

Article

Thermal and Energy Performance Assessment of the Prefab Electric Ondol System for Floor Heating in a Residential Building

Wongun Lee ^{1,*}, Taesub Lim ^{1,*} and Daeung Danny Kim ^{2,*} ¹ Department of Architectural Engineering, Seoul University, Seoul 02192, Korea; wklee34@seoul.ac.kr² Department of Architectural Engineering, King Fahd University of Petroleum and Minerals (KFUPM), Dhahran 31261, Saudi Arabia

* Correspondence: francis9@seoul.ac.kr (T.L.); dkim@kfupm.edu.sa (D.D.K.)

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Abstract: In South Korea, radiant floor heating has been used from old housing to the recently constructed residential buildings, which is called “Ondol”. The Ondol system is generally a water-based system and it uses hot water as a heat medium provided by boilers fueled by natural gas. With great effort to reduce greenhouse gas emissions, electric Ondol panels have been increasingly applied to the recent residential buildings for floor heating. While the prefab electric Ondol panels were developed with the demand for dry construction method, the information about the prefab electric Ondol system is not sufficient. For the present study, the thermal performance of the prefab electric Ondol panels was investigated through field measurement. In addition, the heating energy and economic performance of the electric panel were compared with the conventional Ondol system. As a result, a significant surface temperature difference was observed. Moreover, the heating cost for the prefab electric Ondol system was more expensive than the conventional system, even though a heat loss was observed by the operation of the conventional system.

Keywords: prefab electric Ondol system; thermal performance; heating energy; heating cost; residential building

1. Introduction

As one of the main contributors to building energy consumption in South Korea, a residential building sector has accounted for more than 65% of total buildings in 2017 [1]. According to the report provided by the Korea Energy Economics, about 10% of the total energy was used for residential buildings [2]. Specifically, natural gas and electricity accounted for 46% and 28% of household end-use energy consumption in 2015, respectively, which were the most-used energy sources for residential buildings [2]. In addition, more than half of the annual energy consumption for residential buildings was used for space heating and cooling, and others were used for water heating, lighting, and miscellaneous equipment [3,4].

While the energy consumption for cooling has been recently increased, a significant amount of energy still has used for heating in residential buildings [5,6]. Accordingly, there are several types of heating methods available including central gas heating, district heating, and individual gas heating. As an individual gas boiler has become available with the development of infrastructures since 2000, the individual gas heating method has been dominantly used for residential buildings [7]. Traditionally, most residential buildings in South Korea have preferred to use radiant floor heating. According to the sample data of housing units in the study of Park et al., all housing units have equipped a hydronic radiant floor heating system [8]. For a radiant heating method, it is imperative to use fossil fuels for a

domestic boiler, district, or central heating in South Korea in that the greenhouse gas emissions are still increased. Therefore, it is necessary to find alternative heat sources for radiant heating in residential buildings for the goal of reducing greenhouse gas emissions [9].

The use of radiant heating enables to provide more thermal comfort to occupants in houses as well as an opportunity for the energy-saving more than the conventional air heating systems [10,11]. Many studies have performed investigations for the performance of the radiant heating method. According to the study of Lin et al., the thermal performance of a water-based radiant heating system was compared with a convective heating system in residential buildings. Even though there was little difference between the two systems, the convective heating system might cause local discomfort based on the occupants' surveys [12]. Sun et al. also investigated the thermal performance of a radiant heating system using a heat pipe [13]. In addition, the capillary tube was employed for the radiant floor heating system [14]. While water has been generally used for radiant heating systems as a heat source, radiant heating systems using electric cables have been recently adapted. Lodi et al. analyzed the efficiency of electric radiant heating systems regarding thermal comfort in old buildings [15]. As another type of electric panel, thermoelectric heating panels are used consisting of a radiant plate and several thermoelectric modules [16]. In the case of the study of Fang et al., phase change materials as a thermal storage medium were used for the electric radiant floor heating [17].

For the present study, the energy and economic performance of the electric radiant floor heating system in a residential building were assessed through the measurement and energy simulation. According to the Act on the Promotion of the Development, Use, and Diffusion of New and Renewable Energy, Korea Ministry of Trade, renewable energy systems should be designed for newly constructed residential buildings in South Korea [18]. Therefore, the electricity consumption for electric radiant floor heating systems can be offset by renewable energy systems such as electricity generated by solar PV panels. Moreover, this electric-based radiant heating system can contribute to reducing greenhouse gas emissions. However, there were a few studies for the investigation of the performance of the electric Ondol panels. Thus, this study will evaluate the thermal performance and the economic impact of the electric Ondol systems and discuss the results obtained through the measurement and the simulation. Moreover, the outcomes of the present study will be used to develop more energy and thermally efficient electric Ondol panels.

2. Prefab Electric Ondol System

Traditionally, Ondol has been used for an underfloor heating system in residential buildings, which meant a warm stone [19,20]. From the early nineteenth century to the recent construction, the Ondol system has been used in residential buildings as a representative floor heating method because of the advantage of the radiant heating [19,21,22]. By using hot water as a heating medium, hot water provided by a boiler system circulates pipes embedded in the concrete slab in that the circulation of hot water within the Ondol system can provide radiant heating. Comparing with the conventional air heating method, the Ondol system is more environmentally sustainable and cheaper regarding the life cycle cost [23–25].

In general, the Ondol system was constructed by the wet construction method on site. Nowadays, the modular construction method with prefab Ondol panels is increasingly adapted in residential buildings to enhance the construction quality and shorten the construction period [26]. The use of prefab Ondol panels can make buildings lighter than those made by the wet construction method as well as provide an opportunity to reduce construction waste [27]. While most prefab Ondol panels have used hot water from boilers fueled by natural gas or oil, another type of Ondol panel system using electricity was proposed as shown in Figure 1. According to the study of Jeong, about 10% of total energy-saving was achieved by using the prefab electric Ondol system [28]. However, there are a few studies about the performance of the prefab electric Ondol panels. To assess the performance of the prefab electric Ondol panels more accurately, the present study compared the performance of the prefab electric Ondol panels with the conventional Ondol systems in residential buildings.

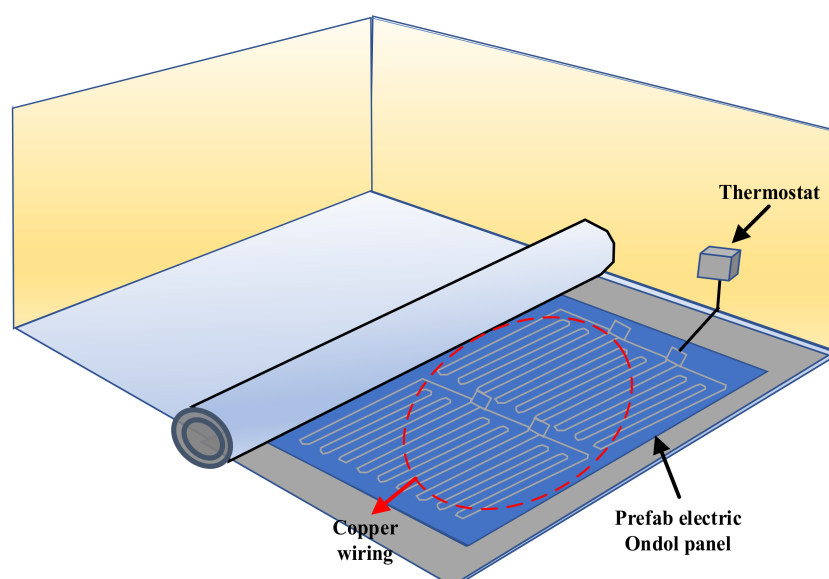


Figure 1. Prefab electric Ondol panel.

3. Methodology

To assess the thermal performance of the prefabricated electric Ondol panels, thermal performance measurement was conducted in a residential building. In addition, energy performance, especially heating was analyzed by using energy simulation.

3.1. Building Description

For the present study, an apartment building located in Seoul in South Korea was selected. The apartment building has 56 units with 16 floors. On the 8th floor of the apartment building, the unit was selected with a total area of 125 m². The measurement was conducted in the living room of the unit facing the southeast. The specification of the building envelopes of the unit was presented in Table 1.

Table 1. The specification of the envelope systems of the reference building.

U-value of walls	0.62 W/m ² K
U-value of ceiling	0.69 W/m ² K
U-value of window systems	2.8 W/m ² K
Shading coefficient	0.6
Air infiltration	2.1 cm ³ /m ²
	3 occupants
Internal heat gain	Lighting: 5.4 W/m ² Equipment: 7.0 W/m ²
Design temperature	26 °C for cooling and 20 °C for heating

3.2. Thermal Measurement

As shown in Figure 2, 9 K-type thermocouples were located on the floor with 50 cm intervals to figure out the surface temperature of the floor heated by using the prefabricated electric Ondol panels. To monitor the indoor air temperature, a thermocouple was located at 1.5 m from the floor. In addition, a thermocouple was also located outdoor. The measurement was conducted from April 27th to May 4th in 2018 and the temperature data were recorded with 10 min intervals by the datalogger. Moreover, a surface temperature on the floor was visualized by using a thermal imaging camera. The energy consumption was also monitored to compare with the energy simulation. The equipment used for the measurement was presented in Table 2.

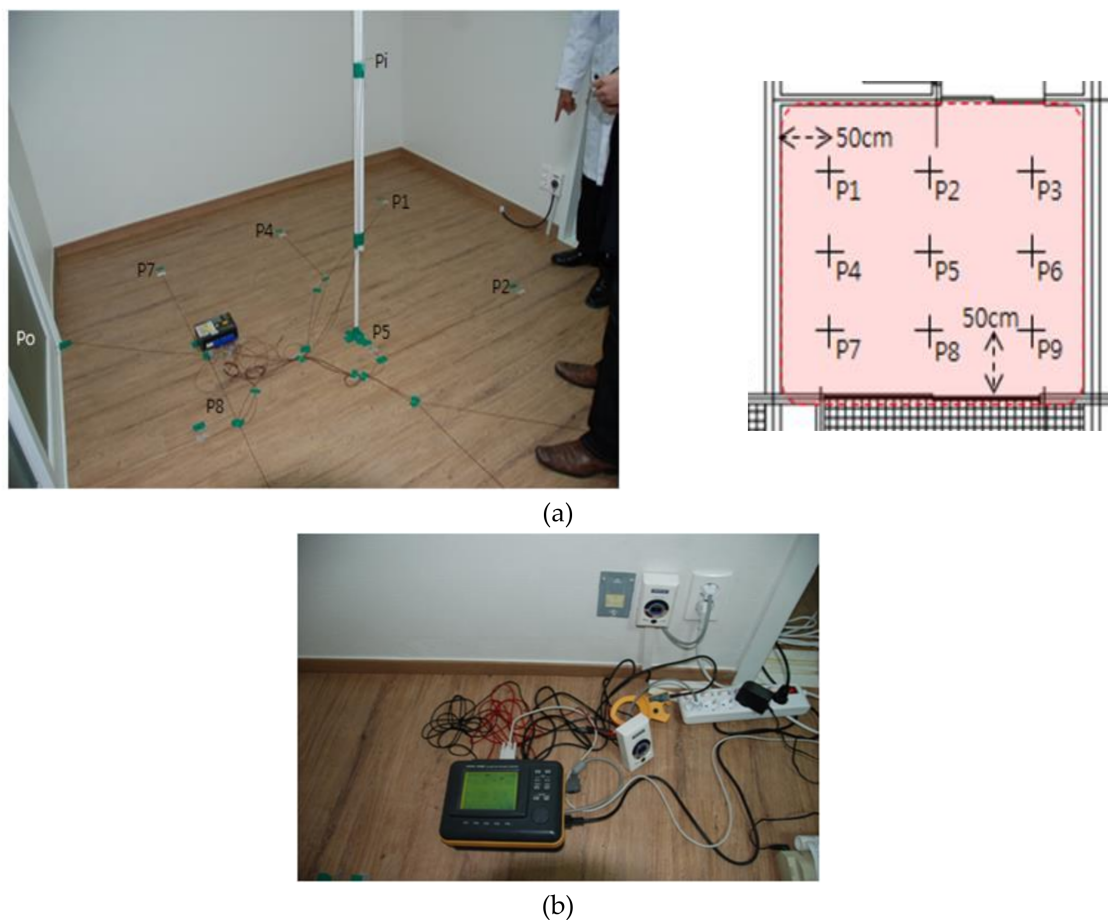


Figure 2. Thermal measurement: (a) The locations of thermocouples, (b) monitoring electricity consumption.

Table 2. Specifications of the equipment.

Power meter (3166 Clamp on Power HiTESTER, US)	- Voltage: 150 V to 600 V - Frequency range: 45 Hz to 66 Hz - Accuracy: AC Voltage: $\pm 0.2\%$ reading. $\pm 0.1\%$ full scale
Datalogger (1250 series Remote Squirrel meter/logger, UK)	AC Current: $\pm 0.2\%$ reading. $\pm 0.1\%$ full scale - Operation range: Temperature $-40\text{ }^{\circ}\text{C}$ to $+85\text{ }^{\circ}\text{C}$ - Accuracy: Temperature: $\pm 0.3\text{ }^{\circ}\text{C}$ - Response time: $<0.7\text{ s}$ (start-up 3 s)
Thermal imaging camera (testo 865, Germany)	- IR resolution of 160×120 pixels - Measuring range: $-20\text{ }^{\circ}\text{C}$ to $280\text{ }^{\circ}\text{C}$ - Accuracy of $\pm 2\text{ }^{\circ}\text{C}$ - Emissivity: 0.01 to 1

3.3. Energy Simulation

To assess the energy performance of the prefabricated electric Ondol panels, the energy simulation was performed by using eQuest 3.61, which is the comprehensive energy simulation tool to evaluate design parameters of energy conservation measures as well as provide detailed information of building energy use [29]. Using this software, the reference apartment building was modeled as shown in Figure 3.

In addition, the energy simulation was performed by using the specification of the reference building in Table 1. The residential building was operated for 24 hours and the HVAC system ran between 5 pm to 7 am. Moreover, the design temperatures for heating and cooling were set at 20 °C and 26 °C, respectively. For the conventional Ondol system, a central water-to-water heat pump system was modeled for providing hot water, while the data obtained from the measurement were used for the prefabricated electric ondol model. The annual energy consumption of the unit by using the conventional Ondol system fueled by natural gas was compared with that operated by the prefabricated electric Ondol panels. For the simulation, the TMY weather data of Seoul in South Korea was utilized. The mean air temperature in Seoul was about 13 °C. The lowest and highest air temperatures were −12.6 °C and 35.4 °C, respectively. The mean wind speed was 2.2 m/s.

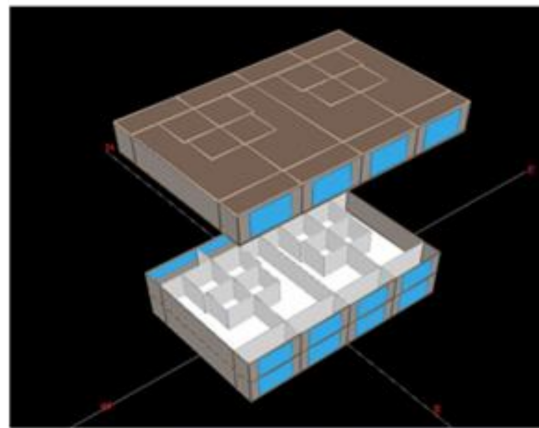


Figure 3. Computational model of the apartment building.

By using the coefficient of variation of the root mean squared error (CV(RMSE)) provided by ASHRAE Guideline 14, the monthly energy consumption of the reference residential building with the conventional Ondol system was compared with the energy simulation [30]. The models will be declared to be calibrated if they produce CV(RMSE)s within ±15% with monthly energy data.

$$RMSE = \sqrt{\frac{\sum_{i=1}^n (M_i - S_i)^2}{n}} \quad (1)$$

$$C_V(RMSE) = \frac{RMSE}{M_{avg}} \times 100 \quad (2)$$

where M_i is the energy consumption of the residential building, while S_i is the monthly energy consumption by energy simulation. n is the period and M_{avg} is the average for the energy consumption of the residential building.

4. Result

4.1. Thermal Performance of the Prefab Electric Ondol Panels

Figure 4 shows the air temperature distributions of the surface on the floor and the indoor and outdoor on May 2nd and 3rd. From 0 to 19:30 h on May 2nd, the heating was off and the indoor air temperature and the surface temperature on the floor were maintained at about 19.5 °C because of the thermal capacity of the building envelopes. From 19:30 h on May 2nd to 24 h on May 3rd, heating was provided by using the prefabricated electric Ondol panels. While the setpoint temperature for the Ondol panels was set at 60 °C at full-load, the maximum surface temperature on the floor was maintained at about 50 °C. In addition, the minimum surface temperature on the floor was about 28 °C. Even though the surface temperature on the floor was increased about 7 °C by the operation of

the Ondol panels, the increase in the indoor air temperature was only about 4 °C with/without the Ondol panels. Thus, the indoor air temperature was about 24 °C. The operation of the Ondol panels took 1.4 kWh of electricity. Moreover, the surface temperature on the floor was visualized by using the thermal imaging camera (Figure 5). As shown in Figure 4, the maximum and minimum surface temperature difference was more than 20 °C and the surface temperature was higher than the indoor air temperature. It can be seen that water from conventional Ondol systems can transfer radiant and convective heat into the indoor fully because of higher heat capacity of water than that of air, while the electric Ondol panels only heated the floor directly. This caused the lower indoor air temperature than the surface temperature on the floor.

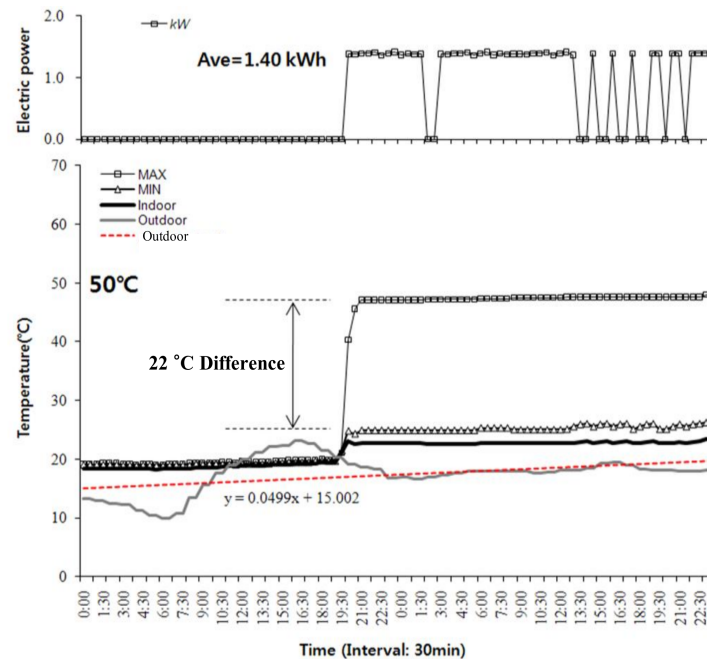


Figure 4. Temperature distribution and the electricity consumption.

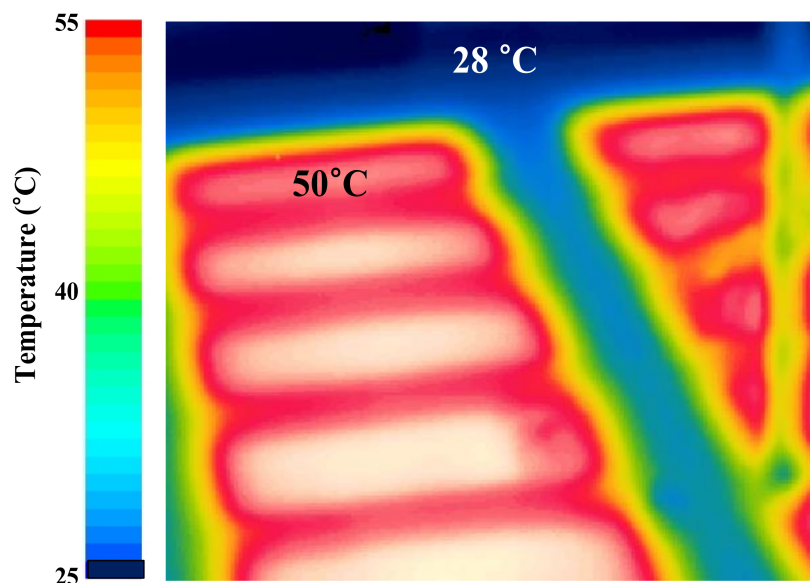


Figure 5. Temperature distribution by the thermal imaging camera.

4.2. The Analysis of the Energy Consumption

4.2.1. The Comparison between Energy Simulation and the Monthly Energy Consumption

To confirm the validity of the energy model, the monthly energy consumption of the selected unit of the apartment building was compared with the energy consumption prediction. The energy simulation modeled the conventional Ondol system fueled by natural gas. As can be shown in Table 3, the total energy consumption of the selected unit and the energy simulation were 7862 kWh and 8611 kWh, respectively. In addition, the root mean squared errors (CV(RMSEs) ranged from 0.18 to 7.77. Even though there was much difference between the data and the prediction in December, all the values were within the acceptable range, the predicted results by the simulation met the requirement by ASHRAE Guideline 14 [30].

Table 3. The monthly energy consumption comparison.

Month	Energy Consumption (kWh)			CV(RMSE) (%)
	The Selected Unit of the Apartment Building	Energy Simulation	Difference	
January	769.3	860.0	−90.7	4.00
February	664.5	779.0	−114.5	5.04
March	640.2	745.0	−104.8	4.62
April	576.0	580.0	−4.0	0.18
May	589.2	512.0	77.2	3.40
June	607.7	648.0	−40.3	1.78
July	748.4	799.0	−50.6	2.23
August	792.5	823.0	−30.5	1.34
September	612.2	786.0	−173.8	7.66
October	564.4	644.0	−79.6	3.51
November	578.5	680.0	−101.5	4.47
December	719.3	755.0	−35.7	1.57

4.2.2. The Heating Cost Analysis

Considering the heating energy consumption, the annual heating cost for the conventional Ondol system and the prefabricated electric Ondol panel system was analyzed for 8 months (October to May) (Figure 6). Tables 4 and 5 show the heating energy consumption and the cost of these two heating methods. The total heating cost for the conventional Ondol system and the prefabricated electric Ondol system were \$140.5 (US dollar) and \$313.2 (US dollar), respectively. As a result, the prefabricated electric Ondol system requires about 53% of the additional heating cost.

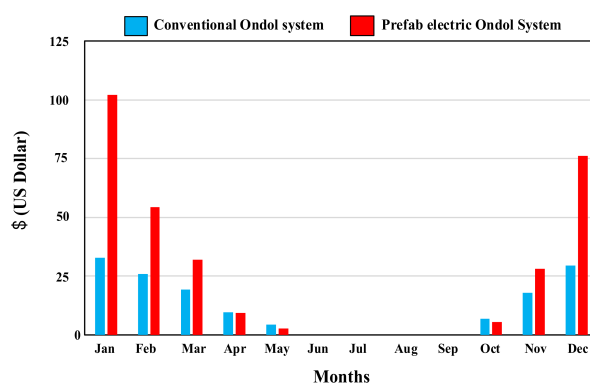


Figure 6. The heating cost comparison between the conventional Ondol system and the prefabricated electric Ondol system.

Table 4. The conventional Ondol system.

Month	Jan	Feb	Mar	Apr	May	Jun	July	Aug	Sep	Oct	Nov	Dec	Total
Heating energy consumption (kWh)	624.7	488	374.4	175.8	66.3	0	0	0	0	119	348.6	559.4	2756
Heating cost Demand charge (\$US dollar)	1.13	1.13	1.13	1.13	1.13	0	0	0	0	1.13	1.13	1.13	-
Energy charge (\$US dollar)	32	25	18	8.6	3.2	0	0	0	0	5.8	17	28.6	-
Monthly total heating cost (\$US dollar)	33	19.4	19.4	9.7	4.4	0	0	0	0	6.9	18	29.7	\$140.5/year

Table 5. The prefab electric Ondol panel system.

Month	Jan	Feb	Mar	Apr	May	Jun	July	Aug	Sep	Oct	Nov	Dec	Total
Heating energy consumption (kWh)	571	446	342	161	61	0	0	0	0	109	319	511	2520
Heating cost Demand charge (\$US dollar)	8.2	4.5	2.4	0.6	0.03	0	0	0	0	0.6	2.4	8.2	-
Energy charge (\$US dollar)	95	50.3	30	9	2.7	0	0	0	0	5.1	26	68.4	-
Monthly total heating cost (\$, US dollar)	103	55	32	9.5	2.7	0	0	0	0	5.6	28.4	77	\$313.2/year

5. Discussion

The present study assessed the thermal and energy performance of the prefabricated electric Ondol panel comparing with the conventional Ondol system. Considering the result of the thermal measurement, a notable surface temperature difference was observed when the prefabricated electric Ondol system was applied. In addition, the increase in the surface temperature on the floor was about 30 °C, while about a 4 °C increase in the indoor air temperature was observed. This can cause thermal stratification, as well as occupants, can be dissatisfied thermally. Finally, it may require a significant amount of energy for thermal comfort. Considering the balance point temperature and the heat gain/loss by building envelopes. Thus, it is also necessary to conduct thermal measurement in a chamber by varying climate conditions.

As shown in Figure 7, the use of the prefabricated electric Ondol panels cost 50% more than that of the conventional Ondol system, while the heating energy consumption of the prefabricated electric Ondol system was about 8.6% lower than that of the conventional Ondol system. This was caused by the progressive electricity billing during the winter period (December to February) in South Korea, while the price of natural gas was the flat rate. Therefore, it requires to find out the criteria for assessing the performance of the prefabricated electric Ondol panel system more accurately.

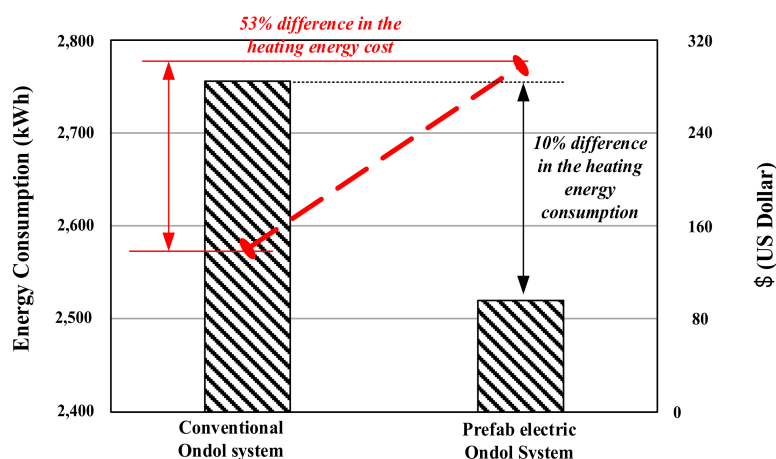


Figure 7. The heating energy and cost comparison.

Another important design consideration for the use of the electric Ondol panel system is electromagnetic waves. According to the National Radio Research Agency in South Korea, the permissible exposure limit is 833 mG, which is quite bigger than the permissible limit of the United States (2 mG) and Swiss (10 mG) [31,32]. Even though the electromagnetic wave of the prefabricated electric Ondol panel system ranges generally 0.4–0.5 mG, it requires further investigation for the electromagnetic waves from this electric Ondol panels and re-assessment with the permissible limit of other countries.

6. Conclusions

With an increasing demand for the dry construction method, the use of prefabricated Ondol panels has simplified building construction methods and shortened construction periods, where Ondol floor systems have been dominant. In addition, the electric Ondol panel system has become attractive due to its simplicity and electricity provided by the solar PV panels. The newly constructed residential buildings in South Korea should equip renewable energy systems. Even though the use of the prefabricated electric Ondol panel system has been rapidly increased, there were a few studies about the performance of this panel system.

For the present study, the thermal performance of the prefabricated electric Ondol system was investigated through the on-site measurement. In a unit of an apartment building, the surface temperature on the

floor and the indoor and outdoor air temperatures were measured. As a result, a significant surface temperature difference was observed. In addition, the use of the prefabricated electric Ondol system rarely influenced indoor air temperature. The increase in the indoor air temperatures was quite lower than the increase in surface temperature on the floor with/without the use of the electric panels. This was also visualized by using a thermal imaging camera. Moreover, the heating cost for these two systems were evaluated by using energy simulation. The heating energy consumption in the unit with the prefabricated electric Ondol panel was about 10% lower than that by the conventional Ondol system fueled by natural gas. However, more than 50% of the heating cost was required for the electric Ondol system than the conventional one. It was caused by different energy sources.

Regarding the views of thermal and heating cost performance, the advantage for the use of the prefabricated electric Ondol panel system is not clear, even though this system has several advantages in terms of construction. For further study, it is necessary to investigate electromagnetic waves from the electric Ondol panels for occupants' safety in buildings. In addition, it requires to conduct measurements with various types of Ondol panels during the winter. To figure out the surface temperature distribution, it is also necessary to employ computational fluid dynamics simulation. Moreover, the life cycle cost analysis is required for the complete investigation of the economic impact of the electric Ondol system.

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