Energy performance of balanced heat recovery systems with different terminal systems

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ABSTRACT
This study investigated the influence of terminal system types on a balanced heat recovery (BHR) system in terms of energy. We compared the energy performance of BHR systems with a convective (Case 1) and with a radiant terminal (Case 2) on their total energy demand when removing loads. The total energy demand of heat production (i.e., a heat pump) and distribution (i.e., a pump and a fan) is sum of all demanded energy. Differences in total energy demand were simulated for a space with simultaneous heating and cooling loads. The total energy demand was lower for Case 2 than Case 1. The main reason for this was the higher efficiency of the refrigeration plant for Case 2 from the smaller temperature difference between the condenser and the evaporator. Moreover, the radiant terminal was more suitable for the BHR system, because the capacity difference between hot from the condenser and cool from the evaporator was smaller than that for the convective terminal.

KEYWORDS
Balanced heat recovery, Energy performance, Terminal system, Comparison study

INTRODUCTION
The occurrence of very large complex buildings, which mostly have simultaneous heating and cooling, has led to an increased need for a balanced heat recovery (BHR) system, which works year-round to recover all the internal cool and hot heat instead of adding external heat (ASHRAE 2012). In addition, the thermal need of the building become more balanced between heating and cooling. Internal heat gain from various electrical equipment increases the cooling demand, and improved thermal envelope requires reduced heating demand and increased cooling demand (Byrne et al. 2009). Several studies presented the feasibility of this system by comparing cooling and

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heating load profiles (Shin et al. 2011, Ghoubali et al. 2014).

The BHR system includes process of production (including storage), distribution, and supply of hot and cool heat to remove heating and cooling loads from zones. To reduce the total energy demand for zone heating load removal, the energy demand for production and distribution, and the heat loss from storage and distribution process should be reduced. Most types of convective and radiant terminals can be applied to remove zone heating and cooling load. These two terminal types require different thermal medium temperature, distribution system, and equipment capacity. The heat flow and energy demand of BHR system could therefore be different for the convective and radiant terminal.

Shin et al. (2012) suggested the possibility of reduced energy demand by applying the radiant terminal in the BHR system, because of the smaller temperature difference between the condenser and evaporator than that with the convection system. With this assumption, they proposed an Energy Balancing System based on BHR system equipped with a radiant terminal. Geothermal and wastewater whose temperatures were similar to that of the return water from radiant cooling were utilized as auxiliary heat sources. In addition, a control strategy of mode selection for balancing, wastewater recovery, and geothermal use was proposed.

This study aimed to investigate the influence of the terminal system types on a BHR system in terms of energy performance. The energy performance of BHR systems with convective and radiant terminal was compared on their heat flow and energy demand during load removal.

RESEARCH METHODS

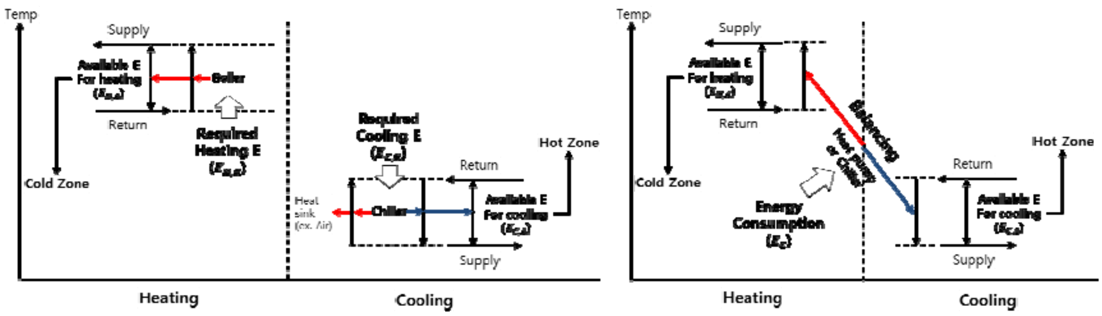
To compare the influence of the terminal system types based on the BHR system's energy performance, 1) the concept of BHR system was defined, 2) the method to evaluate the energy performance of the BHR system based on the heat flow and energy demand were investigated, and then 3) the energy performance of BHR system with a convective and a radiant terminal were compared.

The BHR system

For the heating or cooling, heating or cooling load should be removed by thermal medium. To remove the heating or cooling load, the thermal medium at a certain level of temperature, so it can contain available energy (E_A), should be supplied. To perform heating or cooling effectively and continuously, a process that makes a thermal medium with E_A is necessary. To make a thermal medium with E_A, required heating energy ($E_{H,R}$) and cooling energy ($E_{C,R}$) should be inputted to returned water which doesn't contain E_A.

In conventional heating and cooling, it is general to apply a boiler to make available energy for heating side ($E_{H,A}$) and a chiller to make available energy for cooling side ($E_{C,A}$). In this case, the energy consumption (E_C) is $E_{H,R}$ + $E_{C,R}$ (Figure 1(a)).

In BHR system, the refrigeration plant (e.g. heat pump or chiller) is applied between heating and cooling side to utilize both of heating and cooling capacity. The byproduct cool of heating side could be $E_{C,A}$, and the byproduct heat of cooling side could be $E_{H,A}$ simultaneously. (Shin et al. 2011). When $E_{H,R}$ and $E_{C,R}$ are similar, E_C is not $E_{H,R}$ + $E_{C,R}$ but smaller than $E_{H,R}$ or $E_{C.R}$ when the energy balancing concept of BHR system is applied (Figure 1(b)).



(a) Conventional system (b) BHR system

Figure 1. *Concept diagrams of conventional system and BHR system*

To realize this concept, it is necessary to apply a refrigeration plant (e.g. heat pump and chiller), because of its simultaneous heating capacity (hot heat) at the condenser and cooling capacity (cool heat) at the evaporator. In addition, storage is required, including chilled water tanks (CHWT) and hot water tanks (HWT), to perform balancing more energy by keeping the hot and chilled return waters, because the heating and cooling loads often occur at the different time.

Energy performance of BHR system with a convective or a radiant terminal

General heating, ventilation, and air conditioning (HVAC) systems perform hot and cool production (including storage), distribution, and load removal processes. The energy performance is related to the heat flow and energy demand for each process.

The heat flow is the heat gain or loss from the heat production to the load removal process, passing through the storage and distribution processes. Reducing heat losses in the storage and distribution processes are important, because the heat that needs to be produced is the required heat for heating and cooling in the zone and the heat losses additionally.

The energy demand for specific equipment is the energy input for production and distribution of hot or cool heat. The total energy demand is the summed energy demand of a plant and its distribution equipment.

The BHR system performs the same processes as an HVAC system and consists of the plant (including storage), distribution, and terminal systems to perform each process. A refrigeration plant and storage should be applied in the plant and storage system. Pipes and pumps are required for the distribution system when its thermal medium is fluid and ducts and fans when it is air. The distribution system depends mainly on the terminal system, and the convective and radiant terminals can be applied (Figure 2).

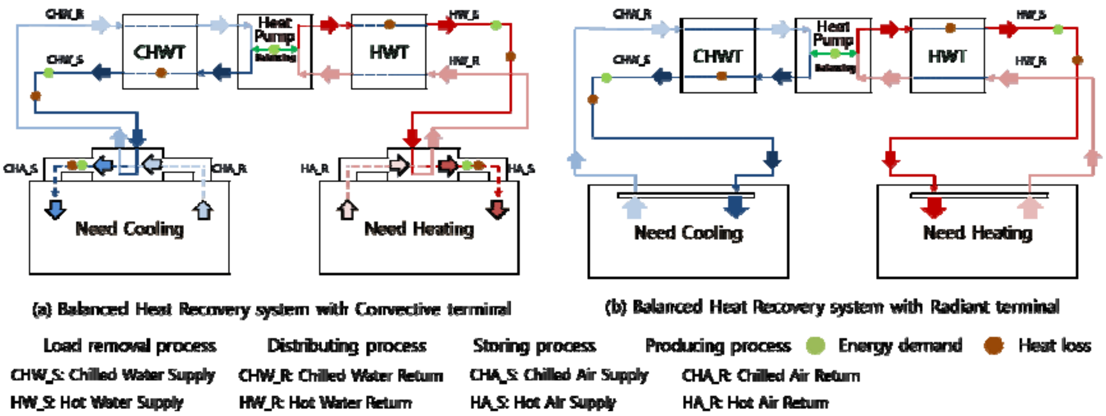


Figure 2. *BHR system with (a) a convective or (b) a radiant terminal system*

These two terminal systems require different temperature and distribution compositions; therefore, the energy demand could be different according to terminal systems. To reduce the total energy demand, it is necessary to reduce the equipment’s energy demand and reduce heat in each process.

To remove zone load in load removal process, required thermal medium temperature, flow rate and pressure should be gained from distribution and production processes.

To reduce energy demand in distribution process, the energy demand of the distribution equipment and the heat loss during the process should be reduced. The distribution equipment’s energy demand could be reduced by enhancing the mechanical efficiency and ensuring the equipment’s ideal operating conditions. The operation conditions are related to the thermal medium flow rate and the required pressure for the load removal process. With a radiant terminal, the medium is water. The flow rate is therefore lower than with the convective terminal, because the thermal capacity of water is higher than that of air. The required pressure is lower than that with the convective terminal, because heating and cooling are performed within a closed-loop. Radiant ceiling panel systems have been reported to reduce air transport energy by 20% (Imanari et al. 1999). The heat loss through the distribution process is related to the thermal resistance of the pipe or duct, the surface area, and the difference between environmental and internal temperatures. The pipe’s internal temperature is lower for heating and higher for cooling with the radiant than with the convective terminal. The heat loss would therefore be lower.

To reduce energy demand in production process (including storage), the energy demand of plant equipment and the heat loss from storage should be reduced in the process. The plant equipment's energy demand could be reduced by enhancing the mechanical efficiency and ensuring the equipment's ideal operating conditions. For refrigeration plants, which should be used in a BHR system, the suitable refrigerant type for a given condition is important (Byrne et al. 2009) to ensure better operating conditions for the equipment. In addition, the difference between the heat source and heat sink temperature is important, because the smaller this is, the smaller the energy demand. The temperature difference between the heating and cooling thermal medium is much lower with a radiant than with a convective terminal. The energy demand for the same required heat would therefore also be lower. The heat loss from storage is related to its thermal resistance, surface area, and the difference between environmental and internal temperatures. With the radiant terminal, the storage internal temperature is lower for heating and higher for cooling than with the convective terminal. The heat loss would therefore be lower.

Comparison study

To evaluate the energy performance, the heat flow and energy demand in each process of the BHR systems for heating and cooling with convective (Case 1) and radiant (Case 2) systems were compared. It was necessary for this comparison to simulate simultaneous and similar heating and cooling loads. It was also necessary to determine the heat flow from the plant to the terminal systems of the BHR system easily. Therefore, simulation rather than experimental methods were used.

The system details and plant control strategy of previous research (Shin et al, 2012) were applied. The simulation input data and equipment are described in Tables 1 and 2 respectively. The input variables for the plant control strategy are described in Table 2. The simulation tool TRNSYS 17 (Klein et al. 2010) was used, which is feasible when applying a user control strategy.

RESULTS AND DISCUSSION

For heat flow, the heat to be produced increased when the heat loss increased. When heating, the quantity of hot heat loss in the storage and distribution process was bigger in Case 1 than in Case 2. Therefore, the plant had to produce more hot heat in Case 1 than in Case 2, although the supplied heat was slightly larger in Case 2 than in Case 1. For cooling, the quantity of cool heat loss in the storage process was also bigger in Case 1 than in Case 2. However, the quantity of cool heat gain was bigger in the distribution process, because the temperature difference between the environmental temperature (set as 20°C) and return air temperature was higher in Case 1 (about 26°C) than in Case 2 (about 20°C). Especially the heat loss during heating was significant, because the temperature difference between the thermal medium and the environment was larger than when removing the cooling load.

***Table 1**. Simulation input data*

Location and Period	Zone	Area (m^2)	Internal load (W)	U-value of Wall and Window (W/m^2K)	Set Temp. (°C)	Max. load (W)
- Location: Seoul,Korea - Period: 1 month: (21st Jan.-21st Feb.)	Cold zone	24.3	0	- Front window: 2.89 - Back wall: - (Virtual surface) - Right/Left wall: 0.254 - Ceiling: 0.179 (Radiant cooling) - Floor: 0.266	20	1,467
	Hot zone	48.6	1840 (for all time)	- Front wall: - (Virtual surface) - Back/Right/Left wall: 0.254 - Ceiling: 0.179 (Radiant Heating) - Floor: 0.266	26	1,410

***Table 2**. Equipment input data for each case*

Equipment (Model)		Parameter / Input(Constant)		
		Description	Design value	
			Case 1	Case 2
Refrigeration Plant (Type 202)		Design load	1,629 W	1,629 W
		Chilled water set temperature	5.5 °C	10 °C
Storage (Type 4)	CHWT	Tank volume	7 m^3	7 m^3
		Design supply temperature	7 °C	15 °C
		Design return temperature	12 °C	20 °C
		Tank loss coefficient	0.88 W/m^2K	0.88 W/m^2K
	HWT	Tank volume	7 m3	7 m3
		Design supply temperature	55 °C	40 °C
		Design return temperature	60 °C	45 °C
		Tank loss coefficient	0.88 W/m^2K	0.88 W/m^2K
Pump (Type 3d)	Cold side → Chiller Hot side→ Chiller	Maximum flow rate	0.50 kg/s	0.50 kg/s
		Maximum power	4.91 W	4.91 W
	CHWT→Zone	Maximum flow rate	0.08 kg/s	0.08 kg/s
		Maximum power	7.54 W	7.54 W
	HWT→Zone	Maximum flow rate	0.07 kg/s	0.07 kg/s
		Maximum power	7.25 W	7.25 W
Fan (Type 3d)	CHWT→Zone	Maximum flow rate	0.16 kg/s	N/A
		Maximum power	214.15 W	N/A
	HWT→Zone	Maximum flow rate	0.22 kg/s	N/A
		Maximum power	294.14 W	N/A
Pipe (Type 31)	CWT - Zone HWT - Zone	Inside diameter	0.025 m	0.025 m
		Pipe length	20 m	20 m
		Loss coefficient	1.75 W/m^2K	1.75 W/m^2K

The total energy demand was lower for Case 2 than Case 1. This was because of four reasons: (a) the refrigeration plant efficiency was higher in Case 2, because of the lower hot water and higher chilled water temperature required as compared to Case 1; (b) the heat loss of storage was lower in Case 2 than in Case 1; (c) the heat loss of distribution when removing the heating load was lower in Case 2 than in Case 1; and (d) no fan power was required in Case 2. Even though the hot heat demands for removing heating loads were slightly higher for Case 2 than for Case 1, the plant energy demand for Case 2 was much lower. The results are summarized in Figure 3.

The quantity of hot and cool heat from the condenser and evaporator were more similar for the BHR system with the radiant terminal than with the convective terminal, because the temperature difference between the condenser and evaporator was smaller with the radiant terminal. This means that the radiant terminal was more suitable for BHR systems when the design process was performed under the assumption that the produced hot heat from the condenser and cool heat from the evaporator were the same. The convective terminal could be partly applied if other loads, like ventilation, dehumidification, and humidification loads, were accounted for so that the energy demand aspect could be changed.

Another advantage of the radiant terminal is the reduced space taken by system in the zone. Application of the convective terminal requires the installation of ducts, which take up much space, while application of the radiant terminal requires the installation of pipes, which take small space. In general, with a convective terminal two ducts can be installed in a zone for supply and return of hot or chilled air, compared to four pipes for supply and return of hot and chilled water with a radiant terminal. This feature is important when the BHR system is applied for a zone with frequent changes between heating and cooling.

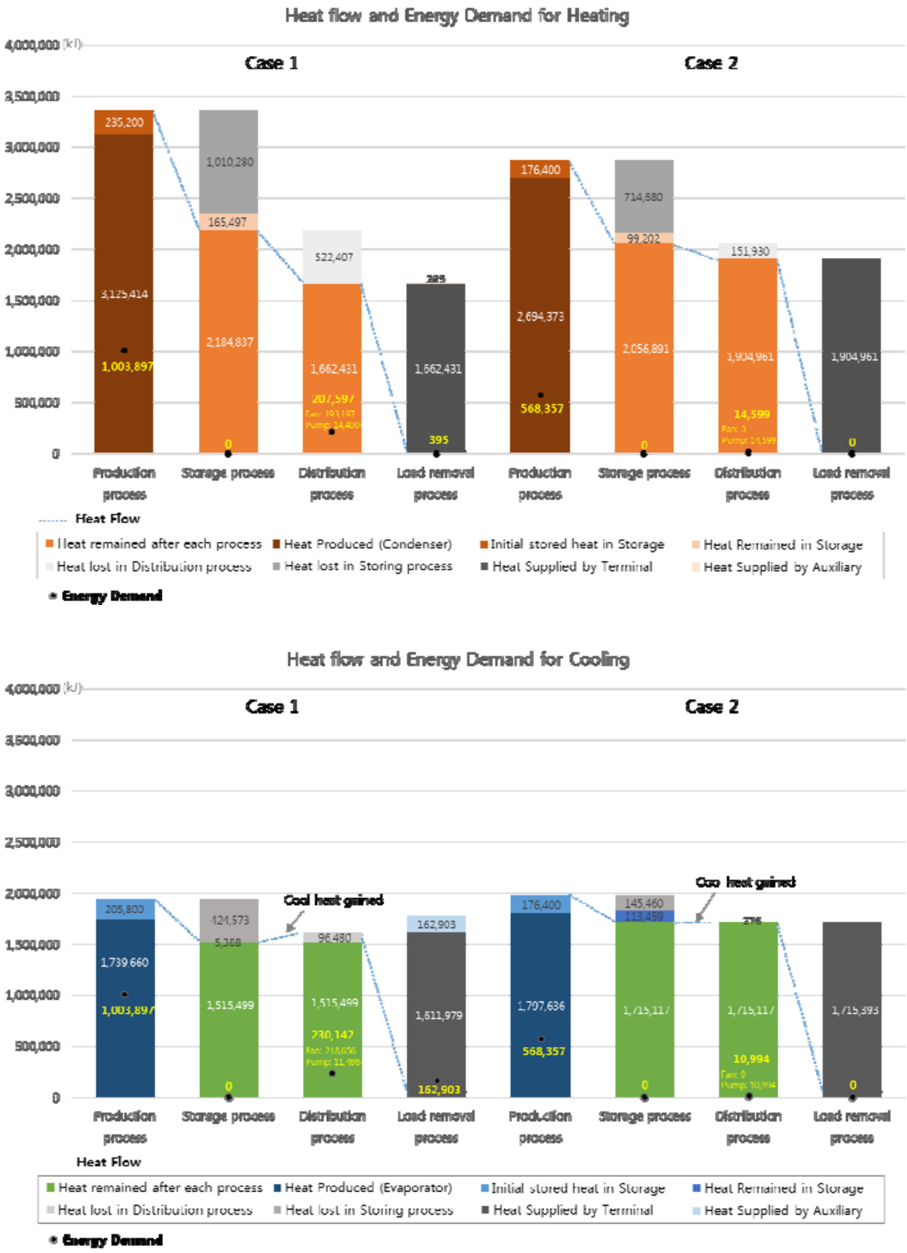


__Figure 3.__ Heat flow and energy demand for heating and cooling

CONCLUSION

In this study, the energy performance on heat flow and energy demand was compared for balanced heat recovery (BHR) systems with convective and radiant terminal systems. The possibility of better energy performance of BHR systems with a radiant than with a convective terminal was investigated and a comparison simulation study was performed to verify the results. The conclusions of this study were as follows:

(1) For the balanced heat recovery (BHR) system, it was possible to apply a convective or a radiant terminal to remove zone loads. The type and required thermal medium temperature differed according to the terminals.

(2) The temperature of hot water was lower and that of cold water was higher for the radiant than for the convective terminal. The efficiency of the refrigeration plant was therefore higher, so energy demands during the heat production is lower. In addition, the heat loss was lower and no fan power was required, so the energy demands during distribution process were also lower.

(3) When BHR design was performed under the assumption that the produced hot and cool were the same, the BHR system with the radiant terminal was more suitable, because the temperature difference between the condenser and evaporator was smaller than with the convective terminal. In addition, the space taken by system in the zone could be reduced when radiant terminal was applied. These findings could help to building designers and owners.

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