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Method and Analysis of a Dynamic Simulation of Ondol Heating

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Key Words
Ondol heating · Indoor environment · TRNSYS on–off control · Constant-flow control · Building energy management · Building simulation

Abstract
Ondol heating, a kind of radiant floor heating, is the main form of heating being used in housing units in Korea. Although Ondol can provide a more comfortable and healthy indoor environment than any other form of heating systems, a more precise simulation is required to further improve the system to prevent over and under heating of the housing environment. However, due to complexity, building energy simulation has so far not been performed, for systems such as Ondol and other relevant facilities. For evaluating energy consumption and indoor temperature variation, a new method has been proposed. In this study, a dynamic simulation of Ondol heating was carried out by combining TRNSYS and EES. This new system of building simulation could contribute to determine over or under heating of the system in a housing unit. The simulation results of a typical housing unit in Korea showed a good trend in a viewpoint of actual behaviour of Ondol heating, maintaining a comfortable and healthy indoor environment with less energy consumption.

Nomenclature

d = inside diameter of ondol coil (m)
f = friction coefficient
l = length of ondol coil (m)
$\dot{m}$ = mass flow rate (kg·s^{-1})
p = pressure (kPa)
v = flow velocity (m·s^{-1})
ρ = density (kg·m^{-3})
n = n-th coil

Introduction

Energy spent on heating and supplying hot water to residential housing accounts for a significant share (13%) of total energy consumption in Korea [1]. Therefore, energy-saving solutions targeting apartment housing units, which account for 58% of all housing in Korea, could have enormous benefits. Several papers concerning

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factors affecting energy consumption have already been published [2–4].

With the proposed proper energy-saving strategies [5–7], however, it is not easy to validate their effects by conducting demonstrations in actual housing units. Computer simulations are often used as an alternative, and DOE-2, TRNSYS, or EnergyPlus have been used extensively to simulate energy consumption in buildings assumed to have an ideal set of heating devices. These simulation cases have generally not involved facilities [7,8].

Ondol is a heating system that uses an individual boiler or a district heating system as a heat source, is used extensively in Korea [9,10]. The simulation of the Ondol heating system would need to take into account of a variety of calculation challenges relating to the complexity of the Ondol heating mechanism itself, thermal storage effects and the delay in system response.

Simulations of energy consumption for apartment buildings, without involving Ondol, are useful; however, such simulations are likely to have considerable gaps between the simulation and reality in terms of forecasting indoor temperature fluctuation and comfort. Simulating building energy consumption without involving facilities may enable a proper estimation of the total energy consumption for continuous heating but show significant deviations in the intermittent heating results [9]. As most Korean housing units use Ondol as the heating mechanism, it would be necessary to include Ondol in energy and comfort simulations to obtain accurate results. The objective of this research was to present a simulation method which could fulfil these conditions and would be applicable to analysis of the on–off control and constant-flow control methods of the Ondol system.

Fig. 1. The plan of an apartment house used in simulation.

Ondol Heating Simulation

Targeted Space

For the simulation, a 100-m^2 class apartment housing unit was selected; whose area includes the common space like the corridor as well as the exclusive space. This type of housing unit accounts for approximately one quarter of all apartment units in Korea, and a housing unit with exclusive area of 84.7 m^2 (ceiling height, 2.35 m; Figure 1). Previous studies were referenced for details of the wall and window conditions [2]. A detailed illustration of the Ondol configuration is shown in Figure 2. The area of each room is described in Table 1, and the initial temperature was set to 20°C.

Ventilation frequency is a variable that can significantly affect the results of building energy simulations; yet, it is largely uncertain [11]. Ventilation frequency was set to 0.3 times per hour from 8:00 PM to 8:00 AM in the next morning, during which time residents almost entirely stay in their apartments, and 0.7 times for all the other hour bands. The balconies in the south and the north-facing rooms were incorporated into the rooms by refurbishment,

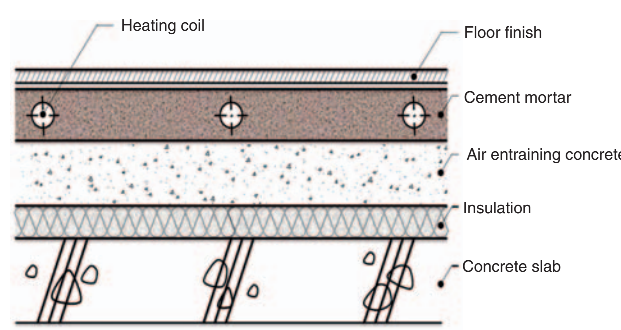

Fig. 2. Section of floor with Ondol coil.

Table 1. Ondol coil specifications in constant-flow control

Zone	Area (m^2)	Length of coil (m)	Equivalent length by valve (m)	Flow rate (lpm)
Bedroom 1	20.7	104	0	3.6
Bedroom 2	10.9	55	80	3.1
Bedroom 3	8.1	41	100	3.0
Living and kitchen	41.2	103 × 2	0	3.6
Bathroom	4.9	25	130	2.9

and all of the windows were assumed to be configured with double-glass panes (4/16/4, 2.83 W/m^2 K).

Hot Water Coil Installation and Control Method

Heating coil length per zone used to be limited to a maximum of 50 m in Korea; however, there is no such restriction now. As too long a coil is likely to reduce flow rate, they tend to be 120 m or shorter in most cases. The typical coil configuration for each zone is shown in Figure 3. Hot water coils are made of plastic and placed in spiral or zigzag forms. Hot water coils that have 16-mm outer diameters are placed on Ondol floors with a 200-mm centre-to-centre distance.

Hot water distributors are installed so as to distribute hot water properly to multiple zones with different lengths of hot water coils. A schematic diagram of a hot water distributor is shown in Figure 3. Water heated in a boiler or heat exchanger is distributed to each zone *via* a supply header of a hot water distributor. Also installed are a manual valve to block the hot water flow, a flow-rate control valve and an automatic valve. Each zone's indoor temperature is controlled by the on–off control, flow-rate control and proportional control features of the hot water controller [12].

This research focused mainly on the flow-rate control method used most extensively. The valve opening was assumed to be set in order to maintain the recommended flow rate of 0.25–0.3 m·s^{-1} for Ondol coil, with 0.3 m·s^{-1} for the largest room and 0.25 m·s^{-1} for the smallest room. The length of the hot water coil installed in each zone is given in Table 1. Furthermore, a twin loop of a 103-m long hot water coil was installed in the living room.

The opening of the flow-rate control valve was adjusted so as to control the flow rate as shown in Table 1, and the equivalent length of coil that would produce the flow resistance for the valve opening, was calculated. If the valve opening was not adjusted, the zone with the shortest coil length would have the highest flow rate, which may result in over-heating. Therefore, it was essential to adjust the flow rate using a flow-rate control valve in order to keep the flow rate appropriate. Once the opening of flow-rate control valve was adjusted, at the initial installation, the valve opening could be controlled in the on–off control mode.

A simple on–off control method was adopted in most apartment housing units until the mid-2000 s and is still distributed occasionally [13,14]. As the on–off control method does not use a flow-rate control valve, the equivalent length by the control valve was 0 in all of the rooms, and the hot water coil installed would not exceed 50 m. For our calculation for the on–off control method, Room 1 was assumed to have two Ondol coil modules of 52 m, and the Living Room was assumed to have four modules of 51.5 m.

Ondol is placed between two layers, the levelling mortar and the light-weight concrete. However, Ondol in the Type 56 of TRNSYS requires the top and bottom layers be made from the same material, and the thickness of the top layer imposed on Ondol must be 30% or more of the centre-to-centre distance of Ondol [15]. Therefore, the virtual mortar layer, which is 60 mm thick, about 30% of 200 mm centre-to-centre distance of Ondol, was used. Thermal conductivity was calculated so as to keep $k/\Delta x$ the same as in the original conditions. In addition, the specific heat was adjusted in order to maintain thermal storage, namely keeping $\rho c/\Delta x$ the same. The bottom layer of Ondol was assumed to be made of the same virtual mortar, and its thickness was assumed to be 30 mm, so as to have the original thermal storage amount (Table 2).

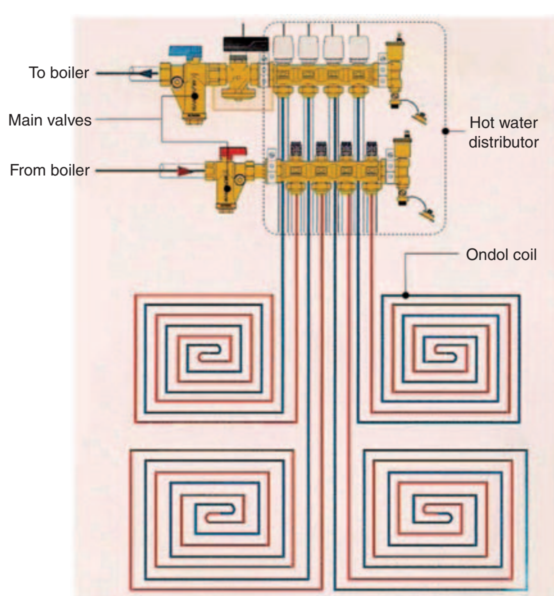

Fig. 3. Ondol coil with hot water distributor.

Simulation Method

A feature that could include an active layer in the wall was added to TYPE 56 of TRNSYS 16.1, which is a dynamic building energy analysis program [15]. As Figure 2 illustrates, the wall consisted of several layers, with the active layer deriving its name from its ability to emit or remove heat from a wall's surface *via* a fluid-flowing coil. Relevant literature was referenced for details of mathematical modelling of the active layer [11].

Table 2. Themophysical properties of floor

	Thermal conductivity ($W \cdot m^{-1} \cdot K^{-1}$)	Specific heat ($kJ \cdot kg^{-1} \cdot K^{-1}$)	Density ($kg \cdot m^{-3}$)	Thickness (mm)
Levelling mortar	0.37	0.79	2000	40
→ Equivalent mortar	0.56	0.53	2000	60
Autoclave light-weight concrete	0.17	1.09	600	50
→ Equivalent mortar	0.56	0.53	2000	30
Expanded polystylene	0.034	1.25	28	30
Concrete	1.62	0.79	2400	150
Gypsum board	0.21	1.13	910	9

As Ondol is a heating mechanism involving installation of an active layer on the floor, the number of hot water coil loops, its inside diameter, and its centre-to-centre distance were set in TRNBuild of TRNSYS.

A constant value, a value from a function or a calculated result from other programs, was entered for the water temperature and flow rate at the Ondol inlet. For the rough calculation, a constant or simple function was acceptable as input. However, to facilitate the actual situation, such values needed to be calculated with precision using another module.

TYPE 56 was the module that was used for modelling multizone buildings and this was used here for this study. Another approach was to import and export the results produced each time step by programs developed in Engineering Equation Solver (EES), Mathlab, Excel and FLUENT with TRNSYS *via* the Dynamic Data Exchange (DDE) of WINDOWS. The EES program has the major function which is capable of solving a set of algebraic equations automatically and, in addition, can solve differential equations and optimization [16].

EES was used in this research study to solve the performance functions of the pump, hot water coil, piping system and boiler simultaneously, as well as to determine the hot water flow rate and inlet water temperature of each zone.

TRNSYS transfers the heating control function of each zone (if 0, OFF and if 1, ON) and the Ondol outlet water temperature value to EES, and EES then calculates the flow rate and supply water temperature of each zone and sends the results back to TYPE 56.

EES Calculation

The quadratic equation representing the characteristic curve of the pump used as a heat circulation pump in a 100-m^2 class apartment unit is shown in Equation (1).

$$\Delta p_{\text{pump}} = 87.6 - 22.8\dot{m} - 167.5\dot{m}^2 \tag{1}$$

The pressure drops between inlet and outlet headers of each hot water coil, shown in Figure 3, are the same, and by Equations (2) and (3):

$$\Delta p_{\text{colis}} = \Delta p_1 = \ldots = \Delta p_5 = \Delta p_n = f\frac{l_n}{d}\frac{\rho \upsilon_n^2}{2} \tag{2}$$

$$\Delta p_{\text{pump}} = \Delta p_{\text{coils}} + \Delta p_{\text{other}} \tag{3}$$

where υ_n, $\dot{m}_n$, Δp are the flow velocity, mass flow rate and pressure drop, respectively, of each hot water coil that satisfy the above equations simultaneously. Therein, the hot water coil length, l_n, is the sum of the original coil length and equivalent length of valve.

As the hot water is blocked from a zone, then the total mass flow rate, $\dot{m}$, is reduced, but the mass flow rates to other zones would increase.

The boiler capacity was assumed to be large enough to supply a maximum heat of 15 kW. Capacity is controlled in reference to the supply water temperature. The boiler was set to be operated at a maximum output of up to 62°C, 40–100% proportionately between 62°C and 67°C and stopped above 67°C.

Result and Discussion

Calculation Result by EES

Prior to the inter-operation with TRNSYS, it was necessary to analyse the validity of the calculation results produced by EES alone. In the initial heating phase, hot water was supplied to all of the rooms (zones) at the same time and blocked from each room that first reached a set temperature. As it is difficult to show all of the on–off combinations of each room, Table 3 describes only some of such combinations.

When the valves in all of the rooms were opened, the pressure drop reached its minimum, and the total flow rate reached its maximum. The total flow rate decreased with more valves closed; however, the flow rate in each room in which the valve was opened, increased. If the valve in only

Table 3. Flow rate and pressure drop

Case	Room 1	Room 2	Room 3	Living room	Bath room	Total (kg·min^{-1})	Δp_{pump} (kPa)
1	3.54	3.11	3.04	7.12	2.90	19.72	62.1
2	4.05	3.56	3.48	8.15	0	19.24	63.1
3	6.04	5.30	5.19	0	0	16.53	68.6
4	7.34	6.45	0	0	0	13.79	73.5
5	8.83	0	0	0	0	8.83	80.6

one room was opened, then the flow rate in this room would increase to its maximum.

The boiler output could vary, subject to the supply water temperature (boiler outlet temperature). Furthermore, the total flow rate and the returned water temperature determined the supply water temperature. In other words, if the total flow rate decreases with more closed valves, then the supply water temperature would rise, even with the same returned water temperature and the boiler output would reduce.

Figure 4 shows the relationship between the supply water temperature and the boiler output according to the return water temperature for Cases 1 and 4 (referenced in Table 3).

The study found that the boiler output could decrease faster in Case 4, in which the valves were opened in only two rooms, than in Case 1, in which the total flow rate was at its maximum with all of the valves open. This was because the supply water temperature approached the setup temperature of 67°C at a faster rate. If only one room was heated, as in Case 5, then the supply water temperature would reach its maximum abruptly, and the hot water supply may be cut off when the indoor temperature would not reach its setup temperature.

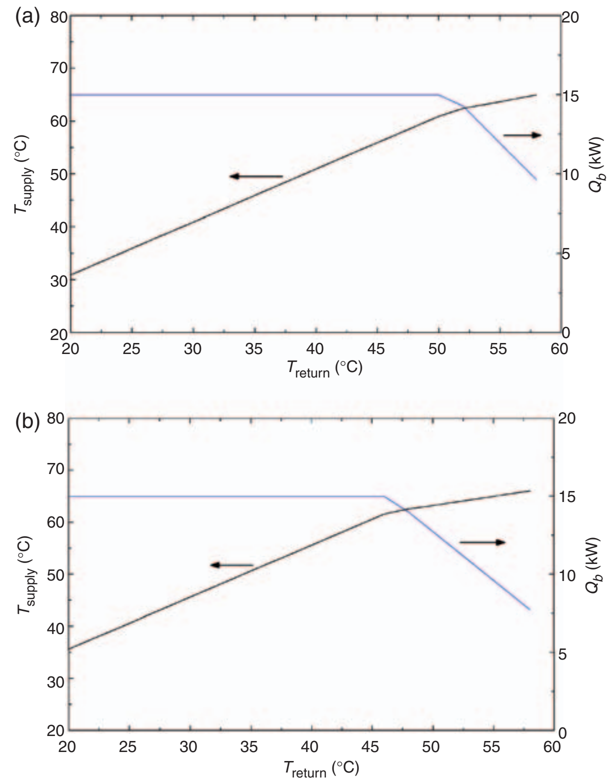

Fig. 4. Return temp. vs supply temp. and boiler output.

Simulation Results and Analysis

Our simulation was conducted on an apartment housing unit (described in Figure 1) at 0.2-h intervals for 1 week, from January 1 to 7, using the standard weather data for Seoul. Table 4 contains the heating energy consumption by the ideal heating and the Ondol heating. The on–off control and constant flow-rate control of Ondol showed similar values, as the constant flow-rate control method would adjust the flow rate with a flow-rate control valve initially following installation and used the same control approach as the on–off control method. Three methods showed significant heating energy consumption on the first day, as the initial temperature was set to 20°C.

For a case of ideal heating, the indoor temperature was set to 24°C, and it was assumed that energy required to maintain this temperature could be supplied without delay. On the other hand, it was set to 23.5–24.5°C in the case of Ondol heating, and the room temperature was set up in such a way that the heating started when the temperature of each room was less than 23.5°C and stopped, after exceeding 24.5°C, until it reached 23.5°C. The average temperature across the entire heating period was 24.0°C; however, there were over- or under-heating segments where the temperature remained outside of the 23.5–24.5°C range, which was a characteristic of Ondol heating resulting from the thermal storage effect, making precision control difficult. This also explains why it is difficult to apply the proportional control, which slows the system's response in air-conditioning of the building,

Table 4. Daily heating energy consumption (GJ)

	1	2	3	4	5	6	7	Total
Ideal	0.401	0.283	0.265	0.255	0.257	0.229	0.252	1.94
On/off	0.461	0.294	0.281	0.279	0.285	0.246	0.283	2.13
Constant flow	0.464	0.300	0.258	0.281	0.291	0.250	0.250	2.11

Table 5. Average room and surface temperatures with over- and under-heating

		Room 1	Room 2	Room 3	Living	Bath
On/Off	Air temperature (°C)	24.0	23.9	24.0	24.3	24.0
	Surface temperature (°C)	26.5	27.1	25.4	27.0	25.1
	>24.5°C (%)	10.8	4.9	6.4	38.6	16.8
	<23.5°C (%)	0	0	0	0	0
Constant flow	Air temperature (°C)	23.9	24.0	24.0	24.1	23.9
	Surface temperature (°C)	26.5	27.2	25.4	26.6	24.9
	>24.5°C (%)	8.3	7.2	12.1	23.2	4.4
	<23.5°C (%)	3.6	0.8	0.6	0	0

despite the advantage of maintaining the setup temperature. Thus, even if the heating stops when the temperature was above 24.5°C, the heat stored in Ondol would be released, which maintained the rise in indoor temperature.

Table 5 shows the average indoor and surface temperatures of Ondol for a week, as well as the over- and under-heating frequencies for 6 days, beginning with the 2nd day. Notably, the relatively higher over-heating frequency in Room 3 was due to the incorporation of the balcony into the room. As Figure 1 shows, the other rooms' balconies were incorporated; yet Room 3's balcony did not, which reduced the heating load. However, the hot water coil length was set up in proportion to the room area without considering the balcony incorporation factor, resulting in a hot water supply beyond the necessary heating load.

Over-heating appeared to be more intensive in the on–off method; however, the under-heating phenomenon, where the temperature falls below 23.5°C, hardly appeared. In other words, under-heating would tend to decrease relatively as over-heating intensified. Of course, it is difficult to conclude that the on–off control method is less advantageous than the constant flow-rate control method in terms of over-heating. However, if the flow rate distribution were inadequate, then the likelihood of over-heating and heating unbalance according to rooms may increase.

Differences in the energy consumption between the ideal heating and Ondol heating are attributable to thermal storage and heating delay effects (Table 4). As previously noted, the wall and indoor temperatures were set to 20°C initially, and a lot of energy was required to bring them up to 24°C. However, in case of Ondol, a lot of heat was released after the boiler stopped operating, with an indoor temperature reaching 24.5°C, which then resulted in the system overheating. Accordingly, more energy was consumed initially and the energy consumption subsequently decreased. The differences occurred in one day; however, these decreased significantly in terms of their cumulative value over a week. Therefore, the building energy consumption analysis and estimation have an assumption in an ideal heating which was found to produce reasonable results, even if the calculation was relatively simple, without accounting for facilities.

Figure 5 shows that the fluctuation of the heating energy supplied by a boiler with a constant flow-rate control method, as in actuality, this followed an intermittent operation pattern rather than a continuous one. Figure 6 shows the changes in the outdoor temperature, indoor temperature and Ondol surface temperature. The temperature exceeded the upper limit of 24.5°C in some of the segments. The average Ondol surface temperature varied slightly among the rooms; however, it was between 26°C and 27°C (Table 4) and seldom reached below 25°C or over 30°C momentarily (Figure 6).

The average surface temperature of Room 3 was lower because the heating frequency was far lower than the other rooms (Figure 7), and, as explained earlier on over-heating, more hot water would be supplied to the room where the heating load was smaller, resulting in more intermittent heating operations. Since such tendencies may reverse if the heating load was larger than the initial design

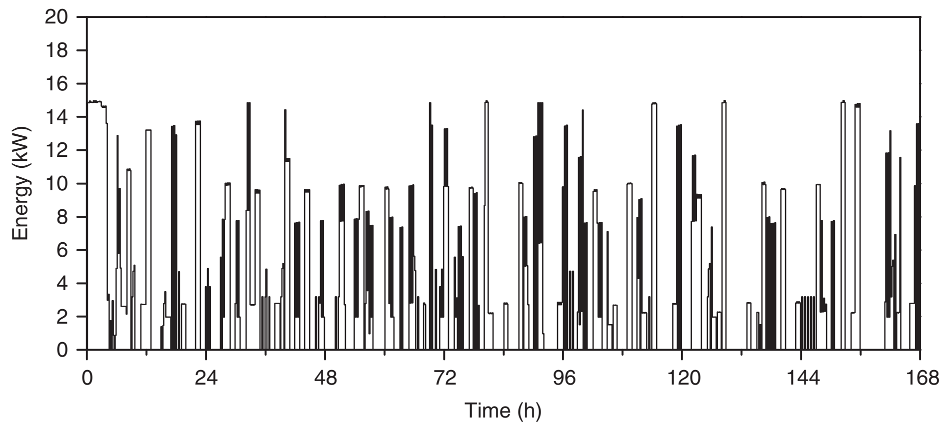

Fig. 5. Energy supplied by boiler.

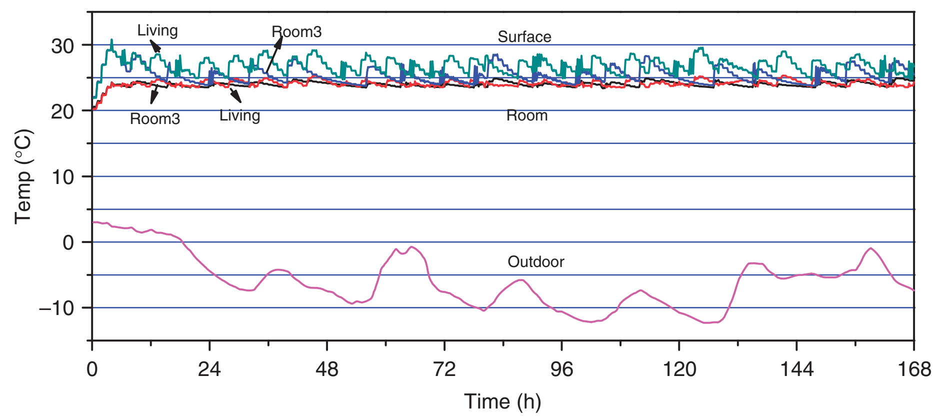

Fig. 6. Indoor, outdoor and Ondol surface temperature.

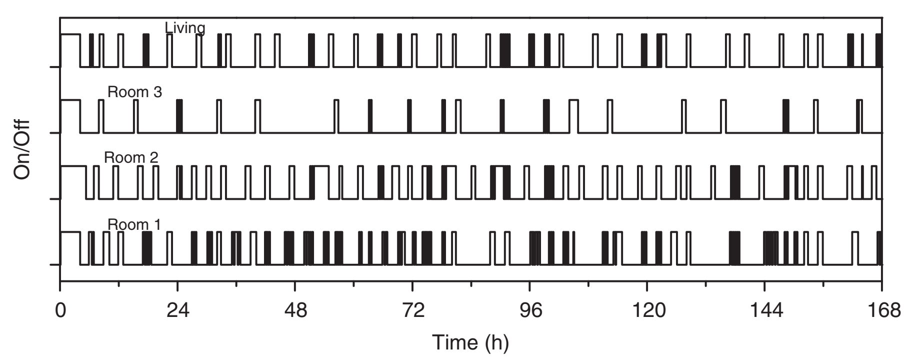

Fig. 7. On/off status of each room.

parameters, as in the case of balcony incorporation in the room extension, the adjustment of the flow-rate control valve is important.

The greater the boiler capacity, the more over- and under-heating may intensify, which results in more energy waste and less comfort for the occupants. Conversely, if the boiler capacity is excessively small, it would take much more time to increase the indoor temperature after the heating begins, resulting in less comfort for the occupants. The latest boiler models would be capable of controlling capacity within 10–100%; and have been deemed to be capable of reducing such phenomena. Subsequent studies will examine intermittent heating, boiler capacity and control of hot water distributors in more detail, including comparisons with the experimental results.

Conclusion

To secure a comfortable and healthy environment without over and under heating and with less energy consumption, a dynamic simulation of Ondol heating, using TRNSYS and EES was conducted by this study. The pump, hot water coil, pipe system and boiler performance were simultaneously solved by EES and the hot water flow rate and supply water temperature of each room calculated by EES, were fed as inputs to TRNSYS TYPE56 at each time step. The calculation results from the EES modelling were found to be well-aligned with reality.

The heating energy consumption of Ondol was greater than that of an ideal heating by 9% in the building energy simulation of an 84.7-m^2 wide apartment housing unit. However, the difference was even more significant at a daily unit, which could be attributed to the thermal storage effect of the Ondol and the intermittent operation of the boiler. The feasibility of the model and its results were confirmed as the indoor temperature exceeded the setup range between 23.5°C and 24.5°C occasionally, as in actuality.

The results from the on–off and constant flow-rate control methods were very similar. However, if the flow rate control was not adequate, most notably with a longer hot water coil than the required load, then more heat than necessary was supplied, resulting in serious over-heating. The study confirmed that the initial setting of the flow-rate control valve opening according to the heating load was very important in the constant flow-rate control method.

Acknowledgements

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