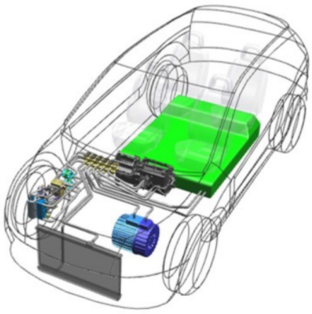
Development of Heating System for Electric Vehicles Combining Refrigerant and Coolant Circuits



TAKAYUKI KOBAYASHI[*1] TOMOYASU ADACHI[*1]
HIROYUKI YAMAMOTO[*2] RYO SHIOZAKI[*2]
MASAHIRO KATO[*2] YUKI ASADA[*2]

As countries around the world have announced their commitment to control CO_2 emissions and improve fuel efficiency in order to suppress global warming, the shift from conventional internal combustion engine vehicles to electric vehicles is being promoted worldwide. Air conditioners for internal combustion engine vehicles use waste heat from the engine as the heat source. However, in the case of electric vehicles, the heat source is insufficient for their air conditioners because there are no engines. Typically, electric vehicles use a refrigeration cycle with a heat pump to absorb heat from the outside air as a heat source. However, due to the physical properties of conventional refrigerants, heating performance is insufficient when the outside temperature is low. Therefore, electric heaters are generally used to ensure heating performance, which increases the overall cost of the vehicle due to the cost of electric heater-related parts. As such, Mitsubishi Heavy Industries Thermal Systems, Ltd. (MTH) has developed an air conditioning system for electric vehicles that can contribute to the improvement in cabin comfort under low outside air temperature conditions by combining refrigerant and coolant circuits without the use of electric heaters. This report introduces the developed system.

1. Introduction

There are two issues that need to be addressed with heating in electric vehicles. First, a heat pump system using a conventional refrigerant (R1234yf) does not provide sufficient heating performance when the outside air temperature is low, resulting in a lack of cabin comfort. Second, frost formation on the outdoor heat exchanger (condensate becomes frost and adheres to the surface of the heat exchanger) reduces the heat absorption performance from the outside air, making it impossible to continuously provide sufficient heating performance.

So, MTH has been working on the construction of an air conditioning system for electric vehicles that can ensure continuous heating performance without using an electric heater by using only compressor power as a heat source without heat absorption from the outside air when the outside air temperature is low. This report introduces the system configuration and heating technology.

2. Configuration of air conditioning system for electric vehicles

Existing automotive air conditioning systems use a single-medium-loop refrigerant circuit to exchange heat between the refrigerant and air. On the other hand, the system examined in this report exchanges heat between the refrigerant and a heat medium (coolant) and then between that coolant and air, which is called a secondary-loop system because it has two medium loops, first loop for the refrigerant circuit and secondary loop for the coolant circuit.

Existing heat pump systems exchange heat between the refrigerant, which has a lower temperature than the outside air temperature, and the outside air in the outdoor heat exchanger to absorb heat from the outside air. The heating performance can be represented by the following equation [(1)].

*1 Engineering Manager, Automotive Thermal Systems Division, Engineering Department, Mitsubishi Heavy Industries Thermal Systems, Ltd.
*2 Automotive Thermal Systems Division, Engineering Department, Mitsubishi Heavy Industries Thermal Systems, Ltd.

$$Qr = \Delta h \times Gr$$
$$Gr = \rho \times Nc \times Vc \times \eta v$$
$$\rho = f(Ts) \qquad \ldots (1)$$

Where

Qr: heating performance, Δh: enthalpy difference between condenser inlet/outlet,
Gr: refrigerant flow rate, ρ: compressor inlet refrigerant density, Nc: compressor speed,
Vc: compressor displacement, ηv: volumetric efficiency, and Ts: compressor inlet refrigerant temperature

The conventional automotive air conditioners experience a decrease in compressor inlet refrigerant density ρ when the outside air temperature becomes lower and the temperature of the refrigerant on the heat-absorbing side decreases. Therefore, to obtain a heating performance Qr enough to make the cabin comfortable, it is necessary to increase enthalpy difference between the condenser inlet/outlet Δh or increase the refrigerant flow rate Gr. However, with the conventional refrigerant, the enthalpy difference does not change significantly even if the refrigerant pressure on the high-pressure side is changed, and the refrigerant flow rate Gr is determined by the displacement Vc and rotation speed Nc of the compressor used, so a large compressor is needed to ensure the necessary heating performance, which increases as the outside air temperature decreases. This report describes the construction of a system that maintains high refrigerant pressure on the low-pressure side to prevent the compressor inlet refrigerant density from decreasing, thereby ensuring heating performance, even at low outside air temperatures.

Figure 1 shows the system circuit diagram. The secondary-loop system has two types of loops: a refrigerant loop and a coolant loop. The refrigerant loop consists of an electric compressor, a high-pressure side refrigerant heat exchanger, an electronic expansion valve, a low-pressure side refrigerant heat exchanger and an accumulator. It has a very simple equipment configuration without multiple low-pressure side refrigerant heat exchangers, high-pressure side refrigerant heat exchangers, and refrigerant switching valves on the refrigerant circuit that conventional single loop heat pump systems have.

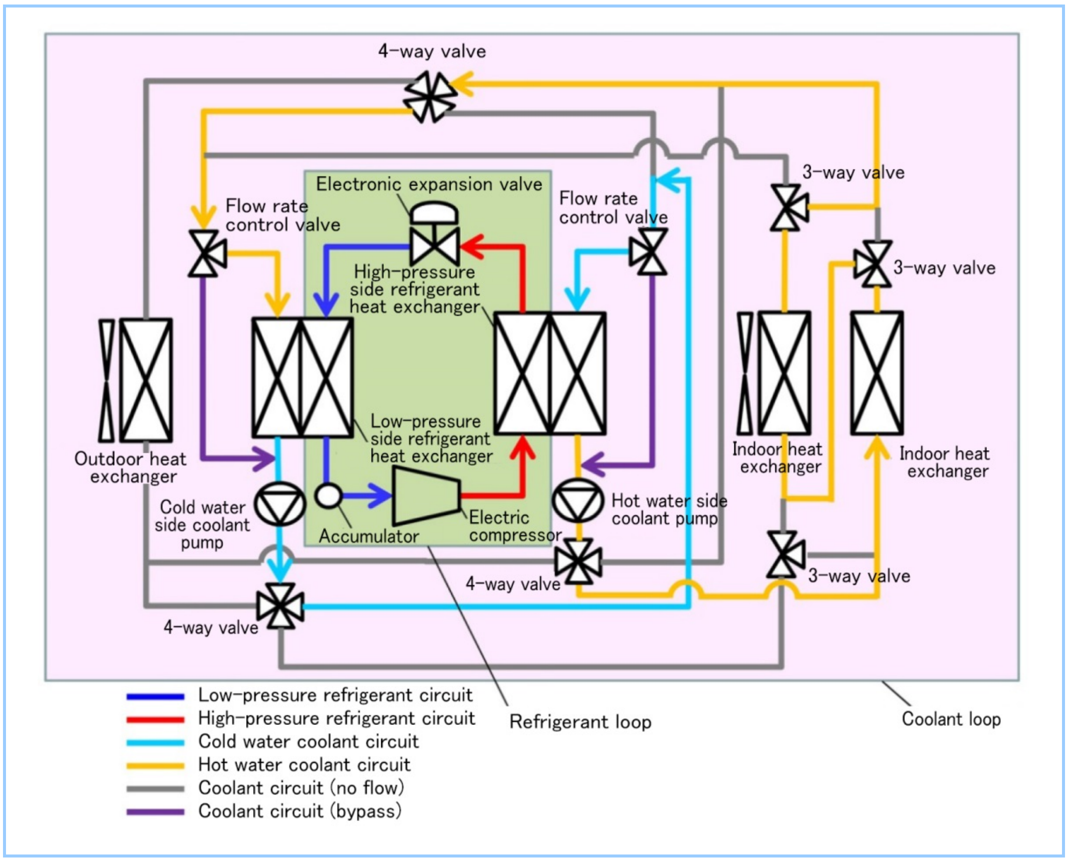


Figure 1 Circuit of air conditioning system for electric vehicles (secondary-loop system)

The coolant loop consists of a cold water side coolant pump, a hot water side coolant pump, an indoor heat exchanger, an outdoor heat exchanger, and several valves (three-way valve, four-way valve, and flow control valve) that switch the coolant loop. Depending on the specifications of the electric vehicle, it may have a loop for coolant flow to the battery, motor, or other equipment to be thermally managed.

In this loop, such conventional automotive air conditioning operations as cooling, heating and dehumidification heating are made possible. The circuit configuration of the refrigerant loop and the flow direction of the refrigerant are the same in all operation modes, while the coolant loop is switched by the coolant valves according to the operation mode.

3. Heating technology with secondary-loop system

The secondary-loop system MTH has developed uses only compressor power as a heat source for heating. By integrating the coolant loops of the low-pressure side refrigerant heat exchanger and the high-pressure side refrigerant heat exchanger on the same circuit, heating without the need for electric heaters or other devices can be achieved. We refer to this as heater mode operation. The heating performance can be represented by the following equation (2).

$$Qr' = \Delta h' \times Gr'$$
$$Gr' = \rho' \times Nc' \times Vc' \times \eta v'$$
$$\rho' = f(Ts') \quad \ldots (2)$$

Where

Qr': heating performance, Δh': enthalpy difference between compressor inlet/outlet,
Gr': refrigerant flow rate, ρ': compressor inlet refrigerant density, Nc': compressor speed, Vc': compressor displacement, ηv': volumetric efficiency, and Ts': compressor inlet refrigerant temperature

Figure 2 compares the operating points of heat pump operation and heater mode operation at low outside air temperatures in a Mollier diagram. In the heat pump operation, the compressor inlet density is small and the heating performance is small. On the other hand, in the heater mode operation, by passing high-temperature coolant through the low-pressure side refrigerant heat exchanger, the compressor inlet refrigerant temperature Ts', compressor inlet refrigerant density ρ', and refrigerant flow rate Gr' can be increased, which can ensure the heating performance Qr'. However, in the heater mode operation, since heat absorption from the outside air is not performed, only the enthalpy difference Δh' between compressor inlet/outlet determines the heating performance.

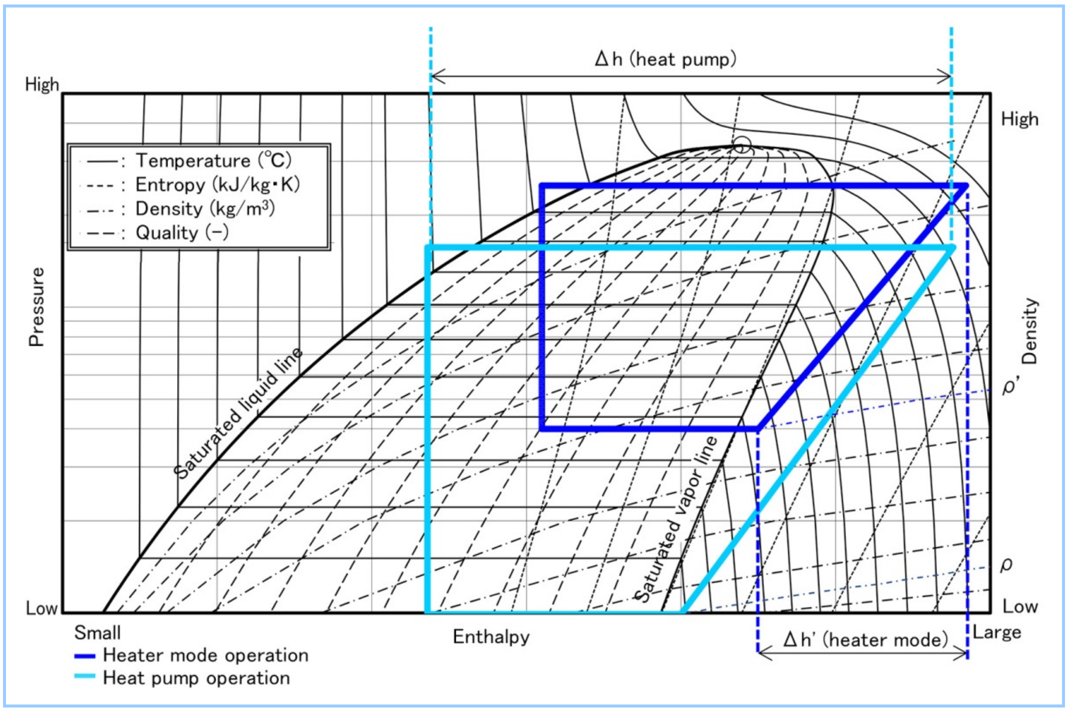


Figure 2 Comparison of operating points of heater mode operation and heat pump operation (Mollier diagram)

For example, when the heating performance is insufficient, the low-pressure side refrigerant pressure is increased by increasing the hot water coolant flow rate to the low-pressure side refrigerant heat exchanger. To increase the temperature of high-temperature coolant in order to increase the temperature of the coolant into the indoor heat exchanger, the amount of cold water coolant passing through the high-pressure side refrigerant heat exchanger is increased to increase the amount of heat transfer to the hot water coolant.

Furthermore, since the heater mode operation of the secondary-loop system does not pass the coolant through the outdoor heat exchanger, the operation is possible even under frosty conditions, allowing continuous heating operation without the need for interruption of heating such as defrosting.

The heat pump operation and heater mode operation can also be switched according to the outside air temperature, coolant temperature, refrigerant temperature, refrigerant pressure, and required performance. Moreover, the high-pressure side refrigerant pressure and low-pressure side refrigerant pressure can be appropriately adjusted while achieving the coolant temperature that meets the user's requirements by switching the valves.

Figures 3 and **4** show the results of tests on actual equipment regarding controllability during heating start-up operation at low outside air temperatures.

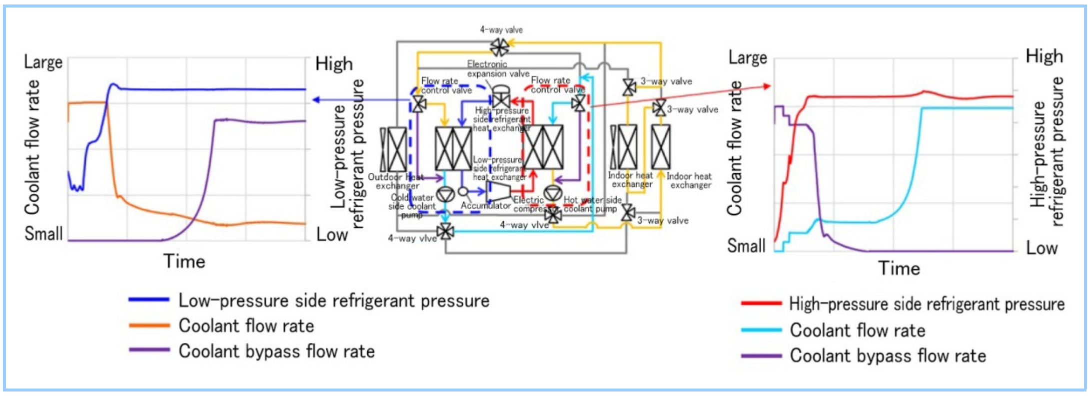


Figure 3 Heating start-up operation (refrigerant pressure control by coolant flow rate)

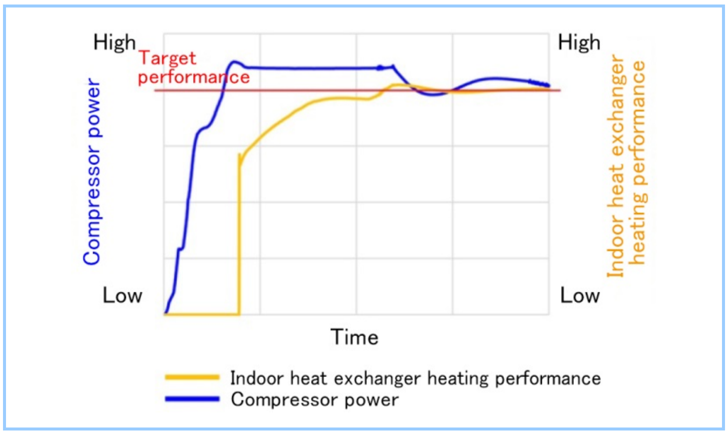


Figure 4 Heating start-up operation (heating performance)

The left graph in Figure 3 shows the relationship between the refrigerant pressure and coolant flow rate in the low-pressure side refrigerant heat exchanger (evaporator). For the low-pressure side refrigerant heat exchanger, when the low-pressure side refrigerant pressure is low at the start of operation, the coolant flow control valve is controlled to stop the flow rate bypassing the low-pressure side heat exchanger, which maximizes the hot water coolant flow to the low-pressure side heat exchanger to increase the low-pressure side refrigerant pressure. Then by adjusting the coolant flow rate to the low-pressure side heat exchanger and the bypassing amount to achieve the set pressure, the refrigerant pressure is maintained.

The right graph in Figure 3 shows the relationship between the refrigerant pressure and coolant flow rate in the high-pressure side refrigerant heat exchanger (condenser). For the high-pressure side refrigerant heat exchanger, at the start of operation, the coolant flow control valve is controlled to increase the flow rate bypassing the high-pressure side heat exchanger in order to increase the high-pressure side refrigerant pressure. Then, by adjusting the coolant flow rate to the high-pressure side refrigerant heat exchanger and the bypassing amount to achieve the set pressure, the refrigerant pressure is maintained. Thus, by adjusting the coolant valve according to the refrigerant pressure sensor value, the system refrigerant pressure can be adjusted regardless of the outside air temperature. As a result, it was confirmed in an actual equipment test that the target heating performance of the indoor heat exchanger can be ensured by the automatic operation control in the heating start-up operation as shown in Figure 4.

4. Conclusion

We have constructed an air-conditioning system for electric vehicles using a secondary-loop system that combines the refrigerant and coolant circuits to ensure heating performance at low outside air temperatures and realize continuous heating without causing frost on the outdoor heat exchanger, thereby improving cabin comfort in electric vehicles at low outside air temperatures.

Moving forward, in addition to the improvement of cabin comfort, we will develop technologies for applying the secondary-loop system to thermal management of batteries and circulating coolant there at appropriate temperatures in order to deal with battery operating conditions (cooling during rapid charging and heating during low temperatures), realize waste heat recovery through motor cooling, and improve heating efficiency. We believe that this technology can reduce the power consumption of electric vehicles and extend their range, which contribute to the reduction of CO_2 emissions.

References

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