Performance and Optimization Study of R290 as Alternative Refrigerant for R22 in Low Temperature Heat Pump System

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Abstract This paper mainly studies the replacement performance of R290 in R22 low temperature heat pump system from the experimental point of view. By comparing the performance differences under different working conditions, it is found that when R22 is directly extracted from the original system and filled with R290, the heat capacity and COP of the system are attenuated, and the compressor discharge temperature and pressure of the R290 system are higher than those of the original R22 system in low temperature environment. Through the analysis of the system components, it can be considered that the main reason for the above phenomenon is that the compressor displacement of the R22 system is too large and does not match the R290 system. Therefore, in order to meet the safety requirements of the system and improve the overall performance of R290 in the low temperature heat pump system at the same time, it is considered to replace the compressor with a smaller displacement which is more matched with R290 in the system. The experimental results show that the compressor displacement optimization of the R290 low temperature heat pump system can effectively reduce the exhaust temperature and pressure of the system and improve the overall performance of the system. The COP of the optimized R290 low temperature heat pump system is 6.5% higher than that of the original R22 system, and the exhaust temperature in the low temperature environment is reduced by 36% to below 80 °C.

1. Introduction
HCFC refrigerant R22 is widely used in household and commercial areas. However, due to its ability to destroy the atmospheric ozone layer and certain greenhouse effect potential, R22 has been banned by the Kigali amendment of the Montreal Protocol. At present, the replacement refrigerant of R22 at home and abroad is mainly divided into two directions: One is the HFCS replacement scheme dominated by the United States and Japan[0], and the other is the natural refrigerants such as R290 (propane) dominated by China and Europe[2].

The attitude of the industry to refrigerant replacement is to try not to make too many changes to the original system, in order to achieve optimal performance at a lower cost[13]. For the selection of R22 alternative refrigerants, many scholars have made the corresponding research [[4]-[6]], Li[7] and others have used the new refrigerant mixture R417A to replace the R22 heat pump hot water system; Zhang[8] also used R417A to replace R22 in the field of household air conditioning; By comparing the thermophysical properties of R22 and R32, Shi[9] and others studied the alternative research of R22 air conditioning in household and commercial fields; Yao[10] and others simulated the thermophysical properties of R22 and R290 by establishing the corresponding parameter relationship equations. Among
the alternatives in the field of household air conditioning, R290 stands out among many alternative refrigerants because of its excellent environmental performance and similar thermophysical properties to R22 due to its ODP and GWP values of 0\cite{11}. Generally speaking, the existing R22 system does not need to be improved too much, and R290, as a by-product of the oil and gas industry, is easy to produce and low cost. Therefore, for low temperature heat pump system, R290 is an ideal substitute for R22\cite{12}.

The existing research on R290 replacing R22 refrigerant mainly focuses on the performance of R290 as an alternative refrigerant in the refrigeration system and the related problems and solutions. There is a lack of research on the alternative performance of R290 in heat pump systems, especially in low temperature environment. Therefore, this paper mainly explores the performance effect of R290 in the low temperature heat pump system from the experimental point of view, and gives the relevant optimization suggestions and direction for the alternative research of R22 in the low temperature heat pump system.

2. Theoretical analysis

It can be seen from Tab.1 that the main physical properties of R290 are very similar to those of R22. And the ODP value of R290 is 0, GWP value is very small, so it has the basic conditions to replace R22\cite{13}.

| Tab.1 Physical properties of R290 and R22 |
|-----------------|-----------------|
| Refrigerant     | R22             | R290            |
| Molecular formula| CHCLF2          | C3H8            |
| Molecular weight | 86.47           | 44.09           |
| Boiling point (°C) | -40.78          | -42.07          |
| Freezing point (°C) | -160            | -187.7          |
| Critical pressure (Mpa) | 4.974          | 4.254           |
| Critical temperature (°C) | 96.2           | 96.8            |
| Critical specific volume (m^3/kg) | 0.001904       | 0.004545        |
| Latent heat of boiling point (kJ/kg) | 234.5          | 430             |
| Saturated liquid density (kg/m^3) | 1412           | 582             |
| ODP value        | 0.055           | 0               |
| GWP value        | 1600            | <20             |

It can be seen from Fig.1 that the saturated gas pressures of R22 and R290 are very close, and because of their similar pressure temperature curves, R22 can be directly extracted from the original R22 system to fill R290 without major changes\cite{14}.
Through the above comparison of R22 and R290, it can be concluded that the characteristics of R290 mainly focus on the following aspects:

1. The latent heat of vaporization of R290 is 1.84 times that of R22, which indicates that the circulation of working fluid can be reduced by using R290 under the same heating capacity.

2. The adiabatic index of R290 is lower than that of R22. At the same compression ratio, the power consumption can be reduced, the exhaust temperature can be reduced, the gas transmission coefficient can be increased, the heat exchange between gas and cylinder can be reduced, the irreversible loss can be reduced, the exhaust temperature can be reduced, the working condition of condenser can be improved, the irreversible heat transfer loss can be reduced, and the energy consumption can be reduced.

3. The thermal conductivity of R290 is higher than that of R22, which can improve the heat dissipation condition of the compressor, increase the heat transfer coefficient of the condenser and evaporator, and further reduce the energy consumption of the system.

3. Experimental study

In order to study the performance of the R290 low temperature heat pump system under different working conditions, especially in a low temperature environment, the original R22 heat pump system was replaced. The charging capacity of the original R22 system is 5kg, and that of the R290 system is 3kg, which meets the relevant standards of GB 4706.32-2012 ‘safety of household and similar electrical appliances - special requirements for heat pumps, air conditioners and dehumidifiers’ about the refrigerant charging capacity M < (130m ^ 3) * LFL of heat pump system.

The heat pump system is mainly composed of a scroll compressor, tube fin heat exchanger, shell and tube heat exchanger, a thermal expansion valve, gas-liquid separator and a liquid storage tank. The experiment was carried out in the enthalpy chamber, which is mainly divided into an evaporation chamber and a condensation chamber. A wind tunnel is respectively arranged in the evaporation chamber and the condensation chamber, which is used to adjust the inlet air volume of the evaporator and the condenser and measure the dry and wet bulb temperature of those two chambers. The temperature and humidity of the evaporation chamber and condensation chamber are controlled by a refrigerating unit, an electric heater and humidifier respectively. In the pipeline of the original machine, holes are drilled in the front and back of each part, and sensors are arranged to measure the pressure and temperature of the system. The experimental platform is shown in Fig. 2 and Fig. 3, and the accuracy analysis of the experimental platform can be referred to Tab.2.
Table 2: Experiments Measurement Accuracy

| Equipments                        | Accuracy |
|-----------------------------------|----------|
| Power meter                       | ±0.2%    |
| Electronic scale                  | ±10g     |
| Pressure sensor                   | ±10kPa   |
| Temperature sensor                | ±0.5K    |
| Electronic nozzle pressure differences | ±2Pa     |

In order to analyze the performance of the heat pump system under different environmental conditions, a total of 20 groups of experimental conditions as shown in Tab. 3 were designed to analyze and compare the performance differences of the two systems.
4. Experimental results and discussion
In order to analyze the specific performance differences between R290 and R22, the heating capacity, COP, exhaust pressure, exhaust temperature and other parameters under different ambient temperatures and the same outlet temperature were compared.

4.1 Comparison of system d and COP
The results show that the heat transfer of the system decreases with the decrease of the ambient temperature, and there is little difference between the two refrigerants. The COP of the R290 system is higher than that of the R22 system at 21 ℃, but the performance degradation of R290 system is greater than that of R22 system. The COP of the R22 system is higher than that of the R290 system under 21 ℃.

![Fig.4 Comparison of heat exchange between R22 and R290](image-url)
Because the latent heat of vaporization of R290 is higher than that of R22, the displacement of the compressor used in the original R22 system is too large for R290. Larger refrigerant flow means that the heat exchange temperature difference required by the system is larger under the same heat exchange conditions. By comparing the relationship between the temperature difference and heat transfer between the condenser and outlet water temperature of the R22 and R290 systems, it can be seen that the overall heat transfer temperature difference of the R290 system is greater than that of the R22, and the overall heat transfer of R22 system is higher than that of R290 system, so the overall heat transfer efficiency of R22 system is higher than that of R290 system. It is worth noting that the heating capacity of R22 in a low temperature environment has obvious attenuation (three points in the lower part of Fig.6), which indicates that the thermal efficiency of R22 is low in a low temperature environment, while the efficiency of R290 is relatively stable at low temperature. This is also reflected in the changes of COP of R290 and R22: the change of COP tends to be stable when R290 is under -6 °C, and the COP attenuation of R22 is more severe. In addition, the overall heat transfer demand and refrigerant flow of the system are small at indoor temperature of 21 °C, so the compressor displacement has little effect on the R290 system. With the larger latent heat of vaporization, the heat transfer efficiency of the R290 system is higher (as shown in the top three points on the left of Fig.7), which also explains why the COP of the R290 system is higher than that of the R22 system at indoor temperature of 21 °C.
4.2 Comparison of exhaust temperature and pressure

In order to analyze the influence of compressor displacement on system performance, the exhaust temperature and pressure of the two systems are compared. It can be seen that the overall discharge pressure of the R290 system is higher than that of the R22 system. The exhaust pressure of the R22 system decreases slightly with the decrease in ambient temperature. The exhaust pressure of the R290 system first increases and then decreases with the decrease of ambient temperature, and reaches the highest exhaust pressure at -6 °C. The exhaust temperature of the R290 system is lower than that of the R22 system when it is above 2 °C, and higher than that of the R22 system when it is below 2 °C. The exhaust temperature of the R22 system increases with the decrease in ambient temperature. The exhaust temperature of the R290 system first increases and then decreases with the decrease in ambient temperature, and reaches the highest exhaust temperature at -6 °C.
This change in trend is mainly caused by the matching problem between the refrigerant and the compressor displacement. When the temperature is 21 ℃, the overall heat exchange demand of the system is small and the refrigerant flow is small, so the compressor displacement has little effect on the R290 system. At this time, the discharge pressure and temperature of the R290 system are lower than those of the R22 system. With the decrease in ambient temperature, the heat load of the system becomes larger. At this time, the mismatched compressor makes the refrigerant flow of the R290 system much higher than that of the R22 system, which means that the compressor load of the R290 system is higher than that of the R22 system, and the discharge pressure and temperature of the R290 system are higher than that of R22 system. At -6 ℃, the exhaust temperature and pressure of the R290 system suddenly increase, which is mainly due to the overheating of the system caused by the too small opening of the expansion valve.

4.3 Data analysis
From the above data results, it can be concluded that when R290 is directly used in the R22 system, the overall performance of the system decreases, and the heat exchange and COP of the system decrease. In a low temperature environment, the compressor discharge temperature and pressure of the R290 system are higher than those of the R22 system. Because too high exhaust pressure and temperature will affect the safety of the compressor, it is more unfavorable for the operation of the system. Through the analysis of the system components, it can be considered that the main reason for the above phenomenon is that the compressor displacement of the R22 system is too large and does not match the R290. Too large displacement of the compressor means that the refrigerant flow of R290 is too large. Therefore, in order to achieve the same level of heating, the heat exchange temperature difference required by the system is larger, which results in higher discharge temperature and pressure of the R290 compressor [17]. Therefore, in order to meet the safety requirements of the system and improve the overall performance of R290 in the low temperature heat pump system at the same time, it is considered to replace the compressor with a smaller displacement which is more match with R290 in the system.

5. Optimization and improvement
In order to ensure the safe and efficient operation of the R290 low-temperature heat pump system, the original compressor with 120cc displacement in the R22 system is replaced by the compressor with 85cc displacement, which is more suitable for the R290. At this time, the optimal charge of the R290 system is reduced to 2.6kg. The test was completed under the same environmental conditions, and the performance of the improved R290 system is compared with that of the R22 system.

Due to the use of a smaller displacement compressor, the overall heat transfer of the improved R290 system is slightly less than that of the original R22 system, but the overall COP of the R290 system is about 6.5% higher than that of the original R22 system.

![Fig. 10 Comparison of heat exchange between R22 system and improved R290 system](image-url)
In the aspect of compressor operation, it can be seen that the discharge pressure and temperature of the improved R290 system have been greatly improved: When the temperature is above 2 °C, the improved R290 system can effectively reduce the discharge pressure of the compressor, and when the temperature is below 2 °C, the R290 system can also reach the same level as the R22 system. At the same time, the exhaust temperature of the improved R290 system can be greatly reduced, especially in the low temperature environment, the exhaust temperature of the original R22 system can be reduced by more than 36%.

Fig.11 Comparison of COP between R22 system and improved R290 system

Fig.12 Comparison of system exhaust pressure between R22 system and improved R290 system

Fig.13 Comparison of system exhaust temperature between R22 system and improved R290 system
From the above data results, it can be seen that after the optimization of the compressor, the overall performance of the R290 low temperature heat pump system has been improved to a certain extent, especially greatly reducing the exhaust temperature of the compressor, effectively improving the overall safety performance of the system.

6. Conclusions
In this paper, the system performance tests of R290 and R22 were completed under different conditions. The heating capacity, COP, exhaust pressure and exhaust temperature were compared at different ambient temperatures and the same outlet temperature. The feasibility of R290 replacing R22 in low temperature heat pump system is analyzed from the experimental point of view:

(1) The thermophysical properties of R290 are similar to those of R22, and R290 is superior to R22 in terms of latent heat of vaporization, ODP, GWP, etc;

(2) The optimization of the compressor displacement in the R290 low temperature heat pump system can effectively reduce the exhaust temperature of the compressor and improve the overall performance of the system;

(3) Compared with the original R22 system, the performance of R290 low-temperature heat pump system after compressor optimization has been greatly improved: COP increased by 6.5%, and the exhaust temperature decreased by 36% under -12°C low-temperature environment to below 80 °C;

(4) In the low temperature heat pump system, R290 instead of R22 has the characteristics of high efficiency, good safety and low cost, so it has a good application prospect.

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