Performance analysis of a vapor injection heat pump using ambient air and recovery electric motor waste thermal

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Abstract. A vapor injection heat pump using electric motor exhaust thermal and ambient air is proposed. This system is applied in pure electric vehicles to improve the air conditioning system consumes too much energy when the ambient temperature is lower than -15°C that affects the vehicle mileage. The compressor of two inlets connected with the high-pressure heat exchanger and the outside evaporator. Mathematical models about vapor injection compressor have been built. The performance analysis is carried out under variable conditions. The results show that the vapor injection heat pump using electric motor waste thermal and ambient air has more performance in low ambient. The optimal opening about the high-pressure electronic expansion valve (EXV) is 13%, and the optimal COP for the air conditioning system is 1.75, the car inside outlet temperature higher than 40°C.

1. Introduction
The traditional vehicles with internal combustion engines consume non-renewable energy and emit a large amount of exhaust gas, leading to air pollution and the greenhouse effect, which causes the transportation industry to face severe energy and environmental problems. [1] With higher fuel economy and emission standards, auto companies are trying to update and improve traditional vehicles and develop new energy-saving and environmentally-friendly vehicles. Electric vehicles are currently the most likely to replace traditional vehicles [2]. Compared with internal combustion engine automobiles, electric vehicles need to cool the motor and consider the different energy utilization efficiency requirements under the battery capacity limited [3].

One of the most important is the heating function of the passenger compartment in a low-temperature environment. Especially in China, the north's low-temperature environment must be considered when a model is launched on the market. In a low-temperature environment, the heat pump system will produce sufficient heat absorption of the ambient air, and it presents good integrability, [4] high efficiency. [5] For the driver and passengers to feel the heating function, the air outlet temperature must be higher than 40°C. Based on the above two conditions, the speed of the compressor will be increased, increasing the energy consumption of the air conditioning system, that is, a reduction in the mileage of the vehicle.

Much research has been done on electric vehicles' thermal management, but most of them improve battery temperature. Heating a cabin in low ambient temperature is the most power-consuming. [6] This
paper proposes an air conditioning scheme for electric vehicles to improve the thermal management system's energy utilization efficiency, as shown in Fig.1.

**Figure 1.** Schematic of air conditioning

2. **System description**

The proposed system is illustrated in Fig.1. It contains a VI compressor, inside the condenser, high-pressure heat exchanger, outside evaporator, low-pressure heat exchanger, accumulator, high-pressure electronic expansion valve, and low-pressure electronic expansion valve.

2.1. **Fundamentals**

After the refrigerant leaves the compressor, it exchanges heat in the condenser. In order to prevent fogging in the car, the heat exchange gas is external air; the refrigerant is divided into two after leaving the condenser, and one part is heated with the other after passing through the electronic expansion valve. Exchange, and then enter the other inlet of the vapor injection compressor, the other part passes through the electronic expansion valve, and then exchanges heat with the ambient air in the external heat exchanger, and then exchanges heat with the cooling water of the electric motor in the chiller, and finally to prevent the compressor from liquid shock. Enter the gas-liquid separator before entering the compressor inlet. A subsubsection.

The pressure-enthalpy (p-h) diagram of the vapor injection heat pump is presented in Fig.2. This heat pump system has an additional heat exchanger where the refrigerant is partially vaporized by the other refrigerant compared with normal heat pump. The system has a higher COP.
Figure 2. Pressure-enthalpy of vapor injection system

2.2. Advantage

Compared with a conventional air source heat pump, the vapor injection heat pump has some foreseeable advantages, including:

First, the use of a condenser makes it possible to absorb more heat from the exhaust gas, which exceeds the heat that can be recovered by a vapor injection compressor with a single inlet. In the single-inlet vapor injection compressor heat pump system, the temperature leaving the indoor condenser is too high, resulting in insufficient waste heat recovery. In this system, the utilization rate of waste heat is improved through two heat exchangers.

Second, the system has a flexible working model. According to the different ambient temperatures, the vapor injection circuit's refrigerant flow ratio and the conventional heat pump circuit can be flexibly adjusted. Moreover, the use of waste heat reduces the problem of frosting compared with the traditional heat pump because part of the heat is absorbed from the motor cooling water, which increases the refrigerant temperature at the compressor outlet.

Third, it is more suitable for heating at -15°C than a standard heat pump and meets the cabin inside the outlet temperature higher than 40°C. For a standard heat pump, when the ambient temperature is lower than -5°C, it cannot satisfy effective heating. Therefore, in combination, the vapor injection heat pump with two-stage compression is more suitable in low-temperature environments. It will increase the COP of the system and ensure the car’s endurance.

3. Result and discussion

In this simulation, the high-pressure electronic expansion valve's influence and the low-pressure electronic expansion valve on the vapor injection heat pump performance are analyzed. Some assumptions are made: (1) The mechanical efficiency of the compressor is 0.8. (2) The flow rate of outside ambient air is one kg/s. (3) The refrigerant is R134a. (4) The flow rate of inside ambient air is 0.05 kg/s. The fan and water pump power are not included, and the pressure drop of refrigerant in the heat exchanger are all ignored. (5) The water temperature is ten ℃.

The proposed vapor injection heat pump system is also suitable for the conventional car because the internal combustion engine will produce more waste heat than the electric motor.

An outside ambient airflow rate of 1 kg/s and inside ambient airflow rate of 0.05 kg/s is reasonable.

3.1. Influence of low-pressure electronic expansion valve

A detailed parameter distribution of the vapor injection heat pump at a variable low-pressure electronic expansion valve is provided in Table 1.
The cabin inside outlet temperature varying with the low-pressure electronic expansion valve's opening is depicted in Fig.3. The larger the opening of the electronic expansion valve, the higher the air outlet temperature. The cop for this vapor injection heat pump is presented in Fig.4 at the low-pressure electronic expansion valve's variable opening. It can be seen from the simulation results that the smaller the opening of the electronic expansion valve, the greater the system superheat, and the higher the COP. A comparison among the superheated for the test and target is presented in Fig.5. To ensure the compressor’s safe operation and prevent damage to the compressor caused by liquid shock, it is necessary to ensure that the refrigerant at the suction port of the compressor is in a dry vapor state. That is, the refrigerant superheat is greater than 0 (K). When the electronic expansion valve's opening degree is between 31% and 41%, the degree of superheat meets the requirements. To meet the heating requirements of automobile air conditioning, the air outlet's temperature should be higher than 40°C. Therefore, the electronic expansion valve's opening degree can be increased in the early stage of the air conditioner startup. After the temperature reaches a certain level, the opening degree of the electronic expansion valve can be reduced to reduce the system's energy consumption.

Table 1. Parameter distribution of the vapor injection heat pump at a variable low-pressure EXV.

| Point | Refrigerant | Flow rate, kg/s | Temperature, ℃ | Pressure, bar/A | Enthalpy, kJ/kg | Status  |
|-------|-------------|----------------|----------------|----------------|----------------|---------|
| 1     | R134a       | 0.026          | 89.82          | 10.8           | 471.66         | Superheated |
| 2     | R134a       | 0.026          | 41.92          | 10.7           | 362.80         | Two-phase |
| 3     | R134a       | 0.015          | 5.93           | 3.61           | 362.80         | Subcooled |
| 4     | R134a       | 0.015          | 41.87          | 3.58           | 434.95         | Superheated |
| 5     | R134a       | 0.011          | 41.91          | 10.7           | 260.56         | Two-phase |
| 6     | R134a       | 0.011          | -28.04         | 0.93           | 260.56         | Subcooled |
| 7     | R134a       | 0.011          | -16.08         | 0.88           | 391.19         | Superheated |

Figure 3. Variations of temperature with the low-pressure EXV
3.2. Influence of high-pressure electronic expansion valve

A detailed parameter distribution of the vapor injection heat pump at a variable high-pressure electronic expansion valve is provided in Table 2.
Table 2. Parameter distribution of the vapor injection heat pump at a variable high-pressure EXV.

| Point | Refrigerant | Flow rate, kg/s | Temperature, °C | Pressure, bar/A | Enthalpy, kJ/kg | Status   |
|-------|-------------|-----------------|-----------------|-----------------|-----------------|----------|
| 1     | R134a       | 0.051           | 68.25           | 10.3            | 449.73          | Superheated |
| 2     | R134a       | 0.051           | 43.26           | 9.9             | 395.92          | Two-phase  |
| 3     | R134a       | 0.033           | 26.64           | 6.98            | 396.08          | Subcooled |
| 4     | R134a       | 0.033           | 43.19           | 6.92            | 426.25          | Superheated |
| 5     | R134a       | 0.018           | 43.25           | 10.01           | 339.57          | Two-phase  |
| 6     | R134a       | 0.018           | -17.34          | 1.49            | 339.56          | Subcooled |
| 7     | R134a       | 0.018           | -18.56          | 1.48            | 387.06          | Superheated |

A comparison among the cabin inside outlet temperature for the 13K superheated and 15K superheated is presented in Fig.6. When the opening of the high-pressure electronic expansion valve is reduced, it is found that the cabin inside the outlet temperature rises. A comparison among the COPs for the 13K superheated and 15K superheated is presented in Fig.7. The COP will rise first and then fall, while the air outlet temperature will continue to rise. Therefore, under the premise of meeting the heating demand, when the air outlet temperature is greater than 40°C and the electronic expansion valve for vapor injection is at 13%, the energy consumption of the heat pump system is the lowest.

![Figure 6. Variations of cabin inside outlet temperature with the high-pressure EXV](image-url)
Figure 7. Variation of COP with the high-pressure EXV

4. Conclusion

The vapor injection heat pump for use in EVs at various startup conditions: the heating system is just turned on; the temperature of the passenger compartment reaches the target temperature. 1. At the cold startup condition, to achieve the rapid temperature rise of the passenger compartment, increase the low-pressure opening to make the superheat greater than 0K, and then control the high-pressure electronic expansion valve to 10%. Although this control method makes the system energy consumption high, and it can increase the temperature of the cabin inside the outlet. 2. After the temperature of the passenger compartment reaches the target temperature, first control the high-pressure opening to 13%, and then control the low-pressure electronic expansion valve to ensure that the air outlet temperature is greater than 40°C, furthermore, the superheat is greater than 0K. The coefficient of performance (COP) and energy-saving of vapor injection heat pump were improved by 12.9% and 203.94w at an ambient temperature of -15 °C, respectively.

Acknowledgments

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