Research on temperature control and influence of the vacuum tubes with inserted tubes solar heater

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Abstract. A novel snake-shape vacuum tube with inserted tubes solar collector is designed in this paper, the heat transfer characteristics of the collector are analyzed according to its structural characteristics, and the influence of different working temperature on thermal characteristics of the collector is studied. The solar water heater prototype consisting of 14 vacuum tubes with inserted tubes is prepared, and the hot water storage control subsystem is designed by hysteresis comparison algorithm. The heat characteristic of the prototype was experimentally studied under hot water output temperature of 40-45℃, 50-55℃ and 60-65℃. The daily thermal efficiency was 64%, 50% and 46%, respectively. The experimental results are basically consistent with the theoretical analysis.

1. Introduction

Solar collector, including solar water heater, air heater, etc., can be categorized into two types of flat type and vacuum tube according to adopted structure of the collector. Wherein, vacuum tube solar collector can be divided into two types of all-glass vacuum tube and glass - metal vacuum tube [1]. All-glass vacuum tubes are widely used in solar water heaters and air collectors due to their technical maturity and low cost [2]. In vacuum tube solar water heater system, the vacuum tube is directly connected to the thermal insulation water tank, and the water is heated in the vacuum tube before heat transfer to the water in the tank via convection and heat conduction. As hot water in the vacuum tube has small thermal convection strength, dirt will appear at the bottom of the vacuum tube after long-term use, causing secondary pollution. To this end, the application of glass-metal vacuum tubes collector in solar water heater has been studied. However, it has not been widely used because of the limitation of process and cost [3-5]. In addition, on the basis of all glass vacuum tubes, the vacuum tube with inserted tubes air collector has been studied and used. For example, Chang W *et al* proposed an efficient all-glass vacuum tube with inserted tubes air collector [6]. The results show that the collector has average efficiency of 49.5% and 63.7% in cloudy and sunny days, respectively, and the instantaneous efficiency of the collector increases with the increase of inlet mass flow. Yuan Y L *et al* designed a new type of vacuum tube with inserted tubes air collector, tested and analyzed the instantaneous heat collection characteristics under different seasons. The study found that stability of the air collector under stable working condition is about 60% in different seasons [7]. Yan S Y *et al* studied structural characteristic and non-steady-state efficiency of glass vacuum tube with inserted tubes solar collector, and obtained ideal non-steady-state efficiency equation [8]. Zeng D Q *et al* studied the air collection performance and flow resistance of tubular solar collector array, and the results show that the heat collection temperature is 87.8℃ and 109.3℃ in winter and summer respectively, with the average heat collection efficiency at 47.4% [9]. Above research shows that the vacuum tube with inserted tubes designed on the basis of all glass vacuum tube has the characteristics of easy processing and low cost. Therefore, in this paper, a vacuum tube with inserted tubes solar water collector is designed, and the influence of heat transfer characteristics in different hot water storage control temperature the system is studied.

2. Structure and heat transfer mechanism of vacuum tube solar with inserted tubes collector

The vacuum tube with inserted tubes collector is the core device for solar thermal conversion and transfer. It is composed of interpolating snake-shape copper tube, bracket and thermal insulation cover on the basis of all-glass vacuum tube. The structural sectional view is shown in figure 1.

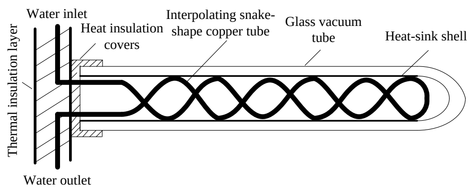

Figure 1. Structure chart of vacuum tube with tubes collector.

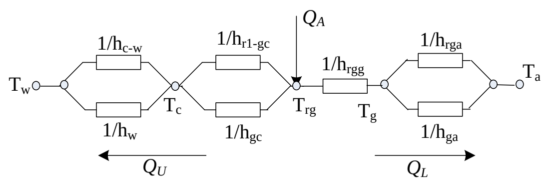

Figure 2. Thermal network diagram of inserted vacuum tube with inserted tubes collector.

In the vacuum tube with inserted tubes collector, the tube heat-sink shell of the glass vacuum tube absorbs the solar radiation energy and transfers it into heat energy. Then, the majority of the heat energy heats the fluid (water) in the copper tube via heat convection and radiation, while a small part passes through the thermal insulation cover on vacuum tube port and outer wall of the vacuum tube, radiating heat to the environment via radiation and convection. In accordance with the law of energy balance, when the solar collector is in the quasi-steady state, useful thermal energy equals to solar radiation absorbed by the collector tube minus heat dissipation of vacuum tube to the environment, as shown in formula (1). The thermal network diagram is shown in figure 2. In figure 2, T_a is the ambient temperature, T_g is the outer glass temperature of the vacuum tube, T_{rg} is the glass temperature of inner tube, T_c is the copper tube temperature, and T_w is the water temperature in the copper tube.

$$Q_u = Q_A - Q_L \tag{1}$$

In the above formula, Q_A is the solar energy absorbed by the vacuum tube per unit time, Q_L is the heat loss of the vacuum tube per unit time, and Q_u is useful thermal energy.

According to structural characteristics of the vacuum tube with inserted tubes collector and heat transfer-related theory [10], the useful thermal energy (unit in W) of a single vacuum tube with inserted tubes collector can be expressed as formula (2)

$$Q_u = D_{ro} L E(\tau\alpha)_e - \frac{A_{rg}(T_{rg}-T_a)\sigma(T_{rg}+T_g)(T_{rg}^{\ 2}+T_g^{\ 2})\left(h_{rga}+\varepsilon_g\sigma(T_{rg}+T_g)(T_{rg}^{\ 2}+T_g^{\ 2})\right)}{\left(\frac{1}{\varepsilon_{rg}}+\frac{A_{rg}}{A_g}(\frac{1}{\varepsilon_g}-1)\right)\left(h_{rga}+\varepsilon_g\sigma(T_{rg}+T_g)(T_{rg}^{\ 2}+T_g^{\ 2})\right)+\left(\sigma(T_{rg}+T_g)(T_{rg}^{\ 2}+T_g^{\ 2})\right)} \tag{2}$$

In the above formula, D_{ro} is the inner tube diameter of the vacuum tube, L is the effective length of the vacuum tube, E is the solar irradiance, $(\tau a)_e$ is the effective product of the transmittance ratio of the outer tube of the vacuum tube and the absorption ratio of the inner tube absorption layer, ε_{rg} is inner tube radiation coefficient of the vacuum tube, A_{rg} is the inner tube area of the vacuum tube, A_g is the surface area of the outer tube of the vacuum tube, ε_g is the surface radiation coefficient of the outer tube of the vacuum tube, h_{rga} is the heat transfer coefficient between the inner and outer tubes, σ is the blackbody radiation coefficient, 5.67×10^{-8} (W/(m^2·K^4).

In addition, according to the relationship between water absorption heat (unit w) and temperature

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variation, the relationship between the system hot water temperature and useful thermal energy can be expressed as formula (3).

$$t_l = \frac{\int_0^T Q_u dt}{mC} + t_i \tag{3}$$

According to formulas (2) and (3), the temperature characteristics of the output hot water of the vacuum tube with inserted tubes solar system under different working conditions are analyzed based on the design parameters shown in table 1. The analysis is shown in figure 3.

Table 1. Structural parameters table of vacuum tube with inserted tubes.

parameter name	Parameter value	parameter name	Parameter value
Inner tube radiation coefficient of the vacuum tube ε_{rg}	0.09	inner tube temperature of the vacuum tube T_{rg}	65℃
Outer tube radiation coefficient of the vacuum tube ε_g	0.88	Outer tube temperature of the vacuum tube T_g	35℃
Inner tube area of the vacuum tube A_{rg}	0.27 m^2	Outer tube area of the vacuum tube A_g	0.32 m^2
Effective product of the transmittance ratio of the outer tube of the vacuum tube and the absorption ratio of the inner tube absorption layer $(\tau\alpha)_e$	0.82	ambient temperature T_a	25℃
		blackbody radiation coefficient σ	5.67×10^{-8} W/ /($m^2\cdot K^4$)
Initial water temperature t_i	25℃	Water mass m	1.2 kg
solar irradiance E	800 W/m^2	Effective sunlight area of the vacuum tube $D_{ro}L$	0.097m^2
Number of vacuum tube in series N	14	Distance between tubes	60 mm

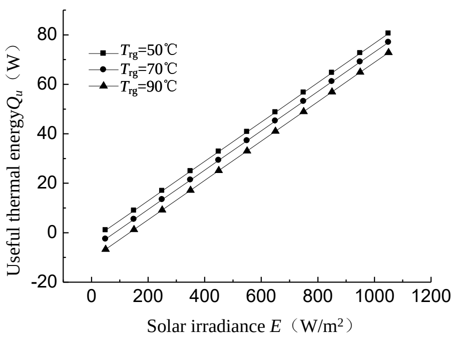

Figure 3.(a) Useful thermal energy

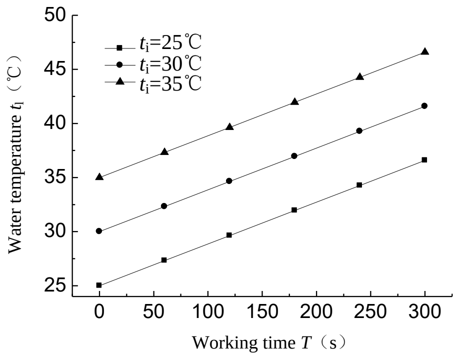

Figure 3.(b) Water temperature

Figure 3. Thermal characteristics of the vacuum tube with inserted tubes collector system (N = 14).

As can be seen from figure 3, for solar water heater using the vacuum tube with inserted tubes, the vacuum tube operating temperature directly affects thermal performance of the system. Taking into account the relationship between hot water temperature of the interpolating tube and operation of the vacuum tube, the analysis result is that the system hot water storage temperature provides theoretical support for influence of system thermal characteristics. Therefore, in the design of vacuum tube with inserted tubes heating system, the optimization design of hot water storage control mode is strengthened, and the influence of hot water control system and its hot water storage temperature on thermal characteristics of the system is studied for different hot water storage temperature.

3. Design and control principle of hot water storage controller

The vacuum tube with inserted tubes solar water heater control system is designed based on single chip AT89C2051. Using hysteresis control algorithm (shown in figure 4(a)), the solenoid valve controls the collector output hot water temperature in a specified set range (such as: 45℃-60℃), as shown in figure 4 (b). The control system consists of hardware and software.

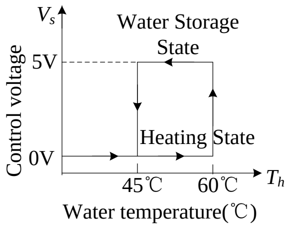

Figure 4. (a) Hysteresis control principle

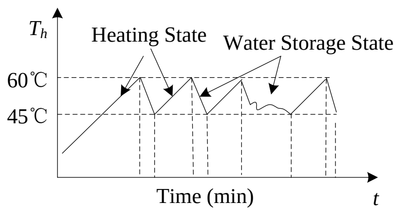

Figure 4. (b) Schematic diagram of system outlet temperature variation

Figure 4. Schematic diagram of hot water storage control process.

3.1. Hardware system design

The hardware system includes: temperature sensor (PT100), ADC0809, single chip AT89C2051 and its peripheral drive circuit. The control system hardware composition is shown in figure 5.

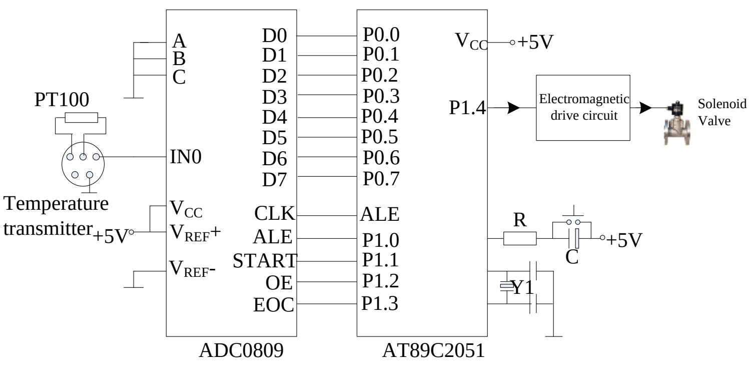

Figure 5. Constitutional diagram of hot water storage control system.

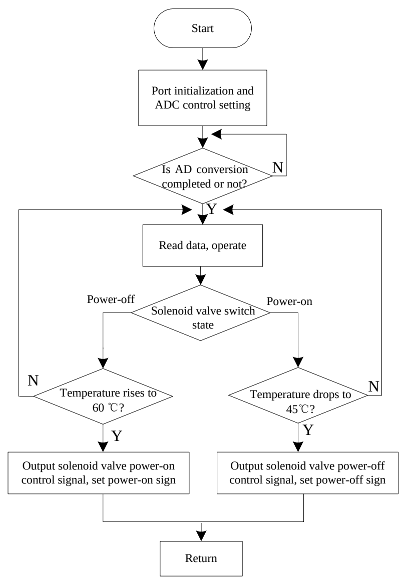

Figure 6. Main program flow chart.

In figure 5, the temperature sensor PT100 is arranged inside the output end of the interpolating copper tube for measuring water temperature. The temperature transmitter is used to convert the

PT100 resistance variation with the water temperature to voltage change information (1-5 V); ADC0809 is used to convert hot water temperature variation information output by temperature transmitter into 8-digit signal; single chip AT89C2051 serves as the core of the control system, which collects hot water temperature information, calculates and outputs solenoid valve power- on/off control signal under the control of the software system.

3.2. Software system design

On the basis of hardware design, the software flow chart is designed as shown in figure 6 for system control function. It consists of system initialization, AD conversion control and hot water storage control. Wherein, there are three states in hot water storage control process including: temperature control initial state, temperature rise holding state and storage control state.

Temperature control initial state: when the system begins operation or water temperature in the copper tube does not reach the minimum control temperature (45℃), the hot water storage controller operates in the temperature control initial state, solenoid valve power-off state flag bit is "1", solenoid valve is in power-off state, the vacuum tube heats the water, and the water temperature gradually rises.

Temperature rise holding state: When the hot water temperature in the outlet pipe reaches the minimum temperature (45°C) and power-off state flag bit of the solenoid valve in the hot water storage controller is "1", the hot water storage controller operates in temperature rise holding state, the solenoid valve is in power-off state, water temperature in the copper tube gradually rises. When the hot water temperature reaches the maximum control temperature (60°C), the temperature rise holding state ends, the hot water storage controller enters storage control state. Meanwhile, the solenoid valve power-off state flag bit is “0" and the solenoid valve power-on state flag bit is "1".

Storage control state: when the hot water temperature reaches the maximum control temperature (60℃), the hot water storage controller operates in the storage control state, the controller outputs solenoid valve power-on (high level) drive signal, hot water is stored in the incubator. Meanwhile, water temperature gradually decreases. When the water temperature lowers to 45℃, the hot water storage controller outputs solenoid valve power-off (high level) drive signal, hot water storage ends, the solenoid valve power-on state flag bit is “0", solenoid valve power-off state flag bit is “1", and the hot water storage controller operates in temperature rise state. In the case of solar illumination, the hot water storage controller circulates between temperature rise holding and storage control states, as shown in figure 4(b).

4. Experiment and analysis

A solar water heater prototype with collector array consisting of 14 vacuum tube with inserted tubes is designed. The distance between the two vacuum tubes is 60 mm in the collector array, and the prototype photo is shown in figure 7.

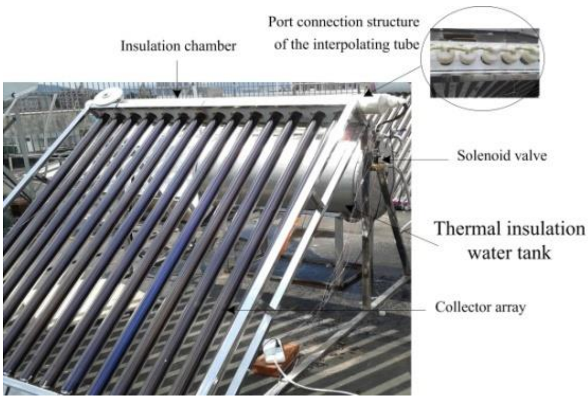

Figure 7. Photo of vacuum tube with inserted tubes solar water heater.

Set the temperature controller on April 14, 15, 19, 2017. The prototype outlet temperature was respectively controlled within the ranges of 40-45°C, 50-55°C and 60-65°C, and thermal characteristics of vacuum tube with inserted tubes solar heating system were tested experimentally. The test system consists of Altay multi-channel data acquisition system, TB-2 solar radiation general table, temperature transmitter and temperature sensor PT100, etc. The outlet flow rate is 17 ml/s during water storage. The test contents include: inlet water temperature of the vacuum tube array, internal temperature of the vacuum tube, outlet hot water temperature of the collector array, ambient temperature and solar irradiance, as shown in figures 8-10.

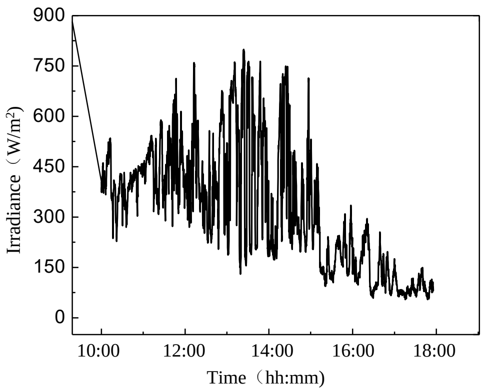

Figure 8. (a) Solar irradiance

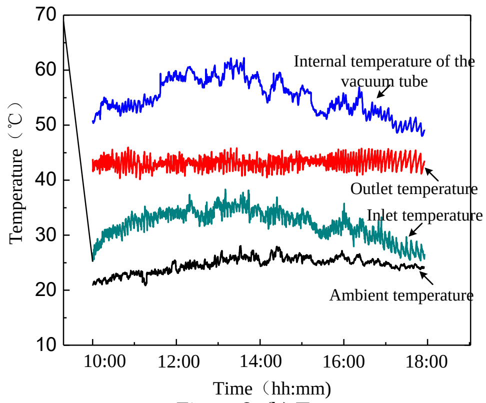

Figure 8. (b) Temperature

Figure 8. Thermal characteristics of the vacuum tube with inserted tubes solar collector system (outlet temperature 40-45℃, 2017.4.14).

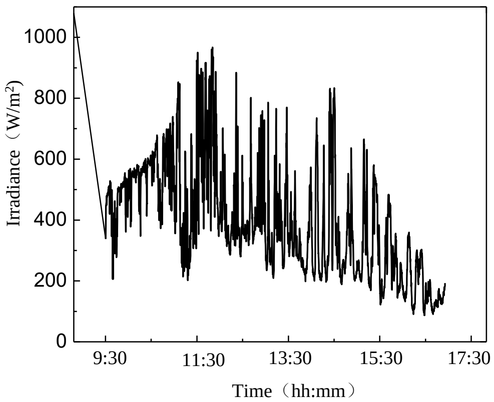

Figure 9 (a) Solar irradiance

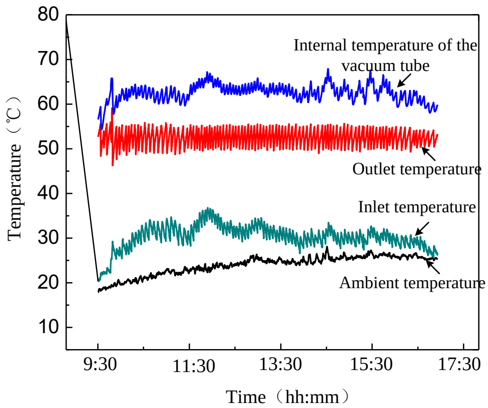

Figure 9. (b) Temperature

Figure 9. Thermal characteristics of the vacuum tube with inserted tubes solar collector system (outlet temperature 50-55℃, 2017.4.15).

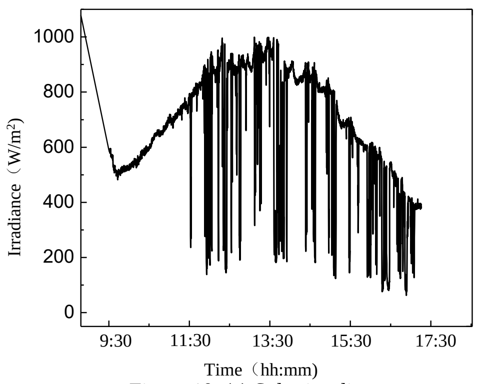

Figure 10 (a) Solar irradiance

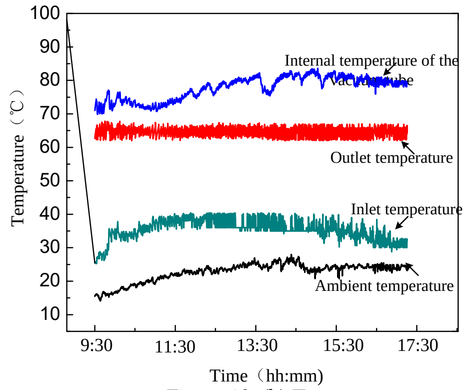

Figure 10. (b) Temperature

Figure 10. Thermal characteristics of the vacuum tube with inserted tubes solar collector system (outlet temperature 60-65℃, 2017.4.19).

During the test, the solar radiation amount (unit, J) of the collector array is obtained by averaging the solar irradiance. The expression is as shown in formula (4):

$$Q_u = \int_{t_0}^{t_l} A \cdot E dt \tag{4}$$

Where, A is the total area of the collector array, and E is the solar irradiance (unit, W / m^2).

At the same time, the available energy generated by system is calculated by the output hot water and expressed in formula (5):

$$Q_u = C \cdot m \cdot \Delta T \tag{5}$$

In the above formula, C is the specific heat capacity of water, m is the mass of output hot water, and ΔT is the difference between the outlet and inlet temperature.

According to the test results, the thermal characteristics of the prototype under three temperature conditions were statistically analyzed. The results are shown in table 2.

Table 2. Statistics table of prototype thermal characteristics under different outlet temperature.

Outlet temperature	Measurement time(t)	Difference outlet and inlet temperature(℃)	Output (kg)	Irradiation (J)	Thermal output (J)	Daily efficiency
40℃-45℃	10:00-18:00	11.93	224.00	17449641	11223744	64%
50℃-55℃	9:30-17:30	23.68	105.55	21147439	10497580	50%
60℃-65℃	9:30-17:30	28.78	130.00	34625989	15773940	46%

As can be seen from the statistical results, prototype thermal efficiency is related to the outlet hot water temperature. The system thermal efficiency reduces as the outlet temperature rises. The main reason is increase of the working temperature and heat loss after outlet temperature rise. In addition, the system hot water output during the test concerns weather conditions such as system operating temperature, solar irradiance. Therefore, based on users' different requirements for output hot water temperature, the system operation can be optimized by adjusting the hot water storage temperature.

5. Conclusions

The designed vacuum tube with inserted tubes solar collector, being ordinary all glass vacuum tube - based, has the characteristics of simple structure, low cost. According to the working principle of vacuum tube with inserted tubes solar water heater, the hot water storage control subsystem (hardware and software) with hysteresis comparison algorithm is designed. For the solar heating system prototype composed of 14 vacuum tubes with inserted tubes, the daily thermal efficiency of the prototype is 64%, 50% and 46% respectively under the output hot water temperature of 40-45℃, 50-55℃ and 60-65℃. The experimental results show that the prototype thermal efficiency is greatly affected by system outlet hot water temperature. The system thermal efficiency lowers as the outlet temperature rises, which is basically consistent with the theoretical analysis. The results will provide experimental support for reasonable optimization of working temperature of vacuum tube with inserted tubes heater. In the meantime, statistics result of the hot water amount output by the prototype during the test shows good practicability of vacuum tube with inserted tubes solar heating system which has simplified installation requirements and simpler usage due to the separation of thermal insulation water tank and the collector.

Acknowledgments
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