Study on the influence of refrigerant charge on performance of heat pump units

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Abstract: Refrigerant charge can be determined by two methods, experiments or theoretical calculation. Experiments are usually carried out under the specific system and working condition, and the results are reliable. However, there have some problems, such as it needs a large amount of experimental work and the results are only suitable for specific systems and working conditions. The method of theoretical calculation to determine the refrigerant charge can be used in different systems and working conditions, but the reliability of the calculation results depends on the degree of coincidence between the void fraction coefficient model and the actual system. Especially for new refrigerants, the applicability of void fraction coefficient model needs further verification. In this paper, the optimum charge quantity of new refrigerant in the water source heat pump unit is studied by methods of experiment and SIMULINK simulation. The results show that the difference between simulation and experimental values is within 10%. The simulation method provides a reference for the optimization of refrigerant charge.

1. Introduction
The refrigerant charge is closely related to the working characteristics of the refrigeration equipment, and the optimization of refrigerant charge is an important part of the optimization of the refrigeration and air conditioning system. If the charge quantity of refrigerant is too small, only part of the evaporator will be infiltrated, and the heat transfer area of the evaporator will not be fully utilized and the total evaporation capacity in the unit time will also be less, so the system cannot meet the suction requirements of the compressor, and the evaporation pressure drops, the flow velocity decreases, the heat transfer coefficient of the evaporator decreases, the superheat of the evaporator outlet and the suction specific volume of the compressor increases, the circulating flow and cooling capacity decreases. If refrigerant is overcharged, it will cause the liquid accumulation in the condenser, the effective heat transfer area decreases, the condensing temperature and the pressure ratio increases, which will lead to the increase of the power consumption of the compressor and the decrease of the cooling coefficient. Void fraction coefficient method is often used to calculate the refrigerant charge in theoretical calculation. Different models will lead to great differences in calculation results. The simulation model has been widely used in guiding the design and performance improvement of refrigeration equipment. On the basis of previous studies, the best charge amount of refrigerant in the water source heat pump is studied by means of experiment and simulation in this paper.

2. Establishment of simulation model of heat pump unit components
2.1. The mathematical model of each component

2.1.1. Theoretical work quantity and exhaust enthalpy of the compressor. The compressor used in this study is a scroll compressor, and the calculating equations for the theoretical work and exhaust enthalpy of compressor are shown in equations (1) and (2):

\[ w_o = \frac{k}{k-1} p_e v_{th} \left[ \left( \frac{p_e}{p_{c}} \right)^{\frac{k-1}{k}} - 1 \right] \]  

(1)

\[ h_2 = h_1 + \frac{N_{\text{com}}}{G_r} \]  

(2)

2.1.2. Rate of heat transfer of condenser and evaporator. The condenser and evaporator are all plate heat exchangers, and the rate of heat transfer are shown in equations (3) and (4) respectively.

\[ Q_c = K_c A_c \frac{t_{w4} - t_{w1}}{\ln \frac{t_{w1} - t_c}{t_{w4} - t_c}} \]  

(3)

\[ Q_z = K_z A_z \frac{t_{d4} - t_{d3}}{\ln \frac{t_{d3} - t_z}{t_{d4} - t_z}} \]  

(4)

2.1.3. Mass flow of expansion valve. The electronic expansion valve is a device for changing the refrigerant flow to ensure the normal operation of the unit by detecting the temperature or pressure of the evaporator outlet. Because the enthalpy of refrigerant before or after expansion is equal, so we only provide the equation for calculating refrigerant flow of electronic expansion valve in this paper:

\[ m_r = C_v A_j \sqrt{2 \rho (p_{in} - p_{out})} \]  

(5)

2.2. The establishment of the simulation model of each component

SIMULINK is a visual simulation tool in MATLAB, which is based on MATLAB block diagram design environment. It is a software package that can realize dynamic system modeling, simulation and analysis. It is widely used in the modeling and Simulation of digital signal processing, digital control, linear system and nonlinear system. SIMULINK provides an integrated environment for dynamic system modeling, simulation and comprehensive analysis. In this environment, complex systems can be constructed by simple and intuitive operation without the need to write complex programs.

According to the equations of each part of the heat pump, the SIMULINK calculation model of the compressor is obtained as shown in Figure 1. The other parts of the model are no longer repeated.
3. Simulation of charge quantity of refrigerant

The purpose of this paper is to study the effect of total refrigerant charge on the overall thermal heating performance of heat pump system, and to optimize the performance of the system by determining the optimal total charge. Based on the distribution parameter integration method, Liu Jinping et al. [7] used Aspen Plus to establish the Linde-Hampson refrigeration cycle model. The mass distribution of the refrigerants in the components of the system and the accumulation of refrigerant liquid are analyzed by the experiment. The results showed that the refrigerant accumulated in the condenser was about 55-64% of the total charge quantity in the refrigeration system without inter heat exchanger, and the refrigerant in the evaporator was about 17-32% of the total charge quantity. This study is based on this conclusion. According to the refrigerant imported parameters of the compressor, the density of refrigerant is calculated by using REFPROP 9.0, so as to calculate the mass flow rate of refrigerant. There is a corresponding relationship between refrigerating flow rate and filling amount. By changing the total charge quantity of the system and distributing to various parts according to a certain proportion, the optimum charge quantity of the system is determined through simulation results.

3.1. Simulation flowchart

The model of heat pump system is coupled by four main components, and the iterative calculation process of the whole model of the heat pump unit is as follows:
3.2. Experimental verification of simulation model
In order to verify the accuracy of the model, the results of the simulation model are compared with experimental data.

The experimental system consists of a water source heat pump unit with scroll compressor, a plate condenser, a plate evaporator and an electronic expansion valve. The heat capacity of the system is 25kW, refrigerant is ternary mixture refrigerant which is composed of R32, R134a and R1234ze(E), the quality ratio is 50%/33%/17%. The experimental conditions are as follows: The amount of refrigerant charge is 6kg, the cold water temperature is 20℃, and the expansion valve opening degree is 60%. Thermodynamic parameters such as enthalpy of refrigerant in simulation are obtained by REFPROP 9.0. The comparison between the experimental values and the simulations is shown in Table1 to Table3. The results showed that the heat capacity, power consumption, COP, the pressure of the inlet and outlet of the expansion valve, and the inlet and outlet temperature of the evaporator and condenser were within
10%, and the precision of the model is enough to meet the requirements. Therefore, this model can be used to simulate and optimize the refrigerant charge of the system.

| Name                      | Heat capacity /kW | Power /kW | COP  |
|---------------------------|-------------------|-----------|------|
| Experimental value        | 24.96             | 5.58      | 4.47 |
| Simulation value          | 27.2              | 5.88      | 4.6259 |
| error %                   | 8.974359          | 5.376344  | 3.4866 |

Table 2. Comparison of test parameters of evaporator and condenser.

| Name                      | Condenser inlet water temperature /°C | Condenser outlet water temperature /°C | Evaporator inlet water temperature /°C | Evaporator outlet water temperature /°C | Condenser outlet temperature /°C | Evaporator inlet temperature /°C |
|---------------------------|---------------------------------------|----------------------------------------|----------------------------------------|----------------------------------------|---------------------------------|----------------------------------|
| Experimental value        | 42                                    | 45.1                                   | 20.5                                   | 17.2                                   | 44.3                            | 10.1                             |
| Simulation value          | 42                                    | 46.8                                   | 20                                     | 15.8                                   | 46.7                            | 9.2                              |
| error %                   | 0                                     | 3.769401                               | -2.439                                 | -8.139535                              | 5.417607                        | -8.91089                         |

Table 3. Parameter verification of expansion valve and compressor.

| Name                      | Compressor exhaust temperature /°C | Compressor suction temperature /°C | Expansion valve inlet pressure /MPa | Expansion valve outlet pressure /MPa |
|---------------------------|-----------------------------------|-----------------------------------|-------------------------------------|-------------------------------------|
| Experimental value        | 78.5                              | 20                                | 2.22                                | 0.74                                |
| Simulation value          | 81.6                              | 21.5                              | 2.32                                | 0.7                                 |
| error %                   | 3.949045                          | 7.5                               | 4.5045                              | -5.405405                           |

4. Analysis of the experiment result
In order to study the effect of refrigerant charge on the system, this paper set up five groups of different refrigerant charge quantity for simulation calculation, the results are shown in Figure 2 to Figure 4.

From the simulation results, it can be seen that the power consumption of the compressor increases with the increase of the refrigerant charge, and the heat capacity of the unit increases first and then decrease with the increase of the charge. The relationship between COP of the unit and the charge quantity of refrigerant is similar with the heat capacity. Overall, when the refrigerant charge is about 7kg, the COP of the system reaches the highest value, which is consistent with the experimental value.
Figure 2. The relationship between the power consumption of compressor and the charge quantity of refrigerant.

Figure 3. The relationship between heat capacity of the unit and the refrigerant charge.

Figure 4. The relationship between COP of the unit and the charge quantity of refrigerant.

5. Conclusions
In this paper, the experiment and simulation of the new refrigerant charge used in water source heat pump unit are carried out, and the following conclusions are obtained:

(1) The experimental results show that under certain working conditions, there is an optimal refrigerant charge makes the heat pump unit's heating performance coefficient reach the maximum value. Less or more charge quantity can’t make the heat pump system perform optimally.

(2) The differences between SIMULINK simulation result and the experimental data are within 10%,
which indicates that the simulation is effective and it can provide guidance for the optimization of the refrigerant charge in practical projects.

(3) The simulation method provides a reference for the optimization of the charge quantity of the new refrigerant.

Acknowledgements
This work was funded by the Beijing Municipal Education Commission and North China University of Technology under the project of Research on the Performance of Water Source Heat Pump Units with Environmental Refrigerant, Project 16021 and 18XN150.

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