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Surface Water Source Heat Pump Air Conditioning System Simulation and Operation Performance Analysis

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Abstract

This paper established a heat pump system model containing heat pump unit model, AC load model and heat exchanger model utilizing the mass and energy balance and the structure’s designing method. This paper also developed the surface water source heat pump air conditioning system simulation program by Visual Basic, and verified the simulation by the actual engineering project. In addition, this paper explored the impact of the surface water temperature and heat exchanger structure on the heat pump air conditioning system operation. The results shows that one degree drop of the surface water temperature leads to 2.3 per cent increase of performance coefficient and a 100m added length of the closed-loop surface water heat exchanger tube leads to 0.08 per cent increase of performance coefficient.

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Keywords: Surface water source heat pump system; Simulation model; Operation performance

1. Introduction

The operation performance of water source heat pump is significantly affected by the temperature of surface water, and it plays a decisive role for the energy-savings of the whole heat pump system. In order to analyze the system

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operation, a reliable simulation for the heat pump system can be conducted on the basis of a relatively simple
calculation model.

Currently, a lot of heat pump simulation models have been developed, these models can be approximately divided
into two types based on the complexity and the extent of experience: formula fitting model and deterministic model
[1]. For the formula fitting model, several equations are fitted according to the performance parameters of sample
provided by the manufacturers. These equations do not contain the specific structural parameters of the unit, so it has
some limitations. For the deterministic model, models of each component are established on the basis of the laws of
thermodynamics and heat and mass transfer principles, then each component model are connected to constitute a
complete heat pump model by certain relationship. The deterministic model method is suitable for the design and
optimization of the system. The formula fitting model of the heat pump was researched by Hamilton and Miller [1] in
1990, the authors carried out formula fitting for the every component, and a system model was formed based on the
thermodynamic relations among components. The typical deterministic model called steady-state model of
reciprocating heat pump unit was proposed by Bourdouxhe [2] in 1994,in this model, characteristics of the each
component of the unit is determined through several specific formula, the model requires only minimal parameters
and experimental data. In 2001, Ding Guoliang et al. conducted a detailed simulation for each component, and
established a neural network prediction model of heat pump performance [3].

At present, the heat pump models have been mostly established based on the product sample parameters provided
by the manufacturers, the reliability and the authenticity of the data is not guaranteed, so the fitting model is not very
convincing. In terms of heat pump air conditioning system, the researches for air conditioning system model with
surface water as heat source are few. So this paper established the model of heat pump air conditioning system based
on the deterministic model and analyzed the impact of surface water temperature and structure parameters of heat
exchanger in surface water on the system performance by the system model.

2. Methods

2.1. Heat pump circuit and heat pump component thermodynamic model

The circuit of the refrigerant is shown in Fig.1. This part utilized the laws of thermodynamics and heat and mass
transfer principles to establish the system component models with the structure’s parameters identified.

Compressor model was established according to the steady-state simulation model [4], while using the empirical
formula to calculate the volumetric efficiency of open refrigeration compressors. A simplified formula introduced by
the literature [5] was applied in horizontal shell and tube condenser modeling and design calculations involving
structural parameters. In the condenser, cooling water goes in the tube and the gaseous refrigerant in the shell. Throttle
model was based on the assumption that enthalpy of the refrigerant stays the same before and after throttling. In the
horizontal dry shell and tube evaporator model, the refrigerant in the tube boils from the state of wet saturated steam
to the state of dry saturated steam and the water outside the tube flows bypassing the fold baffles. The convective heat
transfer coefficient inside and outside the tube referred to this paper[6].Refrigerant physical parameters was calculated
using polynomial fitting method known as Cleland computational model of refrigerant thermal properties[7].

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*Fig. 1. p-h diagram of refrigeration cycle*
2.2. The AC load model

Supposing the air conditioning cooling/heating load entirely eliminated by chilled(hot) water produced by the heat pump, and the chilled(hot) water transporting heat losses ignored, the instantaneous cooling and heating load calculation formula was thus formed.

2.3. Closed-loop surface water heat exchanger model

Closed-loop surface water source heat pump system releases heat and extract heat via the surface water heat exchanger placed in the water. For forced convective heat transfer process inside the tube, Dittus - Boelter formula [8] was used to do the calculation. For natural convective heat transfer process outside the tube of horizontally-placed parabolic heat exchanger, horizontal cylindrical natural convection dimensionless heat transfer correlation sorted by Churchill and Chu was applied, which is applicable to a broad range of Ra and of high accuracy. In order to control the accuracy of the calculation, we set per unit length of tubes as the calculate unit and the outlet temperature of the current pipe segment as the inlet temperature of the next pipe section, and so on it was calculated to the last segment of the exchanger tube.

3. Results

3.1. The simulation’s algorithm of the surface water source heat pump air conditioning system

On the basis of the components’ models and their interrelation, the simulated algorithms for water source heat pump system model was established. As the heat pump components were mutually coupled, we gave initial values for iteration calculation and in order to speed up the convergence of iterative calculation process, we used the dichotomy method.

Based on the above system modeling method, a simulation program of surface water source heat pump system was developed by Visual Basic programming language. The simulation program is very helpful for the analysis of the performance of the surface water source heat pump system. Before simulation, the initial values including some surface water heat pump parameters, surface water heat exchanger structure parameters, the cooling load of air conditioning system etc. were set. When initiation had been done, the program would call refrigerant physical parameters equations to calculate parameters of each state point in the circuit and solve the compressor model, condenser model, throttle model, the evaporator model until the corresponding parameter coupled. Finally, the system parameters such as the water temperature exporting the evaporator and condenser, the input power and refrigerating capacity etc. would be put out at the interface.

3.2. Simulation’s validation for the heat pump model and system model

The heat pump simulation calculation accuracy in a certain range of temperature was known comparing a practical heat pump which’s some non-rated conditions was obtained from the equipment manufacturer. Figure 2 shows the maximum relative error of refrigerating capacity between the simulation and the sample value is no more than 1.5 % and the relative error of the input power and performance coefficient is within 4 %.
The heat pump system simulation calculation accuracy in a certain range of temperature was known comparing to a surface water source heat pump air conditioning system applied in a library in Nanjing. The refrigerating capacity and coefficient of performance of system operation for both simulation calculation and the practical system is shown in figure 3. (a) and figure 3.(b). At 9:36, a chilled water pump was shut down, thus the figure shows a big fluctuation. At 12:00, the simulated value and the measured values are relatively close. Since then, the system becomes basically stable. Refrigerating capacity and coefficient of performance of simulation values tend to be more consistent with the measured values, but there is still deviation.

3.3. The impact of surface water temperature on the system operation performance

The effect of surface water temperature on the operation of the system was investigated under the same condition of specific cooling load that is 3400 kW, certain surface water, the same heat exchanger structure and cooling water flow rate. Figure 4. (a) shows that condensing temperature and evaporation temperature drops with the drop of water temperature. The tendency of heat pump coefficient of performance is opposite to trend of water temperature. As can be seen from figure 4. (b), with the reduction of water temperature, condensing heat load reduced slightly and the heat transfer rate of per unit length is also slightly decreased.
3.4. The impact of the heat exchanger structure on the system operation performance

With maintained natural water temperature and cooling load, the impact of the heat exchanger structure adjustment on the heat pump system operation was studied. The total number of parallel heat exchanger loops was unchanged, only the length of each single branch loop was changed. As shown in figure 5.(a), due to the drop of condensing and evaporating temperature at the same time, the change of the coefficient of performance of the system is complex and the general is on the rise. As shown in figure 5.(b), condensing heat load of the system decreases while single tube length increases and will be levelled off after single tube length of 140 m. In addition, the heat transfer per unit length decreases with the increase of length, dropping from 105.7 W/m at a single tube length of 60 m to 26.9 W/m at 240 m.

4. Discussion

4.1. The model accuracy

According to the validation of heat pump model, the maximum error of the refrigerating capacity is below 1.5 %, the relative error of the coefficient of performance and the input power is less than 4 %. Thus the model is reliable. The results of the system model validation shows the system model can reflect the actual operation performance of the system in a certain extent, so it has a certain practical significance. The modeling method and program for the simulation calculation can be used in system operation simulation and validation of optimization measures.
4.2. Analysis of the impact of surface water temperature and heat exchanger structure on the system operation performance

With the system cooling load, the structure parameters of surface water heat exchanger and the cooling water flow rate unchanged, the reduction of surface water temperature will cause a slight decrease in the amount of heat transfer rate per unit tube length, but the coefficient of performance will be improved. Specific analysis is as follows:

With the decreasing temperature of surface water, the temperature difference between surface water and inner tube water increased, so heat exchange was stronger, which made the temperature of surface water coil outlet reduce. The reduction of the cooling water temperature of the condenser inlet resulted in the drop of the condensing temperature, which made the condensing heat load decrease slightly. Then the temperature of the condenser outlet which was the temperature of heat exchange coil inlet would also decline. So the water temperatures of the coil inlet and outlet were both decreased. But due to the reduction of unit condenser heat, the decline of inlet temperature was greater than the decline of outlet temperature, the heat transfer rate per unit length would decrease slightly. In addition, under the condition of certain cooling load, the reduction of the condensation temperature caused the evaporation temperature drop, but its decline was less than the decline of the condensing temperature, thus the overall trend of coefficient of performance was upward. On average, surface water temperature reduce 1 °C, the coefficient of performance will increase by 2.3 % as a result.

Keeping the natural surface water temperature, the system cooling load and the total number of parallel heat exchanger loops unchanged and only changing the length of each single branch loop, the increase of single tube length leads to the decrease in heat transfer rate per unit length, but improvement of the coefficient of performance. Specific analysis is as follows:

With the increased length of the tube, heat transfer was stronger, which caused the temperature of surface water coil outlet decrease. As a result, the condensing temperature fell. Because of the unchanged cooling load, evaporation temperature would drop. The decline of the evaporation temperature was less than the decline of the condensing temperature, thus the overall trend of coefficient of performance was upward. But this trend was obvious until the length of single loop reached 140m. It comes out that the coefficient of performance increase 0.08 % when the tube length of the surface water heat exchanger increases 100 m. Besides, due to the reduction of the condensing temperature and improvement of the system performance, condensing heat load was reduced, and this trend became smooth after the length reaches 140 m. In addition, because of the increased length and decreased condensing heat load, heat transfer per unit length decreases. When the tube length of the surface water heat exchanger increases 100 m, heat exchange unit tube length decreased 0.07 W/m.

5. Conclusions

- The deterministic model of heat pump has been established. Compared with the pump samples, the result showed that they were in good agreement, so it can be used for further simulation of the surface water heat pump system and validation of optimization measures.
- Based on the heat pump model, load model and surface water heat exchanger model, a complete model for the closed-loop surface water source heat pump system has been established, and a simulation program has also been developed for this system. The program was used to simulate and measure a practical project, and the result showed that calculating value and experimental value are in good agreement.
- This paper has analyzed the influence of surface water temperature and structure parameters of surface water heat exchanger on the system operation performance. On average, one degree drop of surface water temperature results in 2.3 per cent increase of coefficient of performance. In addition, the coefficient of performance can also be improved by increasing the length of each heat exchanger branch.

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