Investigation and Experiment of Coupling Heating Device Based on Solar Energy and Dual Source Heat Pump

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Abstract

The combination of solar heating system and air source heat pump heating system is an effective way to improve the energy efficiency of single energy system. A new type of dual source heat pump is developed, which is equipped with both water source evaporator and air source evaporator. In which case, air-source evaporator extracts energy from air for ASHP heating and the solar collector loop is combined with the water-source evaporator for WSHP heating. The solar heat gain at low temperature will be fully utilized by combining with WSHP. Meanwhile, higher efficiency of solar collector will be obtained due to the lower internal medium temperature. The device we developed takes into account the functions of heating, cooling and hot water. Experiment showed that the instantaneous performance coefficient of heat pump unit (COP_{HP}) reached 3.8~4.4 under the mode of WSHP heating combined with solar energy compared with that of 1.6~2.2 in the condition of ASHP heating. The overall performance coefficient of system (COP_{system}) was as high as 3.1.

Keywords: clean heating, solar energy, air source heat pump, multi-energy complementary

1. Introduction

Solar heating and air source heat pump (hereinafter, ASHP) heating are widely used in China, which are indispensable ways to realize clean heating according to the government report - *Central Financial Support for the Pilot Project of Clean Heating in North China*. However, the efficiency of single energy system is significantly affected by weather condition so that contribution of renewable energy and heating stability are limited (Wang B.Y., 2017). Solar fraction of conventional household solar heating system remains to be promoted because of the low energy flow density and discontinuous fluctuation of solar energy (Liu Y.F., 2016). The ASHP's COP decreases obviously when it's cold outside. Heat pump unit even stop working on account of evaporator defrosting or other factors by control (Wang W., 2009). The combination of solar heating and ASHP heating will make full use of the advantages respectively. Existing studies show that ASHP assisted solar heating system in Kunming and other regions with mild climate in China has good energy-saving benefits, but mainly for domestic hot water (Luo H.L., 2009). For building heating, most systems combine the solar heating system with the condenser of ASHP, and the measured efficiency of the both two kinds of energy has not substantially improved. Besides, the solar heat gain still needs to be improved because the medium temperature in solar collector remains high in the process of continuous heat collection (Liu L.J., 2013).

In order to solve the problems above, this paper develops a new type of coupling heating device based on solar energy and dual source heat pump with better energy saving effect.

2. Scheme of Coupling System

2.1. Principle of overall system

Existing research mostly combines two energy systems above in parallel at the condenser of heat pump, in which case solar heating system and ASHP system independently work according to their respective control logic (Fig. 1). When the solar irradiance is better and outdoor temperature remains relatively high in daytime, the heat will be produced by ASHP caused by the higher COP. Solar energy will be collected and stored in tank meanwhile. When the solar irradiance is insufficient and outdoor temperature drops, the heat from solar energy

doi:10.18086/swc.2019.10.03 Available at http://proceedings.ises.org

in storage will be preferentially used for heating. Until the storage temperature cannot meet the demand of terminal heating equipment, ASHP will be started again to ensure the adequate heating capacity. The theory and practice show that coupling by this method is more energy-saving than either one energy system alone, however the energy efficiency of any renewable energy system has not been substantially improved.

For example, in the case of continuous heating, the temperature of solar collector loop remains still higher than that of heating system. Even if fan coil unit or floor radiation is selected as heating equipment, the internal temperature of collector is about 50~85℃. If the efficiency equation of selected solar collector is η=0.75－4.0T^*, the solar collector efficiency is only 29.1% according to the meteorological parameters in Beijing (634.7W/m^2 of solar irradiance, -2.7℃ of average ambient temperature). In addition, the available heat storage temperature difference is calculated as $\Delta T_{storage}$=85°C−45°C=40°C, resulting in relatively larger storage volume required.

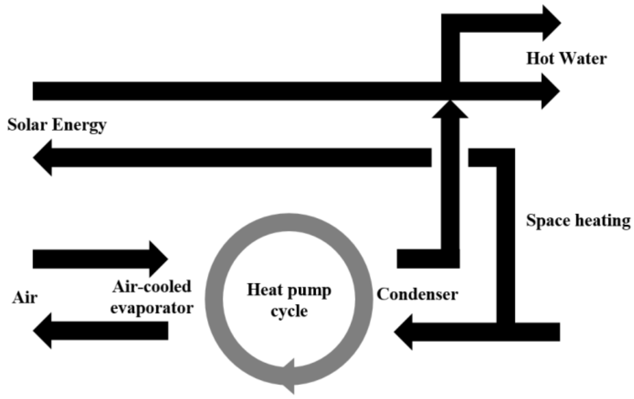

Fig. 1: Principle of coupling system at heat pump condenser

Another coupling form adopted in this paper is to transform ASHP into dual source heat pump equipped with both air-source evaporator and water-source evaporator, in which case the air-source evaporator extracts energy from air for ASHP heating and the solar collector loop is combined with the water-evaporator for water source heat pump (hereinafter, WSHP) heating, shown as Fig. 2. Water-source evaporator combines with solar collector loop to extract solar energy at low temperature (15~50°C), so that solar energy and WSHP are coupled for heating. Compared with the system above, this coupling form adds the new mode of WSHP heating combined with solar energy. When the stored heat shall be used for building heating but the internal temperature is not enough, the water-source evaporator will be switched for WSHP heating and further improve the quality of thermal energy from solar in the range of 15~50°C.

In this way, solar energy can be more fully utilized and COP of heat pump unit will also be improved. According to the meteorological parameters above, the collector efficiency rises to 40.2% thereby the solar heat gain can be increased by 35.4%. Besides, the available heat storage temperature difference is expended as $\Delta T_{storage}$=85°C−10°C=75°C. Thus heat storage capacity and operating power consumption of heat pump will be reduced significantly.

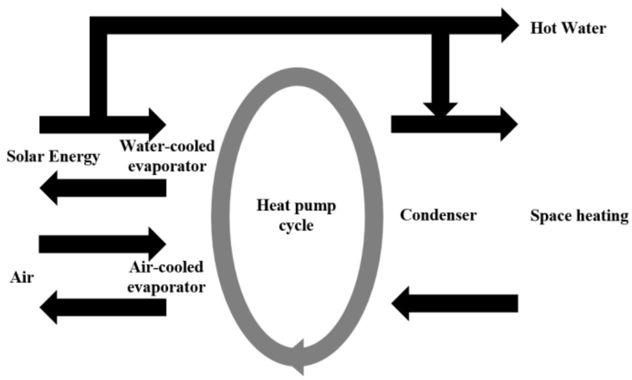

Fig. 2: Principle of coupling system at heat pump evaporator

In conclusion, the combination of solar collector system and ASHP at the evaporator can not only retain the basic functions of solar heating and ASHP heating, but also store more solar heat gain and save the cost of heat storage device as well as the power consumption of heat pump. The new type of coupling heating device developed according to the principle above mainly provides heating, while taking into account both hot water and refrigeration requirements.

2.2. Principle of dual source heat pump unit

The schematic of dual source heat pump is shown in Fig. 3. Parallel installation of two evaporators and refrigerant solenoid valves on each branch are required. Additional refrigerant pipelines are needed compared with the installation in series, however the advantage is to avoid the interaction between two evaporators. Especially, the evaporation temperature of dual source heat pump unit varies widely with the switching of two evaporators, so it is necessary to select appropriate electronic expansion valve to adjust the mass flow of refrigerant according to the suction superheat. The evaporation temperature signal required should be switched between air-source evaporation temperature $T_{e,1}$ and water-source evaporation temperature $T_{e,2}$ according to heating mode, so as to control the voltage and current on the expansion valve and adjust the refrigerant supply.

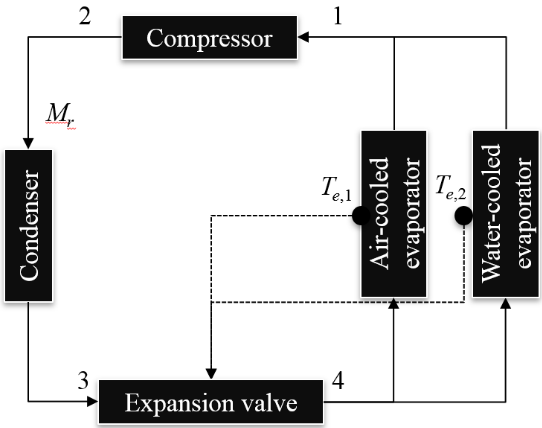

Fig. 3: Principle of dual source heat pump unit

The pressure-enthalpy diagram of the theoretical heating cycle is shown as Fig. 4. Under the mode of ASHP heating, the theoretical heating cycle of heat pump is 1*a*→2*a*→3*a*→4*a*→1*a*. In contrast, when the mode of WSHP heating turns to be enabled, the evaporation temperature of heat pump increases. If the condensation temperature stays constant at 40℃, in addition the supercooling before expansion valve and the suction superheating before compressor are both controlled unchanged. The theoretical heating cycle changes to be 1*b* →2*b*→3*a*→4*b*→1*b*. At this time the refrigerant's specific volume decreases resulting in more mass flow rate. Exhaust temperature of compressor outlet will be relatively reduced. The power consumption of heat pump increases first and then decreases depending on the range of evaporation temperature. The coefficient of performance of heat pump unit (hereafter, COP_{HP}) will promote substantially.

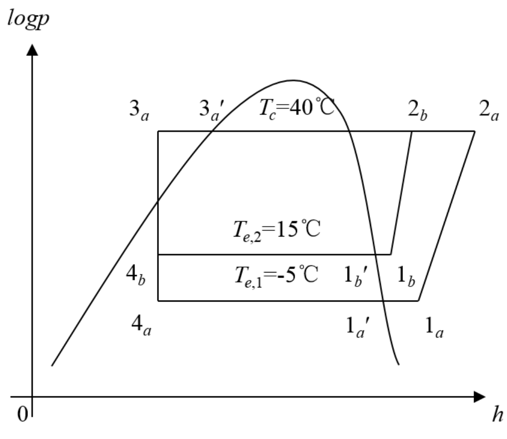

Fig. 4: Pressure-enthalpy diagram of thermal heating cycle

2.3. Automatic Control Strategy

The control strategy of solar collector loop, heat source loop and terminal heating loop are included in heating condition. Solar collector loop is controlled according to the temperature difference between collector outlet and storage tank. The anti-freezing and anti-overheating control are both considered meanwhile to ensure the safety of collectors and tank. Strategy of terminal heating loop guarantees the stable and comfortable temperature of water conveyed to heating equipment.

Five heating modes of heat source loop marked as Mode-1 to Mode-5 are shown in Tab. 1. Based on the VB macro-programming, forecasting functions of weather and heat load are integrated into control system. The execution logic includes: When solar radiates better and outdoor temperature is relatively high, Mode-5 is preferred to get higher COP_{HP} than that of ASHP heating in evening. Meanwhile the solar collector stores enough heat to tank. When solar radiation is general and outdoor temperature is relatively low, Mode-1, Mode-3 and Mode-4 are selected according to the storage temperature from high to low. In particular, in order to realize the smooth switching from Mode-1 to Mode-3 and prevent compressor from overpressure caused by heat source side of heat pump overheated during the heating process of WSHP, device will reduce the supply temperature of heat source side in a short time through Mode-2. In addition, domestic water strategy and ASHP refrigeration strategy are also included to provide domestic hot water and air conditioning refrigeration for building.

Tab. 1: Five heating modes included

Mode Number	Mode process
Mode-1	Direct solar heating
Mode-2	Switching process from Mode-1 to Mode-3
Mode-3	Coupled heating of solar energy and WSHP
Mode-4	Auxiliary heating by ASHP
Mode-5	Compulsory heating of ASHP

3. Development Process

Taking an 180m^2 residential building in Beijing as heating object. The heating load for space heating is 12.5kW which is applied to the selection of heat pump unit. Average heat loss of building is 6.5kW so as to determine the scale of the collector system. The main equipment included in device are as follows.

1) Solar collector

The solar collector selected has been tested by National Center of Quality Supervision and Testing of Solar Heating System (Beijing) whose efficiency equation is η=0.75−4.0T*. According to Chinese standards, the thermal efficiency of solar collector is 40%. 12 flat-plate collectors with aperture collector area of 1.85m^2 are used. Two groups of collectors are connected in parallel while each group consists 6 solar collectors in series.

2) Storage tank

The closed water storage tank with diameter of 745mm, height of 2030mm and volume of 500L is selected. The rated pressure is 0.7MPa. In order to satisfy the heating demand of different temperature and make full use of the temperature stratification characteristics of water tank, solar collector loop is connected to the lower interface and heat source loop is connected to upper interface of tank. The outlet of domestic water is located at the top.

3) Heat pump

ASHP unit is purchased and further reformed to dual source heat pump. Considering the heating load, unguaranteed hours and heat storage effect, the main parameters of ASHP are confirmed as follows: Under the nominal conditions (-12°C of dry-bulb temperature, -14°C of wet-bulb temperature, 41°C of water supply temperature), the rated heating capacity is 12.0kW and COP is 2.26.

4) Evaporator

The finned-tube heat exchange is used as evaporator for ASHP heating. The fins are added outside the coil and therefore the heat transfer area is enough to ensure the better evaporation capacity and more heat absorbed from air. The plate heat exchanger with better efficiency and compactness is selected as evaporator for WSHP heating. Compared with shell-and-tube exchanger, the weight can be reduced by 70% and installation area can be reduced by 25%~50%. Besides, the heat transfer efficiency is higher because of forced turbulence and small hydraulic diameter.

5) Heat exchanger

Considering the requirement of pressure resistance, corrosion resistance and occupied space, two groups of spiral coil heat exchangers installed inside storage tank indirectly exchange heat with solar collector loop and heat source loop, whose area of heat transfer is 2.0m^2 and 1.45m^2 respectively. Spiral coil heat exchangers mainly consist of smooth stainless-steel coils with inner diameter of 20mm, thermal conductivity of 340W·m^{-2}·K^{-1} and enamel outer surface.

6) Heating equipment

Two fan-coil units with rated heating capacity of 7.5kW are selected for the terminal heating equipment, which can effectively reduce the water supply temperature compared with the radiator.

7) Automatic control system

Data acquisition, monitoring, recording and control operations are completed by PLC and configuration program. Automatic control system ensures unattended operation of equipment throughout the day. We take the building in Daxing District of Beijing as heating object to test the heating performance.

Fig. 5: Experimental dual source heat pump unit and solar collectors

4. Test Data

4.1. Outdoor environmental parameters

The average/minimum outdoor temperature of 10 February, 11 February and 12 February is -5.1°C/-10.7°C, 4.2°C/-6.7°C, and 0.0°C/-5.4°C, respectively. The solar irradiation per unit solar collector area reaches 23.4MJ/m^2, 24.7MJ/m^{2}and23.9 MJ/m^2, respectively.

4.2. Solar collector performance

The internal temperature of collector is generally 15~20°C when the pump of solar collector loop starts through which collectors absorb and convey the solar heat gain. When the solar collecting process is completed in a day, the temperature inside the collector is generally 65~70°C (Fig. 6). Compared with the conventional solar heating system in China, the range of working temperature and effective collecting time are both relatively enlarged. According to the statistics, the total solar irradiation on collectors during February 10, February 11 and February 12 is about 430.1MJ, 441.6MJ and 439.1MJ while the available solar heat gain reaches 179.0MJ, 168.5MJ and 188.7MJ respectively. The efficiency of solar collector system is 41.5%, 38.1% and 43.0%, respectively.

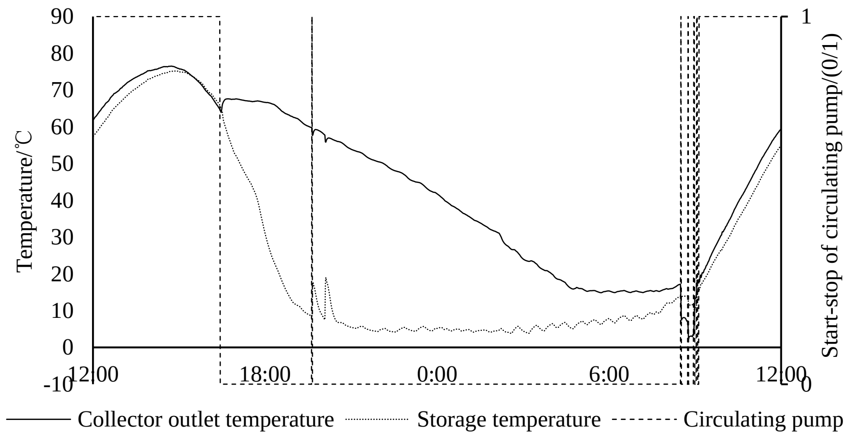

Fig. 6: Test data of solar collector performance

4.3. Solar collector performance

According to the compressor working temperature and evaporation temperature (Figs. 7 and 8). Under the process of coupled heating of solar energy and WSHP (Mode-3), the hot water which transfers the solar energy stored in tank turns to be the heat source of WSHP, whose inlet temperature is set to 15~18°C for higher evaporation temperature. At this time, the suction temperature of compressor is stable in the range of 10~15°C, which is lower than evaporation temperature because the on-off solenoid valve on the branch of air-source evaporator is not completely closed and part of refrigerant flows through it. Besides, absolute insulation measures have not been taken on pipes between plate heat exchanger and four-way reversing valve. In such situation, exhaust temperature of compressor and compression ratio reduce significantly. As a result, the instantaneous COP_{HP} of WSHP unit reaches 3.8~4.4.

Under the process of compulsory heating of ASHP (Mode-5) and auxiliary heating by ASHP (Mode-4), the suction temperature of compressor is generally lower than outdoor temperature of 2~8°C. The mass flow rate of refrigerant regulated by electronic expansion valve decreases immediately and exhaust temperature of compressor rises to 90~110°C. The instantaneous COP_{HP} of ASHP unit is lower than that of WSHP mode introduced above, which is measured as 1.6~2.2.

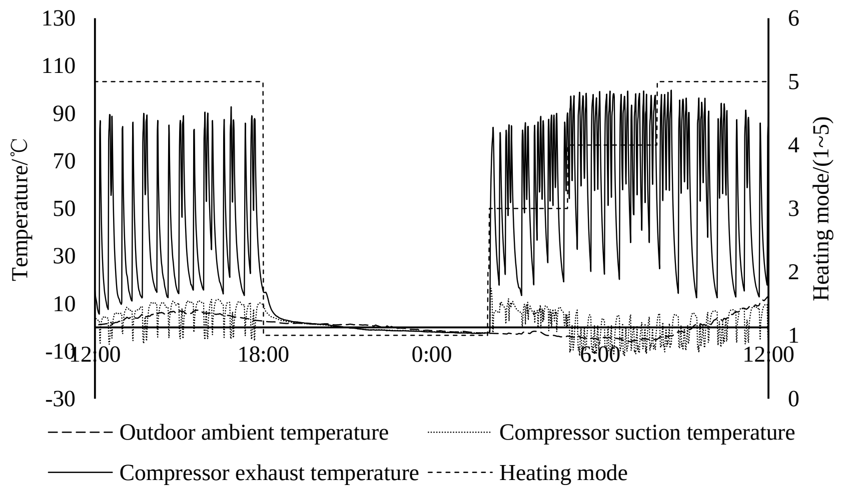

Fig. 7: Test data of compressor working temperature

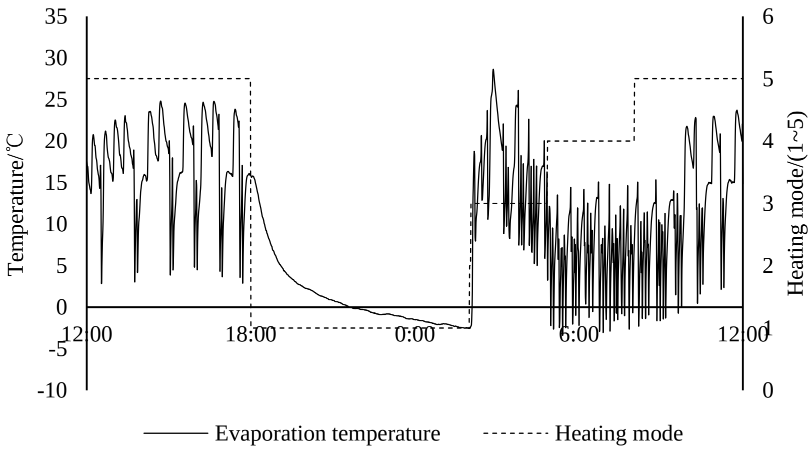

Fig. 8: Test data of evaporation temperature

4.4. Heating system

The temperature record of terminal heating loop (Fig. 9) shows that input and output temperature of heating equipment are relatively maintained stable through the internal control system of heat pump unit in the process of Mode-3, Mode-4 and Mode-5, whatever heating by ASHP or WSHP. In order to reduce the switching time from Mode-1 to Mode-3 and adjust the water temperature input to the heat source side of WSHP, the minimum setting temperature of heating water supply is modified to 30°C, which is lower than the rated heating temperature of fan coil units. However, the actual period of heating water supply temperature in the range of 30~40°C is relatively short enough to has little effect on indoor temperature. That is why the process of switching process of Mode-2 is relatively fast, during which time the heating water supply temperature has even dropped to 28°C, but the fluctuation range of indoor temperature is acceptable.

Fig. 10 shows the data of indoor and outdoor ambient temperature. During the testing period, the actual indoor ambient temperature stays always higher than that of design operation at 15°C, which fluctuates periodically between 15~18°C due to the influence of the cold and heat sources inside the building.

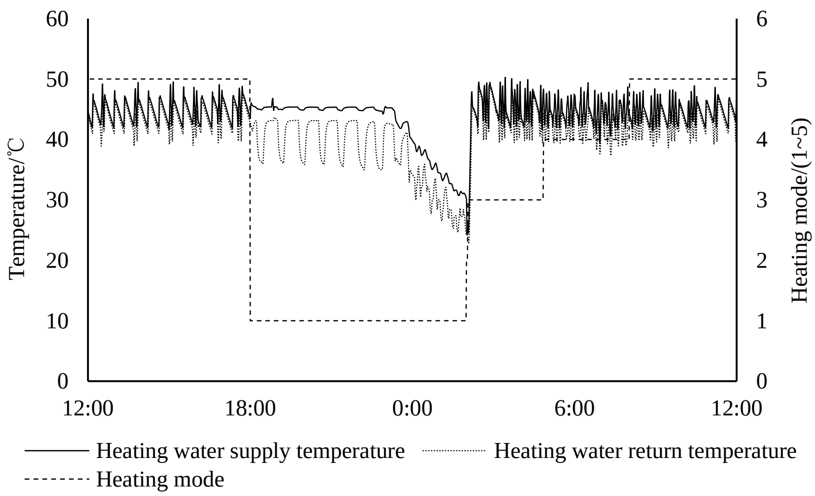

Fig.9 Test data of heating system temperature

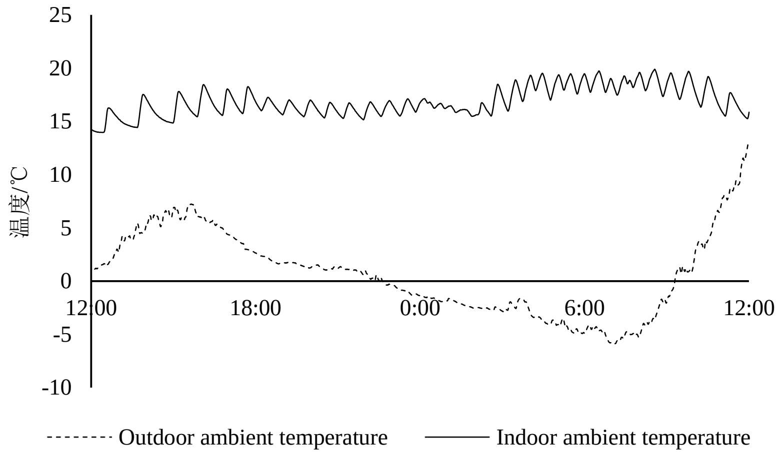

Fig.10 Test data of ambient temperature

4.5 Energy Efficiency

During the test period, the heating period of Mode 1 to 5 cost 1142min, 15min, 458min, 1142min and 1563min, respectively. It is noteworthy that the startup time of Mode-4 accounts for 25% of total, which usually occurs late at night. Currently it's relatively cold outdoor resulting in the debasement of performance coefficient of heat pump. It is necessary to shorter that start-up period by optimizing the strategy and ensure that ASHP heating runs under the condition of higher outdoor temperature in a day as far as possible. When it is cold outside, heating should mainly be provided by Mode-1 or Mode-3.

Total heat supply is 830.2MJ. Mode 1 to 5 contributs 211.2MJ, 2.1MJ, 120.8MJ, 275.4MJ and 220.7MJ, respectively. Mode-1 directly makes full use of solar energy to heat and provides 25% of total heat supply with less heating time. Mode-3 provides more heat than Mode-4 in unit time thanks to the water source of heat pump with higher temperature, which generally occurs at night when heat loss of building is relatively large. Mode-5 is generally used in daytime, so the proportion of heating is comparatively small.

The performance coefficient of system (hereafter, COP_{system}) is used to describe the energy saving effect of the system, whose calculation method is the ratio of the heat supply to the total power consumption of total system. Statistical results show that average COP_{system} corresponding to Mode-1 to Mode-5 is 26.0, 22.0, 4.1, 2.0 and 1.9 respectively. The overall COP_{system} is as high as 3.1 during the test period.

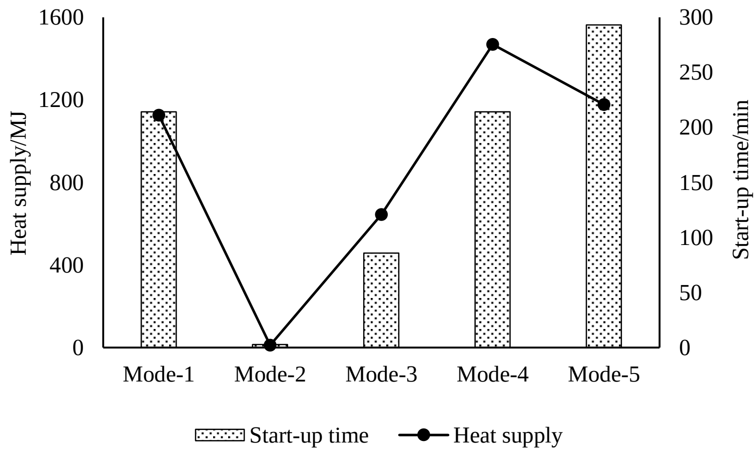

Fig.11 Start-up time and heat supply

5. Results

In this research, a new form of coupling heating system based on solar energy and dual source heat pump is put forward. The prototype of device has been developed and tested in practical building. The main conclusions through theoretical calculation and experimental research are as follows:

1) Dual source heat pump equipped with water-source evaporator and air-source evaporator can realize heating with one compressor under two kinds of heat source by the adjustment of refrigerant supply. Water-source evaporator combines with solar collector loop to extract solar energy at low temperature. When the stored heat shall be used for building heating but the internal temperature is not enough, the water-source evaporator will be switched and further improve the quality of thermal energy from solar in the range of 15~50°C. The performance coefficient of heat pump unit (COP_{HP}) increases significantly. Heat storage capacity and operating power consumption of heat pump will be reduced.

2) The new type of coupling heating device developed mainly provides heating, while taking into account both hot water and refrigeration requirements. Forecasting functions of weather and heat load are integrated into control system. When the outdoor temperature is relatively high, the mode of "Compulsory heating of ASHP" is preferred and solar collectors store heat to water tank. When the outdoor temperature is relatively low, the modes of "Direct solar heating", "Coupled heating of solar energy and WSHP" and "Compulsory heating of ASHP" are selected according to the storage temperature, through which the optimal utilization of solar energy and air energy can be realized.

3) The measured results show that the efficiency of solar collector system can reach 40%~45%. Under the mode of WSHP heating combined with solar energy, the suction temperature before compressor increases, whereas the exhaust temperature decreases. The instantaneous performance coefficient of heat pump unit (COP_{HP}) reaches 3.8~4.4 compared with that of 1.6~2.2 in the condition of ASHP heating. The overall performance coefficient of system (COP_{system}) is as high as 3.1 during the test period.

6. Acknowledgments

All authors are also grateful for the financial support provided by the *National Key R&D Program of China* (Grant No. 2016YFC0700400) and the *Applied Technology Research Fund of CABR* (Project No. 20180109331030016).

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