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Performance evaluation of multi-functional cascade heat pump system for a residential building

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Abstract

With increasing fossil fuel usage in building air-conditioning systems, air-source heat-pump systems are in the spotlight as an alternative HVAC system to reduce carbon emissions. The aim of this study is to evaluate a multi-functional cascade heat pump system for a residential building. A design method suited in residential buildings was applied to evaluate system performance of the proposed system. A reference system as separate two heat pumps was selected in charge of cooling, heating and hot water supply. The target building was set to residential of 100m², 5 occupants are in the building. The thermal load of the target building was derived with commercial transient simulation tool, thermodynamic equations, and model equations built-in EnergyPlus were used. As a result, the proposed system saves 13% energy in cooling mode and 10% in heating mode compared with the reference system. The energy saving effect was occurred at the compression ratio of each high- and low-cycle decreasing due to the effect of recovering unused waste heat in summer and increasing the temperature of the refrigerant in winter.

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Keywords: Cascade heat pump; Air-source; Multi-functional system; Building energy-saving; Residential building

1. Introduction

With increasing fossil fuel usage in building air-conditioning systems, air-source heat-pump systems are in the spotlight as an alternative HVAC system to reduce carbon emissions [1]. Heat pump technology can treat indoor air condition and heat domestic hot water through heat absorption in an evaporator and heat dissipation in a condenser [2]. The absorbed heat by the evaporator for indoor cooling should be discharged to outdoor air. In contrast, and the heat should be absorbed from heat sources by the evaporator for indoor or water heating. If the temperature of the heat source is in an extremely low state or the load side requires a high temperature, the temperature difference between the evaporator-condenser increases, which can put a heavy load on the compressor. This may cause problems in that energy consumption increases and system efficiency decreases.

This problem can be solved by reducing the compressor load in each cycle by using a cascade type multi-stage heat pump system. If the heat absorption and heat emission properties of each cycle of the cascade heat pump system are used well, it has the potential to be used as a multi-functional system for zone cooling, heating, and domestic hot water in the building. The previous studies on cascade heat pumps have conducted experimental system performance analysis or optimization according to the refrigerant charging amount and expansion valve opening rate [3,4]. However, the capacity calculation and energy simulation of the system reflects building design constraints, such as thermal load, have not conducted for the case of applying of cascade heat pump system to a building. Therefore, in this study, a design procedure for the application of multi-functional cascade heat pump system was presented, and energy simulation was conducted for a residential building that requires both heating and cooling and domestic hot water. An existing air-source heat pump system responsible for cooling, heating, and domestic hot water was set as a simulation comparison.

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2. System overview

2.1. Cascade heat pump system

A cascade heat pump system consists of two heat pump cycles exchanging heat in an intermediate heat exchanger. The low-cycle of the system is in charge of the zone air-cooling, and the high-cycle heats domestic hot water for zone radiant floor heating and hot water supply. It was assumed that the refrigerant of the low-cycle heat pump was R410A, which is widely used in general air conditioners, and that of the high-cycle heat pump was R134a to supply high temperature heat [5]. The proposed cascade heat pump in Figure 1 is to supply zone cooling in the low-stage cycle in summer, and supplies hot water in the high-stage cycle in winter.

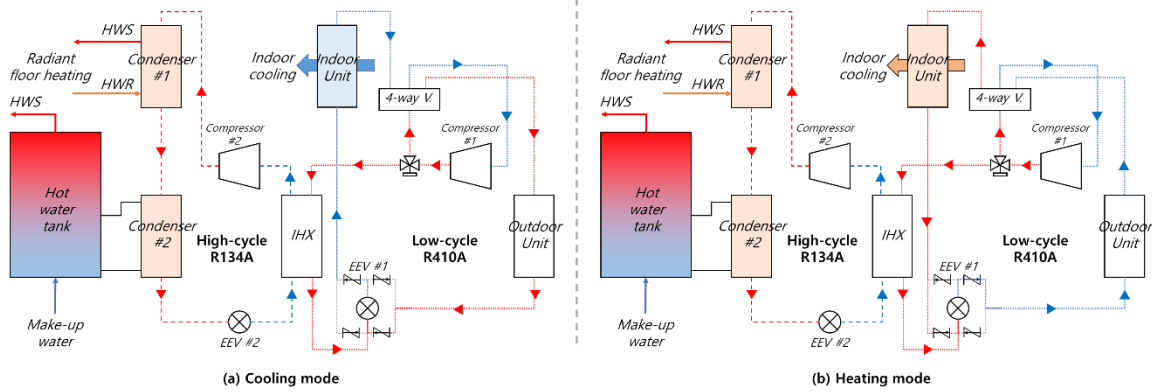


Fig. 1. Schematic of cascade heat pump system.

2.2. Reference heat pump system

In order to compare the performance of the proposed system, single heat pump systems were applied for each function required in a residential building [6]. The system to be compared is an air-source heat pump system as same as the proposed cascade heat pump system. A structure of the reference system is illustrated on Figure 2. The R410A refrigerant was used for the zone cooling cycle, and the R134a refrigerant was used for water heating cycles.

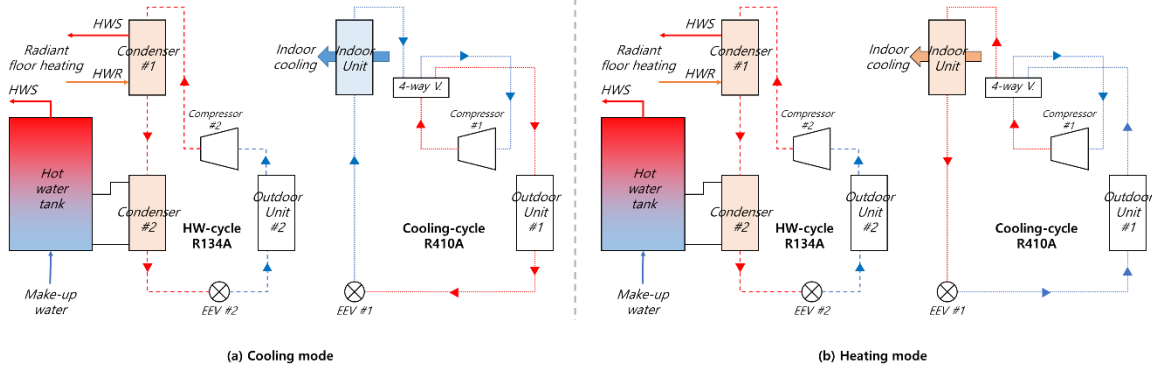


Fig. 2. Schematic of reference heat pump system.

3. Simulation overview

3.1. Sizing process logic

The sizing process algorithm for system capacity calculation was shown in Figure 3. First, design constraints for applying the system to residential buildings are set [7]. After the building information is determined according to the design constraints, the transient thermal-load simulation tool was used to calculate the thermal load of the model building [8]. The capacity of the low-cycle heat pump was determined

preferentially based on the cooling peak load. Finally, the capacity of the high-cycle heat pump that can satisfy the peak load of heating and domestic hot water load was determined.

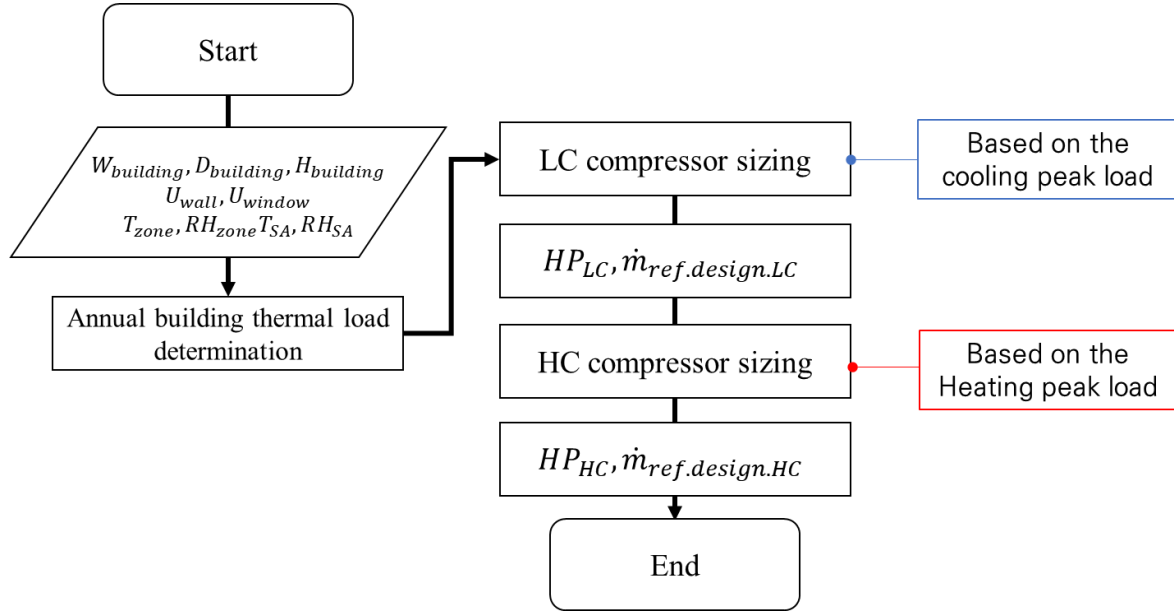


Fig. 3. Flow chart of system sizing for cascade heat pump system.

The parameters of each heat pump can be calculated by thermodynamic equations as follows (Eq.1-5) :

$$\dot{m}_{ref.LC} = \frac{\dot{Q}_{load.zone}}{\Delta h_{evap.LC}} \quad (1)$$

$$\dot{m}_{ref.HC} = \frac{\dot{Q}_{load.hw}}{\Delta h_{cond.HC}} \quad (2)$$

$$W_{comp} = \dot{m}_{ref} \Delta h_{comp} \quad (3)$$

$$\dot{Q}_{cond} = \dot{m}_{ref} \Delta h_{cond} \quad (4)$$

$$\dot{Q}_{evap} = \dot{m}_{ref} \Delta h_{evap} \quad (5)$$

3.2. System design constraint

The design constraints necessary to apply the cascade heat pump system to residential buildings were set as follows. First, the air conditioning supply conditions must be 15°C and 80% relative humidity. Second, the target water temperature for floor heating and domestic hot water supply is set to 60°C. Third, the calculated cooling, heating and hot water supply performance of the heat pump must satisfy both the building heat load derived through the heat load simulation tool. R410a refrigerant was used for the LC of the heat pump, and R134a refrigerant was used for high-temperature heat supply for HC. Compressor and heat exchanger efficiencies, which is defined as the ratio of the actual work performed to the work input, were assumed to be 0.75 and 0.8, respectively, and superheat and subcooling degrees were assumed to be ±5°C [9]. Lastly, it is assumed to operate at full load without partial load.

3.3. Building thermal load determination

The building information are shown in Table 1. A 3 m-high-building of 100 m² was simulated through the TRNSYS program, and a total of 5 occupants were set based on the ASHRAE standard [10]. After calculating the building heat load, the indoor temperature and humidity conditions and the heat pump simulation were calculated through the EES program.

Table 1. Input data for building thermal load simulation.

Regime types	Parameters	Values
Floor area [m ²]		100
Number of floors [-]		3
Occupants [person]		15
Infiltration [1/h]		0.6
Zone condition	Temperature [°C]	26
	Relative humidity [%]	50
Supply air condition	Temperature [°C]	15
	Relative humidity [%]	80
Heat gain	People [W/person]	130 (sensible, latent)
	Equipment [W/m ²]	0.4
	Lights [W/m ²]	7
U-value	Outdoor wall [W/m ² K]	0.17
	Floor [W/m ² K]	0.17
	Roof [W/m ² K]	0.15
	Window [W/m ² K]	1.12

4. Simulation result

The results of this study were divided into 5 parameters and analyzed. There are capacity of the system derived from the results of the required thermal load simulation, the refrigerant and enthalpy difference by p-h plot, the system COP, waste heat recovery analysis, and primary energy consumption.

4.1. System design capacity

The thermodynamic simulation result of the heat load of the building was shown in Table 2 during peak load in summer and peak load in winter. The cooling cycle HP size was determined based on the summer peak load, and the heating and domestic hot water cycle size was determined based on the heating peak load and domestic hot water load in winter. The capacity of the heating and hot water cycles was designed after the capacity of the cooling cycle was pre-determined.

Table 2. Peak load data of the model building.

Peak data	T_{oa} [°C]	RH_{oa} [-]	T_{zone} [°C]	RH_{zone} [-]	\dot{Q}_{sen} [kW]	\dot{Q}_{lat} [kW]	\dot{V}_{hw} [L]
Cooling	31.3	0.535	39.22	0.3664	2.716	0.8611	20
Heating and water heating	-13.65	0.835	12.24	0.3054	-2.522	-0.6548	26

The designed capacity of cooling cycles, which refers the compressor power, were the same at 1.1 HP on both systems. However, the size of the cycles responsible for heating and domestic hot water was three times higher than the proposed system at 1.8 horsepower in the existing heat pump system.

Table 3. Design capacity of each system.

System	For cooling [HP]	For water heating [HP]
Cascade system	1.1	0.6
Reference system	1.1	1.8

4.2. p-h graph on peak day

First, to examine the behavior of the two systems, p-h diagrams were drawn for the two systems during peak load in summer, as shown in Figure 4. The low cycle, (i.e. the cooling cycle), showed the same cycle behavior in summer because the cooling operation of the two systems was the same. Since only domestic hot water was needed in summer, one can see that the thermal load is low, and the temperature difference between the evaporator-condenser of the blue-dash line is smaller. The refrigerant was same in both systems in cooling mode (i.e., 0.03018 kg/s of \dot{m}_{ref}). In contrasts, the cascade cycle in the hot water cycle needs more refrigerant (i.e., 0.00364 kg/s for cascade heat pump, 0.00350 kg/s for reference heat pump). As for the enthalpy difference, the heat absorption enthalpy difference of evaporator is large and the enthalpy difference in the compressor is small.

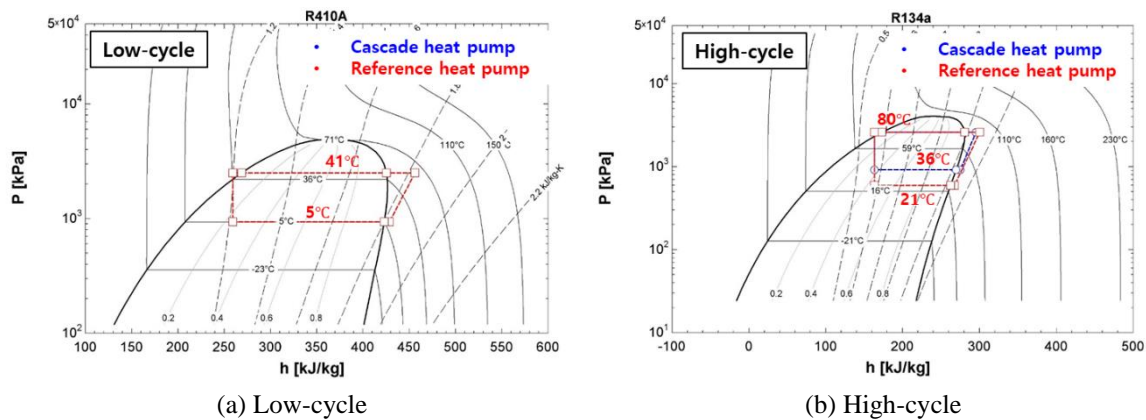


Fig. 4. Flow chart of system sizing for cascade heat pump system in cooling mode

Figure 5 shows the system in the winter condition. Under the condition, only the cycle of the cascade heat pump was visible in that cycle. This is because the reference system does not perform cooling operation in winter. The cascade system should be run a low cycle even in winter for multi-stage temperature rise. In winter, both systems were operated at a high cycle because residential buildings require floor heating and domestic hot water. It can be seen that the temperature difference between the evaporator-condenser of the reference system was very large. However, when matching the thermal load of the target condenser at high cycle, the amount of refrigerant in the reference system is operated with a small amount, and the heat absorption enthalpy difference in the evaporator is also small. This is because it is difficult to absorb a lot of heat from the outdoor air because the outdoor temperature is very low in winter, and it can cause the enthalpy difference of the compressor is up to 4 times larger.

Therefore, Cascade heat pump system has a high heat absorption of evaporator in high-cycle (heating), which reduces the required input power of the compressor and reduces the overall energy consumption. As a result, the amount of work that goes into the compressor is greater with the reference system.

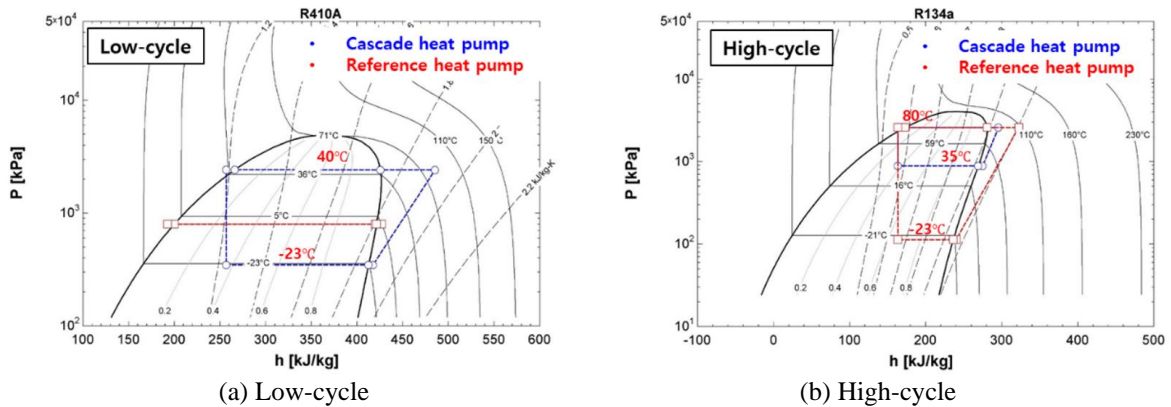


Fig. 5. Flow chart of system sizing for cascade heat pump system in heating mode

4.3. Coefficient of performance

Figure 6 reveals the total COP for each cycle of the heat pump, which was analyzed in 24 hours on the day when the cooling and heating peak load occurred. First, in the cooling mode, Hot water cycle showed higher COP in cascade heat pump system. The compressor load was low by receiving the waste heat of the low-stage cycle and supplying hot water with a higher heat source than the reference system. When operating in the cooling and hot water mode, the COP of the cascade heat pump was relatively high except for the cooling cycle. Conversely, in case of heating mode in winter, the cooling cycle of reference heat pump does not operate in winter, so the COP was zero. Each cycle COP of cascade heat pump is derived relatively high. When operating in heating and hot water mode, the COP of proposed system compared to reference system was relatively higher.

As a result of deriving seasonal COP, the result of high COP of cascade heat pump was derived in each season. This is thought to be the result of relatively low compressor energy consumption of the Cascade heat pump.

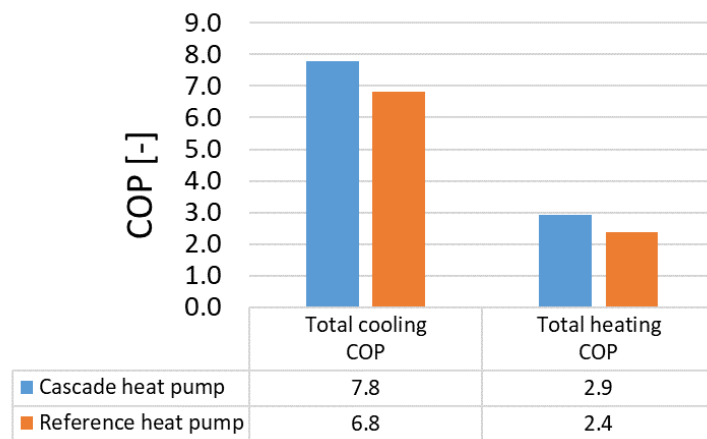


Fig. 6. Seasonal COP of the heat pump system.

4.4. Waste heat recovery in summer

The amount of heat dissipation from the condenser of the cooling cycle in summer was 9621.4 kWh. In summer, the Cascade heat pump recovers heat from the low-stage cycle and uses it as a heat source for the high-stage cycle. About 18% of the waste heat was recovered.

4.5. Primary energy consumption

As a result of energy consumption analysis, along Figure 7, it was confirmed that the energy consumption of the proposed cascade heat pump system was lower than that of the reference system in both seasons. The

Cascade heat pump compared to the reference heat pump in energy consumption was confirmed to save energy by 13% when operating in cooling mode and 10% when operating in heating mode. In the cooling mode operation, there was no significant difference between the two systems in the cooling cycle, but a difference in energy consumption was confirmed in the hot water cycle.

In heating mode operation, the cascade heat pump system operated all cycles, but the total energy consumption was derived less than reference system, which was only operated with HW-Cycle and had any energy consumption of cooling compressor and outdoor fan. In the case of the fan, it was confirmed that the energy consumption of the reference system was slightly higher in the outdoor fan.

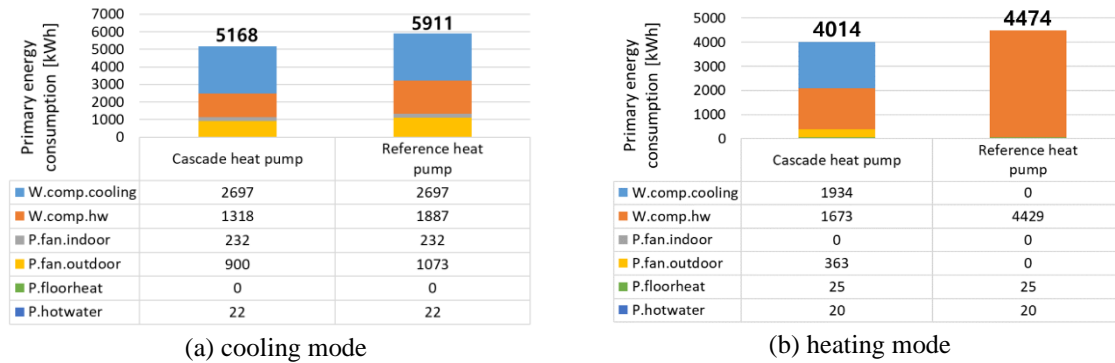


Fig. 7. Primary energy consumption of heat pump systems.

5. Conclusion

In this study, when the cascade heat pump system is applied to a building, the High-cycle capacity was determined after the low-cycle capacity is determined according to the cooling load. As a result of the energy simulation, it was confirmed that the energy consumption of the Cascade heat pump is superior to the reference heat pump system (i.e., cooling, heating, and hot water supply, respectively). The cooling season COP improved by 14% and the heating season COP by 22%. In addition, energy consumption during the cooling season was 13%, and energy consumption during the heating season was 10%, resulting in a total annual energy savings of 12%. This indicates that the Cascade heat pump system has a high heat absorption of evap. in the high-cycle (heating), and as a result, the input power required for the compressor is reduced, resulting in a decrease in total energy consumption and an increase in COP. In conclusion, it is considered that each heat pump compressor has a smaller energy load than the compressor of a single stage heat pump system due to waste heat recovery in summer and multi-stage temperature increase in winter. It is necessary to conduct experimental study through future work to validate the energy saving performance of the cascade heat pump system.

Acknowledgements

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