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Application of Improved Cooling & Heating System to Long-Range Electric Vehicles for Higher Power Efficiency

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Abstract

The challenge for long-range electric vehicles is to increase the driving distance by maintaining the highest battery energy density level and by managing energy efficiently. An effective battery thermal management system is required to control the operating temperature of the battery for optimal battery energy density. For efficient energy management, more efficient cabin heating system is needed because they consume a lot of energy during winter. In this paper, the performance of the dual coolant-cooled battery cooling system was studied. In addition, the heat pump system that utilizes battery waste heat was studied to further improve the energy efficiency of the existing heat pump using the ambient air heat and power electric module waste heat. The results showed that a dual coolant-cooled battery cooling system combined with a radiator and Air Conditioning (AC) system can reduce power consumption by 75% at the ambient temperature of 15°C compared to using the AC system only. In addition, the use of battery waste heat in the heat pump system increased mileage by up to 9% at the low ambient temperature of -7°C.

Keywords: Cooling system, Air-conditioning system ,.Battery thermal management, Heat pump system ;

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1. Introduction

As environmental regulations on greenhouse gas emissions tighten, interest in Electric Vehicles (EVs) has increased [1]. The main issues for the development of EVs are to select an appropriate energy storage system and to use the battery energy efficiently to improve mileage [2]. Lithium-ion (Li-ion) batteries are considered to be the most suitable energy storage devices for EVs because they have a higher energy density, higher power, lighter, lower self-discharge rate, and a longer lifespan than other rechargeable batteries such as nickel-cadmium [3]. However, since the performance of the Li-ion batteries is sensitive to varying temperature, the driving distance of the EVs will be reduced if the battery temperature is not controlled properly [4]. Therefore, the Battery Thermal Management System (BTMS) is needed to increase the mileage of EVs. Pesaran [5] suggested that the Li-ion battery operating temperature range should be maintained between 15°C and 35°C and the maximum temperature difference should be kept below 5°C.

Hyundai Motor Company (HMC) defines “short-range EVs” as the vehicles with below 200 miles/one full charge represented by Ionic EV and “long-range EVs” as vehicles with over 200 miles/one full charge represented by Kona EV. For long-range EVs, high current is used to reduce charging time, thus the heat generation inside the battery and On Board Charger (OBC) can be more increased [6]. This additional battery waste heat requires a more powerful battery cooling system, but on second thought, it can be used as cabin heating for EVs. For Mitsubishi I-MIEV, the driving distance is reduced by up to 45% during heating operation and up to 27% during indoor AC operation [7]. By utilizing the waste heat of the battery in addition to the

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waste heat of the power electric (PE) module, it is possible to improve the heating performance to minimize the reduction of the EVs mileage. Therefore, in order to improve the mileage, a cooling system is needed to maintain the battery temperature properly, and its waste heat is effectively utilized for cabin heating.

In this paper, a dual coolant-cooled battery cooling system that can use both radiator and AC system was studied as a way to relieve the self-heating of high energy density batteries and high-efficiency heat pump system that utilizes battery waste heat as well as conventional PE waste heat was studied.

2. Main subject

2.1. Application of dual coolant-cooled battery cooling system

2.1.1. Importance of battery thermal management

The performance of Li-ion batteries is closely related to temperature, so it is important to understand the heat generation inside the battery. According to Thomas and Newman [8], Li-ion cells are known to generate heat by reversible entropy, resistive dissipation, a concentration gradient of cells and relaxation of chemical reactions, as expressed by Gu et al. [9] in Eqn. (1). Q is the heat generation rate, I is the current through the cell, U is the battery open-circuit voltage, and V is the cell voltage.

$$\dot{Q} = I(U - V) - I(T\frac{dU}{dT}) \tag{1}$$

The relationship of battery lifespan to temperature is shown in Fig. 1 [10], which shows that the battery life will be drastically reduced when the temperature is out of the proper level. In addition, the relationship between the performance of the battery and the temperature has been studied extensively. Amine et al. [11] showed a capacity reduction of 72% as a result of repeating 140 charge and discharge cycles with a C/2 discharge rate at 55°C. Ehrlich [12] studied the performance decrease after 500 iterations at 1C discharge rate at 45°C. Therefore, battery performance is directly related to the driving distance of the EVs, requiring a suitable cooling system to dissipate battery heat.

2.1.2. Cooling system for battery thermal management

The battery cooling system was reviewed by Kim et al. [13] in terms of cycles. According to them, the independent use of air-cooled cooling system and system without vapor compression cycle (VCC) for long-range EVs battery cooling are difficult due to the efficiency and performance limitations of the system. Mahle [14] also compared each system using the VCC as shown in Table 1 and found that the liquid (coolant) cooling system is superior in terms of cooling performance and efficiency. The air-cooled cooling system utilizes cabin air for the battery cooling, and only needs some additive parts such as fans and ducts, so it is advantageous in terms of weight and price. However, due to the low heat capacity (Cp) of the air, as shown in Eqn. (2), a large amount of an air flow rate ($\dot{m}$) is required to remove heat (Q) generated from the battery, resulting in larger fan power consumption and bulky ducts and manifolds. Therefore, it is difficult to accumulate a large number of cells in a limited pack because the spacing between the battery cells must be wide, which makes it difficult to apply to long-distance EVs. Liquid cooling systems, on the other hand, are suitable for long-distance EVs as they use liquid coolant with higher heat capacity and higher heat transfer rates than air, which allows the battery to be cooled more effectively with less mass flow rate.

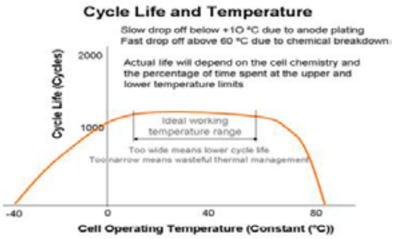

Fig. 1. Battery life graph according to battery temperature [10]

Table 1. Comparison of Battery Cooling Systems (Mahle [14])

- Bad, O Normal, + Good	Air		Coolant	Refrigerant
	Extra HVAC unit	Cabin air used		
System Weight	-	+	-	+
System Package	-	O	O	+
System Costs	-	+	-	O
Energy Efficiency	O	+	+	O
Availability (Winter)	-	+	+	-
Applicant Effort	O	+	+	O/-
Cooling Power	O	-	+	+

$$\dot{Q} = \dot{m} C_p \Delta T \tag{2}$$

2.1.3. Dual coolant-cooled battery cooling system

In the case of Kona EV, HMC's long-range EVs, the heat generation of the PE module and battery increased more than twice compared to Ionic EV under HMC cooling test conditions as shown in Fig. 3. The Kona EV is limited to existing air-cooled battery cooling systems in order to keep the battery temperature at an appropriate level. Therefore, a liquid-cooled cooling system has been developed and applied. According to the battery cooling method, the structure of the battery is different as shown in Fig. 4, and the research of the dual coolant-cooled battery cooling system for cooling the coolant has been conducted.

A dual coolant-cooled battery cooling system is used to cool the battery with the radiator and AC system by constructing the battery cooling system circuit as shown in Fig. 5 (a). The battery coolant line is connected to the cooling circuit for the PE module and OBC so that the battery can be cooled through the existing radiator without any additional parts. On the side of the refrigerant circuit, the system consists of the evaporator for cabin cooling and the battery chiller for the battery cooling. Therefore, the dual coolant-cooled battery cooling system can be installed by the addition of minimal parts to the existing cooling system and AC systems. The cooling mode of this system is operated as follows. First, if the battery cell temperature is lower than the coolant temperature passing through the radiator, the battery cooling line is disconnected from the PE module cooling line and the coolant flows into the battery chiller, where the cold refrigerant flows. Second, if the battery cell temperature is higher than the coolant temperature through the radiator, the AC is not activated to cool the coolant while the battery cooling line is connected to the PE module cooling line to cool the battery with coolant cooled by ambient air temperature in the radiator as shown in Fig. 5 (c). By adding a 3way valve to the coolant circuit, the two modes described above can be operated.

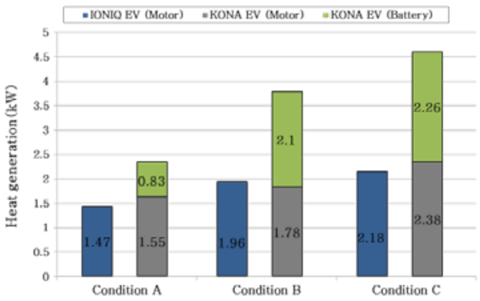

Fig. 3. Ionic EV and Kona EV Heat generation value

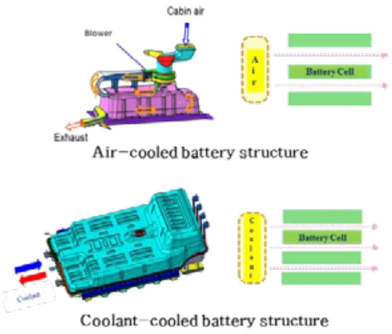

Fig. 4. Comparison of battery structures by cooling method

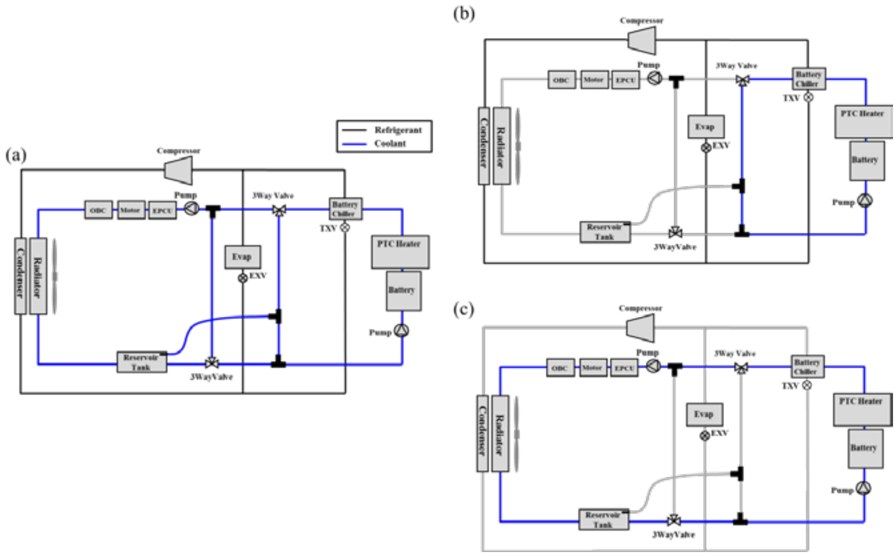

Fig. 5. (a) Dual coolant-cooled battery cooling system circuit diagram, (b) battery cooling mode utilizing AC system, (c) battery cooling mode utilizing radiator

The specifications of the main components of the dual coolant-cooled battery cooling system applied to Kona EV are shown in Table 2. Existing Ionic EV components were basically used, and the newly added battery chiller was evaluated for the different number of plates in consideration of the heat generated from the HMC cooling evaluation condition to look for the optimum capacity. The battery chiller test results are shown in Fig. 6. As the number of plates increased, the cooling performance was improved by an enlarged heat transfer area, but the pressure drop of the coolant decreased. In this study, 20 plates were selected in consideration of the HMC target for the chiller heat dissipation.

Table 2. Main component specifications of the system

Component	Type	Specification	Unit
Compressor	Scroll	33	cm3
Condenser	Micro channel HX	572.6x365x20	mm
Evaporator	Micro channel HX	215x256.5x45	mm
Radiator	Micro channel HX	610x411.5x14	mm
Chiller	Dimple	102x64x62	mm

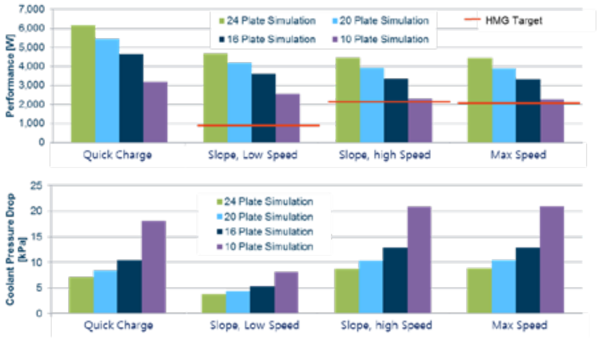

Fig. 6. Battery chiller performance test results

2.1.4. Effect of dual coolant-cooled battery cooling system

The two modes of the dual coolant-cooled battery cooling system proposed in this paper were evaluated by comparing the cooling mode using the AC system and the cooling mode using the radiator. The system bench test for each mode under the same conditions at an ambient air temperature of 15°C showed that AC utilization mode increased cooling performance by 1.57% compared to radiator utilization mode, but consumption power increased by 75%, resulting in a 58.3% reduction in COP (Fig. 7 (a).). In addition, the comparison of the two modes with the initial temperature conditions of 30°C, 110km/h and three-hour continuous driving conditions at ambient air temperature of 25°C showed improvement of up to 4% in terms of vehicle power consumption by reducing cooling power consumption when using the radiator compared to cooling using the AC system (Fig. 7 (b).). In other words, the use of a radiator was advantageous in terms of efficiency compared to using an AC system to cool the battery at low outside temperatures. This is because the compressor consumes a lot of electricity to operate the AC system. If the ambient temperature is high, the cooling mode utilizing the AC system will only operate because the battery cannot be cooled by utilizing the radiator.

2.1.5. Optimal control of battery cooling and cabin cooling

The biggest problem with the application of the battery cooling system using AC is the temporary rise in indoor discharge temperature due to increased cooling load when the battery cooling system is operated. In such a case, a sudden hot wind occurs during the operation of the AC, which may cause customer dissatisfaction such as unpleasantness and odor in terms of AC productivity. The conventional thermal expansion valve allows only passive expansion in proportion to the temperature and pressure of the vapor phase refrigerant passing through the chiller. There was a problem of instantaneous flow of refrigerant to the chiller side during operation of the battery cooling system and during indoor cooling, resulting in a rapid increase of the indoor discharge temperature. In order to solve this problem, an electronic expansion valve that can actively control the opening amount is applied to the battery side, and the superheat degree is controlled after stabilizing the evaporator temperature. As a result, the cooling performance was stabilized by preventing an initially large flow rate to the chiller side. The solenoid thermal expansion valve is applied to the evaporator side for the cabin cooling to realize the battery cooling on mode when the AC is off and the battery cooperative control point of view.

2.2. Cabin heating using battery waste heat

2.2.1. Importance of battery waste heat

EVs without engine waste heat sources use electric heaters with an efficiency of 0.8 to 0.9 when heater operation is required, such as spring and autumn comfort temperature control and winter heating. However, when the electric heater is used, the driving distance of the vehicle is excessively reduced because the power consumption is large. Therefore, in order to maintain the driving distance during heating, it is advantageous to use a heat pump system with high efficiency (COP of 2 to 3) by utilizing an external heat source. However, this system has a problem that it is difficult to secure the heat source as the outside air temperature is lower in winter so that the operating condition is limited at a low temperature below -10°C. The existing Ionic EV heat pump system utilizes the PE module waste heat as well as the outside air heat to increase efficiency. In

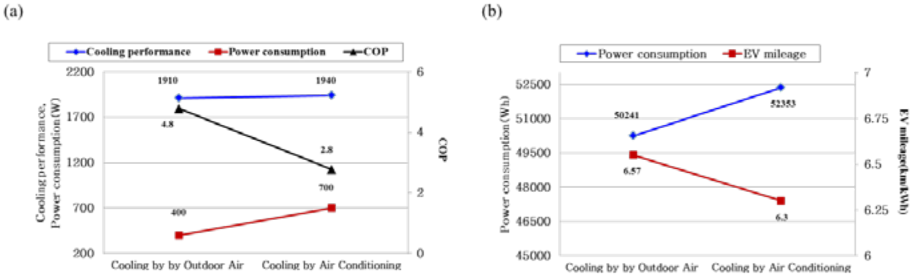

Fig. 7. Comparison of Battery Cooling Mode with Ambient Temperature and Battery Cooling Mode with A ((a) ambient air temperature 15°C conditions, (b) ambient air temperature 25°C and 110 km/h driving conditions)

long-range EVs, battery generated heat is greatly increased in addition to the PE module, numerous studies have been conducted on heat pump systems utilizing battery waste heat [14]. However, as shown in Table 3, there were very few EVs using heat pump system utilizing battery waste heat. Therefore, research on the heat pump system utilizing battery waste heat as well as the outdoor heat source and waste heat of the PE module is needed to minimize the reduction of driving distance.

Table 3. Heat Pump Operating Modes of Global EVs

Application Mode	HYUNDAI IONIQ EV	TESLA	GM BOLT EV	NISSAN LEAF	HYUNDAI KONA EV (This Paper)
Heating of waste heat recovery in PE module	O	X	X	△	O
Heating of waste heat recovery in PE module and batteries	X	X	X	X	O
Heating and Dehumidification of waste heat recovery in PE module	O	X	X	△	O
Heating and Dehumidification of waste heat recovery in PE module and batteries	X	X	X	X	O
Heating of waste heat recovery in PE module (Recognition of frost formation)	O	X	X	X	O
Heating of waste heat recovery in PE module and batteries(Recognition of frost formation)	X	X	X	X	O

2.2.2. Utilization of battery waste heat

In the existing short-range EVs, as shown in Fig. 8 (a), the heat pump was operated using only waste heat from the PE module, and the battery heat was thrown into the air. In this paper, to improve the performance of the heat pump system, the system that utilizes the waste heat from the battery, OBC and PE module is constructed by using the dual coolant-cooled battery cooling system as shown in Fig. 8 (b). A more specific schematic of this system is shown in Fig. 9. This system circulates coolant through PE module, OBC, and battery, and recovers waste heat through heat exchange with refrigerant in waste heat recovery chiller and uses it for heat pump heating.

2.2.3. Performance and efficiency impact of increasing battery waste heat

To analyze the heat pump performance according to the amount of waste heat, the proposed system was evaluated while increasing the waste heat to 0.55kW, 1kW, and 2kW under the condition of -20°C and 50km/h. The refrigerant pressure-enthalpy diagram to the evaluation of the system is shown in Fig. 10 (a). As the waste heat is increased, the evaporative pressure and temperature and condensation pressure and condensation are increased, and the heating performance is improved, but the refrigerant flow rate is increased by increasing the density of refrigerant entering the compressor. This is because the refrigerant does not have to be expanded to lower pressure in order to recover waste heat. More specific performance results are shown in Fig. 10 (b). Increasing the waste heat by 1.45 kW, the heating capacity is increased by 0.6 kW, but the compression work is increased by 0.15 kW, and the heating efficiency is increased from 2.33 to 2.57.

Table 4. Power consumption of cabin heating according to the use of battery waste heat

Application mode	Compressor power consumption (kWh)	PTC power consumption (kWh)	Heating power consumption (kWh)	Heating power savings (%)
Battery waste heat not used	0.574	0.5	1.074	Base
Battery waste heat used	0.52	0.354	0.874	18.6

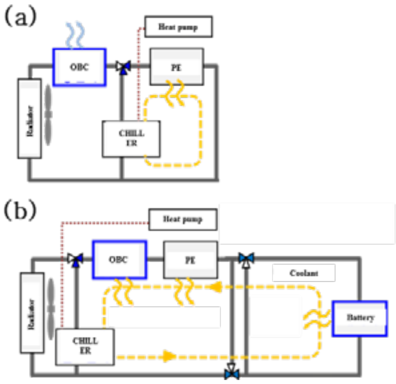

Fig. 8. Electric vehicle heat pump system ((a) utilization of waste heat from PE module, (b) utilizes waste heat from PE module, OBC and battery)

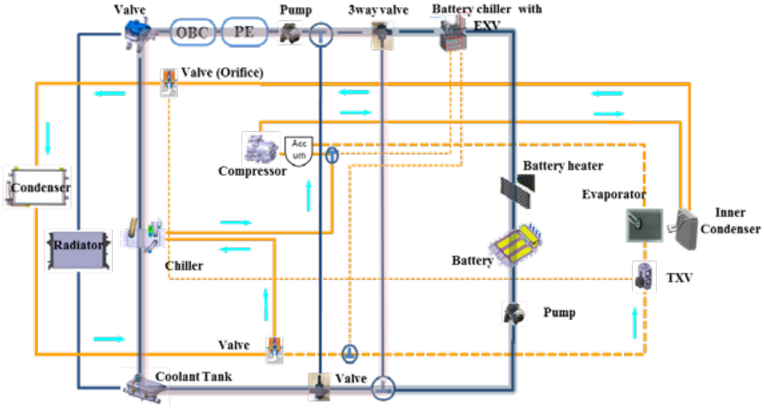

Fig. 9. Heat pump system circuit diagram using battery waste heat

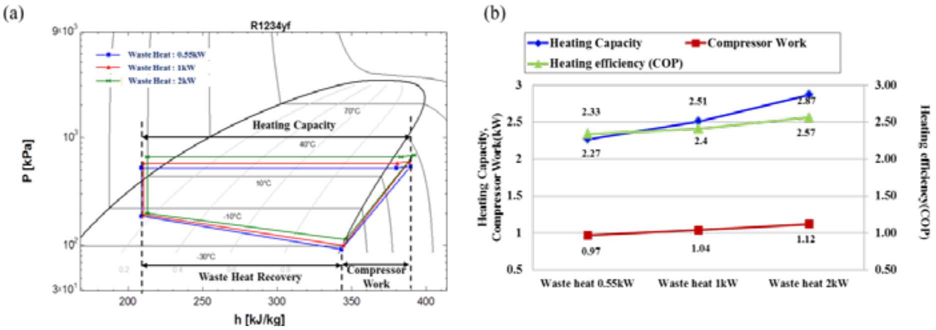

Fig. 10. (a) System refrigerant pressure-enthalpy diagram according to waste heat, (b). Evaluation result of heating performance according to waste heat

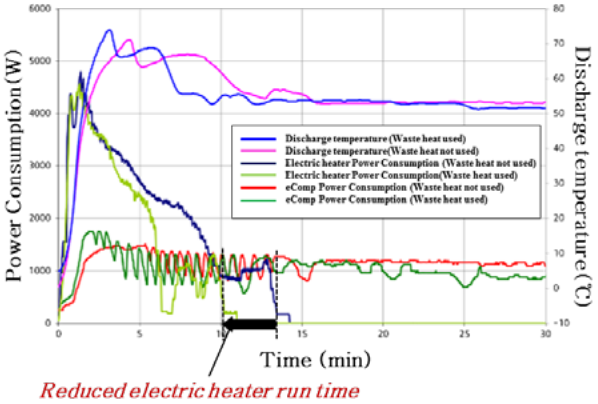

Fig. 11. Evaluation result of heating performance with or without battery waste heat

In order to confirm the effect of the heat pump system using the battery waste heat, the use of the waste heat during the cabin heating at normal temperature 0°C, FATC (Full Auto Temperature Control) 23°C and vehicle speed 50km/h after charging was compared and evaluated. The results of the performance assessment based on the availability of waste heat for 30 minutes are shown in Fig. 11. More simply, the numerical results are shown in Table 4. The reduction of electric heater consumption by improving the efficiency of the heat pump system reduced the heating power consumption by 0.2kWh, resulting in 18.6% reduction in heating power consumption. Calculating these effects as mileage improvements is estimated to be 6.8%. According to the real vehicle assessment, the Ionic EV had a 19% difference in driving distance when heating on / off, but the Kona EV reduced the difference by 9% due to the improved efficiency of the cooling AC system due to the increase of available waste heat source.

3. Conclusion

In this paper, the following conclusions were obtained through the study of the dual coolant-cooled battery cooling system and the heat pump system utilizing battery waste heat.

(1) A dual coolant-cooled battery cooling system is to supply low-temperature cooling coolant to the battery. It is possible to supply low-temperature coolant by heat exchange through AC system in chiller or heat exchange through outdoor air temperature in the radiator.

(2) When using the AC system to cool the battery, the cooling performance increased by 1.57% compared to the radiator utilization mode under ambient air temperature of 15°C, but the power consumption increased by 75%, resulting in a 58.3% reduction in overall efficiency (COP). In other words, if the ambient temperature is low, it is better to use the radiator to cool the coolant than the AC system.

(3) With 1.45 kW waste heat, heating capacity is increased by 0.6 kW, but compression work is increased by 0.15 kW. Therefore, it is advantageous to recover waste heat since heating efficiency is increased from 2.33 to 2.57.

(4) Utilizing waste heat generated when charging batteries, heating consumption power was reduced by 0.2 kWh due to reduced use of electric heater when operating heat pumps, resulting in an 18.6% reduction in AC consumption power, improving driving fuel economy by 6.8%.

(5) As a result of the evaluation of low-temperature, full-charging driving distance certification, Ionic EV had a 19% difference in driving distance when heating was turned on / off. On the other hand, Kona EV narrowed the gap by 9% due to the improved efficiency of the cooling AC system as the available heat source and waste heat increased.

Reference

[1] De Wilde HPJ, Kroon P. Policy options to reduce passenger cars CO2 emissions after 2020.ECN. ECNE13005 2013
[2] Lukic SM, Cao J, Bansal RC, Rodriguez F, Emadi A. Energy storage systems for automotive applications. IEEE Transactions on industrial electronics 2008;55:2258-67
[3] Lowe M, Tokuoka S, Trigg T, Gereffi G. Lithium-ion batteries for electric vehicles. Duke University Center on Globalization, Governance and Competitiveness, Tech. Rep., 2010
[4] Bandhauer TM, Garimella S, Fuller TF. A critical review of thermal issues in lithium-ion batteries. Electrochemical Society 2011;158:R1-25
[5] Pesaran AA. Battery thermal models for hybrid vehicle simulations. power sources 2002;110:377-82
[6] Wang Q, Jiang, B, Li B, Yan Y. A critical review of thermal management models and solutions of lithium-ion batteries for the development of pure electric vehicles. Renewable and Sustainable Energy Reviews 2016;64:106-28
[7] K. Umezu, H. Noyana, "Air Conditioning System for Electric Vehicles, i-MiEV", JSAE 2010 annual conference, 2010
[8] Thomas KE, Newman J. Thermal modeling of porous insertion electrodes. Electrochemical Society 2003;150:A176-92.
[9] Gu WB, Wang CY. Thermal-electrochemical modeling of battery systems. Electrochemical Society 2000;147:2910-22.
[10] SAMADANI, Ehsan, et al. Impact of temperature on the A123 Li-ion battery performance and hybrid electric vehicle range. SAE Technical Paper, 2013.
[11] Amine, K, Liu J, Belharouak I. High-temperature storage and cycling of C-LiFePO 4/graphite Li-ion cells. Electrochemistry communications 2005;7:669-73.
[12] Ehrlich, G. M. Lithium-ion batteries. Handbook of batteries, 2002.35-53.
[13] Jaewan Kim, Jinwoo Oh, Hoseong Lee, Review on Battery Thermal Management System for Electric Vehicles, ATE, 149, 192-212
[14] Markus Wawzyniak (mahle), Battery thermal managment architectures and components, 2015