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Performance analysis of hybrid operating modes for dual coolant-source heat pump system applied to electric-driven vehicles

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Abstract

An efficient heating system for the cabin of electric-driven vehicles (xEVs) is required to minimize the reduction in the driving range. However, studies regarding heat pumps that use waste heat from fuel cell stack, PE(Power Electronics) and battery in xEVs are limited. In this study, the heating performance of dual coolant-source heat pump using waste heat in xEVs is investigated by varying coolant temperature, and coolant volumetric flow rate to have enough capacity in severe ambient conditions. A developed triple-fluid heat exchanger is introduced to recover waste heat from the fuel cell stack and PE with high level and battery with relatively low level at different temperatures. The heating performance of the coolant-source heat pumps using one coolant and dual coolants shows different characteristics owing to the different temperature levels of the coolants and heat transfer between two coolants. This study suggests optimum heat pump system of xEVs with respect to driving range characteristics under severe ambient conditions.

Keywords: dual coolant-source heat pump; heating performance; triple-fluid heat exchanger; coolant temperature; coolant flow rate;

1. Introduction

In response to regulations pertaining to fossil fuels for addressing environmental concerns [1], automotive companies have developed zero-emission vehicles as an alternative to internal combustion engines (ICEs). Accordingly, numerous studies regarding the development of “green cars,” which do not use fossil fuels, have been conducted. The most prominent zero-emission green cars include battery electric vehicles (BEV) and fuel cell electric vehicles (FCEVs) [2–4]. Their power sources are batteries, a hybrid battery system charged by an ICE, and electricity generated by a stack of fuel cells, respectively. All three types of vehicles, so called xEVs, are considered promising, based on the development undertaken by major automotive companies [5,6]. However, laboratory and on-road tests reveal various engineering short-comings of xEVs, including their system efficiency, stack performance, thermal-management technology, and compatibility with other components under high-voltage conditions. These inadequacies must be solved to achieve a performance similar to that of ICE vehicles [7].

Recently developed electric vehicles generally have maximum driving ranges of approximately 400 km for battery-only vehicles and approximately 600 km for FCEVs. However, these driving ranges can be reduced by over 40% when the heating system of a vehicle is operated under cold ambient conditions [8–11]. Conventional positive temperature coefficient (PTC) electric heaters have been widely used in electric vehicles owing to their simple utility. However, it can consume a significant amount of power from the battery because of its low energy transition efficiency (90%–95%) from electricity to heat, resulting in a significantly reduced fuel economy. The efficiencies ranging from 90% to 95% may seem to be enough; however, be-cause a typical heat pump has a heating efficiency of more than 300%, the PTC electric heaters have significantly lower efficiencies than the heat pumps. Therefore, an efficient heating system for the cabin of electric vehicles must be developed to minimize the reduction in the driving range.

In this study, the heating performance of dual coolant-source heat pump using waste heat from the fuel cell stack and PE(high temperature level) and battery(low temperature level) in xEVs was measured and analyzed by varying coolant temperature and coolant volumetric flow rate using developed triple-fluid heat exchanger.

2. Experimental Method

Fig. 1 shows a schematic illustration of the test setup used to measure the performance of a coolant-source heat pump with a triple-fluid heat exchanger for use in xEVs. The heating performance of the coolant-source heat pump was measured in psychrometric chambers. The psychrometric calorimeter in the indoor chamber was designed to precisely maintain the temperature and humidity settings using a cooling coil, heating coil, and humidifier. The temperature and humidity conditions in the outdoor chamber were controlled using an air-handling unit.

The tested coolant-source heat pump comprised an electric compressor, an inner condenser, triple-fluid heat exchangers (evaporator), and an electronic expansion valve (EXV). An electrically driven scroll compressor with a displacement volume of 33.0 cm^3 rev^{-1} at 360 V was adopted along with an inverter driver. The inner condenser, which simulates the cabin of the vehicle, was a parallel-flow type louvered-fin brazed-aluminum heat exchanger measuring 232.0 mm in width, 144.0 mm in height, and 54.0 mm in depth. An EXV with an orifice diameter of 1.6 mm was used to regulate the refrigerant mass flow rate. In addition, an accumulator was installed at the compressor inlet. Table 1 lists the specifications of the coolant-source heat pump with a triple-fluid heat exchanger.

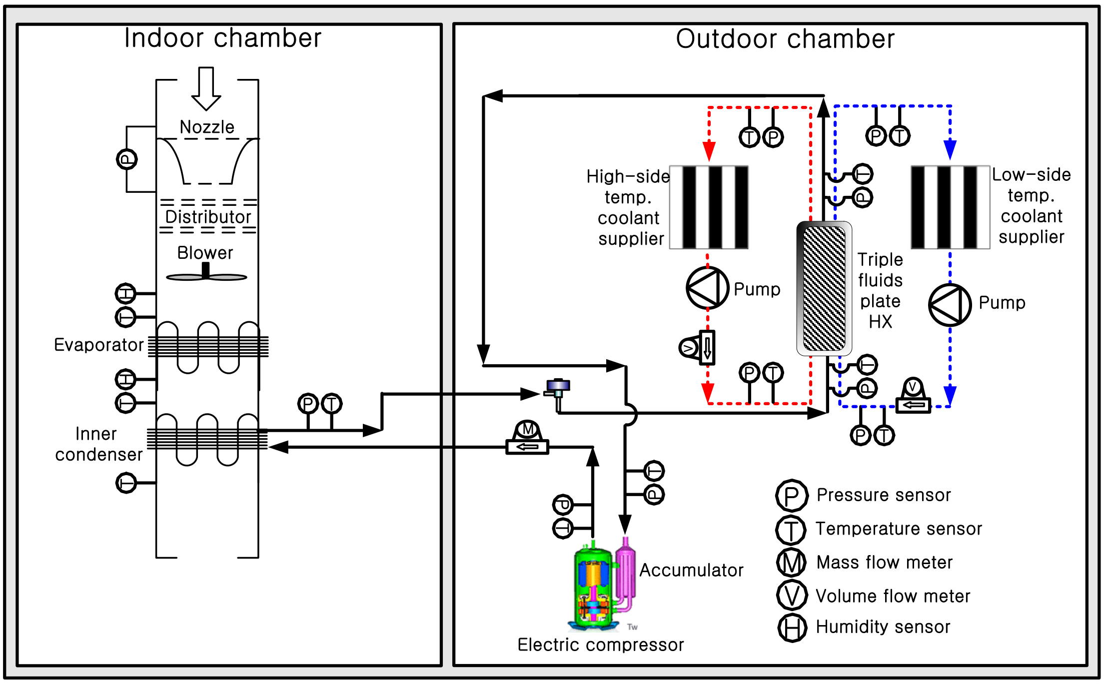

Fig. 1. Schematic of experimental setup for coolant source heat pump system

Table 1. Specifications of coolant source heat pump system

Component	Specifications
Inner condenser (Size, mm)	Parallel-flow type louvered-fin brazed-aluminum heat exchanger 232W × 144H × 54D
Triple-fluid heat exchanger (Size, mm)	Counter-flow plate-type brazed-aluminum heat exchanger 190W × 225H × 80D
Electric compressor (Displacement, cm^3)	Scroll type (33.0)
Expansion devices (Diameter, mm)	Electronic expansion valve (EXV) 1.6

Accumulator (cm^3)	950

A triple-fluid heat exchanger was developed to enable heat exchange between the refrigerant (R-134a) and two types of coolants, where different operating temperatures were considered for the fuel cell stack and PE(Power Electronics, such as driving motors, converters and inverters) (High temp. side) and battery (Low temp. side). The triple-fluid heat exchanger was a counter-flow-type aluminum plate heat exchanger measuring 190.0 mm in width, 225.0 mm in height, and 80.0 mm in depth. Fig. 2 shows the configurations of the triple-fluid heat exchanger. In this heat exchanger, 63 rows (35.0%) were used for high temperature coolant cooling, and 117 rows (65%) were used for low temperature coolant cooling. In the preliminary experiment, excessively high condensing temperature was observed when the channels were equally assigned for high temperature side and low temperature side, because the triple-fluid heat exchanger was used as a heat sink of the heat pump for cooling mode. Accordingly, for high temperature side, the number of channels in the triple-fluid heat exchanger was decreased to 35% owing to higher temperature difference between a coolant and a refrigerant.

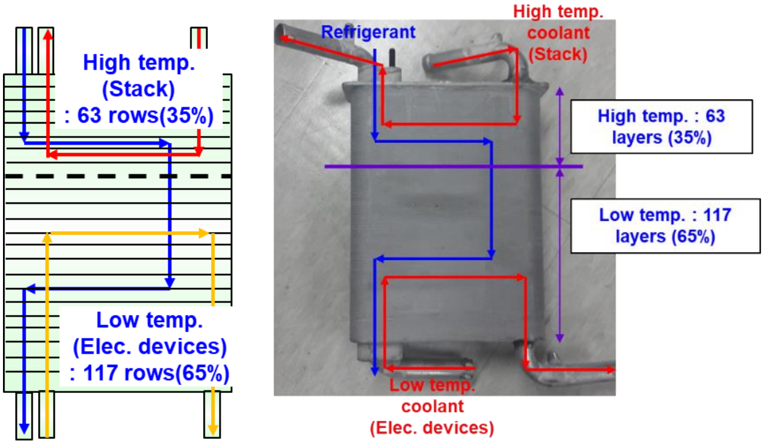

Fig. 2. Triple fluids heat exchanger and channel configurations for coolant source heat pump system

Table 2 lists the test conditions used in the study. The test conditions were set based on the actual coolant temperature profiles of the stack (or PE) and battery under cold ambient conditions under the designed driving pattern, as shown in Fig. 3. The air temperature on the interior side was varied from -20 °C to 0 °C at intervals of 10 °C, and the relative humidity was 50.0%. The air flow rate on the interior side was fixed at 300 $m^3\ h^{-1}$. The stack coolant temperature was maintained within 20 °C–40 °C at intervals of 5.0 °C, whereas the volumetric flow rate at the stack side was varied from 5 to 20 L min^{-1} at intervals of 5 L min^{-1}. The electric device cool-ant temperature was maintained within -20 °C to 0 °C at intervals of 10 °C, whereas the volumetric flow rate at the electric device side was varied from 5 to 20 L min^{-1} at intervals of 5 L min^{-1}. Meanwhile, the compressor speed was varied from 2000 to 4000 rev min^{-1} at intervals of 1000 rev min^{-1}.

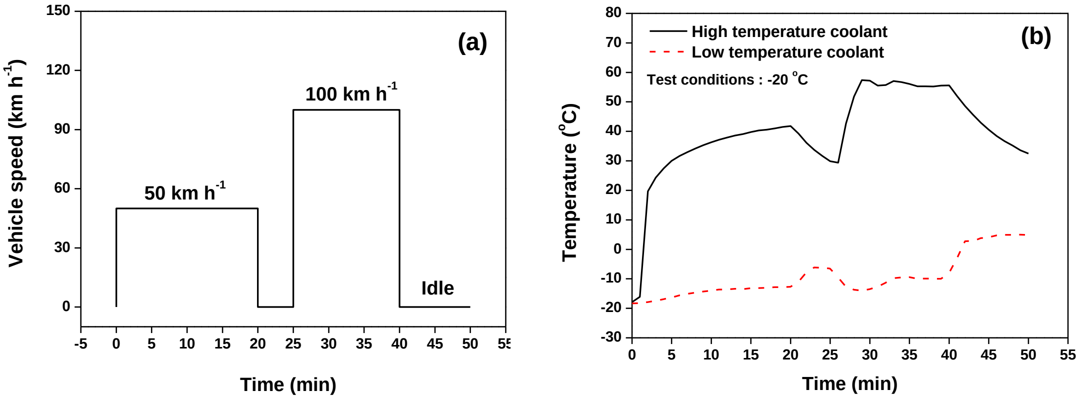

Fig. 3 – (a) Designed driving pattern of xEVs and (b) coolant temperature profiles for high-side and low-side under cold conditions.

Table 2. Test conditions of coolant source heat pump system

Components			Range
Compressor speed (rev min^{-1})			2000, 3000, 3500, 4000
Inner condenser		Air flow rate ($m^3 h^{-1}$)	300
		Air temperature (°C)	-20, -10, 0
Triple-fluid heat exchanger (Coolant)	Stack and PE (High-side temp.)	Volumetric flow rate (L min^{-1})	5, 10, 15, 20
		Coolant temperature (°C)	20, 30, 35, 40
	Battery (Low-side temp.)	Volumetric flow rate (L min^{-1})	5, 10, 15, 20
		Coolant temperature (°C)	-20, -10, -5, 0
Refrigerant			R-134a
Coolant			Ethylene glycol 50%, water 50%
Working fluid			Air

3. Result and Discussion

3.1. Single coolant-sourced heat pump system

Fig. 4 shows the heating capacity and COP of the coolant-source heat pump in the high temperature level's coolant mode with respect to the coolant temperature and volumetric flow rate. Only the high temperature level coolant was used in the high temperature level coolant mode. As the coolant temperature and volumetric flow rate increased at a fixed compressor speed and EXV opening, the heating capacity increased because of the increase in the evaporating pressure. However, the heating COP decreased as the coolant temperature and volumetric flow rate increased owing to the increase in the compressor power consumption. The coolant temperature significantly affected the heat capacity, whereas the heating capacity became constant as the coolant volumetric flow increased beyond 15 L min^{-1}.

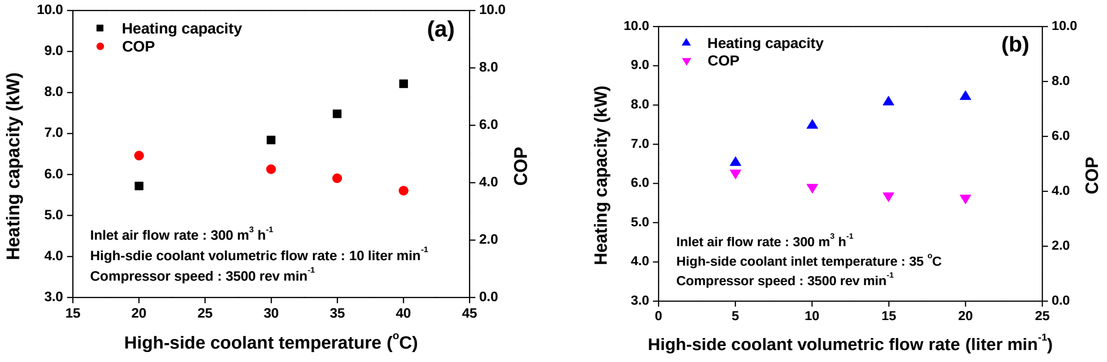

Fig. 4 – Heating capacity and COP in high temperature level coolant mode with respect to (a) temperature and (b) volumetric flow rate of high temperature level coolant.

Fig. 5 shows the heating capacity and COP of the coolant-source heat pump in low temperature level's coolant mode with respect to the coolant temperature and volumetric flow rate of battery cooling. The heating capacity and COP increased with lower-side coolant temperature and volumetric flow rate at a fixed compressor speed and EXV opening. As the coolant temperature increased from -20 °C to 0 °C, the heating capacity increased by 100%, whereas the compressor power consumption increased by 50%, resulting in an increase in the COP. This was attributed to a lower increase in the refrigerant flow rate with respect to the coolant temperature in the lower temperature coolant mode compared with that in the high temperature coolant mode. Additionally, as shown in Figs. 4 and 5, the low temperature coolant mode exhibited a relatively lower heating capacity than the high temperature level coolant mode. Accordingly, the operation mode in the coolant-source heat pump should be determined based on the heating load under actual driving conditions.

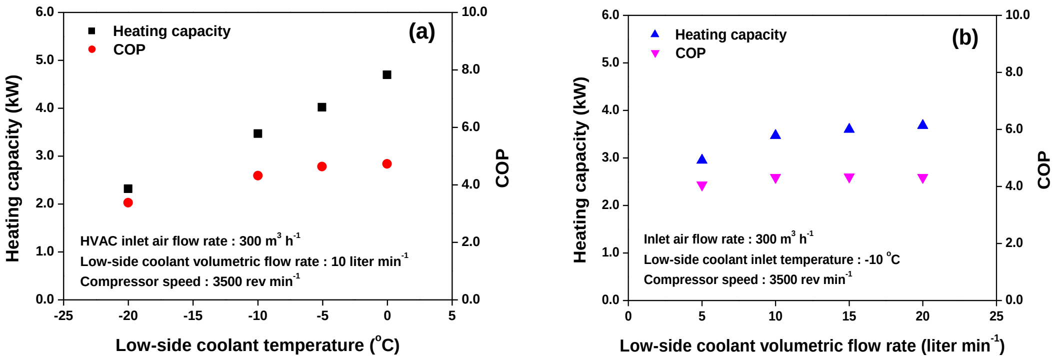

Fig. 5. Heating capacity and COP in low temperature level coolant mode with respect to (a) coolant temperature and (b) volumetric flow rate.

3.2. Dual coolant-sourced heat pump system

The hybrid coolant mode, which uses both coolants as heat sources, was investigated to utilize all possible waste heat in xEVs. When driving under cold ambient conditions, the coolant temperatures in two kinds of coolants remained at -10 °C and -20 °C to 50 °C, respectively. Therefore, the low-side coolant temperature in the hybrid coolant mode was set to -10 °C at various high-side coolant temperatures and EXV opening percentages. As shown in Fig. 6, in the hybrid coolant mode, the EXV opening percentage did not significantly affect the heating capacity and COP of the coolant-source heat pump. However, the heating capacity in the hybrid coolant mode decreased by 50% and 12% compared with that in the high temperature level and low temperature level coolant modes, respectively. This was because the heat was transferred from the higher temperature of the stack (or PE) coolant to the lower temperature of the battery cooling coolant. Owing to a similar reason, as shown in Fig. 6, the heat capacity and COP of the coolant-source heat pump in the hybrid coolant mode were not affected by the high temperature level coolant temperature.

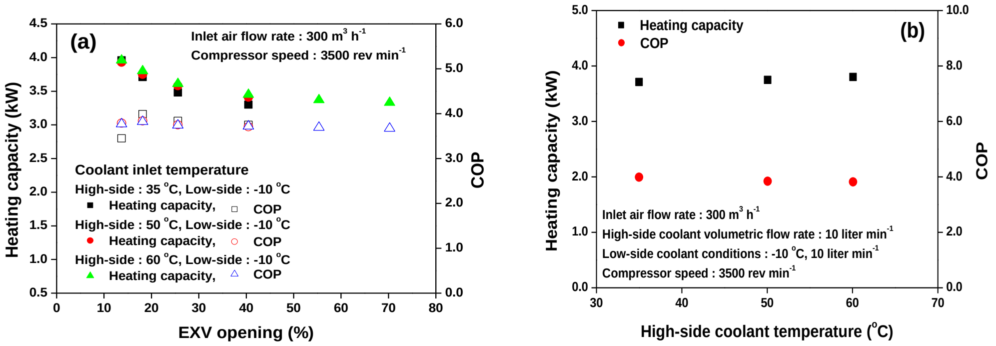

Fig. 6. Heating capacity and COP in hybrid coolant mode with respect to (a) EXV opening and (b) high temperature level coolant temperature.

4. Conclusion

In this study, the heating performance of a coolant-source heat pump using waste heat from the fuel cell stack and PE(high temperature level) and battery(low temperature level) in xEVs was measured and analyzed by varying the inlet air temperature, compressor speed, coolant temperature, and coolant volumetric flow rate. A developed triple-fluid heat exchanger was developed to recover waste heat from battery and fuel cell stack (or PE) which have different temperature levels. The coolant-source heat pump indicated a higher refrigerant flow rate than the air-source heat pump owing to the higher evaporating pressure and higher heat source temperature. Accordingly, the superheats at the compressor inlet and outlet in the coolant-source heat pump were lower than those in the air-source heat pump. The heating performance of the coolant-source heat pump was significantly affected by the compressor speed, and the heating capacity was inversely proportional to the COP.

Additionally, the effects of the coolant temperature on the heating performance of the coolant-source heat pump were investigated in the stack and PE(high temperature level), battery(low temperature level), and hybrid coolant modes. In the high temperature level coolant mode, as the coolant temperature and volumetric flow rate increased, the heating capacity increased owing to the increase in the refrigerant flow rate, whereas the heating COP decreased owing to the increase in the compressor power consumption. However, in the low temperature level coolant mode, both the heating capacity and COP increased with the coolant temperature and volumetric flow rate owing to a lower increase in the refrigerant flow rate. Furthermore, the hybrid coolant mode was inferior to one coolant-source mode in terms of performance; this was because in the hybrid coolant mode, heat was transferred from the stack and PE(high temperature level) to the battery coolant(low temperature level)

Acknowledgements

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