SOLAR THERMAL CONTROL SYSTEM BASED ON VARIABLE FREQUENCY HEAT EXCHANGER CONTROL TECHNOLOGY

by

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Frequency conversion exchanger control is the critical technology of solar water heaters. It can integrate solar thermal technology and heat pump technology and makes solar thermal energy conversion efficiency higher. Based on this research background, the paper first discusses the principle of the technology. Then, it optimizes the system control strategy based on maximizing the utilization of heat energy and the highest efficiency ratio. Finally, the article established a deep learning model of solar radiation based on different time-sharing. The experimental simulation confirmed that the thermal energy control optimization algorithm model proposed in this paper could effectively predict thermal energy exchange.

Key words: solar energy, variable frequency heat exchanger control technology, heat prediction, energy-saving control

Introduction

Solar water heaters convert low temperature heat sources into high temperature heat sources for daily use by absorbing solar radiation, which is energy-saving and environmentally friendly [1]. It is a concrete manifestation of the application of solar energy to energy conservation and environmental protection. When the light intensity is insufficient or the spare time is short, solar heat collectors' heat collection efficiency is low, affecting users' needs for hot water. In weather conditions with sufficient solar radiation, solar water heaters have many incomparable advantages over other hot water production methods. However, solar radiation has intermittent and randomization characteristics, which causes solar water heaters to change with the weather. The direct expansion solar heat pump hot water system produces hot water by combining solar heat collection technology with heat pump heat collection technology. The refrigerant in the evaporator can absorb solar radiation energy and exchange heat with the surrounding air. When the intensity of illumination is insufficient, it can continue to work, collect heat, and meet users' all-weather hot water demand [2].

The fixed-frequency compressor speed is uncontrollable, so it is not easy to control the system's heating time to achieve the best energy-saving effect. This paper proposes a water source heat pump system controlled by a solar variable frequency heat exchanger based on this research background. The article analyzes the system's working principle to make hot water formulate a reasonable and effective control strategy. This method enables the unit to maximize the use of solar energy to save high level energy and improve the overall energy efficiency ratio

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of the system. The method proposed in this article has played a positive role in promoting the development of the hot water equipment industry.

Direct expansion variable frequency heat exchange solar heat pump hot water system Structure composition of heat pump hot water system controlled by a solar variable frequency heat exchanger

The heat pump hot water system controlled by the solar variable frequency heat exchanger is shown in fig. 1. From the structural point of view, the heat pump hot water system controlled by the solar variable frequency heat exchanger includes two parts: one part is a solar heat collection system composed of a solar heat collector, a hot water storage tank, a cir-



variable frequency heat exchanger

culating water pump, and a solenoid valve; the other part is a compressor, evaporator, condenser, throttle valve, circulating water pump, water source, and solenoid valve composed of variable frequency heat exchanger controlled heat pump hot water system [3]. The PVR (Triple Polypropylene) pipe, water pump, and solenoid valve connect these two parts. At the same time, we develop intelligent controllers to control the operation of solenoid valves, water pumps, and water source heat pump units. So the research results of the thesis formed a solar water source heat pump hot water system [4].

In this system, the solar collector adopts a new solar collector with a gravity heat pipe as the core element. During the working process, the solar heat absorber absorbs solar radiation through the heat-absorbing surface and converts it into heat energy. The heat energy is absorbed through the evaporation section of the heat pipe, and the working fluid in the line undergoes phase change gasification. When the steam encounters a low pressure condensing chamber, it condenses into a liquid state and releases a large amount of heat. This part of the heat is transferred to the water circulation pipe-line through the heat conduction flow channel to heat hot water. The heat pump unit uses a water source heat pump unit. The water source of this unit comes from the cooling water in the heat exchanger, and its temperature change range is moderate. Therefore, the water source heat pump unit operates stably. The solar heat collection system and the water source heat pump unit are connected in parallel to heat the hot water storage tank, and the two parts of the system do not affect each other's heating of the hot water storage tank [5].

Working principle analysis

The water source heat pump system is a system that uses solar energy and water source thermal energy as heat sources to produce hot water. Solar energy and water source thermal energy can complement each other in the process of making hot water. Use solar energy when there is enough solar radiation. When the solar radiation is not enough, the water source heat is used. Therefore, the water source heat pump system controlled by the solar variable frequency heat exchanger has incomparable advantages over the solar hot water system or the water source heat pump system. The heating energy efficiency ratio of the system is also higher than that of a single heat source. According to solar radiation intensity and daily hot water de-

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mand changes, the system adopts different working modes to operate. The system can realize the alternate operation of multiple working conditions through the transformation of some pipeline valves.

Research on the control strategy of the solar variable frequency heat exchanger

Mathematical model of a hot water storage tank

This article will study the control of a water source heat pump system controlled by a solar variable frequency heat exchanger under a constant water temperature make-up mode. The solar heat pump system currently on the market adopts a constant water temperature replenishment mode. The auxiliary heat source control is mainly a simple temperature difference control. When the water temperature of the water tank is lower than a particular value of the target water temperature, the heat pump unit is turned on for auxiliary heating. The system uses this principle to heat the system and ignores solar energy heating when the solar radiation is intense. This method reduces the overall energy efficiency ratio of the system. When the solar heat pump system is operating in the combined hot water heating mode, we will analyze the conservation of mass and energy of the hot water storage tank. The schematic system diagram is shown in fig. 2.



Figure 2. Principal diagram of mass conservation of hot water storage tank

According to the top chart of mass conservation in fig. 2, the change equation of the water quality of the hot water storage tank:

$$\rho \frac{\mathrm{d}V}{\mathrm{d}t} = m_{\mathrm{S}} + m_{\mathrm{p}} + m_{\mathrm{r}} - m_{\mathrm{cos}} - m_{\mathrm{S}} - m_{\mathrm{p}} \tag{1}$$

where ρ [1.0 · 10³ kgL⁻¹] is the water density in the normal state, V [L] – the volume of the remaining water, m_s [kgs⁻¹] – the user consumes hot water flow in the process, m_p [kgs⁻¹] – the hot water flow rate of the hot water storage tank that finally supplements the water flow rate, m_{cos} [kgs⁻¹] – the user consumption hot water flow, and m_r [kgs⁻¹] – the hot water storage tank replenishing water flow. Assuming that the two parts have the same amount of water entering and leaving the hot water storage tank, the previous formula can be re-written:

$$\rho \frac{\mathrm{d}V}{\mathrm{d}t} = m_r - m_{\mathrm{cos}} \tag{2}$$

Using Euler's equation solve eq. (2):

$$V_2 = V_1 + \frac{m_r - m_{\rm con}}{\rho} \Delta t \tag{3}$$

where V_2 [L] is the volume of the remaining water at time Δt and V_1 [L] – the volume of the initial remaining water at time Δt . Then the change equation of the energy obtained by the hot water storage tank:

$$\rho c \frac{\mathrm{d}VT}{\mathrm{d}t} = q_s + q_p + q_r - q_{\mathrm{con}} - q \tag{4}$$

where q_r [W] is the heat received by refilling the hot water tank per unit time, q_{con} [W] – the heat consumption per unit time of the user, and q [W] – the heat loss per unit time of the hot water storage tank. We use Euler's equation solving eq. (4):

$$T_{2} = \frac{1}{V_{2}} \left[V_{1}T_{1} + \frac{\Delta t}{\rho c} \left(q_{s} + q_{p} + q_{r} - q_{con} - q \right) \right]$$
(5)

where T_2 [°C] is the water temperature of the hot water tank and T [°C] – the initial storage water temperature. The hot water storage tank obtains the solar heat collection q_s , the user's heat per unit time, and the heat loss per unit time q. The calculation formula:

$$q_s = A_s I_T \eta \tag{6}$$

$$q_p = COP_T P \tag{7}$$

$$q_r = cm_r T_r \tag{8}$$

$$q_{\rm con} = cm_{\rm con}T_1 \tag{9}$$

$$q = U_{\rm st} A_{\rm st} (T - T_{\rm a}) \tag{10}$$

where A_{st} [m²] is the outer surface area of the hot water storage tank and T_a [°C] – the ambient temperature. Putting eqs. (3), (8) and (9) into eq. (5):

$$T = \frac{\rho V_1 T_1 + \frac{\Delta t}{c} (q_s + q_p + q_r - q_{con} - q)}{\rho V_1 + (m_r - m_{con}) \Delta t}$$
(11)

Equation (11) is the calculation formula for the change model of the water temperature of the hot water storage tank under the influence of multiple factors per unit time. The following will use this formula to study the control strategy of the system under the condition of solar radiation during the day to improve the energy efficiency of the system.

System control strategy research

The system uses a constant water temperature replenishment mode. Part of the hot water is consumed due to user water demand. To heat the water tank temperature to the target temperature, we need to run the system to make hot water. For the conventional system, at this time, it is determined whether to turn on the auxiliary heating of the water source heat pump unit according to the appropriate temperature difference requirements. This method ignores the effect of solar radiation and reduces the overall energy efficiency ratio of the system. As a high

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efficiency energy-saving product, the solar heat pump system is used to measure its energy-saving rate. For products with heat pumps, it is the energy efficiency ratio COP. A high COP means that the system's energy efficiency is high. The energy-saving effect is good. On the contrary, it means that the system's energy efficiency is low, and the energy-saving product is not ideal. According to the First law of thermodynamics, the overall energy efficiency ratio COP of the system is the ratio of the total heat obtained by the hot water storage tank to the total power consumed:

$$COP = \frac{Q_s + Q_p}{W_{\text{comp}} + W_{swp} + W_{pwp}}$$
(12)

Establishing a forecasting model for heat pump water heating system controlled by the solar inverter heat exchanger

The hot water system load, Q, always represents the hot water heater that the entire system needs to produce every day, equivalent to the hot water load:

$$Q_{\text{total}} = nq_r c(T_{\text{end}} - T_i)\rho \tag{13}$$

where *n* [L] is the number of people using water, q_r – the average daily water consumption per capita, usually 70-100 L/(λd), ρ [1.0 · 10³ kgm⁻³] – the density of water in the normal state, and c [4178 JKg⁻¹°C⁻¹] – the specific heat capacity of water at constant pressure, T_{end} [°C] – the target heating water temperature set by the system, and T_i [°C] – the average water temperature in the water tank at the judgment time. For the entire heat pump unit, the calculation formula of its heating capacity Q_p :

$$Q_{p} = COPP(t_{b} - t_{a}) \tag{14}$$

For heat pump units, the unit's energy efficiency ratio COP value during the entire operation process is not constant. It changes with the changes in some parameters.

System testing and analysis

The solar collector used in this experiment is a new type of heat pipe solar collector. Each solar collector structure includes tempered glass with a light transmittance of 92%, a thickness of 3 mm, an aluminum alloy frame with a size of 1132×1105 mm, and a heat collecting plate with an absorption rate of 95% and a measure of 950×890 mm. The effective daylighting area of the solar collector is 963.4 × 855.7 mm. The experiment uses two solar collectors, and the solar collector is placed at an inclination angle of 45° above the metal bracket. Before the investigation, the water storage tank was refilled until the water tank's water level reached two-thirds, and the water storage capacity of the water tank was 100 L. The experiment at the solar tarted at 9:00 in the morning and lasted until 17:00. The experiment uses the day's experimental data to verify the solar heat collection system heat collection optimization method [7].

This experiment first tested the variable-frequency solar heat pump hot water system's parameters and performance during the hot water production process by fixing the compressor operating frequency. The ambient temperature and radiation intensity are the parameters of the environment where the evaporator is located. During data processing, several representative experimental conditions were selected to analyze and process the overall results. Table 1 fixed frequency performance test is the data tested in June.

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Serial number	1	2	3	4	5	6	7	8
Environment temperature [°C]	24.3	24	23.45	24.5	25.8	24	26.3	26.2
Radiant lighting [Wm ⁻²]	502	386	284	658	756	363	728	757
Heating time [minute]	404	378	348	289	245	234	200	195
Initial temperature [°C]	15.15	13.6	15.1	14.6	15.3	15.4	15.45	14
Termination temperature [°C]	55.14	55.3	55.27	55.42	55.2	55.06	55.6	55.45
Heating capacity [W]	1372	1501	1587	1920	2216	2303	2732	2892
Average power consumption [kw]	0.243	0.27	0.312	0.357	0.476	0.59	0.671	0.759
СОР	5.54	5.56	5.03	5.38	4.66	3.91	4.07	3.81
Frequency [Hz]	38	42	46	50	60	75	80	86

Table 1. Fixed frequency performance test

It can be seen from tab. 1 that the direct expansion solar heat pump water heater has a relatively high heating performance in June, with a COP basically above 4.0 and a maximum of 5.56. In tab. 1, when the compressor runs at 42 Hz and 75 Hz, under the same ambient temperature and slight difference in radiation intensity, the system's performance when running at 42 Hz is significantly higher than when running 75 Hz. Therefore, when the external environment is the same, passing the compressor frequency and extending the heating time will help improve the COP of the system. When running at 38Hz or lower, the heating time of the system is close to 7 hours. The heating time is longer, but the system efficiency is not significantly improved. Therefore, the compressor operating frequency cannot be reduced indefinitely [8]. It is necessary to select the appropriate operating frequency. The control system to complete the heating in a proper time can meet the user's demand for hot water time, and it is also beneficial to improve the system performance.

Table 2 shows the performance data of the variable frequency system under different frequency and water temperature conditions. When the compressor's operating frequency remains unchanged, and the water temperature rises, the heating capacity does not change much, but the system COP gradually decreases. When the compressor's operating frequency increas-

 Table 2. Performance data of variable frequency system under different frequency and water temperature conditions

	-	-				
Environment temperature [°C]	Radiant lighting [Wm ⁻²]	Initial temperature [°C]	Termination temperature [°C]	Heating capacity [W]	Average power consumption [kW]	COP
24.1	257	14.6	22	1624	0.181	8.97
23.4	212	22	30	1728	0.211	8.19
23.5	310	30	36	1540	0.242	6.37
23.7	331	36	42	1944	0.278	6.99
24.4	381	42	48	1201	0.275	4.37
24.2	384	48	55	1465	0.371	3.95
23.3	424	14.6	22	2189	0.232	9.44
22.8	707	22	30	2093	0.272	7.7
23	744	30	36	1944	0.327	5.94
23.3	744	36	42	2093	0.368	5.69
24.2	736	42	48	2268	0.413	5.49
24.3	670	48	55	1868	0.466	4.01

es, the water temperature does not change. In the variable interval, the heating capacity gradually increases, and the compressor operating frequency gradually decreases. It can be seen that the system heating capacity and system COP are closely related to the compressor frequency and water tank water temperature and have a significant impact on the performance of the whole machine. Therefore, the compressor operating frequency adjustment is the key to the natural expansion variable frequency solar heat pump hot water system [9].



Under the same environmental conditions, heating time, and heating water volume, the analysis of the influence of frequency changes

Figure 3. The COP value under three heating methods

on the system can be divided into three modes: constant speed heating, rising speed heating, and falling speed heating, as shown in fig. 3. Based on the experimental data, the three methods are theoretically calculated through mathematical techniques, and the differences in COP of the three heating methods are compared:

 when the ambient temperature is 24±2°C, the radiation intensity is 750 W/m². The water temperature is 45 °C, the system heating capacity and COP are shown in fig. 4 at different press operating frequencies.



Figure 4. Variation curve of heating capacity and COP with frequency

when the ambient temperature is 24±2 °C, the radiation intensity is 750 W/m², and the compressor operating frequency is 60 Hz, the system heating capacity and COP are shown in fig. 5.

The heating power and COP curves with frequency and water temperature in figs. 4 and 5 show that the healing power and COP have a linear relationship with the operating frequency after fitting.

When the temperature irradiation is high, reduce the operating power to achieve the most energy-saving effect. When the temperature irradiation is low, increase the active management to ensure that the unit is in the most effective heat-absorbing state. The system water temperature heating range is set to 15-55 °C. The heating limit time needs to be determined based on experimental tests of parameters such as ambient temperature and solar irradiation conditions. The empirical test data is summer operating condition data, so the heating time is set



Figure 5. Heating power and COP change curve with water temperature

to 270 minutes, and the experimental test data can be imported to obtain the system parameters. When the heating time is different, the system COP changes significantly. The longer the heating time, the higher the COP. Therefore, operating at a lower speed and extending the heating time within the allowable range of the specified time is the key to obtaining a higher COP. Adjust the compressor's operating frequency by controlling the heating time of the system. Adjust the compressor's operating frequency according to the temperature rise rate of different water temperature sections [10]:

- Determine the required heating time according to heating requirements and real-time environmental parameters, and calculate the average heating power required to complete the heating of the solar water heater [11].
- Determine the initial frequency of the compressor according to the formula between the heating capacity and the initial frequency *f*.
- Calculate the actual heating capacity of different water temperature sections in the heating process of the compression mechanism, and compare the actual heating capacity with the expected heating capacity. When the actual heating capacity is more significant than expected, it can be judged that the external environment or the irradiation conditions are better than when heating is started. Therefore, it is beneficial to heat pump heating, reducing the operating frequency of the compressor and extending the healing time. On the other hand, when the actual conditions are less than expected, it can be judged that the external environment or the irradiance is worse than when the heating is started. According to the comparison result, the most effective heating state.
- Adjust the compressor frequency in real-time.

Conclusion

Many factors are influencing the performance of direct expansion variable frequency solar heat pump hot water system. This article only analyzes system operation and heating time and uses a fixed frequency method to obtain the change law of system operating parameters under different compressor operating frequencies. To better adapt to changes in the external environment and meet users' needs for hot water time, controlling the heating time according to the operating frequency of the compressor is proposed. After data simulation and experimental analysis and verification, a method to control the press's operating frequency is obtained. The control system's heating time is maintained through data analysis and experimental validation and the feasibility of adjusting the operating frequency of the press according to the comparison between the expected temperature rise and the actual temperature rise. This method can Wu, L., *et al.*: Solar Thermal Control System Based on Variable Frequency ... THERMAL SCIENCE: Year 2021, Vol. 25, No. 4B, pp. 3063-3071

accurately control the heating time while ensuring the variable frequency heat pump system's efficient operation, and the system has apparent energy-saving effects. Therefore, it has a particular guiding significance for promoting the direct expansion variable frequency heat pump hot water system.

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