and preservation of the environment. Thus, the radiant floor cooling system using Ondol is proposed as an alternative. In radiant cooling, heat is exchanged with cooled surfaces, so that the probability of condensation is great at the cooled surface in a hot and humid climate such as one of Korea. In addition, the lifestyle of the Korean people is based on sitting on the floor. Thus, to apply radiant cooling to already built apartment buildings, research is necessary on system control techniques to prevent condensation and on thermal comfort related to touching the surface of the floor. This paper carries the objectives of proposing methods to prevent condensation and of investigating thermal comfort with various room temperatures and floor temperatures.

To induce methods of preventing condensation and to investigate thermal comfort, analyses are performed on the control performance of conventional control methods, the relationship between condensation and control variables, floor surface temperature distribution, and on the vertical temperature distribution of the room, using thermal analysis simulations and model tests.

2. COMPUTER SIMULATION FOR THE EVALUATION OF CONTROL METHODS

2.1 Controls for Radiant Floor Cooling

A slab with embedded tubes can be controlled by two parameters, water flow and water temperature. Based on these two parameters, various control methods for heating have been presented through previous practices and researches.

There are two types of control methods, on/off bang-bang control and on/off pulse-width control, in controlling the flowrate of supply water. On/off bang-bang control, so called on/off control, is applied to almost apartment buildings in Korea. The water temperature control methods are classified into two types. One is outdoor reset control, in which supply water temperature is controlled sensing the outdoor temperature, and the other is outdoor reset with indoor temperature feedback control, in which supply water temperature is controlled sensing both the outdoor temperature and the room air temperature.

In this study, on/off bang-bang control, variable flow control as a water flow control, and outdoor reset with indoor temperature feedback control as a water temperature control were tested through the experiment of the laboratory setting.

2.2 Conditions for Computer Simulation

The room for simulation: The typical Ondol room in the mid-floor of an apartment building is selected. The room has one wall facing outside, and the ceiling, the floor, and the three other walls are in contact with identical Ondol rooms.

The structure of Ondol floor: The commonly used Ondol floor structure of the construction companies of Korea consists of a 135mm concrete slab, 55mm ALC, 20mm cement mortar embedded with a 230mm-spaced XL pipe, and 25mm cement mortar as a finish layer.

Outdoor temperature: The simulations are performed in the summer according to the standard meteorological data of Seoul(SAREK 1998).

Simulation program: The simulations are performed with the aid of the dynamic simulation program(Kim 1999). The simulation program can analyze the thermal behaviour of multi-rooms with unsteady state calculation. The program is validated in a previous research(MOICE 1996).

2.3 Results and Discussion

During the cooling period, the temperature of cooled water, which is supplied according to outdoor reset control with indoor temperature feedback, is shown in Figure 1. The lowest temperature of supply water is about 17℃ during the period that has the highest temperatures in Seoul. At that supply water temperature, the floor surface temperature is about 23℃, which is higher than the 19℃ of the recommendation of ASHRAE and ISO for floor surface temperature. The lowest floor surface temperature does not always occur at the highest outdoor temperature due to the thermal storage effect of Ondol and solar radiation.

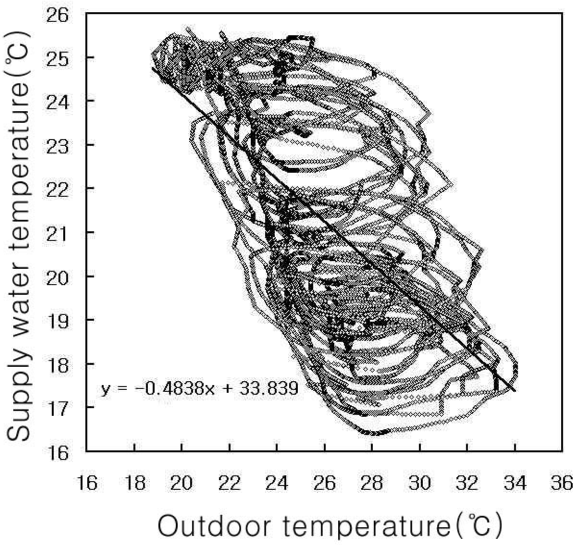

Figure 1 – Relation between outdoor temperature and supply water temperature

After the room air temperature is controlled by manipulating water flow or temperature according to the control method, the room air and floor surface temperatures, PMV, and frequency of condensation are analyzed in order to compare the performances of the control methods.

Figure 2 shows the profiles of room air temperature, floor surface temperature, and PMV for the week of the highest outdoor temperatures, in which room air temperatures are maintained in the range of set temperature ±1℃ with all three control methods. In the cases of on/off control and flow variable control, however, fluctuation of floor surface temperature is larger than that with outdoor reset with indoor temperature feedback control. As shown in the profile of room air temperature, the room air temperature is well maintained in the range of the set temperature in the order of outdoor reset with indoor temperature feedback control, on/off bang-bang control, and variable flow control. The frequency of room air temperature dropping 0.5℃ below the set temperature with on/off control and variable flow control is higher than in the case with outdoor reset with indoor temperature feedback control. It can be considered that cooled water remaining in the embedded pipes absorbed heat from the room, even though the supply of cooled water was stopped.

The hours corresponding to PMV ranges during the cooling period. More values of PMV with outdoor reset with indoor temperature control are in the comfort range than those with on/off control and variable flow control. Shorter times of condensation occurrence are given in the order of outdoor reset with indoor temperature feedback control, on/off control, and variable flow control, as shown in Table 1. In particular, since condensation may occur even when cooled water is not supplied in the case of on/off control, a countermeasure is required in real application.

According to the analysis of condensation occurrence by each control method over the entire cooling period, the frequency of condensation occurrence with outdoor reset with indoor temperature control is lower than those with the other control methods. In the case of all three control methods, condensation occurred at almost the same period. Taking into account condensation occurrence only, the radiant floor cooling is possible during about 73% of the total cooling period with on/off control, 75% with variable flow control, and 78% with outdoor reset with indoor temperature control. The period during which none of the control methods show condensation is about 67% of the total cooling period.

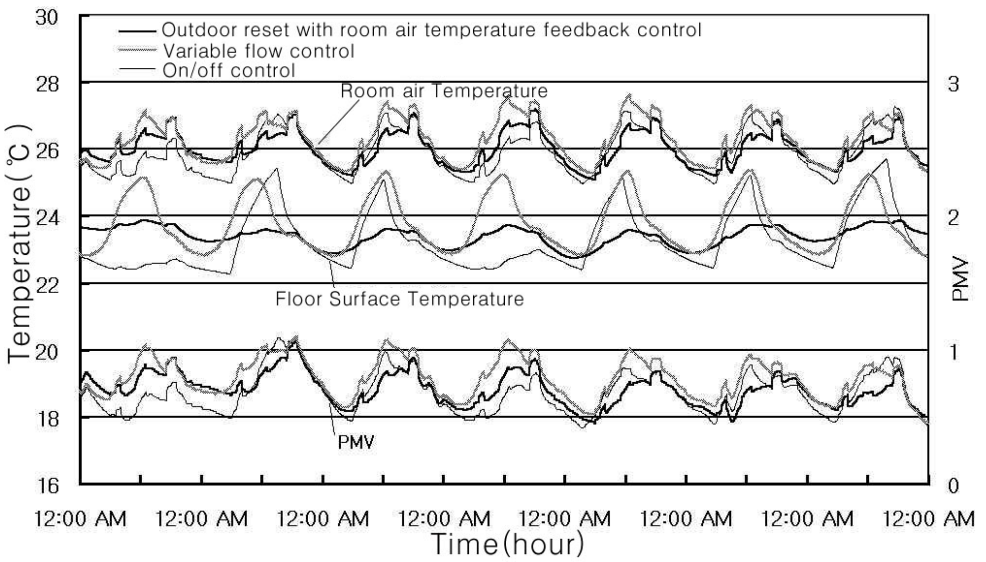

Figure 2 – Comparison of control methods in terms of room air temperature, floor surface temperature, and PMV

Table 1. Comparison of on/off bang-bang control, variable flow control, and Outdoor Reset with indoor temperature feedback control

		On/off bang-bang control		Variable flow control		Outdoor reset with indoor temperature feedback control
		On	Off	Open	Fully closed	
Time of condensation occurrence(hr)		284.6	59.5	314.9	19.0	287.3
		344.0		333.9		
Room air temperature (℃)	Average	25.7		25.7		25.9
	Standard deviation	0.7		0.7		0.5
	Maximum	27.5		27.2		27.4
	Minimum	24.3		24.1		24.3
Floor surface temperature (℃)	Average	24.3		24.2		24.6
	Standard deviation	1.0		0.8		0.6
	Maximum	26.0		25.6		25.5
	Minimum	22.5		22.6		22.5
PMV	0～0.2	6.0		39.5		10.0
	0.2～0.4	196.0		233.5		141.0
	0.4～0.6	490.5		467.0		516.0
	0.6～0.8	413.5		376.5		493.5
	0.8～1.0	166.0		155.5		110.5

3. EXPERIMENTAL TESTS

In order to compare efficiency of each control method through model riment, supply water temperature was determined by the outdoor reset with indoor temperature feedback control, as shown in the simulation. After setting the water temperature of On/off bang-bang control and variable flow control, flow rate of supply water was controlled by room air temperature feedback from each control method. Experiment I was designed to obtain reset ratio and analyze supply water temperature using outdoor temperature feedback. Experiment II was conceived to control room air temperature by installing control valve into test cells in each control method.

After calculating heating and cooling load of a test cell, flow rate was determined so that temperature gap between supply water and return water could be kept within 2℃ while cooling. Its value was 1.2 lpm, which was close to that of the real designed flow rate in apartment buildings for heating. And set temperature in each cell was fixed at 26℃, the standard temperature for cooling system design in Korea. Room air temperature for feedback was measured at the height of 1.1m where thermostats in apartment buildings are usually located.

3.1 Test Cells

Test cells with 4 walls, a window at south, a door at north, a ceiling and the radiant floor for cooling were made which were modelled by one of the rooms of apartment buildings standing in north-south direction. Those walls and window intended to have the same quantities of the heat gain per floor area and those radiant floors for cooling to be the same layers as one of the present apartment buildings' in Korea. Piping system is divided into the 2 parts; one was planned to go through test cells and the other to go through ice storage tank(see Figure 3)

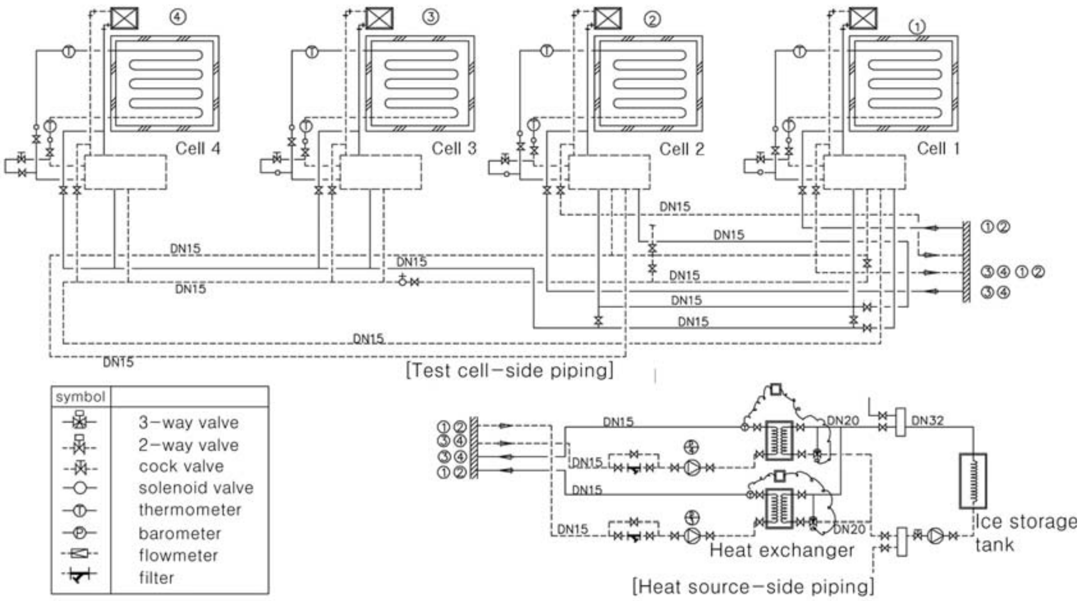

Figure 3 – Test cells and piping

3.2 Experimental Equipment, Measurement Device and Control Equipment

There are cooling source, pump and distribution devices, temperature and humidity sensors in space, water temperature sensors and water flow meter in supply water, weather observation devices, analogue input and output devices and computer with algorithm to be programmed for controlling these devices.

In the on/off bang-bang control and the variable flow control, the water was cooled by ice storage and controlled by heat exchanger to meet the set temperature and supplied to the cell. In the outdoor reset with indoor temperature feedback control, the water was readjusted to the calculated temperature and supplied to the cell using 3-way valve.

Solenoid valve, 2-way valve and 3-way valve were utilized to control flow rate and temperature of supply water in the on/off bang-bang control, variable flow control and outdoor reset with indoor temperature feedback control, respectively.

Weather data types such as room air temperature and humidity, floor surface temperature, surface temperature of walls and windows, supply and return water temperature, globe temperature, outdoor temperature and humidity were measured. In order to remove the effect by radiation, room air temperature was measured inside a double concentric tube with T-type thermocouple. In measuring surface temperature, T-type thermocouple was posted on walls and floor with aluminium tape. Sensor pocket with T-type thermocouple was installed inside pipes to measure supply and return water temperature. Measured data were stored in computers using analogue input device and data logging system. Among these data, direct and diffuse irradiation were measured using extra sensors at the rooftop. Measurement of wind direction and speed were also performed using additional equipments.

To realize the various cooling modes in radiant floor cooling, input and output board for sensor and valve interface was integrated with the computer which contains algorithms to control these devices.(see Figure 4)

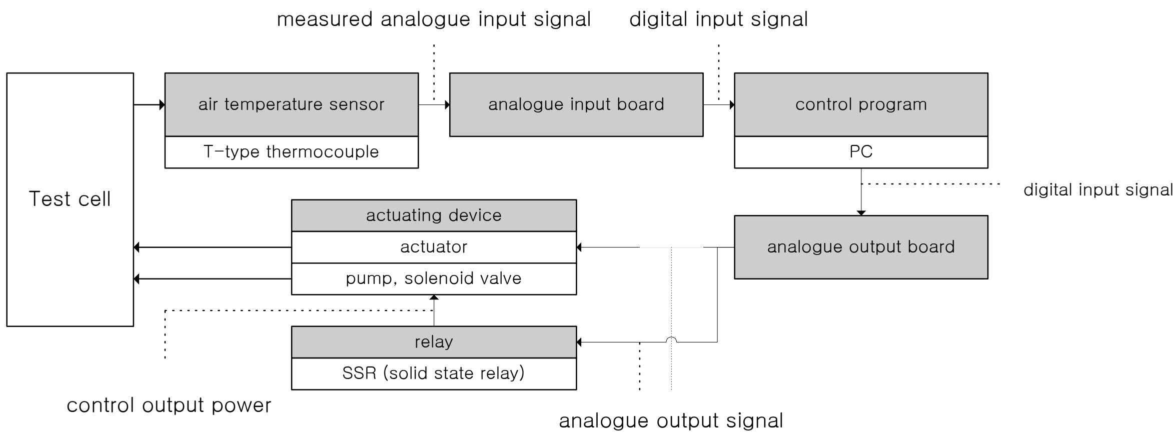

Figure 4 – Scheme of Control System

3.3 Results and Discussion

(1) Experiment I

In this experiment, relations between the outdoor temperature and the supplied water temperature, the outdoor temperature and the floor surface temperature, the floor surface temperature and the deviation of the floor surface temperature are analyzed, and room comfort is analyzed by evaluating the radiation asymmetry of the floor surface and the vertical distribution of the room air temperature.

Figure 5 (left) shows the relation between the outdoor temperature and the supply water temperature in outdoor reset control. In this figure, the supplied water temperature is about 15℃ in accordance with the design outdoor temperature for cooling systems in Seoul(31.1℃). This temperature is a little below that given by the simulation(17℃). Because the temperatures of the simulation and experiment are higher than the temperature of water which is produced using a compressive chiller(about 7℃), secondary transition, as in a heat exchanger, should be used for the cooling source. Figure 5 (right) shows that the experimental correlation between the outdoor temperature and the supplied water temperature is linear although the error is changed with the operating time of the 3-way valve and the water temperature sensor.

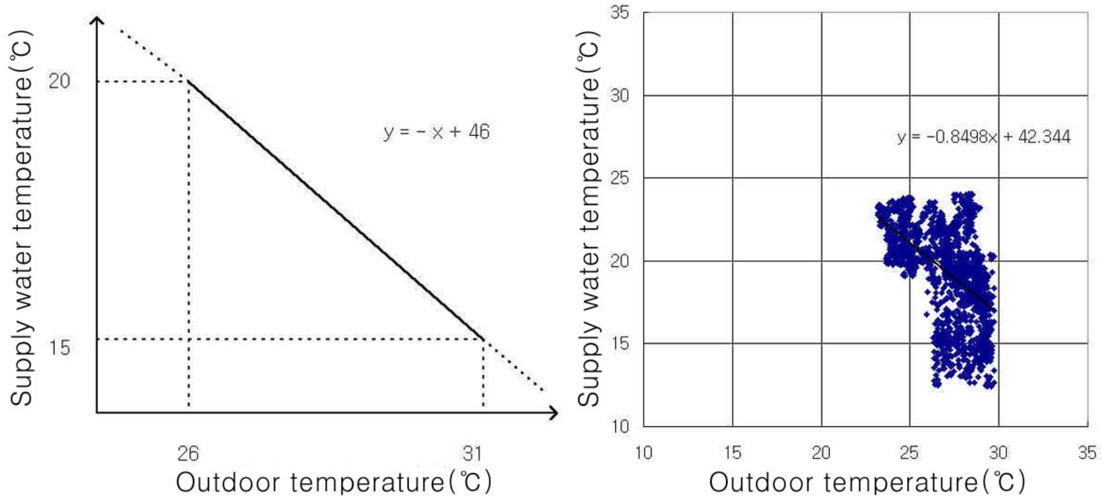

Figure 5 – Relation between outdoor temperature and supply water temperature

Figure 6 shows the change in the room conditions when the radiant floor cooling is applied. In this figure, as the outdoor temperature changes with the deviation of 7℃ and the outdoor relative humidity changes with the deviation of 15%, the room air temperature is controlled at the base of the set-point temperature and the room air relative humidity is maintained at an average of 78%. Occasionally, floor condensation occurs in the period between 6 and 7 p.m, when the outdoor temperature begins to drop and the floor temperature is the lowest.

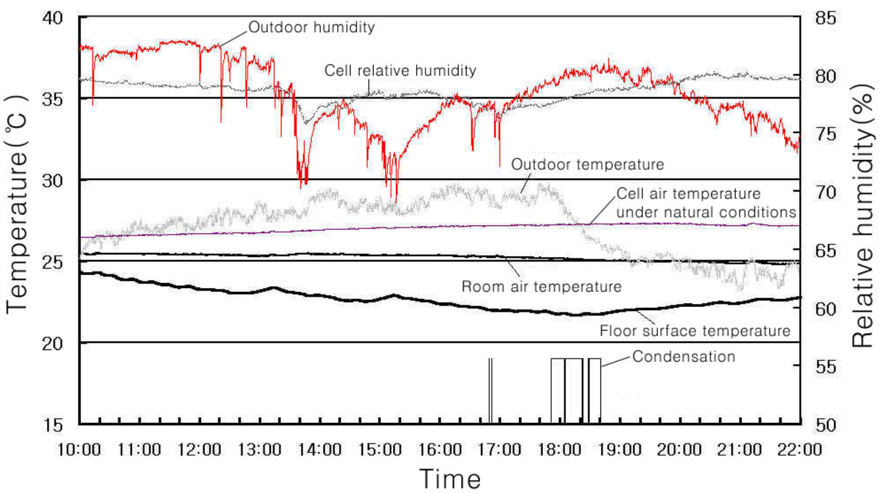

Figure 6 – Profiles of room conditions

To evaluate the comfort of the room, the distribution of the floor surface temperature, the differential of the temperature at the walls and windows, and the vertical distribution of the room air temperature are analyzed. At first when the floor surface temperature varies with the outdoor temperature, Figure 7(a) shows that the surface temperature is above 20℃ and is higher than the standard for the minimum floor surface temperature for comfort in ASHRAE 1992 and ISO 1994. In Figure 7(b), it is seen that the difference in the floor surface temperature between the point right above a pipe and that in the middle of a pitch is less than 2℃, and does not affect comfort. Also, as the temperature difference among surfaces in a space using radiant floor cooling system is less than 10℃,(see Figure 7(c)) we may conclude that the radiant floor cooling system should not cause discomfort. In the case of vertical temperature distribution, Figure 7(d) shows that our results fall within the recommended maximum temperature difference of comfort, which is 3℃ between the height of an ankle(0.1m) and that of the head(1.1m) of a seated person.

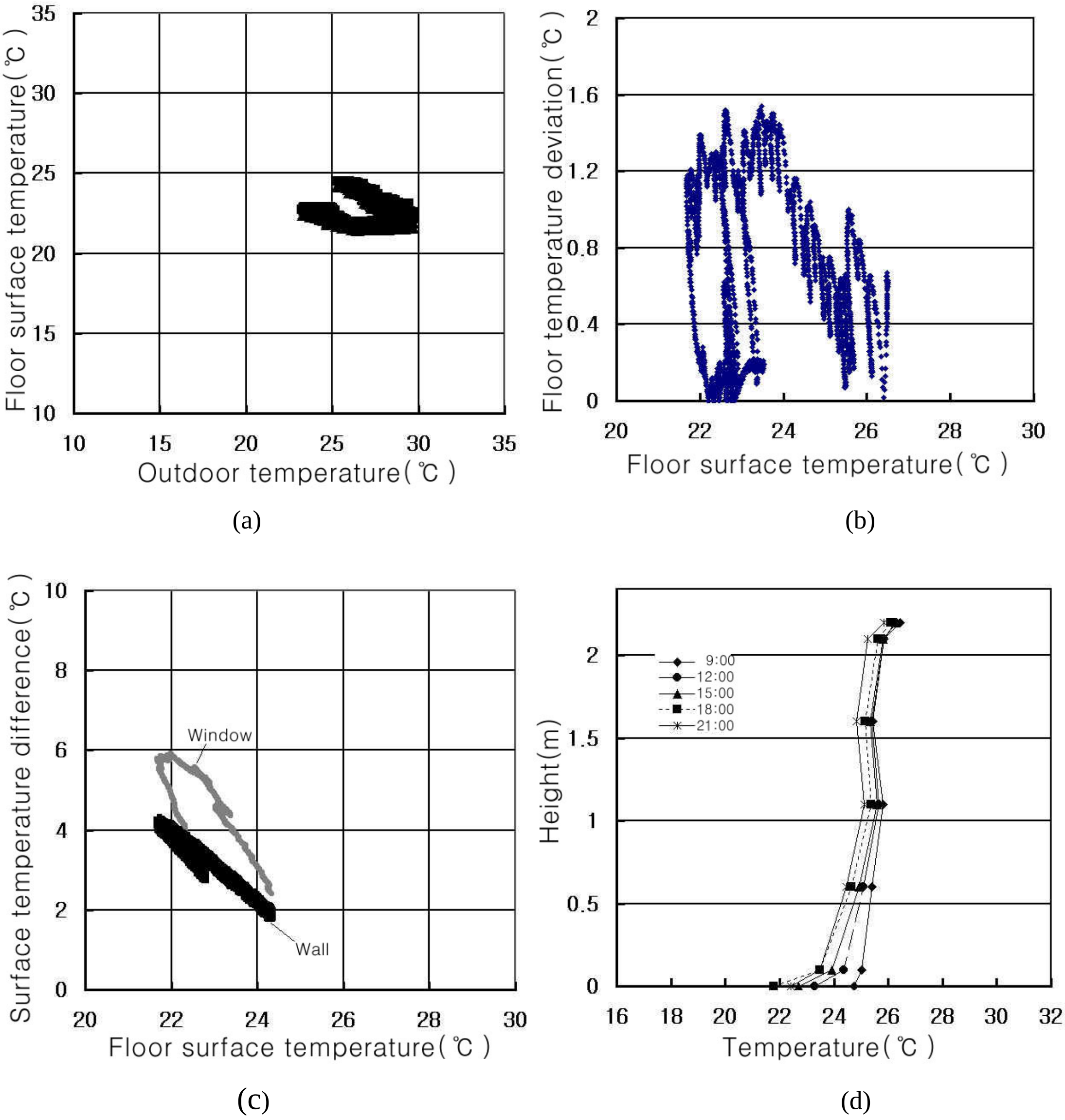

Figure 7 – Profiles of surface temperature of floor and wall, and vertical air temperature

(2) Experiment II

In this experiment, the temperature changes are compared in the air and surface of a room controlled by each system, and the supply water temperature, on/off time, and flow rate of the supply water are examined with outdoor reset with indoor temperature feedback control, on/off bang-bang control, and variable flow control, respectively.

In the case of outdoor reset with indoor temperature feedback control, (see Figure 8) overshooting and undershooting are produced at first due to its late response to cooling load. However, the temperature deviation decreases as time passes.

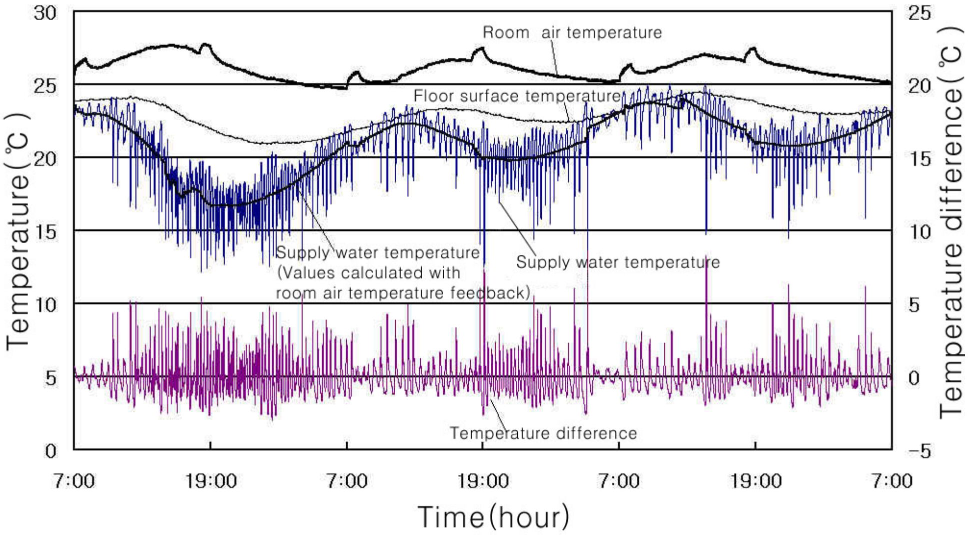

Figure 8 – Profiles of temperatures for outdoor reset with indoor temperature feedback control

This is because in the early phases supply water of low temperature is required to cool the slab, while the magnitude of the change in supply water temperature decreases over time with the stabilization of the structure. Therefore in continuous cooling, although time delays may occur in stabilizing structures at first, after the delay, supply water temperature rises gradually over 20℃, and due to the thermal inertia of the structure, room air temperature and floor surface temperature are stabilized in the end.

The errors between the calculated temperature of the supply water and the real temperature of the supply water in the experiments are within approximately ±2℃. Although the smaller error means more accurate control of temperature, it can vary according to the quality of each control valve and the supply water. Therefore, it is important to select the type of valve that fits the specific system. In addition, as the complexity of the heat source and the piping system can increase the error, the control system should be directly connected to heat source.

As shown in Figure 9, on/off bang-bang control is more accurate than the outdoor reset with indoor temperature feedback control in the beginning. This is because the solenoid valve needs a simpler system in composition and is easier in temperature control than the 3-way valve. However, as its large variation of the floor surface temperature shown in the simulation makes it more difficult to control condensation, a more sensitive control method is required, such as adopting surface temperature as a control variable.

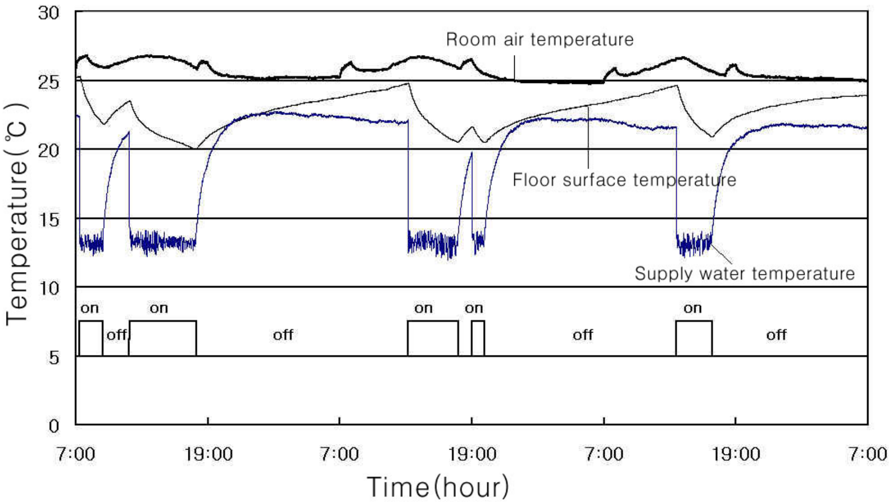

Figure 9 – Profiles of temperatures and flow for on/off bang-bang control

The solenoid valve opens and closes according to indoor/outdoor cooling load changes and is generally open for 6 hours a day. The opening is at about 1 p.m., which means it cools down the structure at the hottest time of the day and its effect lasts overnight. In this experiment, considering the heat gain from the pump and piping in the real distribution system, the supply water temperature is about 13.5℃, which is slightly lower than the desired supply temperature. This makes the supply water circulate through the distribution system for only 35% of the total experiment period. If the supply water temperature is higher than this, the circulation period can be extended and the deviation of the floor surface temperature can be decreased, although the response to cooling load can become slower.

As shown in Figure 10, the movement of the valve stem is great and frequent in maintaining the initial temperature. However, due to the excessive movement of the stem, change in the floor surface temperature occurs more frequently than necessary. This is because distortion of the equal percentage valve characteristics is nearly linear as valve authority is very small. From this, the importance is seen of selecting a control valve pressure drop of at least 25% to 50% from a design standpoint if the system loop pressure drop to provide as high a valve authority as feasible to maintain the equal percentage curve shape.

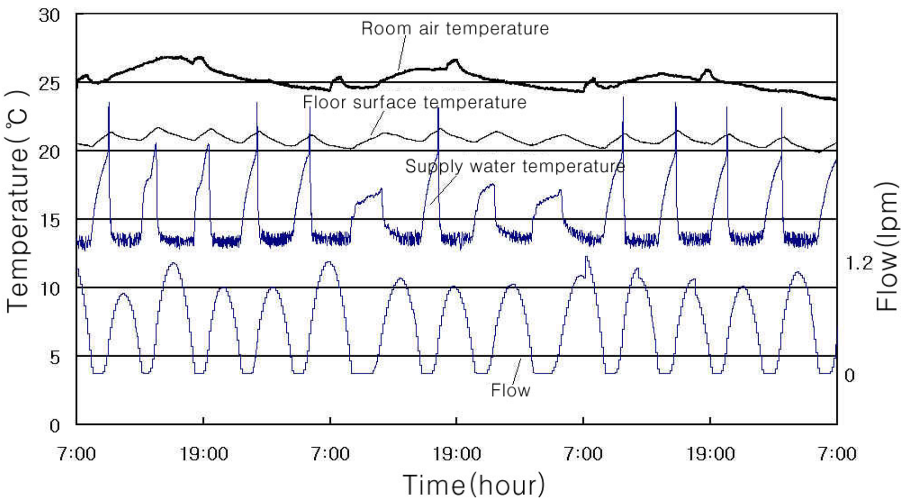

Figure 10 – Profiles of temperatures and flow for variable flow control

Analyzing the flow rate of the system, we observe that during 45% of the experimental period, the system has been operating under conditions of low flow rate (from 0 to 0.3 lpm). When the 2-way valve operates with low flow rate, the control valve's throttling plug should be provided with an equal percentage characteristic and a suitable rangeability. Therefore, to apply variable flow control to the radiant floor cooling system in apartment buildings where low flow rate is needed for cooling, it is important to select the 2-way valve in accordance with the valve authority and valve rangeability of the system.

4. CONCLUSIONS

The results of computer simulations and experiments show that the water temperature control is better than the flow control with respect to room temperature stability and response to prevent surface condensation and to coping with instantaneous load changes. Also, the results of model tests applying radiant cooling show that the floor surface temperature remained above 20℃, the surface radiation instability remained below 2℃, and the vertical temperature difference remained below 1.9℃, conforming well to comfort standards. And, the present heating floor is found to be sufficient to cover the cooling capacity for most of the summer season.

REFERENCES

Haines, Rodger. W., 1983, Control Systems for Heating, Ventilating and Air Conditioning, Chapman & Hall Inc., pp. 80-85

Koo, S., 2000, A Study on the Applicability of Radiant Cooling Using Ondol, *Korean Journal of Air-Conditioning and Refrigeration Engineering*, Vol. 12, No. 2, pp. 200-208

Korea Institute of Construction Technology (KICT), 1996, Thermal Performance Improvement of Floor Heating System in Apartment Housing(II), *KICT*

Kim, Y., 1999, A Study on the Applicability of the Time-Division Hot-Water Supply Heating for Ondol, Proceedings of IBPSA 1999, Seoul National University, Seoul, Korea.

McQuiston, Faye C., 1992, Cooling and Heating Load Calculation Manual(2nd Edition), ASHRAE, p. 5.7.

Michel, E., and Isoardi J.P., 1993, Cooling floor. Proceedings of Clima 2000. London.

Olesen, B.W.(1997), Possibilities and Limitations of Radiant Floor Cooling, ASHRAE Transactions 1997, p. 42.

Olesen, B.W.(1977), Thermal comfort requirements for floors occupied by people with bare feet, ASHRAE Transactions 83(2).

Udagawa, M., 1986, Calculating Methods of Air Conditioning, Ohm Inc., p. 179

Yeo, M. et al., 1998, A Comparative Study on the control Method of Hydronic Radiant Floor heating in Apartment Buildings, Proceedings of the SAREK '98 Summer Annual Conference, pp. 1627-1632, Seoul, Korea