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Dynamic Simulation System of Air Source Heat Pump System Based on Building Hourly Load

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Abstract: As the important facilities of the energy efficiency buildings, the heat pump air-conditioning has aroused people's wide concern. The use of simulation technology in the field of heat pump has played a very important role in operating characteristics and product innovation of heat pump air-conditioning system. The building load calculation model and air source heat pump system model were studied and built. The building load calculation model was established by dividing the building into several zones. The air source heat pump system calculation model was established including the air source heat pump units, auxiliary heat source and simple construction computation module. And then on the basis of TRESYS software, the building hourly load simulation system was established. The results show that the established dynamic simulation system of air source heat pump is reliability and accuracy. AND it is conducive to the operation and product innovation of the heat pump.

Key words: Hourly load, air source heat pump, dynamic simulation, TRESYS

INTRODUCTION

As the important facilities of the energy efficiency buildings, the heat pump air-conditioning has aroused people's wide concern. The use of simulation technology in the field of heat pump has played a very important role in operating characteristics and product innovation of heat pump air-conditioning system (Yan *et al*., 2006; Chen *et al*., 2010). Air source heat pump system (Zhang *et al*., 2007), ground source heat pump system (Xing and Yu, 2009) and water source heat pump system were studied in detail by simulation technology (Tang and Ding, 2011). However, these studies have ignored the hourly load of building itself and simulation is only under ideal conditions on the simulation of a single air-conditioning equipment, there are a lot of limitations.

This study focuses on the principle of building loads and the calculation of air source heat pumpsystem. During the calculation process, the building is divided into several hot zones. Besides, dozens of air nodes were attributed to the hot zones in order to establish the building load calculation model. Meanwhile, the air source heat pump module is established by the air source heat pump system, air source heat pump units, auxiliary heat source and a simple building thermal calculation module. Finally, an example shows that the system is reliable and accurate.

MATERIALS

Building load calculation principles: In the simulate calculation, the building is divided into several hot zones, the air of each heat zone is set to an air node. The specific calculation model is as follows:

- **Convective heat transfer from the air node:**

$$Q_i = Q_{surf,i}+Q_{inf,i}+Q_{vent,i}+Q_{g,c,i}+Q_{cplg,i} \quad (1)$$

where, $Q_{surf,i}$ is the convective heat transfer between of air and the construction of the respective inner surface, W; $Q_{inf,i}$ is the convective heat transfer due to the penetration of ventilation brought by the building, W; $Q_{vent,i}$ is the convective heat transfer of the building hvac system ventilation, W; $Q_{g,c,i}$ is the convective heat transfer of internal heat source (human, equipment), W; $Q_{cplg,i}$ is the convective heat transfer by ventilation of the adjacent areas, W.

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- **Radiation heat transfer of the building envelope:**

$$Q_{r,wi} = Q_{g,r,i,wi}+Q_{sol,wi}+Q_{longwi}+Q_{wall-gain} \quad (2)$$

where, $Q_{r,wi}$ is radiation heat gained from temperature node of wall surface, W; $Q_{g,r,I,wi}$ is radiation heat transfer between the inner source heat due to walls, W; $Q_{sol,wi}$ is the amount of solar radiation absorbed by walls through the window, W; $Q_{long,wi}$ is long-wave radiation between the building envelope, W; $Q_{wall,gain}$ is the wall of the internal heat source, W.

- **Heat transfer model collection of building envelope:**

$$\dot{q}_{s,i} = \sum_{k=0}^{nb_s} b_s^k T_{s,o}^k - \sum_{k=0}^{nc_s} C_s^k T_{s,i}^k - \sum_{k=1}^{nd_s} d_s^k \dot{q}_{s,i}^k \quad (3)$$

$$\dot{q}_{s,o} = \sum_{k=0}^{na_s} a_s^k T_{s,o}^k - \sum_{k=0}^{nb_s} b_s^k T_{s,i}^k - \sum_{k=1}^{nd_s} d_s^k \dot{q}_{s,o}^k \quad (4)$$

where, $S_{s,i}$ is the amount of radiation absorbed by the inner surface, W; $S_{s,o}$ is the amount of radiation of outer surface, W; $q_{r,s,t}$ is the amount of net radiation in the other face of thermal area, W; $q_{r,s,o}$ is the amount of net radiation out of the each face of thermal area, W; $q_{s,i}$ is the convection heat from the inner surface, W.

The time series of surface temperature and heat flow equation is calculated based on the time step. Superscript k refers to the time series. For previously, k = 1, etc.

- **Windows heat transfer model:** The windows are generally considered as the exterior wall of the heat capacity and the solar radiation can penetrate but the long-wave radiation cannot. In this study, the windows were considered to be a two-site model shown in Fig. 1
- **Building shield calculation model:** Building azimuth is defined by sloped inclination and azimuth. Relative to the positioning of the building, the vertical shield face shown in Fig. 2a is through face angle and elevation angle to define. An angle on spherical coordinate system for tilt is needed to define for the sloped shield face shown in Fig. 2b to locate the building

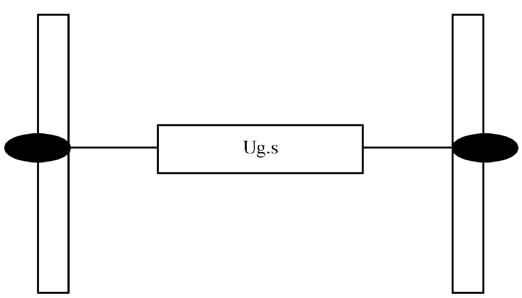


Fig.1: Model of two-site window

The shading coefficient of the building is revised by calculating the proportion of shield when light incident on the coordinates.

- **Effective sky temperature calculation model:** The effective sky temperature used to calculate the long-wave radiation heat transfer of the building facade with the surrounding environment. The effective sky temperature is calculated as follows:

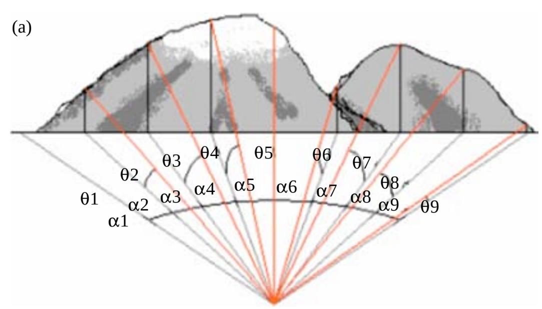
$$C_{cover} = (1.4286\frac{E_{Dif}}{E_{Glob,H}} - 0.3)^{0.5} \quad (5)$$

$$P_{atm} = P_0 e^{\frac{g\rho_0 h}{P_0}} \quad (6)$$

$$\varepsilon_0 = 0.711 + 0.005T_{sat} + 7.3\times10^{-5}T_{sat}^2 + 0.013\cos[2\pi\frac{time}{24}] + 12\times10^{-5}(P_{atm} - P_0) \quad (7)$$

$$T_{sky} = T_{amb}[\varepsilon_0 + 0.8(1-\varepsilon_0)C_{Cover}]^{0.25} \quad (8)$$

(a)



(b)

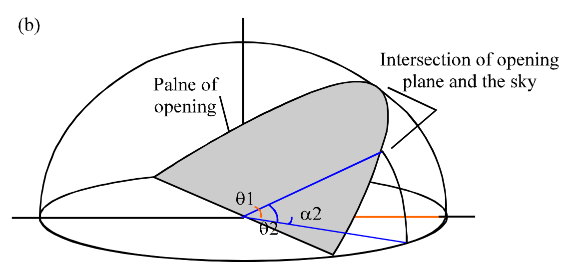


Fig. 2(a-b): Face angel and elevation angle of vertical barrier and sloped barrier (a) Face angel and (b) Elevation angle where, C_{cover} is sky transparency, [0-1]; E_{dif} is horizontal plane scattered radiation, kJ h^{-1} m^{-2}; E_{Dir} is horizontal plane direct radiation, kJ h^{-1} m^{-2}; E_{total} is total horizontal radiation; G: acceleration of gravity, m sec^{-2}; H: altitude, m; P_{atm} is atmospheric pressure, atm; P_0 is the atmospheric pressure at the height of h_0, atm; ρ_0 is the atmospheric density at the height of h_0, kg m^{-3}; ε_0 is emissivity in sunny, [0-1]; T_{amb} is ambient temperature, °C; T_{sat} is the dew point temperature of the environment, °C; T_{sky} is sky temperature, °C.

Air source heat pump system mechanism

- **Air source heat pump units:** The part of the cold and heat source is air source heat pump units. It provides cold and heat source for the entire system and it is also the heart of the whole system. The main factors affecting its refrigeration heating capacity and power consumption for a given air source heat pump units are evaporation temperature and condensing temperature. In the manual of thermal unit product, usually given the cooling heat capacity and the corresponding power consumption corresponding to the units according to the inlet water and air temperature and flow of different source side and user side. Based on the inlet temperature, inlet air temperature and flow, the amount of cooling (heating) and energy consumption could be gained by adopting the linear interpolation method. Then the temperature on both sides of the heat pump units source side, heat transfer and COP hourly data will be calculated. In heating conditions:

$$COP = \frac{Cap_{heating}}{P_{heating}} \tag{9}$$

$$Q_{absorbed} = Cap_{heating} - P_{heating} \tag{10}$$

$$T_{source,out} = T_{source,in} - \frac{Q_{absorbed}}{m_{source} Cp_{source}} \tag{11}$$

$$T_{load,out} = T_{load,in} - \frac{Cap_{heating}}{m_{load} Cp_{load}} \tag{12}$$

where, Cap is heating capacity; P is power; $Q_{absorbed}$ is heat pump heat gain from the source side; Cp is specific heat.

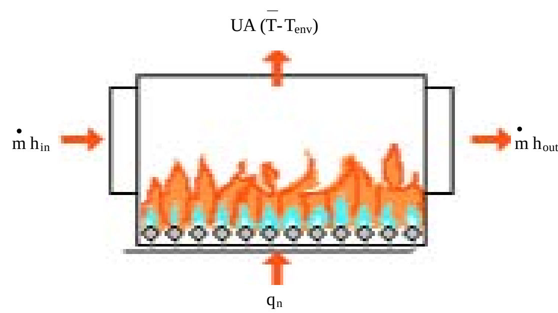


Fig. 3: Auxiliary heat source heat exchanger model

- **Auxiliary heat source:** Auxiliary heat source provides heat to the heat pump source side, the air is heated to a fixed temperature and then enters to the unit to prevent the source side of the unit frosts when the source-side temperature is low. As shown in Fig. 3, the strategy of operation of the auxiliary heat source is that the source side of the auxiliary heat source is not turned on when entering the unit source-side air temperature is higher than the set value. Open the auxiliary heat source, the auxiliary heat source works in the power settings when the source-side temperature is below the set value

The formulations of heat exchanger model are as follows:

$$h_{out} = h_{in} \tag{13}$$

$$h_{air,out} = h_{air,in} + \frac{q_\eta}{\dot{m}} - \frac{UA}{\dot{m}}(\bar{T} - T_{env}) \tag{14}$$

where, h_{out} is outlet air enthalpy, kJ kg^{-1}; h_{in} is inlet air enthalpy, kJ kg^{-1}; h_{out} is outlet air enthalpy, kJ kg^{-1}; h_{in} is inlet air enthalpy, kJ kg^{-1}. m: air flow, kg h^{-1}; q_η is the efficiency of auxiliary heat source, kg h^{-1}; UA is heat loss of auxiliary heat source specific heat, kJ kg^{-1}; $\bar{T}$ is the auxiliary heat nosocomial average air temperature, °C; T_{env} is ambient temperature, °C.

- **Simple building thermal calculation module:** For the feedback temperature of building indoor in air source heat pump system, the building thermal calculation module is set. The module considers building as the lumped parameter method, the equation of the interior architecture temperature and humidity changes is as follows:

$$\frac{dT}{dt}=\frac{UA}{cap}(T_{amb}-T)+\frac{\dot{m}_{vent}Cp_{air}}{cap}(T_{vent}-T)+\frac{\dot{m}_{inf}Cp_{air}}{cap}(T_{inf}-T)+\sum Q_{gains} \quad (15)$$

$$\frac{d\omega}{dt}=\frac{\dot{m}_{inf}}{\rho V}(\omega_{inf}-\omega)+\frac{\dot{m}_{vent}}{\rho V}(\omega_{vent}-\omega)+\frac{\sum \omega_{gains}}{\rho V} \quad (16)$$

$$\Sigma Q_{gain}+Q_{lights}+Q_{equip}+Q_{peop} \quad (17)$$

where, U is the overall heat loss of the building, kJ^{-1} h^{-1}×m^{-2}×c^{-1}; Cap is building hot melt, kJ c;$^{-1}$ Cp_{air} is specific heat of air, kJ^{-1} kg^{-1}×c^{-1}; ρ_{air} is air density, kg m^{-3}; Area is the outer area of the building, m^2; Vol is construction cascade, m^3; T_{vent} is mechanical ventilation temperature, °C; ω_{vent} is mechanical ventilation and humidity; m_{vent} is the amount of mechanical ventilation, kg h^{-1}; T_{amb} is outdoor air temperature, °C; ω_{amb} is outdoor air humidity, °C; m_{inf} is penetrate the ventilation rate, kg h^{-1}; Q_{lights} is lighting heat gain: kJ h^{-1}; Q_{equip} is the heat gain of the device, kJ h^{-1}; Q_{peop} is the sensible heat of the person in the room, kJ h^{-1}; ω_{gain} is the obtained wet in a given indoor, kg h^{-1}; T_{zone} is indoor temperature, °C; ω_{Zone} is indoor humidity, °C; Q_{inf} is the ventilation heat of penetration, kJ h^{-1}; Q_{vents} is sensible heat of mechanical ventilation, kJ h^{-1}; Q_{ventl} is latent heat of mechanical ventilation, kJ h^{-1}.

METHODS

Previous researches on the building heat pump systems do not consider the hourly load. Therefore, this section designs a rational simulation system with building hourly load calculation principles and air-source heat pump system operating principles.

Simulation design of building hourly load: Buildings, as for the objects of heat pump system, create building hourly cooling and heating load calculation platform in TRNSYS according to the theoretical basis. This calculation platform focuses on the external structure heat transfer model. The model can gives full consideration to the periphery structure of the surface heat transfer coefficient, the activities of the person in the room, lighting, heating equipment, ventilation on the indoor environment. Then the human thermal comfort evaluation index PMV PPD can be transmitted online. It can not only reflect the heating load change of the building itself but also revise shading coefficient to proposed a simple, scientific and correction method.

Simulation design of air source heat pump system: Build a variety of heat pump systems computing model by choosing unit types on the basis of calculating the building load. According to the characteristics of the heat pump air conditioning system, the hvac system is abstracted into the flow chart shown in Fig. 4, three important content is included: The number of the water pump and heat pump equipment is adjusted according to load; heat pump host gets infinitely variable control according to part load rate, the water pump works in the condition of fixed frequency and variable frequency.

RESULTS

Building hourly load calculation: This study selected a 18 floors office building, the construction parameters

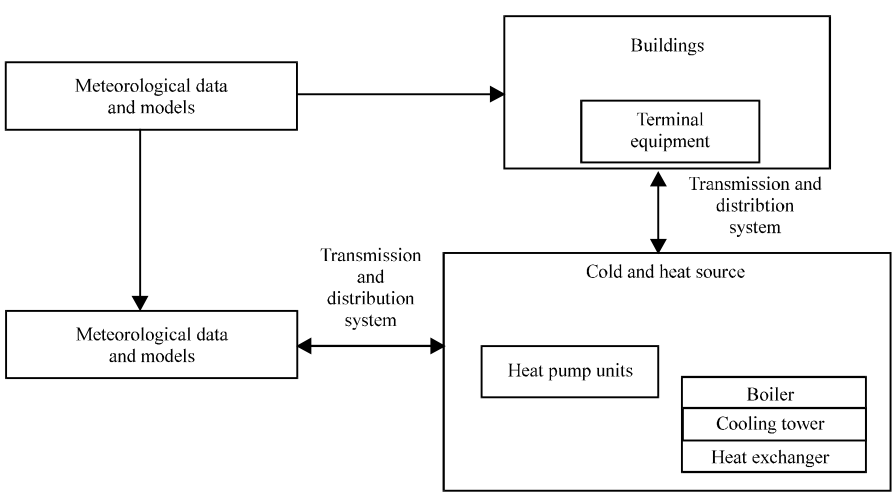


Fig. 4: Flow chart of heat pump system

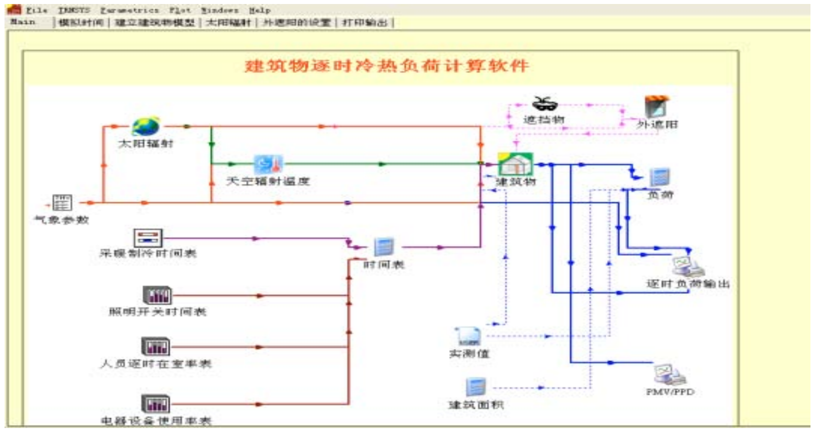


Fig. 5: Main interface of building hourly load calculation software

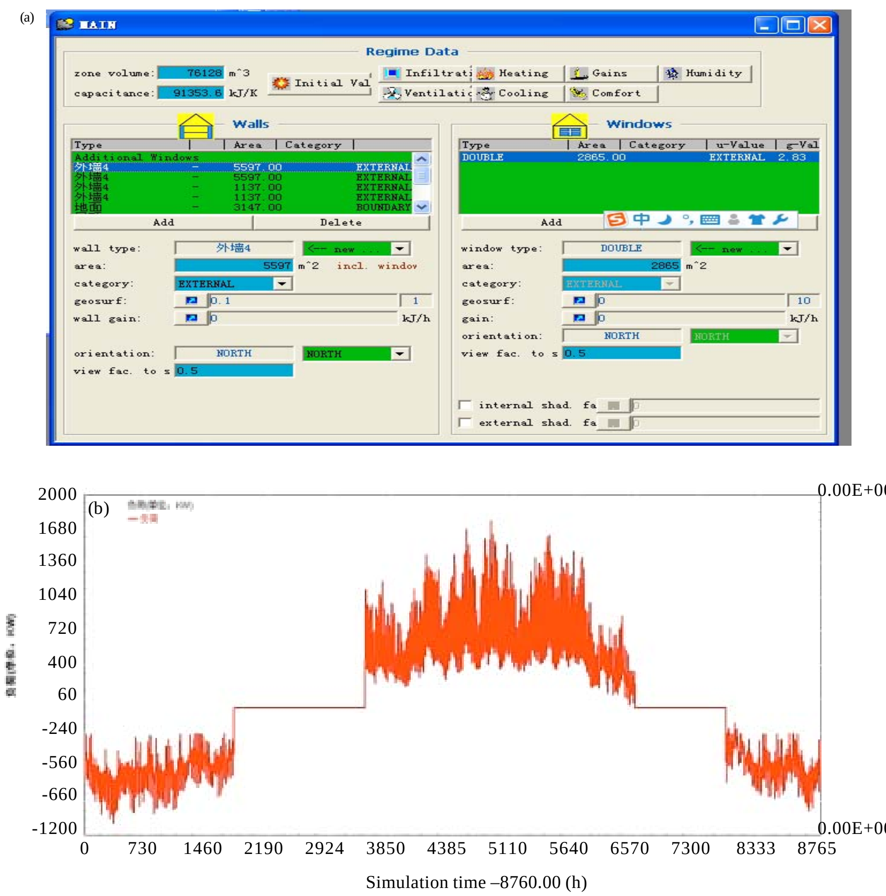


Fig. 6(a-b): Parameter input and calculation results of building hourly load calculation software, (a) Parameter input and (b) Calculation results

shown in Table 1. The main interface of building hourly load calculation software is shown in Fig. 5. The parameter input of the model is presented in Fig. 6a and the calculation results shown in Fig. 6b.

Air source heat pump system calculation: This simulation example heating peak load is 1078.9 kW and cooling peak load is 1760 kW.There are 4 heat pump host units and the cold pump and heat pump are one-to-one correspondence. The cooling capacity of the heat pump host is 450 kW. The single pump flow is 75750 kg h^{-1} in summer and 46500 kg h^{-1} in winter. The pump head is 25 m, the total pump efficiency is 0.60 and pump motor efficiency is 0.90. Auxiliary heating heat source is 20 kW, open the source when the air temperature is lower than 3°C. There are 150 fan coils, each of Fan coil is 50 W with efficiency of 0.80, including 6 empty sets, each of set is 3.0 kW with efficiency of 0.80. This Air-source heat pump system also consists of 6 newly-built Fans. Besides, the number of Exhaust Fan in this system is 6. The power of each Fan and Exhaust Fan is 3.7 kW and the efficiency is 0.80. Source and load side are fixed-frequency control, load side water temperature in winter is 50 and 7°C in the summer.

The main interface of air source heat pump system software is shown in Fig. 7. The parameter settings of air source heat pump and turbine are shown in Fig. 8a and b, respectively and other parameters are shown in Fig. 8c.

Table 1: Relevant parameters and description of typical construction

Construction parameters	Description
Building orientation	South
Construction area	18858 m^2
Building volume	76128 m^3
Shape coefficient	0.218
Sum of the exterior wall area	8167.8 m^2
Sum of the areas of the exterior windows	5237.4 m^2
Area ratio of northern window	0.52
Area ratio of western window	0.05
Area ratio of southern window	0.4
Area ratio of eastern window	0.05
House area	1050 m^2

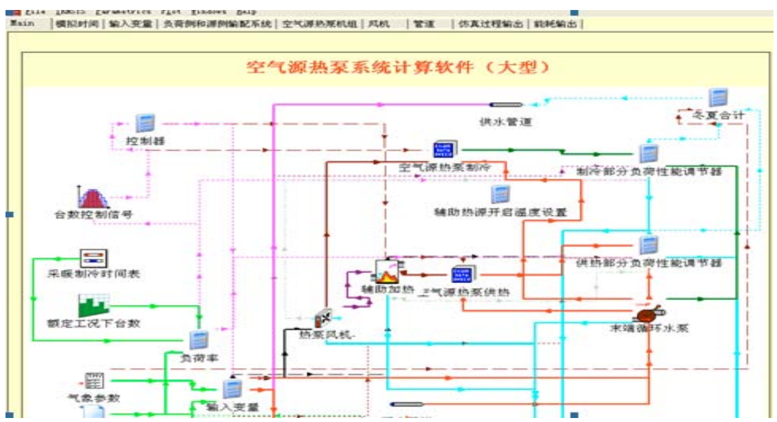


Fig. 7: Main interface of air source heat pump system software

(a)

Fig. 8: Countinue

(b)

(c)

Fig. 8(a-c): Parameter settings figure of air source heat pump, turbine and others, (a) Parameter settings figure of air source heat pump, (b) Parameter settings figure of turbine and (c) Parameter settings figure of others

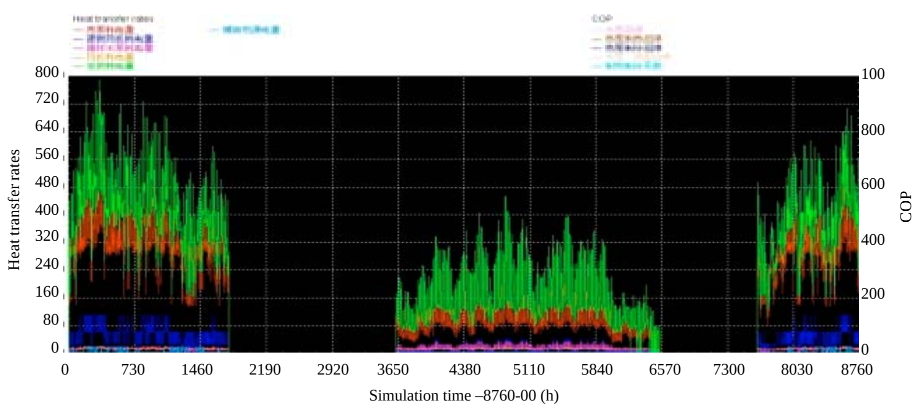


Fig. 9: Chart of device power consumption

The output parameters of calculation results include the power consumption of the device, the host COP, as well as start and stop signals, the source-side and load-side temperature and the number of device turned on, as shown in Fig. 9-12.

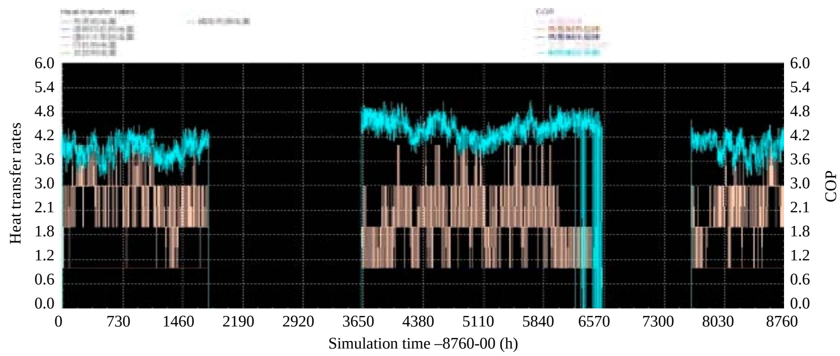


Fig. 10: Diagram of Host COP and start and stop signals

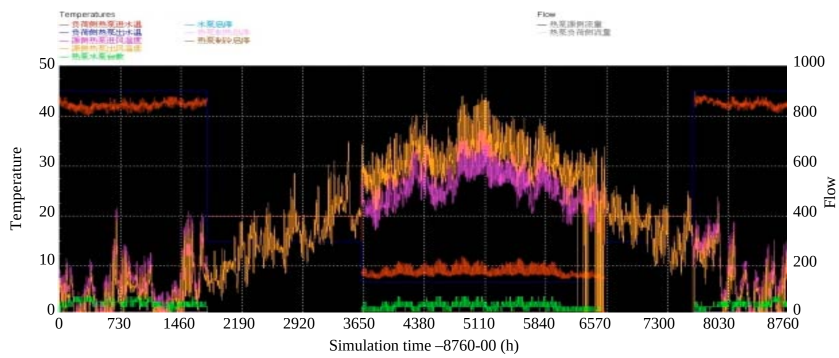


Fig. 11: Figure of source side and load-side temperature

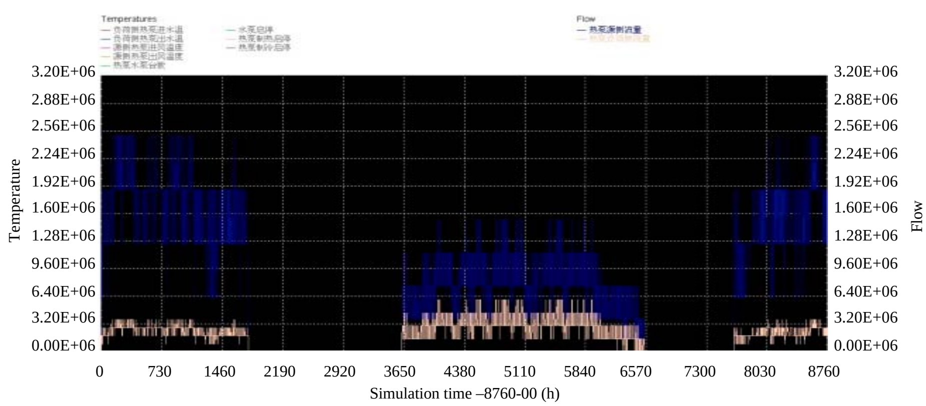


Fig. 12: Figure of the number of turned on units

CONCLUSION

It can draw the following conclusions based on the above analysis:

- In this study, the principles and algorithms of the building load and air source heat pump system are studied and build the building load calculation model and air source heat pump system model
- On the basis of TRESYS software, the building hourly load simulation system is established. Three contents is included: the number of the water pump and heat pump equipment is adjusted according to load; heat pump host gets infinitely variable control

according to part load rate, the water pump works in the condition of fixed frequency and variable frequency. And on this basis, the dynamic simulation system of air source heat pump system based on building hourly load is established

- The example this study shows that the design of the simulation system is accurate and reliable

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