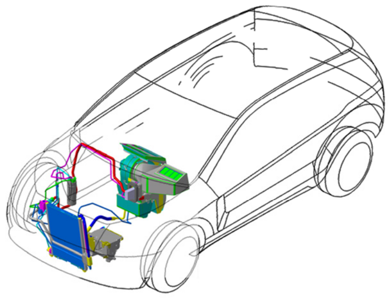
Development of Automotive Air-Conditioning Systems by Heat Pump Technology



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In the future, the market for electric and hybrid vehicles is expected to expand against a background of environmental protection and tightened CO_2 emission controls. This report describes the inspection of a heat pump air-conditioning system that uses thermal energy in the outside air to heat the vehicle cabin. When applied to electric and hybrid vehicles, this system reduces energy consumption by 20% to 60% compared to current systems.

1. Introduction

The market for next-generation vehicles such as electric vehicles (EVs) and hybrid vehicles (HEVs and PHEVs) is expected to expand in the future. However, because of problems such as a shorter driving mileage, higher price, and undeveloped infrastructure, they have not yet become commonplace. In particular, improved energy efficiency is required for air-conditioning systems used in next-generation vehicles to extend their driving mileage. Existing air-conditioning systems significantly decrease the driving mileage due to their electric power-consumption during heating operations. Therefore, air-conditioning systems that reduce electric power-consumption are currently under development.

2. Current Situation and Issues

2.1 Current situation

The heating operation of an air-conditioning system on a vehicle equipped with an internal combustion engine uses exhaust heat transported by hot water drawn into the vehicle cabin from the engine cooling system. For an electric vehicle, however, exhaust heat is lower than that of a conventional internal combustion engine, and is insufficient for heating operation, since the electric motor has a high energy-conversion efficiency, and the kinetic energy of the vehicle is recovered as regenerative electric power during braking. At present, systems equipped with an electric water heater are commonly used to compensate for the heat shortfall (**Figure 1**).

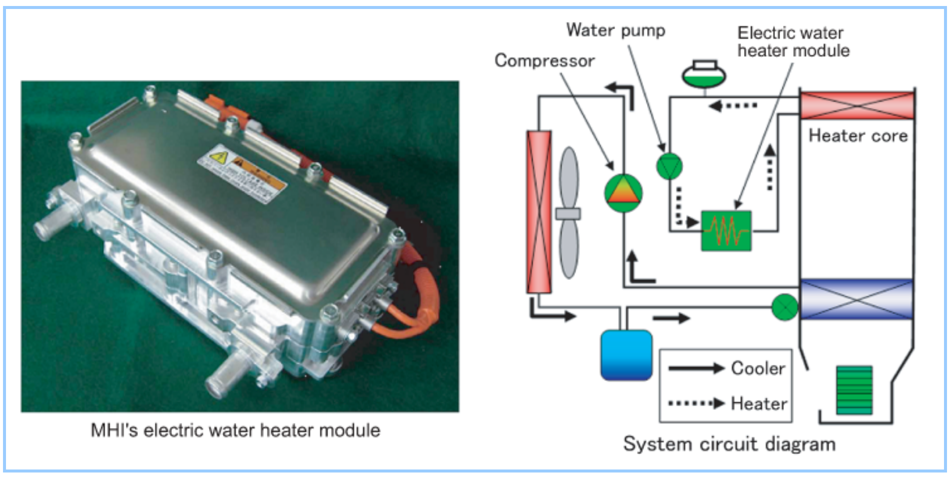

Figure 1 Electric water heater

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These systems offer advantages such as the following. First, development costs can be reduced because parts and components can be shared with existing production vehicles (excluding the electric water heater). Second, one need not route the high-voltage cables into the vehicle cabin if the electric water heater is mounted outside, and hence a measure of passenger safety during a crash can be incorporated into the vehicle design.

2.2 Issues

Although an electric water heater system provides beneficial features such as those described above, it also gives rise to major issues when used in an electric vehicle. Its heating operation requires a larger proportion of electric energy for the entire vehicle, and the driving mileage accordingly decreases (**Figure 2**). Extending the driving mileage by increasing the battery capacity, however, creates difficulties with regard to battery mounting space, weight, and cost.

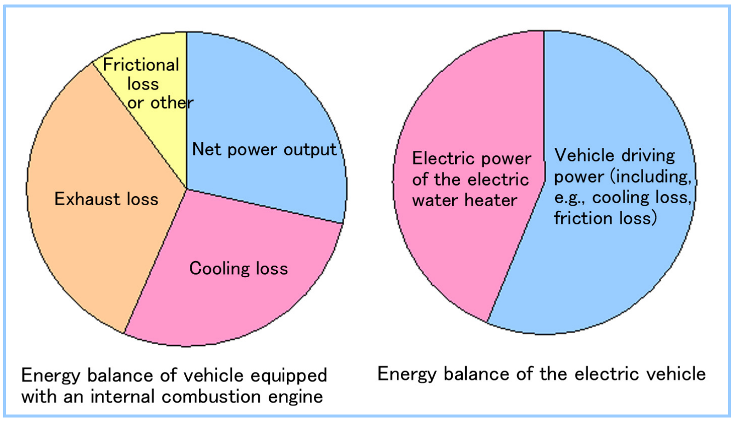


Figure 2 Energy balance
In vehicles equipped with an internal combustion engine, exhaust heat from cooling loss is used for the heater. In electric vehicles, the electric power required for the heater is supplied by the battery.

3. Application of Heat Pump Air-Conditioning System to Eco-Friendly Vehicles

Mitsubishi Heavy Industries, Ltd. (MHI) has chosen heat pump technology for automotive air-conditioning systems as a solution to the problems described above, and carried out an inspection with particular emphasis on improvement of energy efficiency during heating operations.

3.1 Selection of heat source and refrigerant

The heating performance of a heat pump system is greatly affected by the heat source that is used for heating, and thus selection of the heat source is important. For a heat pump used in an automotive air-conditioning system, possible heat sources for its heating operation are as follows:

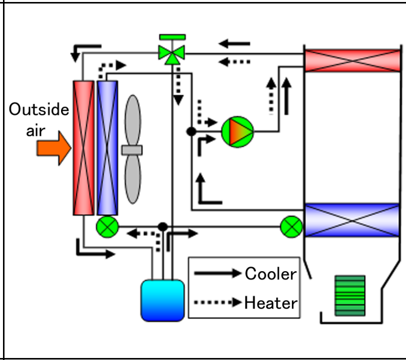
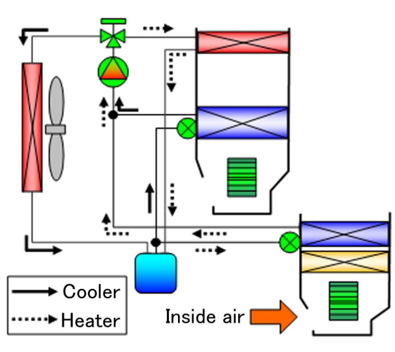
- Thermal energy in the outside air;
- Thermal energy from the ventilation air in the cabin.

In this research, existing refrigerant (R134a) was used because of its availability and affordability. **Table 1** compares heat pump systems using the two possible heat sources. As a result of this comparison, MHI selected the system using outside air for further inspection, owing to its simple structure and possible cost reduction, both of which are important factors in achieving wider distribution. The details of this system are presented below.

3.2 Overview of the heat-pump system using outside air heat source

The heat-pump system using the outside air consists of a compressor, a condenser located inside of the cabin, a 3-way valve, a receiver, an expansion valve, a evaporator located outside of the cabin, a evaporator located inside of the cabin, a condenser located outside of the cabin, and plumbing that connects these components. It uses thermal energy in the outside air as the heat source for heating the vehicle cabin (**Figure 3**). The heating performance depends on external conditions such as the outside air-temperature, weather, and vehicle speed. Hence, adequately investigating the influence of such conditions is important when a heat-pump using outside air heat source is applied to an automotive air-conditioning system. For example, the performance of a typical heat pump system may be compromised by frost formation on the outside evaporator during heating operation in cold weather. Thus, verifying that the system is unlikely to experience such frost formation is necessary.

Table 1 Comparison of systems

			Heat pump system A	Heat pump system B
Heat source for the heater			Outside air	Ventilation air in the cabin
System diagram				
Heating medium			R134a	R134a
Heater capacity	Outside temperature 0°C	Capacity	☺	☺
		COP	☺	☺
	Outside temperature 10°C	Capacity	☺	☺
		COP	☺	☺
Cost			☺	😐

The heat pump system using outside air can improve energy efficiency and reduce cost because of its simple structure, even though it is subject to an outside temperature limit.

☺ good > 😐 > 😖 bad

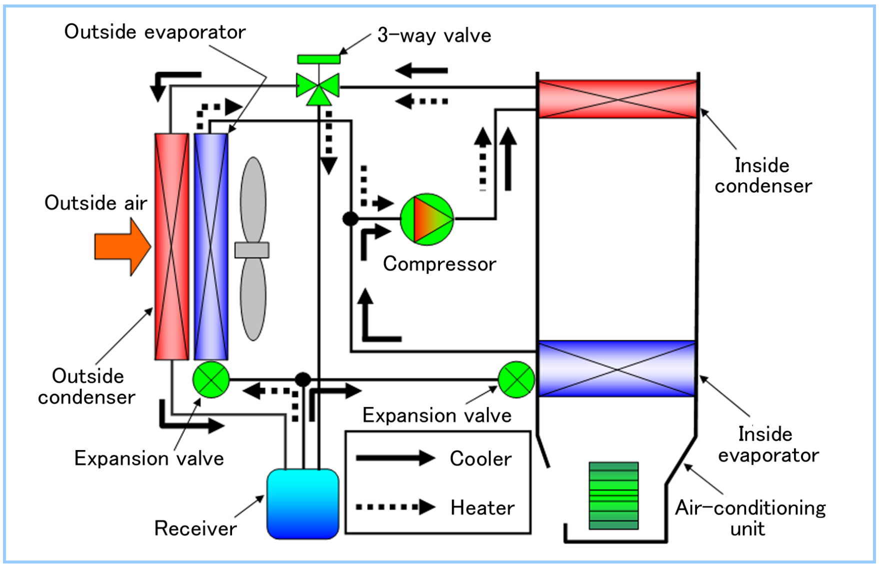


Figure 3 Circuit diagram of the heat pump system using outside air
This system uses thermal energy in the outside air as the heat source for the heater.

3.3 Component characteristics

The characteristics of the outside evaporator and inside condenser, both of which were newly designed for the heating operation of this system, are described below.

(1) Evaporator located outside of the cabin (for heating operation)

The evaporator for cooling operation (located inside of the cabin) has a compact design and uses a double-row refrigerant flow path to increase the heat exchange rate per unit area, allowing it to fit into a constrained mounting space inside the cabin, while attaining the necessary capacity. In addition, the heat exchanger surface has a special finish to prevent condensed water from flying off. The evaporator for heating operation, however, must fit into the constrained mounting space provided for the cooling components located outside the cabin, while attaining the necessary airflow. Accordingly, MHI adopted a thin, low-pressure-loss design, whose heat exchange rate per unit area is smaller than that of the evaporator located inside of the cabin (**Figure 4**). Since one must consider frost formation during heating operation, MHI designed the heating evaporator with headers at the top and bottom, and a vertical refrigerant flow path, also taking account of dewatering (**Figure 5**).

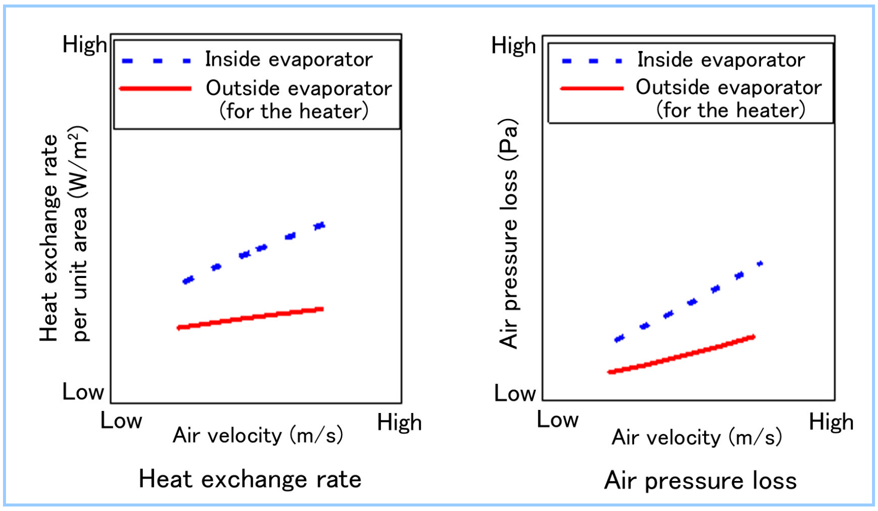


Figure 4 Unit performance of the outside evaporator for the heater
Comparison of characteristics of the inside evaporator and outside evaporator

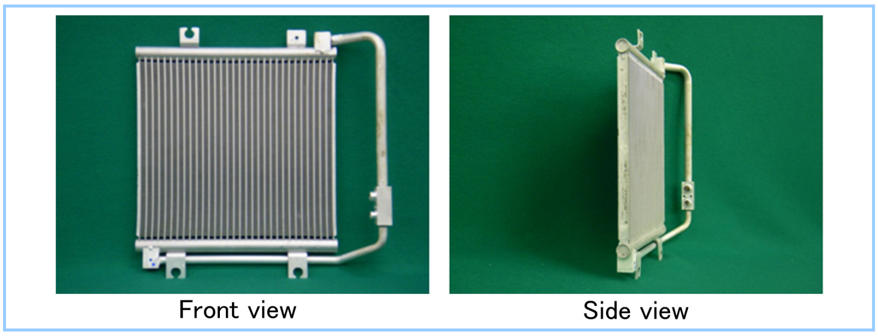


Figure 5 Outside evaporator for the heater

(2) Condenser located inside of the cabin (for heating operation)

The condenser for cooling operation (located outside of the cabin) has a thin, low-pressure-loss design to fit into the constrained mounting space provided for the cooling components located outside the cabin, while attaining the necessary capacity and airflow. The condenser for heating operation located inside of the cabin, however, must fit into a constrained mounting space inside the cabin, while attaining the necessary capacity. Hence MHI adopted a double-row structure, whose heat exchange rate per unit area is greater than that of the condenser for cooling operation located outside of the cabin (**Figure 6**).

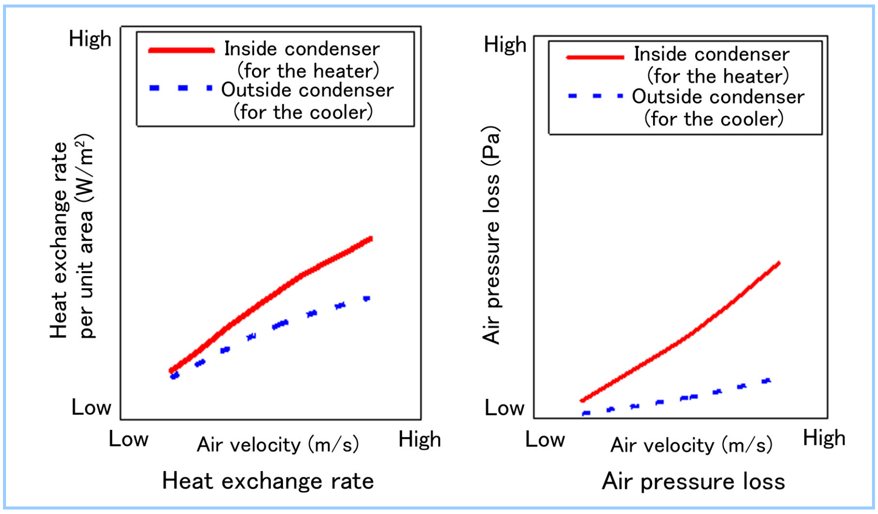


Figure 6 Unit performance of the inside condenser for the heater
Comparison of characteristics of the inside condenser and outside condenser

In addition, for the sake of compatibility with air-conditioning units on vehicles powered by internal combustion engines, MHI designed the size and structure of the heating condenser so that it can be replaced with a heater core (**Figure 7**).

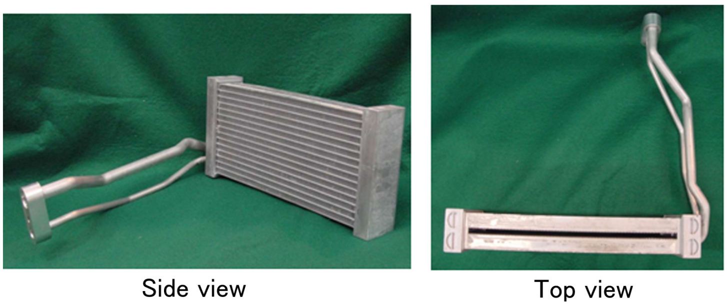


Figure 7 Inside condenser for the heater

3.4 Vehicle level heating and defroster performance

Performance evaluation tests on an electric vehicle equipped with the heat-pump system using outside air heat source yielded the following results.

3.4.1 Heating performance

To evaluate the heating performance, the electric power consumption of the heat pump system was compared to that of the electric water heater system as the outside temperature changed from 0ºC to 10ºC, while the cabin temperature was maintained at a comfortable 25ºC. **Table 2** lists the test conditions and **Figure 8** shows the test results. The results verify that the heat pump system can reduce electric power consumption by 20% at an outside temperature of 0ºC, and by 60% at 10ºC. The higher the outside temperature is, the greater the reduction rate will be, presumably because the system recovers thermal energy from the outside air. Thus, less electric power is required for thermal energy recovery when the difference between the cabin temperature and the outside temperature is smaller. In addition, the experiment verifies the feasibility of a continuous heating operation to maintain a comfortable cabin temperature, provided the outside temperature is within the experimental range.

Table 2 Test conditions used to evaluate heater performance

	Test condition
Vehicle	Electric vehicle (A-segment)
Outside temperature	0ºC to 10ºC
Cabin temperature	25ºC
Vehicle speed	40 km/h

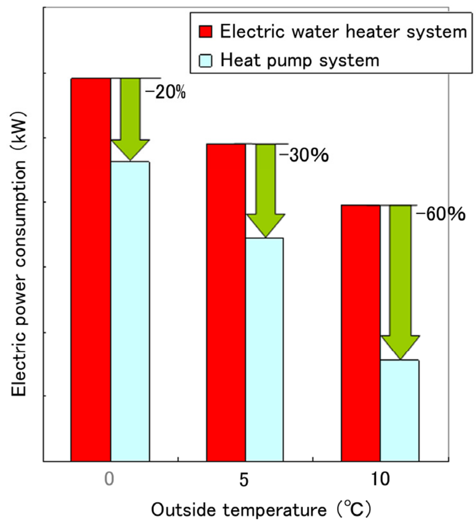


Figure 8 Comparison of electric power consumption
The heat pump system can reduce electric power consumption by 20% to 60%, while maintaining a comfortable inside temperature.

3.4.2 Windshield defroster performance

A performance test of the windshield defroster in securing visibility at low outside temperature was also carried out. **Table 3** lists the test conditions and **Table 4** presents the test results. The results confirm that this heat pump system satisfies domestic regulations regarding defrosters. In addition, the experiment verifies the feasibility of continuous defroster operation.

Table 3 Test conditions used to evaluate defroster performance

	Test condition
Vehicle	Electric vehicle (A-segment)
Outside temperature	–8ºC
Standard	Japanese regulations for defroster performance
Vehicle speed	0 km/h

Table 4 Windshield defroster performance test results

Area	Required value	Test result	Judgment
Driver side	80% or more (after 20 minutes)	80%	Accepted
Passenger side	80% or more (after 25 minutes)	100%	Accepted
Wind shield	95% or more (after 40 minutes)	100%	Accepted

4. Conclusions and Future Prospects

The performance evaluation of an actual electric vehicle equipped with the heat-pump system using outside air heat source verified that the heating operation of the system can improve energy efficiency, while continuously maintaining a comfortable cabin temperature at an outside temperature between 0ºC and 10ºC. In addition, effective defroster operation was confirmed even when the outside temperature dropped to –8ºC. In the future, MHI will improve the integrity of the system by verifying its practicality under various driving situations. MHI already possesses development technologies for electric water-heater systems, and aims to combine the benefits of the heat pump system and the electric water-heater system to devise enhanced heating systems and meet user needs through cooperation with manufacturers of next-generation vehicles.