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# Air-Type Vacuum-Tube Solar Collector Design and Heat Collection Performance Test

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**Abstract:** With the continuous development and utilization of clean energy, the thermal utilization of solar energy is an important research direction. In view of the problems of the low utilization rate of solar heat in alpine regions of solar energy, an air-type vacuum-tube solar collector (AVSC) with air as the heat-exchange medium was designed. The vacuum tube of the solar heat collector adopted a double-pass spiral direct-current structure, and the vacuum tube had a built-in heat-storage rod. In order to test the heat collection performance of the designed air evacuated-tube solar collector, a heat collection performance test of the collector was conducted. The results showed that the average heat collection efficiency of the vacuum tube solar collector without phase-change heat-storage rods was 38%. The evacuated-tube solar collector using water as the heat transfer medium had an average heat collection efficiency of 58%. The average equivalent heat collection efficiency of the AVSC with a built-in phase-change heat-storage rod was 61%.

**Keywords:** solar collector; phase-change heat storage; heat-storage rod; ammonium aluminum sulfate dodecahydrate/stearic acid composite material; hot-water storage tank



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## 1. Introduction

In China, central solar heating accounts for 5% of clean energy heating, and the national solar heating area has reached 6.73 million square meters [1]. The development of solar thermal utilization technology has received extensive attention. The key piece of equipment in the utilization of solar heat is the solar collector, and a considerable amount of research on solar collectors has been conducted, including the geometric structural optimization of the collector [2], the combination of heat pipes and phase-change materials [3], and the optimization of a heat-exchange fluid [4]. At present, in the field of solar thermal utilization, the generally used solar collector is the evacuated-tube solar collector. Water is used as the heat-exchange medium, and the outdoor temperature is low in cold northern areas. Adding a certain amount of antifreeze cannot effectively solve the freezing problem of the heat-exchange medium. An auxiliary heat source needs to be added for heat preservation treatment, and liquid leakage is prone to occur, which restricts the use of solar energy.

In order to improve the solar collector efficiency, Owens of Illinois developed an all-glass evacuated-tube solar collector (ETSC) in 1976 [5]. Due to the low price and easy processing of all-glass evacuated-tube collectors, its market share is as high as 93%, and it has developed into the most widely used solar collector [6], which is used in applications including food drying, seawater desalination, heating systems, and solar auxiliary heat-pump systems. However, the thermal efficiencies of evacuated-tube solar collectors in practical engineering applications still need to be further improved, and the working time still needs to be extended. In recent years, researchers have combined the application of phase-change heat-storage materials with vacuum tube solar collectors [7], which can effectively solve the problems of instability and periodicity in solar energy utilization and improve the efficiency of solar collectors. Phase-change thermal-storage materials (PCMs) are used to store the excess heat energy collected by the collector and release it when needed, which can achieve the effect of peak shaving and valley filling [8]. The latent heat characteristics of a phase-change material can also solve the problem of the low specific heat capacity of the heat-exchange fluid of the air-type heat collector, reduce the temperature fluctuations in the vacuum tube, and extend the heating time of the heat collector [9]. Thermal storage evacuated tube solar collector composed of a solar evacuated tube, phase change material, and thermal insulation cover was designed. The solar energy conversion efficiency of the collector vacuum tubes in parallel and series parallel was tested, and the results showed that the conversion efficiency reached 56.9% and 48.46%, respectively [10]. Qu et al. [11] studied the energy-saving effect of installing a double-tank latent heat-storage system in the traditional solar auxiliary heat-pump system. The results showed that by using $Na_2SO_4 \cdot 10H_2O$ as the PCM, the heat collection efficiency increased by 50%. In order to improve solar thermal evaporators, compared with traditional evaporators, In contrast to traditional evaporators, solar radiation accounts for approximately 36% of the thermal performance of solar thermal evaporators [12]. Therefore, the research on solar thermal evaporators is crucial to improving their performance. Kaygusuz [13] proposed a method to calculate the area of the solar heat-pump collector evaporator based on a solar-assisted heat-pump experiment. The results showed that the area of the collector evaporator had little effect on the coefficient of performance (COP) of the heat pump. Georgiev [14] tested the performances of solar collectors as the heat source of the heat-pump system. The results showed that the temperature of the condenser fluid, the mass flow rate of the fluid passing through the condenser, the evaporator fluid, and the temperature of the evaporator fluid had an effect on the heat pump COP and the efficiency of the collector. In heat-pipe solar-collector evaporators, early research showed that the heat-pipe solar collector saved energy [15]. The use of heat-pipe solar collectors could improve the performance of direct-expansion solar heat-pump system water heaters [16]. The system adopted heat-pump mode when the solar radiation was low and heat-pipe mode when the sun intensity was high. The system COP in hybrid mode could reach 3.32, while the COP of conventional heat-pump mode was only 2.58.

In summary, the researchers' research on solar collectors has focused on changing the collector geometry, adding nanoparticles to enhance heat transfer, and combining phase change materials, and have achieved certain results. However, few studies have been conducted to solve the problem of the low efficiency of solar collectors when used in alpine regions. There are also few studies to solve the problems of poor heat storage performance and instability of phase change materials matching solar thermal utilization.

In this study, we designed an air-type evacuated-tube solar collector with air as the heat-exchange medium and conducted an experimental analysis of the collector's heat collection performance. The advantages of air include no freezing blocking problem in cold areas, small damping in the flow process, and being suitable for solar collectors with phase change heat storage rods. The disadvantages include small specific heat capacity and low heat exchange efficiency. A heat-storage rod was set in the vacuum tube of the heat collector, and the heat-storage rod was filled with phase-change material. The phase-change material was an ammonium aluminum sulfate dodecahydrate/stearic acid (AASD/SA) composite material [17]. The vacuum tube had a double-pass spiral direct-current (DC) structure, which could ensure the smooth circulation of the air heat-exchange medium, and the spiral structure at the end of the vacuum tube could buffer the stress. In order to study the heat collection performance of the heat collector, the heat collector was connected to a hot-water storage tank, and the heat collection efficiency of the heat collector was measured by testing the heat input from the heat collector to the hot-water storage tank for a period of time.

## 2. Design of Air-Type Vacuum-Tube Solar Collector (AVSC)

Aiming at the problems in the use of evacuated-tube solar collectors, an air-type solar collector using air as the heat-exchange medium was designed. The vacuum tube of the solar collector adopted a double-pass spiral DC structure. One end of the double-pass spiral DC vacuum tube had a wide mouth, which was an air inlet, and the other end was a thin-caliber glass tube with a spiral structure. The structure could realize the inflow and outflow of the heat-exchange medium (air), and the spiral structure could play a role in buffering the stress. The heat-exchange medium entered the air-inlet header of the vacuum-tube solar collector from one end of the vacuum tube and flowed into the air outlet header of the vacuum tube solar collector from the other end. Since the specific heat capacity of air in the standard state was only a quarter of that of water, the heat-exchange efficiency was poor. Therefore, a phase-change heat-storage rod was arranged in the double-pass spiral vacuum tube, and the phase-change heat-storage rod was filled with a composite phase-change heat-storage material to store heat and increase the utilization rate of solar energy. The schematic diagram of the structure of the AVSC is shown in Figure 1, and the parameters are shown in Table 1.

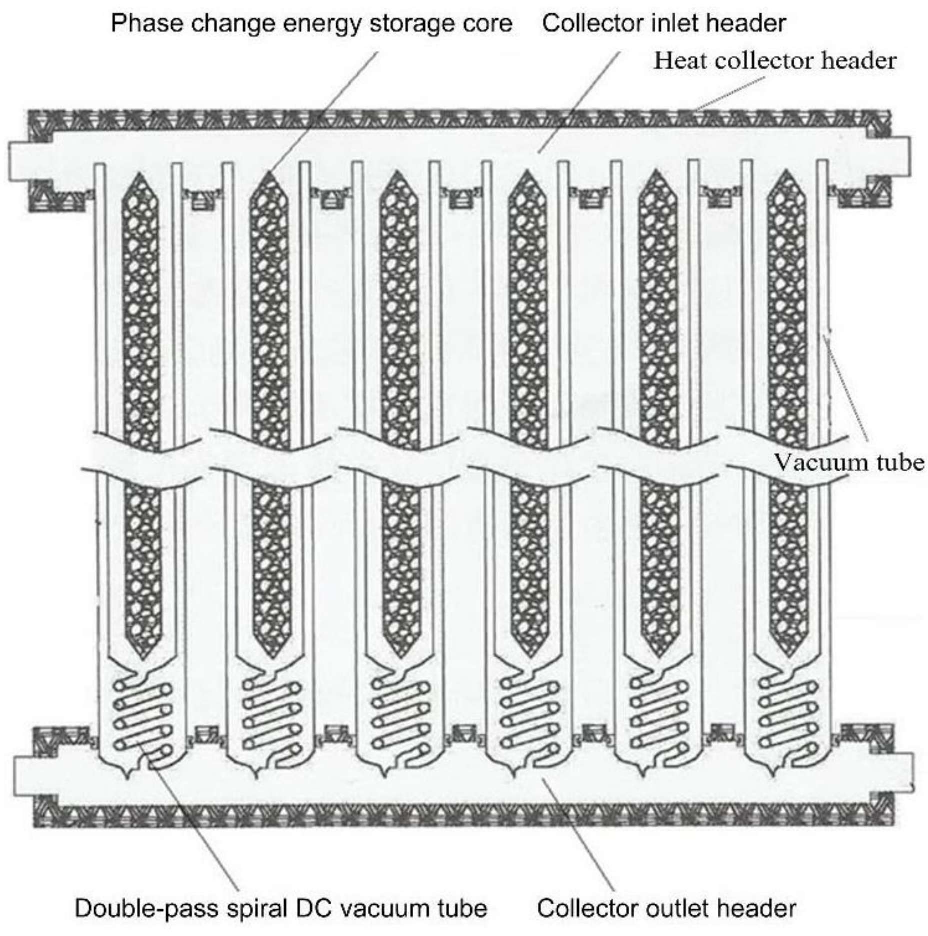


**Figure 1.** Schematic diagram of solar air collector.

**Table 1.** Solar air collector parameters.

| Numbering | Name | Parameter |
|---|---|---|
| 1 | Vacuum tube length | 1800 mm |
| 2 | Outside diameter of vacuum tube | 58 mm |
| 3 | Air inlet diameter of vacuum tube | 44 mm |
| 4 | Outlet diameter of vacuum tube | 10 mm |
| 5 | Collection area of AVSC | 4 m2 |
| 6 | Coating material | Solar absorption rate ≥ 0.89; reflectivity ≤ 0.08 (in standard conditions: 353 K ± 5 K) |

The schematic diagram of the structure of the phase-change heat-storage rod in the solar heat collection vacuum tube is shown in Figure 2. The phase-change heat-storage rod was composed of an externally sealed aluminum tube and a phase-change material. The aluminum tube had good plasticity and high thermal conductivity. The heat-storage material not only absorbed solar heat but also reduced the temperature fluctuations in the solar collector. The length of the phase-change heat-storage rod was determined based on the length of the vacuum tube, supported by a stainless-steel spring. Part of the heat obtained by the air-type vacuum-tube solar collector in a certain period of time was taken away by the air heat-exchange medium, and the other part was stored in the phase-change heat-storage rod. Based on the heat balance, the radius of the heat-storage rod was determined. The heat balance equation is as follows:

$$SJ_T\eta(1-\eta_s)t = Cm_1\Delta T_1 + \rho_{pcm}\rho_m L_m \pi r_m^2 \quad (1)$$

where $S$ is the collection area of the solar collector in m$^2$, $J_T$ is the average daily solar radiation on the solar collector in 15 MJ/m$^2$, $t$ is the testing time in h, $\eta$ is the solar collector heat collection efficiency in %, $\eta_s$ is the loss rate of the solar collectors (15% was selected based on experience), $\rho_m$ is the phase-change material density in kg/m$^3$, $\rho_{pcm}$ is the phase-change heat-storage density in kJ/kg, $L_m$ is the phase-change heat-storage rod length in m, $r_m$ is the radius of the phase-change heat-storage rod in $m$, $C$ is the specific heat capacity of air at constant pressure in kJ/(kg·K), $\Delta T_1$ is the temperature difference between the inlet and outlet of the collector in K, and $m_1$ is the quality of the air flowing through the vacuum tube in kg. The parameters of the phase-change heat-storage rod obtained by the design calculation are shown in Table 2.

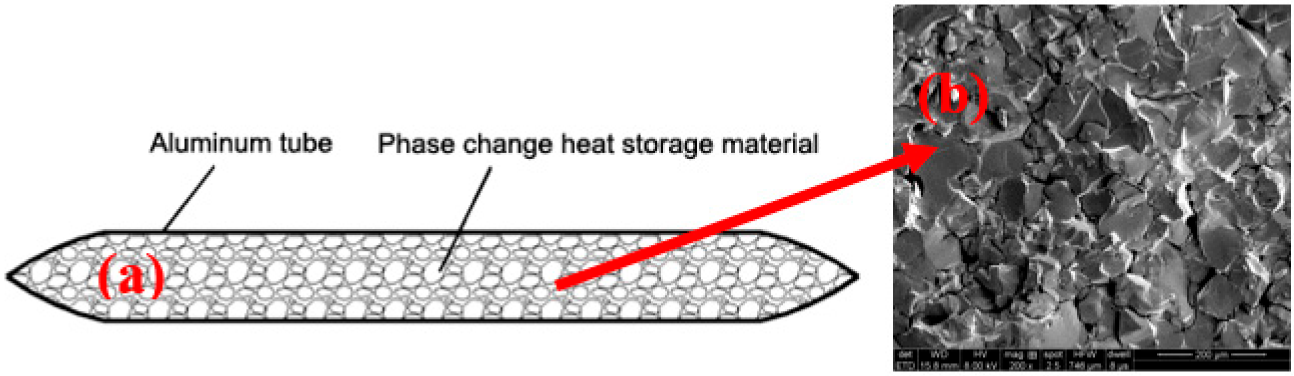


**Figure 2.** (**a**) Schematic diagram of phase-change energy-storage rod. (**b**) The SEM images of AASD/SA composite material.

**Table 2.** Phase-change energy-storage rod parameters.

| Numbering | Name | Parameter |
|---|---|---|
| 1 | Length of heat-storage rod | 1650 mm |
| 2 | Outer diameter of heat-storage rod | 35 mm |
| 3 | Weight of single heat-storage rod | 1.6 kg |

The composite phase-change heat-storage material filled in the heat-storage rod was an ammonium aluminum sulfate dodecahydrate/stearic acid composite material. The mass percentages of ammonium aluminum sulfate dodecahydrate, stearic acid, $CaF_2$, and deionized water were 92.2%, 5%, 1.8%, and 1%, respectively [17]. The composite phase-change heat-storage material had good heat transfer characteristics. The subcooling degree was 10 K, the phase-change latent-heat value was 246 kJ/kg, and the phase-change temperature was 358 K. It could better match the utilization of solar heat and the utilization of trough electric heat. Figure 3 shows the differential scanning calorimetry (DSC) curve of the AASD/SA composite material.

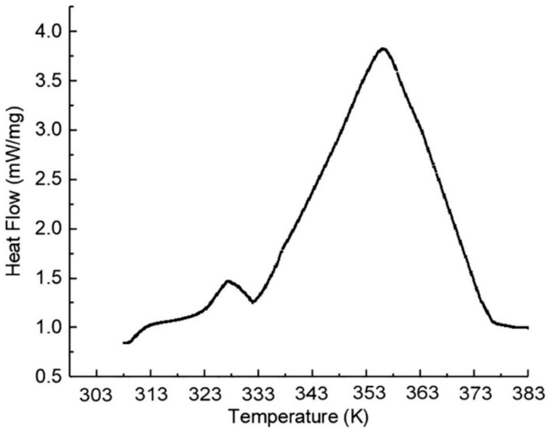


**Figure 3.** Differential scanning calorimetry (DSC) results of the ammonium aluminum sulfate dodecahydrate/stearic acid (AASD/SA) composite material.

## 3. Heat Collection Performance Test of AVSC

In order to test the designed AVSC heat-collection performance, the heat collector was tested in Suqian City, Jiangsu Province (33.96° N) (The solar radiation intensity is 3780–5040 MJ/$m^2$). The installation inclination angle of the solar collector was 45° [18], the test date was 4 May 2018, and the weather was good. The test procedure followed the GB/T 4271-2007 solar collector thermal performance test method and the GB/T 26975-2011 all-glass heat-pipe vacuum solar collector tube standard. Figure 4 shows a schematic diagram of the performance test of an AVSC. The heat collected by the air-type solar collector was transported to the water tank through a fan for heat exchange. The heat collection of the air-type solar collector was determined by heating water and measuring the temperature increase.

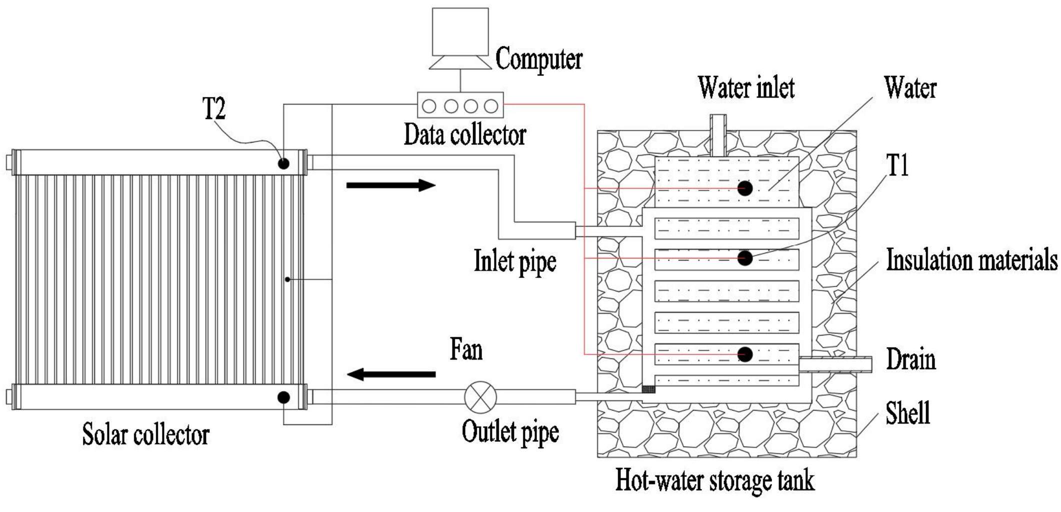


**Figure 4.** Schematic diagram of performance test of solar air collector.

The test was divided into two parts: an environmental, meteorological parameter test and a collector performance test. The measured environmental and meteorological parameters mainly included the outdoor ambient temperature and the solar radiation intensity. The amount of solar radiation involved in this study was measured by a solar radiometer. The collector test parameters mainly included the temperature, the air volume of the inlet and outlet air of the collector, and the change in the water temperature at the center of the hot-water storage tank. The main test equipment is shown in Table 3.

**Table 3.** Summary of test equipment.

| Equipment Name | Measurement Parameters | Accuracy |
|---|---|---|
| Thermal resistance Pt100 | Temperature | ±0.2 K |
| Radiometer TBQ-2 | Radiation intensity | 11.009 μV/W·m$^{-2}$ |
| Data collector Agilent 34970A | Temperature data | Frequency 30 s |
| Intelligent electromagnetic flowmeter FEM-32SM | Flow | |

The volume of the hot-water storage tank was 300 L. The tank was filled with water at a temperature of 298 K, and a set of four AVSCs were installed outdoors in parallel. When the temperature sensor T2 placed in the air-type solar heat collector showed that the temperature reached the set temperature of 373 K (adjustable), the fan was started for heat exchange. When the heat-exchange temperature difference T2 − T1 < 10 K, the heat-exchange effect was poor, and the fan was turned off. The temperature value of the temperature sensor T1 in the water tank was recorded, and the total heat collection of the air-type solar collector was calculated as follows:

$$Q_J = (T_1 - 25)c_p m_0 \tag{2}$$

where is the total heat collection of the air-type solar collectors in kJ, $T_1$ is the temperature value displayed on T1 at the end of the experiment in K, $c_p$ is the specific heat capacity of water at constant pressure in J/(kg·K), and $m_0$ is the quality of water in the water tank.

The efficiency test of the air-type solar collector was determined by recording the inlet and outlet temperature values of the solar collector, and the instantaneous heat supply of the solar collector was calculated as follows:

$$Q = Cm\Delta T \tag{3}$$

where $Q$ is the instantaneous heat supply from the solar collectors in W, $C$ is the specific heat capacity of air at constant pressure in kJ/(kg·K) (selected as 1.022 kJ/(kg·K) based on the average temperature of the test air, 358 K), $m$ is the air mass flow in kg/s, and $\Delta T$ is the temperature difference between the inlet and outlet of the solar collector in K.

A group of four air-type solar collectors was selected, and the amount of instantaneous radiation collected by the solar collectors was calculated as follows:

$$Q_o = SI_o \tag{4}$$

where $Q_o$ is the instantaneous irradiance of the solar collector in W, and $I_o$ is the instantaneous irradiation intensity in W/m$^2$.

With the area of the solar collector as a reference, the heat collection efficiency of the solar collector was calculated as follows:

$$\eta = \frac{Q_J}{\sum Q_0} \tag{5}$$

$$\eta_p = \frac{Q}{Q_0} \tag{6}$$

$$\eta_m = \frac{\sum \eta}{h} \tag{7}$$

where $\eta_p$ is the instantaneous heat collection efficiency of the evacuated-tube solar collector in %, and $\eta_m$ is the average heat collection efficiency of the solar collector over time $h$ in %.

## 4. Results and Discussion

During the test, the data were recorded every 20 min. Figure 5 shows the curve of the internal and ambient temperature of the AVSC versus the intensity of the solar radiation. The solar radiation intensity reached the maximum value of 947 W/m$^2$ at 11:40 in the morning during the test, and the average radiation intensity was 727 W/m$^2$. The ambient temperature was less affected by the intensity of the solar radiation, fluctuating between 294.2 and 306.6 K. The initial temperature inside the AVSC was 305 K, and the maximum temperature of 437 K appeared in the afternoon at 13:40, which was 2 h from the time at which the maximum radiant intensity appeared. Because the phase-change heat-storage rod inside the AVSC absorbed part of the heat, it delayed the increase in the internal temperature of the solar collector. When the solar radiation intensity dropped rapidly, the phase-change heat-storage rod released heat, which slowed the drop in the internal temperature of the solar collector.

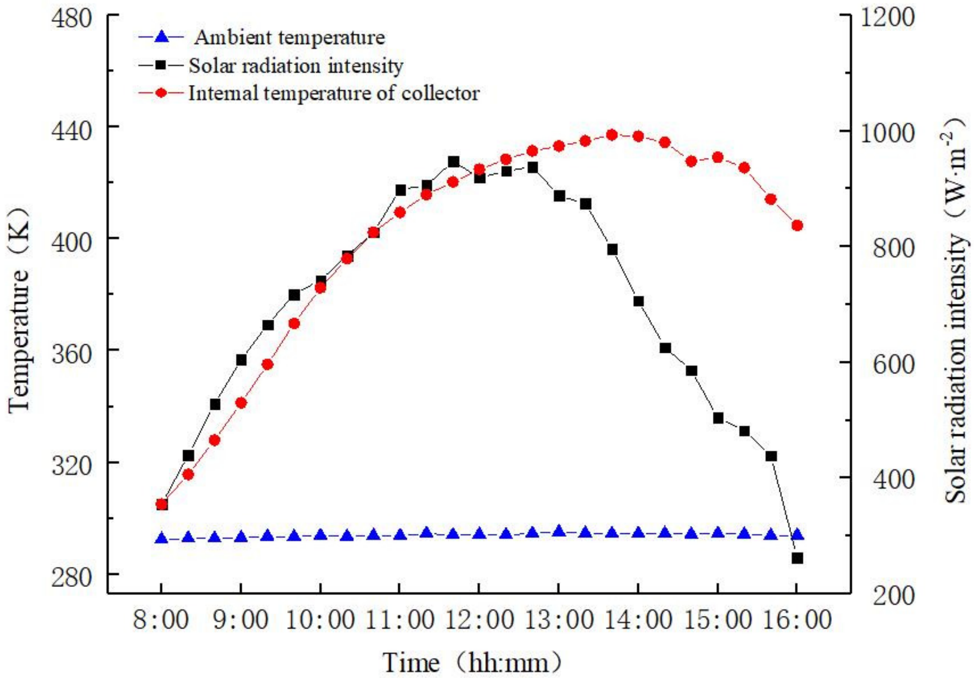


**Figure 5.** Variations of internal and ambient temperatures of air-type vacuum-tube solar collector (AVSC) with irradiation intensity.

Figure 6 shows the variations in the inlet and outlet air temperatures of the AVSC. The variation trend of the outlet temperature of the solar collector was similar to that of the internal temperature of the solar collector. The temperature rise rate of the outlet air temperature of the solar collector from 8:00 to 11:00 was greater than that from 11:00 to 14:00. This was due to the rapid increase in solar radiation intensity from 8:00 to 11:00, and the phase-change heat-storage rod absorbed less heat. After 14:00, the solar radiation intensity dropped rapidly, but the rate of decrease in the wind temperature at the outlet of the solar collector was slower than that from 8:00 to 11:00. This is when the phase-change material began to slowly release heat, maintaining a stable wind temperature at the outlet of the solar collector.

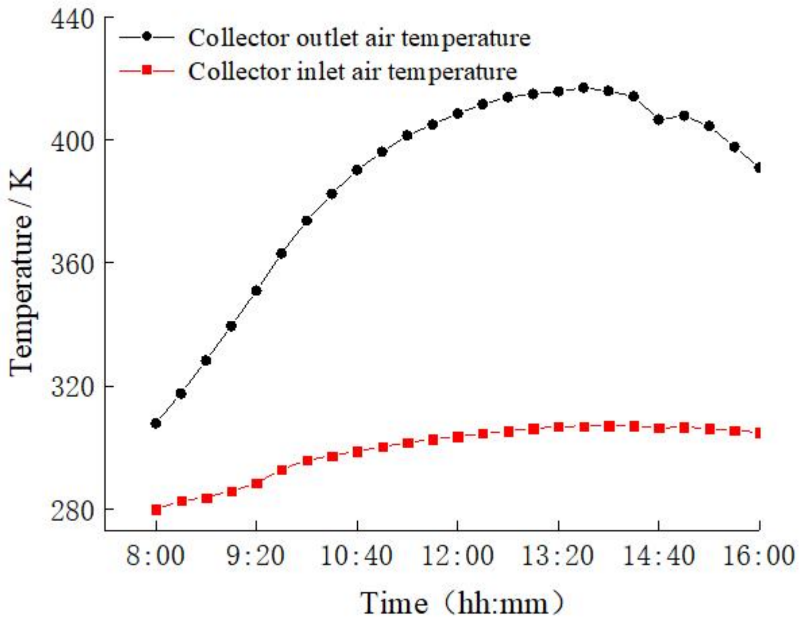


**Figure 6.** Change in inlet and outlet air temperatures of AVSC.

The heat collection efficiency variations in the AVSC are shown in Figure 7. The instantaneous heat collection efficiency of the vacuum tube solar collector without a phase-change heat-storage rod was 24–49% [19], and the average heat collection efficiency was 38%. The heat collection efficiency of the evacuated-tube solar collector using water as the heat-transfer medium was 53–63%, and the average heat collection efficiency was 58% [20]. The average equivalent heat collection efficiency of the AVSC with built-in phase-change heat-storage rods was 61%. Since there are certain fluctuations and errors in the test data of this experiment, some mutation values were removed, and the calculated value was calculated by the average value to reduce the data deviation caused by the measurement error.

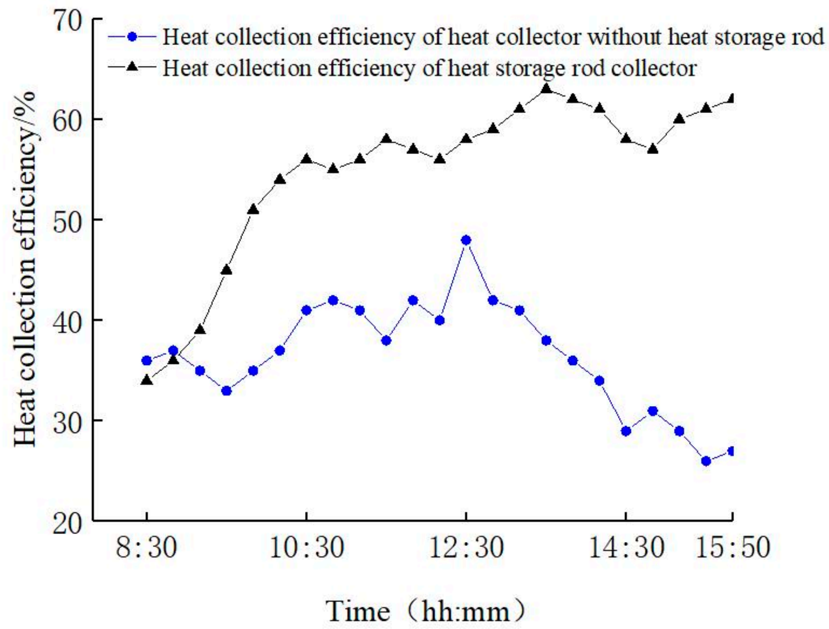


**Figure 7.** AVSC heat collection efficiency variations.

In the early morning, the intensity of solar radiation was low, and the phase-change heat-storage material needed to absorb heat. Therefore, the heat collection efficiency of the AVSC with built-in phase-change heat-storage rods before 8:42 was lower than that of the vacuum-tube solar collectors without phase-change heat-storage rods. From 9:00 to 10:40, due to the increase in the solar radiation intensity. The internal temperature of the collector increased rapidly, and the heat collection efficiency of the collector also increased rapidly. In addition, the heat collection efficiency of the AVSC with built-in phase-change heat-storage rods began to be higher than that of the vacuum-tube solar collectors without phase-change heat-storage rods, and the gap gradually widened.

## 5. Conclusions

In view of the shortcomings of the currently widely used vacuum-tube solar collectors, this article proposes a new air-type solar collector. Air was used as the heat-exchange medium to assist the phase-change heat-storage rods, and the heat collection performance of the collector was tested. The results showed the following:

(1) The AVSC used air as the heat-transfer medium. A phase-change heat-storage rod filled with the AASD/SA composite material was designed. The use of phase-change energy storage rods could reduce the effect of the poor heat exchange caused by the low thermal conductivity of the heat-exchange medium;

(2) The phase-change energy-storage materials could store excess solar heat, and the heating could be extended. The use of heat-storage rods could increase the effective utilization of solar energy;

(3) The average heat collection efficiency of the vacuum tube solar collector without phase-change heat-storage rods was 38%. The evacuated-tube solar collector with water as the heat-transfer medium had an average heat collection efficiency of 58% [20]. The average equivalent heat collection efficiency of the AVSC with built-in phase-change heat-storage rods was 61%;

(4) The designed AVSC had the same level of heat collection efficiency as that of the evacuated-tube collector using water as the medium. However, it could improve the reliability of the solar collector in cold areas and prevent the vacuum tube from freezing and cracking.

**Author Contributions:** C.Z.: Writing—Original Draft, Methodology; X.D. and Y.C.: Data Curation, Investigation; S.Y.: Supervision, Writing—Review & Editing; Q.L.: Software, Visualization. All authors have read and agreed to the published version of the manuscript.

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**Conflicts of Interest:** The authors declare no conflict of interest.

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