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Energy Saving Potential of an Air Source Heat Pump Heating System Compared with a Radiant Floor Heating System with Ventilation in an Apartment Building

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Abstract

This study aims to investigate and compare the energy performance of an air source heat pump heating system and a radiant floor heating system with an energy recovery ventilator in an apartment building. The thermal load for a conditioned zone was derived using simulation tool TRNSYS 18, and the total energy consumption of the systems was calculated using an engineering-equation-solver (EES) for each component model. The coefficient of performance (COP) of the heat pump was calculated as 3.16, and the efficiency of the boiler in a radiant floor system was established as 0.9. The results indicate that the proposed system reduces energy consumption by 21.8% compared with the conventional floor heating system. The primary reason for this result is because the COP of the heat pump is dominant, even though the primary energy factor of electricity is 2.75.

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1. Introduction

Radiant floor heating systems have been developed and used in Korea for residential buildings for over 500 years. The traditional radiant floor heating system is called Ondol, and it is very efficient because the floor is heated using waste heat leftover from kitchen use in the past [1]. Furthermore, the system provides abundant thermal comfort for a sedentary lifestyle [2]. In modern times, people have applied radiant heating systems by laying water pipes under the floor, instead of using waste heat.

It is recent knowledge that energy consumption in buildings accounts for a significant portion of total energy use, and therefore, various methods to minimize building loads have been suggested. One system that can minimize load is the heat pump, which has been adapted to numerous HVAC systems and is classified as a renewable energy source in Europe [3]. Worldwide, there has been considerable research undertaken regarding the heat pump and how to improve its performance under various operation conditions [4,5]. However, in Korea, heat pumps are only installed in commercial buildings and office buildings [6,7], because radiant floor heating systems have traditionally been used in Korea and are heavily preferred for residential buildings.

In addition, apartments recently built in Korea are equipped with built-in air conditioners for cooling the air during the summer. Although a single heat pump can be used for both cooling and heating, the heat pump-based air conditioners in Korea are used for cooling in the summer; however, they are not used for heating in the winter. Instead, the space is heated by radiant floor heating in the winter. By separating the cooling and heating systems, the construction and management costs and time are increased.

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In this study, the potential of integrating cooling and heating into a single heat pump system was investigated. This would eliminate the need for two different systems. Additionally, the energy use of a radiant floor heating system was compared with a heat pump air heating system.

2. System Overview

2.1. Air heating system

Figure 1 shows an air heating system with an air-source heat pump and an enthalpy recovery ventilator. Explained briefly, a heat pump used in the reverse cycle (to the vapor compression cycle) will result in the pump pulling up low heat from the source to the high heat storage. A heat pump consists of a compressor, a condenser, an evaporator, and an expansion valve. Refrigerant absorbs heat in the evaporator and releases it out to the heat sink in the condenser, using input power. The released heat is then used to heat the conditioned zone by supply air.

For this research, the type of air source was selected so that the heat pump obtained heat from the outside air. This was because the system was already installed for cooling in the summer, as is common in Korean apartments, and thus was available for both heating and cooling. Simply driving the vapor-compression cycle in the reverse direction, the air conditioner functioned as a heat pump cycle. However, it could not be used for heating due to the differences in the ambient and supply air temperatures of summer and winter. Because the amount of heat absorption and dissipation depends on the operating conditions, the design for the existing air conditioner had to be redesigned for heating use. The detailed temperature setting and design process for each component is covered in the simulation overview below. In the case that the air supply cannot reach the desired target point (due to insufficient capacity), a heating coil was added before supply to be achieved through as an auxiliary heater.

The air heating system was separated from the ventilation system, which is different from conventional heating, ventilation, and air conditioning (HVAC) systems. Thus, the heat pump only recirculates the indoor air, and effectively handles the building load.

In an enthalpy recovery ventilator (also called an energy recovery ventilator (ERV)), an enthalpy exchanger can be used to transfer the energy, including sensible and latent heat. During the heating season, the system takes heat from the return air and uses it to heat the outdoor air and supply fresh air into the room. Generally, an enthalpy recovery ventilator is used to pre-cool, or pre-heat, before air-conditioning. This process not only reduces system loads, but also satisfies ventilation requirements. For this study, the enthalpy recovery ventilator was separated from the heating systems.

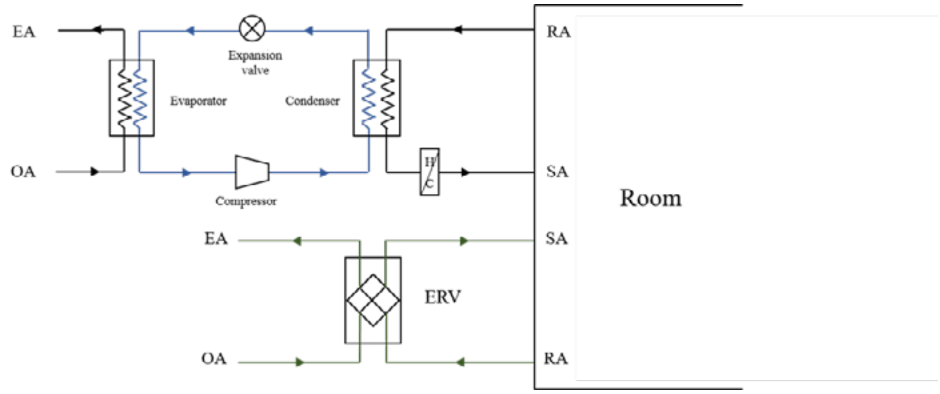


Fig. 1. Schematic of Air Heating System with an Air Source Heat Pump and an Enthalpy Recovery Ventilator (ERV)

2.2. Floor heating system

Figure 2 shows a floor heating system with a radiant floor and enthalpy recovery ventilator. Radiant floor heating system have water pipes buried in the floor. As hot water flows through the pipes, the heat is absorbed by the floor, and released to the room above.

The heat is transferred by conduction from the water pipes to the concrete layers, then by convection from the flooring to the air through natural stratification, and by radiance between the heated floor and other walls according to temperature differences. The heating capacity of the radiant floor depends on the spacing of the pipes, diameter of the pipe, heat conductivity of the pipe, heat resistance of the concrete layer and floor structures, water temperature, and the mass flow rate through the pipes. Because the process of heat transfer is complex and relies on several variables, it is difficult to calculate the heating capacity of radiant floor heating systems.

Radiant floor heating systems make structures (such as floors) warm first, and then use the structures to heat the room. This is different from heat pump heating systems that heat the air and supply directly. In terms of the energy used for heating, indirect heating systems use more energy than direct heating systems.

Similar to the air heating system described above, the floor heating system was separated from the ventilation system. Thus, the radiant floor only handles the building load and ventilation load of the space by itself. An enthalpy ventilator in the proposed floor heating system was operated in the same way addressed previously for the air heating system.

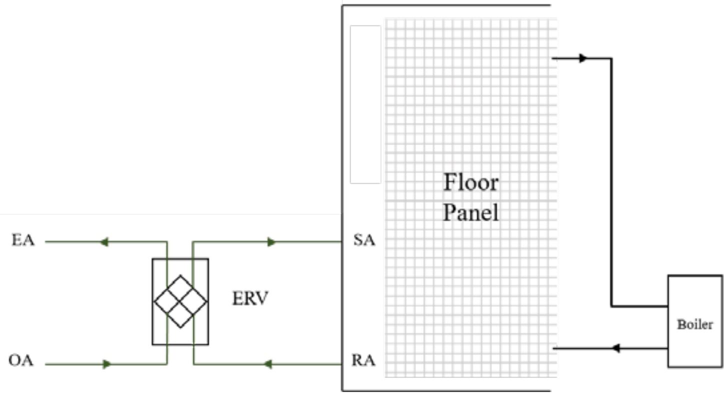


Fig. 2. Schematic of Floor Heating System with a Radiant Floor and an Enthalpy Recovery Ventilator

3. Energy Simulation

3.1. Simulation overview

The energy simulation to calculate the performance of the air heating system and the floor heating system was conducted using engineering-equation-solver (EES). The heating loads to be handled by the systems were derived through an energy simulation tool TRNSYS 18. The model space was designed to have a floor area of $100\ \mathrm{m}^2$ with $3\ \mathrm{m}$-height, located in Seoul, South Korea. Structures such as walls, floors, ceilings, and windows, were designed to satisfy the U-values of domestic legal standard. There were five occupants in the space and the room temperature was maintained at 22 ºC. For both systems, the simulation was set to turn on only when residents occupied the space. Additional physical information for the model is described in Table 1.

Table 1. Model building parameters

Location	Seoul, South Korea	
Volume	$10\ \mathrm{m} \times 10\ \mathrm{m} \times 3\ \mathrm{m}, 300\ \mathrm{m}^3$	
Window-to-Wall Ratio	0.25	
U-value	Ceiling	$0.117\ \mathrm{W/m^2}K$
	Wall	$0.117\ \mathrm{W/m^2K}$
	Window	$0.95\ \mathrm{W/m^2K}$
	Floor	$0.132\ \mathrm{W/m^2K}$

Schedule	20:00 – 8:00 on weekdays, all day on weekends

The ventilation load (Q_{vent}) was acquired by calculating the temperature of the air passing through the enthalpy recovery ventilator (T_{erv}), and the airflow rate of ventilation requirements ($\dot{V}_{vent}$) through Eq. (1). The airflow rate of ventilation to fulfill the requirements for five residents was set to follow the ASHRAE standard 62.1 [8]. The temperature passing through the enthalpy recovery ventilator was calculated for sensible and latent heat exchange efficiencies. The efficiency was set to 70%, and 50% for the sensible heat exchange and for the latent heat exchange, respectively [9]. As shown in Figs. 1 and 2, an energy recovery ventilator was included in both systems. Thus, an equal ventilation load was added to the building load for both systems. For an enthalpy recovery ventilator, the heat exchange takes place between the outdoor air and return air from the conditioned zone. The outdoor air takes heat from the return air and supplies fresh air to conditioned room.

$$\dot{Q}_{vent} = \rho \cdot \dot{V}_{vent} \cdot c_p \cdot (T_{ra} - T_{erv}) \tag{1}$$

3.2. Air heating system

In order to design the optimal heat pump size for the residential place, it was important to make the compressor small, so that the temperature to be pumped up from the heat source was reduced. The design flow rate of the supply air (V_{sa}) was set to 1000 m^3/h, adequate for residential spaces, and the design temperature of the supply air (T_{sa}) was set to 34 °C to manage the derived heating load. Thus, the design temperature of the condenser was set to 40 °C. The flow rate of the supply air ($\dot{V}_{sa}$) was variable and determined by the loads to be managed, as described in Eq. (2). The design temperature of the evaporator was set to −20 °C because it had to absorb sufficient heat from the cold outdoor air. Assuming that the evaporator exchanges sufficient heat with outdoor air by a large enough flow rate. The flow rate of the exhaust air ($\dot{V}_{ea}$) was controlled by the amount necessary at the condenser, calculated using Eq. (3) within 1000 m^3/h, that is the design flowrate of exhaust air. The load to be absorbed from the outdoor air was acquired by multiplying the cooling capacity at the evaporator ($Q_{hp,evap}$) and circulated amount of refrigerant (G). The coefficient of performance (COP) of the heat pump was considered as a fixed value, because the inverter control of the compressor in the heat pump was adapted by calculating the amount of refrigerant circulated (G) required every hour [10]. Hence, when the amount of heat from 1000 m^3/h of outside air at the evaporator was lacking compared with the amount required at the condenser for the heating load, the heating coil was turned on to heat up the supply air. The heat exchange efficiency between the outside air and the evaporator was assumed as 70%, and the heat exchange efficiency between the return air and condenser was also assumed as 70%. The compressive efficiency of the compressor was also 70% (used commonly) and the actual enthalpy of compressor was derived using the compressor efficiency. The design parameters of the heat pump are organized below in Table 2.

$$\dot{V}_{sa} = \frac{Q_{heating\ load} + Q_{ventilation\ load}}{\rho_{sa} \cdot cp_a \cdot (T_{sa} - T_{ra})} \tag{2}$$

$$\dot{V}_{ea} = \frac{Q_{hp,evap} * G}{\rho_{ea} \cdot cp_a \cdot (T_{oa} - T_{ea})} \tag{3}$$

Table 2. Designed specifications of the heat pump

Specifications	Values
Heating capacity	4 kW
COP	3.16
Circulating refrigerant	70 kg/h
Nominal horse power	2.5 PS

As explained in the details above, the heating coil was turned on only when the supply air did not reach its desired value. The primary energy consumption of the electric heating coil was multiplied by the primary energy factor of electricity.

The power of the variable flow fans was estimated using the general variable-air-volume fan power equation stated by ASHRAE 90.1 [11]. The part load ratio of the variable flow fan is the ratio of the present airflow rate to the design airflow rate. The efficiency of each fan was assumed to 50%. The design pressure drop of each fan was referred from previous studies [12]. In particular, for the supply fan and exhaust fan, the pressure drop was used by referring to the value from the variable air volume (VAV) system.

3.3. Floor heating system

Similar to the way we calculated the performance of the heat pump system with the inverter control, the performance of the floor heating system was also calculated using the boiler by part load ratio. The performance of floor heating systems has been evaluated by several previous studies [13].

To manage the required heating load for the floor heating system, a conventional gas boiler was used to supply hot water to the pipes buried under the floor. The boiler was operated using the modulated part load ratio, depending on the heating load to be administered. The part load ratio of the boiler is the ratio of the present heating load to the design heating capacity of the boiler. It was set to 0.4 as referred to from previous studies [14].

The boiler energy ($\dot{Q}_{boiler}$) was calculated using the simple hot water boiler Eq. (4) suggested by Energy Plus, which takes into account the efficiency of boiler ($\varepsilon_{\mathrm{boiler}}$) and the boiler efficiency performance curve (BEC). The efficiency of the boiler was set to 90% for this research.

$$Boiler\ Efficiency\ Curve = f(PLR_{boiler}) \tag{5}$$

$$\dot{Q}_{boiler} = \dot{Q}_{heating}/(\varepsilon_{boiler} \cdot Boiler\ Efficiency\ Curve) \tag{6}$$

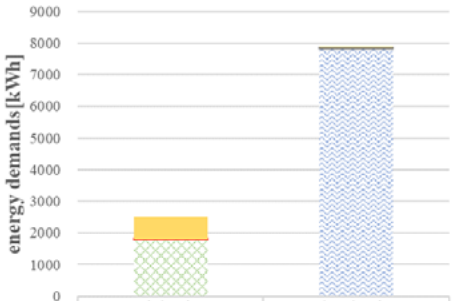
There was only one pump in the floor heating system supplying hot water. The power calculation of the pump was estimated by the fan power equation, suggested from Energy Plus, and the efficiency of the pump was assumed to be 60%.

4. Simulation Results

The energy performance evaluation of the air heating system and the floor heating system was conducted for four months, during the heating season from December to March. Figure 3 shows the total energy demands of each system, and also the demands of each component.

In the air heating system, the heat pump was only used to heat the room, and for managing the heating load and ventilation load as indicated in the simulation overview section. As shown in Fig. 4, fan power comprised a significant amount of energy needed for the heat pump heating system. This was because the equation used was a function of the part load ratio and pressure drop of the fan. Because the fans used in the air heating system were designed to have 1000 m^3/h, a significant pressure drop was applied.

In the floor heating system, the energy consumption was calculated assuming that a boiler produces hot water for traveling through the pipes to satisfy the heating and ventilation load. Thus, a gas boiler was controlled to modulate as required to reduce energy consumption. As a result, the air heating system requires 68.3% less energy than the floor heating system.



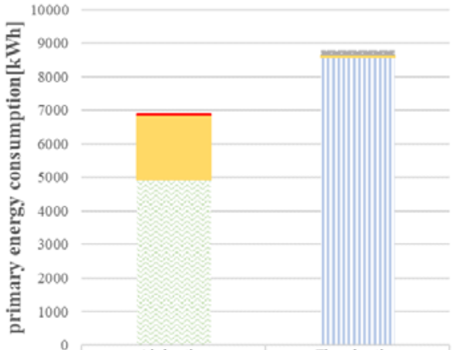
	Air heating	Floor heating
Fan	699	13
HC	10	0
Pump	0	57
Boiler	0	7811
HP	1791	0

HP Boiler Pump HC Fan

Fig. 3. Energy Demands of Air Heating Mode and Floor System during Heating Season (Dec, Jan, Feb, Mar)

To compare the equivalent energy performance of both systems, and because the two systems have different energy sources, primary energy factors adequate for each system were applied. For the air heating system, the heat pump, fan, and auxiliary heater (electric heating coil) all use electricity. For the floor heating system, the boiler uses natural gas, however, the fan and pump both use electricity. The applied local primary energy factors are 2.75 for electricity, and 1.1 for natural gas. Because both systems process equivalent sensible loads, including ventilation load, the energy consumption of an energy recovery ventilator (ERV) fan was applied for both systems. As seen in Fig. 4, the primary energy consumption of the air heating system became larger than energy demands for it, and yet the air heating system still consumes less energy than the floor heating system.

In conclusion, it was observed that the air heating system consumed a total of 21.8% less primary energy when compared with the floor heating system using a conventional gas boiler in total.



	Air heating	Floor heating
Pump	0	157
HC	28	0
Fan	1921	36
HP	4924	0
Boiler	0	8592

Boiler HP Fan HC Pump

Fig. 4. Primary Energy Consumption of Air Heating Mode and Floor System in Heating Season (Dec, Jan, Feb, Mar)

5. Conclusion

For this research, an air heating system with a heat pump and floor heating system with radiant floors were compared from the view of total energy consumption. The air heating system required 68.3% less energy than the floor heating system to handle total loads. Furthermore, the air heating system consumed 21.8% less energy than the floor heating system, even though a significant energy factor was observed because electricity was adapted for the system. If a gas heat pump was to be applied, instead of an electricity heat pump, it is calculated that an additional reduction of approximately 55% or more of reduced energy will be seen.

While floor heating systems are poor choices in view of the high energy consumption they require, they still are a strong preference among building occupants in regard to thermal comfort. Further studies in terms of occupant thermal comfort are required in the future. If further studies establish that floor heating systems are preferred for thermal comfort, combined heating systems using radiant floor heating and a heat pump can be adapted to apartments in Korea.

Acknowledgements

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