THEORETICAL AND EXPERIMENTAL RESEARCH ON THE THERMAL ENERGY MANAGEMENT SYSTEM OF DIRECT EXPANSION SOLAR HEATING

by

Weifang YU[a,b*]

[a] College of Intelligent Manufacturing, Wuxi, China
[b] Wuxi Vocational College of Science and Technology, Wuxi, China

Original scientific paper
https://doi.org/10.2298/TSCI2302991Y

The author has established the experimental device of the direct expansion solar heat pump system. In this device, the bare plate solar collector is also used as a heat pump evaporator. Under the sunny weather in May, the author conducted an experimental study on the heat pump system. The experimental results show that during the whole experiment, the COP, and the heat collection efficiency of the system reached 2.50-3.35 and 50.0-75.2%, respectively. At the same time, the influence of solar irradiance, condensation temperature and other parameters on the COP and heat collection efficiency of the system is analyzed and discussed, so as to provide some reference for the application of the system.

Key words: *direct expansion, solar heating, management system*

Introduction

With the enhancement of people's awareness of energy conservation and environmental protection, developing new energy, utilizing renewable energy, saving existing energy and improving energy utilization have become one of the important topics of human development in the 21st century. Solar energy has attracted more and more attention because of its huge energy, clean and pollution-free, renewable and other advantages. However, the flow rate of solar energy is low and is highly influenced by weather and season. We will combine the heat pump with solar energy technology to form a solar heat pump, which cannot only overcome the shortage and interruption of solar energy, but also has high energy saving, environmental pollution reduction, good growth and utilization capacity. According to the combination of solar collector and evaporator heat pump, solar heat pump can be divided into indirect type and direct expansion type. In the direct-expansion system, the solar collector and the heat pump evaporator are combined into one, that is, the refrigerant directly absorbs the solar energy in the solar collector and evaporates, avoiding the freezing problem of water as the heat carrier. Moreover, the evaporation of refrigerant will cool the hot collector plate, thus reducing the heat loss of convection and radiation of the collector, thus improving the heat collection efficiency of the solar collector and improving the heat pump performance. In addition, the heat exchange equipment between the non-direct-expansion intermediate heat collection cycle and the heat pump cycle is saved, and the initial investment of the system equipment is greatly reduced. As early as 1955, Sporn *et al*. proposed the concept of direct-expansion solar heat pump, and verified its advantages through experiments, fig. 1.

* Author's e-mail: 1301806@wxsc.edu.cn

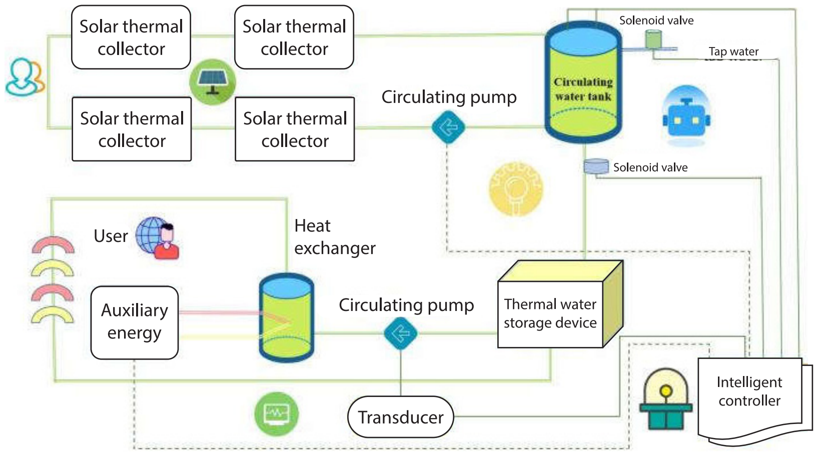

Figure 1. Thermal energy management system of direct expansion solar heating

Literature review

The BP World Energy Statistics 2019 Yearbook pointed out that with the continued downturn of the economy, the growth of global energy consumption slowed down. In 2020, the global primary energy consumption increased by 1.0%, lower than the average value of 1.9% in the past decade. This is the lowest global growth rate since 2001. Among them, as the country with the largest global energy consumption for 15 consecutive years, China will further slow down its energy consumption growth in 2020, making major contributions to the slowing down of global energy consumption growth. In recent years, the energy issue has received widespread attention, and the global energy strategy has been continuously promoted to improve the utilization rate of various fuels in terms of technology and application scope. Countries have continued to explore and develop traditional energy, and renewable energy has also continued to develop vigorously, with rapid technological progress, including solar and wind energy. On this basis, the coal consumption ratio will decrease and the global coal production will decrease. The transformation of energy structure from coal based to natural gas and renewable energy has slowed down the growth of carbon emissions, which has been basically flat for the first time, this is good news for the global greenhouse effect, energy conservation and emission reduction have achieved initial results. However, countries should not relax their vigilance, the challenges to energy and environment are still formidable. As the world's first energy consumer, China will account for 23% of the world's energy consumption and 34% of its growth in 2020 [1]. In recent years, the economy has grown rapidly, ranking the second in the world and playing a decisive role. In 2020, China's economic growth will gradually slow down and face the transformation of industrial structure. Nevertheless, China's total energy consumption continues to grow, as shown in fig. 2.

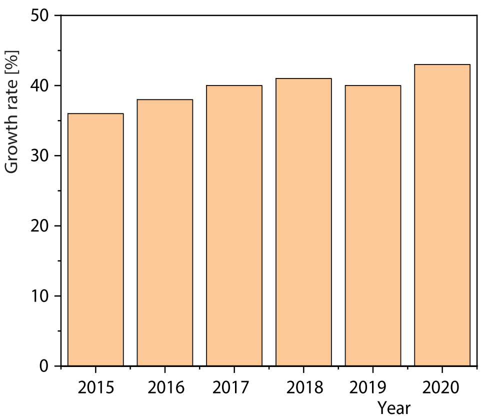

Figure 2. Total energy consumption in China

Research Methods

Solar thermal utilization

As an important renewable energy, solar energy is widely distributed, clean and inexhaustible, it is a hot new energy and has gained more and more attention and technical input. Solar energy utilization has great potential and space. About $1.08 \cdot 10^{14}$ kW of the total energy released by the sun is received by the earth. If mankind can find an effective way to convert 1/10000 of the energy into electric energy, the total energy will still be four times of the current global power generation. The Sun's lifespan is believed to be at least four billion years, long enough for human development. In the future, the world's energy supply is facing problems, and the use of solar energy is an important way to solve these problems. Solar energy will grow rapidly this century, and it is estimated that by 2050 it will account for 30% of the world's electricity consumption. At the end of this century, it will replace nuclear energy as the first energy of mankind. China is rich in solar energy resources and attaches importance to the development and utilization of solar energy. In 2019, China announced a new Renewable Energy Policy that will provide a sixth opportunity for solar energy development. Currently, solar energy technology mainly includes solar energy and photovoltaic energy. Thermal consumption is an important factor in the use of solar energy. The principle of photo-thermal utilization is to use a variety of technical means, mainly absorb solar energy and flow through the medium, convert solar energy into heat energy and concentrate on application. Solar thermal utilization is currently the most widely used and mature solar energy utilization mode, including solar thermal power generation and solar building energy. Home energy production includes solar heating, air conditioning and hot water. Solar water heating is used to generate electricity to provide domestic hot water. Solar heat pumps are required for heating and cooling. Solar water heaters have developed a mature business, some of which are efficient replacements for heating oil and electric water heaters, saving energy. Figure 3 shows annual changes in global solar water heater capacity. The figure shows that the total number of solar water heaters in the world is steadily increasing, with glass collectors accounting for an equally large share [2, 3].

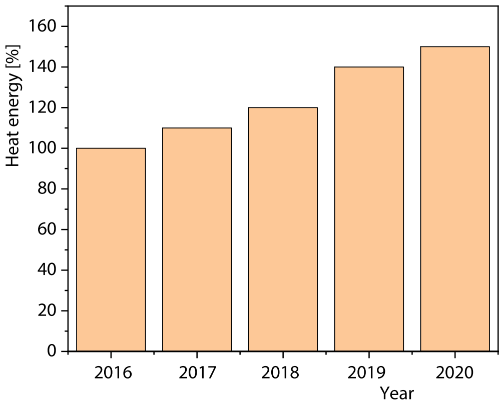

Figure 3. Global solar water heater capacity switch

China's solar technology is also developing. Following the people's lifestyle and the country's urbanization process, China's domestic electricity consumption accounts for 20% of the total electricity consumption of the society and is increasing. The application of photo-thermal technology can reduce the proportion of traditional energy in building energy consumption, introduce solar energy, and make it more environmentally friendly and clean. Table 1 shows the benefits of energy conservation and emission reduction from the application of solar energy collection systems in China from 2015 to 2019. It can be seen that the number of solar energy heat collection systems is increasing year by year, which effectively helps to save coal and electricity, while reducing the emissions of pollutants such as soot and carbon dioxide, and has significant environmental benefits. The 13th Five Year Plan for Building Energy Efficiency put forward the goal of continuing to improve the utilization rate of renewable energy in building energy consumption. In addition the solar heat collection system, the country also plans to realize the heating and cooling demand of 10% of the urban area provided by solar energy by 2023 [4].

Table 1. Energy saving and emission reduction benefits of solar heat collection system

Year	Ownership [km^2]	Saving standard [t]	Equivalent power saving [kW]	Emission reduction O_2 [Ta^{-1}]	Smoke emission reduction [Ta^{-1}]
2015	3330	500	140	17	13
2016	4300	620	170	20	15
2017	5100	700	200	25	19
2018	7800	1000	320	30	20
2019	8000	1100	350	40	22

Thermal energy of direct expansion solar heating

Domestic electricity consumption accounts for one-third of total local energy consumption, including refrigeration, heating and hot water. Efficient use of solar energy and reducing home energy consumption is a good way to solve energy problems. The system combines solar energy and a heat pump to make the solar pump use clean energy, recycle solar energy, and improve the efficiency of the pump. The direct solar heat pump (DX-SAHP) has the advantages of compact structure and low cost, and prevents the collector from freezing at night. It has been proven that the heating efficiency of the DX-SAHP system is better than that of the heat pump. However, there is much to learn in the DX-SAHP system. First, the DX-SAHP system has two uses: heating and hot water. Most experimental research, limited to experiments, has focused on hot water applications in DX-SAHP systems. In heating applications, the system uses hot air to heat it, as opposed to heating cold water when making hot water. As an important application form of DX-SAHP, the performance of DX-SAHP system in heating application still needs further study. Second, the existing experimental research is mainly carried out in the outdoor environment, and the system test conditions are limited by the atmospheric conditions, which cannot determine the impact of environmental parameters on the system performance. Therefore, it is necessary to conduct experimental research under indoor steady-state conditions, quantitatively analyze the system performance, and study the system performance under standard conditions. Third, frosting, an important problem in the application of heat pump systems in winter, is a hot spot in heat pump research. The thermal performance and frosting characteristics of DX-SAHP system under frosting conditions must be discussed when considering the winter application of DX-SAHP system. However, there is almost no research on this aspect [5, 6].

The DX-SAHP concept was first proposed in 1955. Some researchers have found that the COP of solar heat pumps is higher than that of traditional air conditioning heat pumps. The DX-SAHP has been widely studied at home and abroad, including experimental research, theoretical research, and optimization. Krakow *et al*. analyzed the performance of the direct-expansion heat pump using a flatless collector in cold regions, and concluded that using a flatless collector in cold regions is more beneficial to the system operation, while using a flatless collector in warm regions is more beneficial. Some researchers have studied DX-SAHP hot water using bare plates. The COP in solar mode is 2.0-3.0. The COP in fan mode is about 1.5. Their research results confirm that DX-SAHP has significantly improved performance compared with traditional heat pumps. Other scholars have tested the household DX-SAHP system, and the

COP of the system is between 2.6 and 3.3. Further, they studied the performance of DX-SAHP system using a 2 m^2 bare plate flat plate collector. The monthly average COP of the system is 4-6, and the heat collection efficiency is 40-60%. It is pointed out that the system performance is mainly affected by radiation intensity, heat collection area and compressor speed. Most of the existing DX-SAHP experiments are outdoor heating experiments. Under such conditions, various environmental factors, including ambient temperature, wind speed, radiation intensity, *etc.*, change with time, and the test conditions are uncontrollable, which are limited by weather conditions. The test results can partly reflect the system performance, but it is difficult to quantitatively compare and analyze various variable factors. A few studies have studied DX-SAHP system in controllable steady-state environment. Others tested the performance of DX-SAHP hot water system in a thermostatic hot box. The system uses bare plates as evaporators. The tests were carried out at different ambient temperatures, but all were without solar radiation. According to the experimental results, the changes of heating capacity, COP and other parameters of the system are analyzed. In the research of heat pump system using water-cooled condenser, the heating capacity can be calculated by measuring the water temperature. But for the heat pump system using air cooled condenser, it is very difficult to test the heating capacity through experimental means. Therefore, most of the experimental studies on SAHP analyze the hot water system. Based on the experimental results, the simulation research also analyzes the hot water system more, and the research on the SAHP heating system is less. The research shows that the COP of the heat pump system is 2.6 to 3.3 under the heating mode. The performance of DX-SAHP system using air-cooled condenser to realize heating under steady-state conditions is still worth further analysis and research.

Experimental study

Experimental equipment and test method

The experimental device is self-designed, which is the schematic diagram of the experimental principle of the direct expansion solar heat pump system. The main components and structural parameters of the device are: 1 – compressor: the QX-16 piston compressor, its rated power is 0.7 kW, 2 – condenser: a tubular condenser consisting of two kinds of seamless steel tubes and copper tubes with different diameters, which are sleeved together and bent into a spiral tube, the refrigerant condenses in the casing space and the cooling water flows in the inner tube, both of which flow countercurrent, its structural dimension is that the diameter of outer pipe is 43 mm, the diameter of inner pipe is 9 mm, the number of inner pipes is 5, and the pipe length is 4.94 m. Solar collectors (also used as heat pump evaporators): Self-made bare plate solar collectors, that is, without glass cover plate and without thermal insulation on the back, are mainly composed of aluminum sheets and copper tubes, which are tied together by tube expansion technology, thermal conductive adhesive is applied at the joint to reduce the contact thermal resistance, in order to effectively absorb the solar incident radiation, both sides of the top and bottom are evenly coated with blackboard paint, with a heat collection area of 1.86 m ‘and an inclination of 35°, and 3 – throttling device: thermal expansion valve.

Test method

The types of test data in this experiment include solar irradiance, temperature, pressure, water flow, compressor power and outdoor ambient wind speed. Among them, the American Eppley8-48 solar irradiance meter is used to measure the solar irradiance, when measuring, it is installed on the same inclined plane of the collector, the electronic professional computer with printer manufactured by the company is equipped to read data, which can continuously display and print the cumulative value of solar irradiance at a fixed time (the printing interval can be any one of 1 minute, 10 minutes, 60 minutes). See tab. 2 for measurement of other parameters [7].

Table 2. Test parameters and instruments

Test parameters	Measuring instrument
Ambient temperature, inlet and outlet water temperature of cooling water, inlet and outlet refrigerant temperature of condenser and heat collector	Mercury temperature
Inlet and outlet pressure of solar collector and condenser	Pressure gauge
Cooling water flow	LZB glass rotameter
Compressor power	D-40W standard power meter

Experimental data processing and result analysis

Experimental data processing:
- Inlet and outlet temperature and water flow of cooling water: adopt the average value of multiple measurements.
- Collection temperature and condensation temperature: take the average value of refrigerant inlet and outlet in the solar collector and condenser.
- Solar irradiance: since the data measured by the solar radiometer used are cumulative values, the average value of a certain period of time shall be calculated when calculating solar irradiance.
- Heat pump performance coefficient COP: 111.

Table 3. Typical experimental results of direct expansion solar heat pump system

Ambient temperature [°C]	Solar radiation [J]	Condensation temperature [°C]	Compressor power consumption [kW]	Heat pump performance parameters, COP	Collecting temperature [°C]
24	705	37	480	3	15
23	710	41	460	4	16
22	760	40	440	3.2	17
21	720	38	430	4.1	18

Analysis of overall system performance

The test was conducted in sunny weather in May. During the experiment, the outside air temperature is 22-24 °C, and the solar radiation is 700-1000 W/m^2. The test rig starts at 10 a. m. and collects data every 10 minutes. Those, tab. 2 shows the experimental results. It can be seen from tab. 3:
- The COP of the heat pump can reach 2.69-3.35, which shows that the energy saving is obvious.
- The temperature range of the collector of the system is 15~18 °C, and the temperature of the collector is lower than the ambient temperature. It can be seen that the surface temperature of the collector is also low. The collector is a low temperature flat plate collector, which will improve the efficiency of the solar collector, thus greatly reducing the cost of the collector. The efficiency of the collector of the system is 59.4~75.2%; However, for the heat pump

system, low collecting temperature is unfavorable. How to solve this contradiction needs to be further explored in combination with its specific application fields.
– Solar irradiance, condensation temperature and ambient temperature will be the main parameters that affect the COP of the system and the efficiency of the solar collector [8].

Impact of main parameters on system performance

Under the condition that the ambient air temperature is 22.9-31.00, the condensation temperature is controlled between 40~41 °C, and the relationship between the heat pump performance coefficient, COP, and the solar collector efficiency with solar irradiance, I, is analyzed. With the increase of solar irradiance, COP increases, while η decreases. Because for a given condensing temperature, T, the greater the solar irradiance, the higher the heat collection temperature, T, so the COP increases. However, at the same time, the refrigerant in the collector absorbs more heat, which increases the vapor content in the refrigerant, decreases the heat transfer coefficient of the collector, and decreases η. In addition, in this test, the COP of the system is about 2.55~3.25, and η can reach 60-70%. It can be seen from the figure that the COP and η range of the system under this working condition are 2.50~3.25 and 50~70% respectively. With the increase of finger condensation temperature, both COP and η decreased. Because with the increase of the condensing temperature, the collector temperature increases, but the increase is smaller than that of the condensing temperature [9, 10].

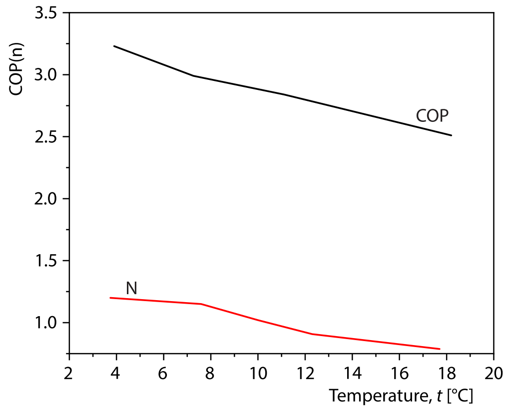

Figure 4. The COP changes with condensation temperature

Conclusions

For the self-made test equipment of the extended direct solar heat pump system, the test performance is carried out in an outdoor environment with an air temperature of 22-24 °C and solar radiation of 700-1000 W/m the following conclusions can be drawn are as follows.

- The COP and heat collection efficiency of the system reach 2.50-3.35 and 50.0-75.2, respectively, indicating that the system is energy efficient.
- The heat pump performance coefficient of the system increases with the increase of solar irradiance, and the heat collection efficiency η decreases, but both decrease with the increase of condensation temperature.
- There is a connection between the area of the solar system and the capacity of the heat pump, that is, the coefficient of thermal efficiency decreases as the temperature of the heat collection increases, the heating device decreases, and the pump increases. Those, according to the actual situation, the relationship between the two should be considered necessary for the economic functioning of the system.
- When determining the cooling charge and permeability, the direct effect of the solar heat pump can be used to heat the small hot air, especially in conjunction with the electric floor heating system to reduce the heating dependence. The water supply temperature of the hot air electric floor heater is usually 40-60 °C, so it can be installed in the gas system and achieve energy saving results.

Reference

[1] Chen, Y., *et al*., Energy, Environmental-Based Cost, and Solar Share Comparisons of a Solar Driven Cooling and Heating System with Different Types of Building, *Applied Thermal Engineering: Design, Processes, Equipment, Economics*, *211* (2022), July, 118435

[2] Patel, S. K., *et al.*, Optimization of Metamaterial-Based Solar Energy Absorber for Enhancing Solar Thermal Energy Conversion Using Artificial Intelligence, *Advanced Theory and Simulations*, *5* (2022), 8, 2200139

[3] Serrano, A., *et al*., Tailored Transition Temperature Plastic Crystals with Enhanced Thermal Energy Storage Capacity, Solar Energy Materials and Solar Cells: *An International Journal Devoted to Photovoltaic*, *Photo-Thermal, and Photochemical Solar Energy Conversion*, *220* (2021), Jan., 110848

[4] Ravi, K. K., *et al*., Solar Thermal Energy Technologies and Its Applications for Process Heating and Power Generation – A Review, *TERI Information Digest on Energy and Environment: TIDEE*, *20* (2021), 1, 125296

[5] Mehari, A., *et al.*, Multi-Functional Three-Phase Sorption Solar Thermal Energy Storage Cycles for Cooling, Heating, and Heat Transformer, *Applied Thermal Engineering: Design, Processes, Equipment, Economics*, *189* (2021), May, 116765

[6] Banakar, A., *et al*., Energy Analysis and Assessing Heating and Cooling Demands of Closed Greenhouse in Iran, *Thermal Science and Engineering Progress*, *25* (2021), Oct., 101042

[7] Zheng, Z., *et al*., Solar Assisted Air Source Heat Pump Systems for Campus Water Heating in China: Economic Optimization of Solar Fraction Design, *Applied Thermal Engineering*: *Design, Processes, Equipment, Economics*, *213* (2022), Part 2, 118767

[8] Chen, J., *et al*., Investigation on Transient Response of the Direct Expansion Solar Assisted Ejector-Compression Heat Pump Cycle for Water Heater, *Applied Thermal Engineering: Design, Processes, Equipment, Economics*, *213* (2022), Part 1, 118700

[9] Zhang, Y., *et al*., Direct Solar Energy-Mediated Synthesis of Tertiary Benzylic Alcohols Using a Metal-Free Heterogeneous Photocatalyst, *ACS Sustainable Chemistry and Engineering*, *10* (2022), 1, pp. 530-540

[10] Acarog, H., Marquez, F. P. G., A life-Cycle Cost Analysis of High Voltage Direct Current Utilization for Solar Energy Systems: The Case Study in Turkey, *Journal of Cleaner Production*, *360* (2022), Aug., 132128

Paper submitted: June 13, 2022
Paper revised: August 14, 2022
Paper accepted: August 25, 2022