Study on convection improvement of standard vacuum tube

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Abstract. For the standard all-glass vacuum tube collector, enhancing the vacuum tube axial natural convection can improve its thermal efficiency. According to the study of the standard all-glass vacuum tube, three kinds of guide plates which can inhibit the radial convection and increase axial natural convection are designed, and theory model is established. Experiments were carried out on vacuum tubes with three types of baffles and standard vacuum tubes without the improvement. The results show that T-type guide plate is better than that of Y-type guide plate on restraining convection and increasing axial radial convection effect, Y type is better than that of flat plate type, all guide plates are better than no change; the thermal efficiency of the tube was 2.6% higher than that of the unmodified standard vacuum tube. The efficiency of the system in the experiment can be increased by 3.1%.

1. Introduction

Solar energy is the important content of the development and utilization of renewable energy and new energy [1]. Further study of solar photovoltaic and photothermal applications is of great significance for the effective collection, utilization, and storage of solar energy. In the solar energy application, standard all-glass vacuum tube collector has the advantages of lower heat loss coefficient and higher thermal efficiency [2]. Therefore, the research on the performance of all glass vacuum tubes has attracted much attention in solar thermal utilization. However, due to the complexity of the flow field in the vacuum tube, there are few studies on the flow field of the vacuum tube and the convection heat transfer of the internal fluid.

At present, the research on convection improvement of vacuum heat collecting tube is mainly based on the simulation with FLUENT software to study the flow field and convection heat transfer process in the tube. Then the simulation results are summarized and the factors affecting the convective heat transfer in the pipe are summarized.

The density difference in widely used vacuum tube is caused by the absorption of heat by the fluid in the pipe, which makes the fluid in the tube flow upper and lower reversely, and the hot water flow into the water tank along the axial direction of the pipe. But some of the hot water flows back before it reaches the top of the tube, the hot water flows back before it reaches the top of the tube, which can have disturbances or even eddy currents. In the process of hot and cold water circulation, there is no circulating water at the bottom of the pipe, forming a flowing stagnation zone, which has an adverse effect on convective heat transfer and reduces the efficiency of the collector.

According to the standard vacuum tube collector experimental study shows: In order to suppress the radial convection of the fluid in the vacuum tube, and to enhance axial convection to improve thermal efficiency of vacuum tubes, different shapes of baffles can be added into the vacuum tube to form a double-channel or even a multi-channel flow in the pipe. It can make the fluid ordered flow and stratification obvious, thus ameliorate the heat transfer of mixed cold and hot fluid, and improve its thermal efficiency.

2. Theoretical basis of convection heat transfer in vacuum heat collecting tube

2.1. The influence factors of vacuum tube collector efficiency

Wind direction, wind speed, optical power density, temperature, effective lighting area, the energy absorbed by the collector, convective heat transfer loss, flux, collector installation angle and its own performance and other parameters affect the efficiency of the collector. The paper studies the impact of vacuum tube heat transfer on heat efficiency.

The collector efficiency is defined as: Under steady-state conditions, the ratio of the energy output by the collector heat transfer material during the specified period to the area of the collector and the product of the solar irradiance incident on the collector at the same time [4].

$$\eta = \frac{\int Q_u dT}{A_c t \int G dt} \tag{1}$$

Take a small element dv in the vacuum tube, the temperature at the in element is:

$$T = T_1 + \frac{T_2 - T_1}{2} I \tag{2}$$

The energy absorbed by the element:

$$dQ = C\rho 2\pi r^2 (T_1 + \frac{T_2 - T_1}{2} I - T_0) dI \tag{3}$$

The heat absorbed by the whole tube is:

$$Q = \int_0^L C\rho 2\pi r^2 (T_1 + \frac{T_2 - T_1}{2} I - T_0) dI \tag{4}$$

In the above formulas, C—The specific heat capacity of the fluid J/(kg•k); ρ—The density of fluid kg/m^3; G—Solar irradiance J/m^2; A_C—Effective lighting area m^2; T_2— Nozzle temperature ℃; T_1—Tube bottom temperature ℃; T_0—Initial water temperature ℃; t—Time S. The lighting area of vacuum tube selected in this paper is 0.093 m^2.

2.2. Convection heat transfer in vacuum tube

2.2.1. Convection heat transfer principle. Heat convection refers to the exchange of heat caused by relative motion of fluids of different temperatures. When the solar radiation intensity reaches a certain value, the natural convection occurs due to the different temperature of the cold and hot water in the vacuum tube. The natural convection in the pipe includes axial convection and radial convection. The basic formula is as follows:

$$\phi = hA(t_w - t_f) \tag{5}$$

$$q = \phi A = h(t_w - t_f) \tag{6}$$

h—surface heat transfer coefficient W/(m^2•K)

2.2.2. Factors affected convection heat transfer of vacuum tube collector. The convective heat transfer of hot and cold fluid in vacuum tube has great influence on its thermal efficiency. The convective heat transfer of the internal fluid in the all-glass standard vacuum tube type collector is very complicated. The performance parameters of the vacuum tube, the installation angle, the stratification of the fluid temperature in the tank, the inlet and outlet temperature, the solar irradiance and other factors can have an impact on it. The analysis of the flow field in the tube has an important contribution to suppressing the radial convection of the fluid in the vacuum tube. The same also contribute to enhancing the axial convection, improving the convective heat transfer efficiency and improving the collector performance [4].

2.3. Convection heat transfer model and governing equations vacuum tube

2.3.1. Governing equation. Continuity equation (Derivation basis - conservation of mass): During the same time interval, the net mass of the inflow element is equal to the increment of the mass in the unit.

$$\frac{\partial \rho}{\partial t} + \frac{\partial(\rho u)}{\partial x} + \frac{\partial(\rho v)}{\partial y} + \frac{\partial(\rho \omega)}{\partial z} = 0 \tag{7}$$

Vector representation: $\partial \rho / \partial t + div(\rho v) = 0$ (8)

ρ—fluid density; t—time; u, v, ω—the components of the velocity vector in the x, y, z directions, respectively.

Momentum conservation equation: According to Newton's second law, combined with the actual situation of this paper, the fluid is Newton's fluid, get the momentum conservation equation:

X-direction:

$$\rho \ (\frac{\partial \rho}{\partial t} + \frac{\partial(\rho u)}{\partial x} + \frac{\partial(\rho v)}{\partial y} + \frac{\partial(\rho \omega)}{\partial z}) = -\frac{\partial p}{\partial x} + \mu \ (\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} + \frac{\partial^2 u}{\partial z^2}) + F_X \tag{9}$$

Y-direction:

$$\rho \ (\frac{\partial v}{\partial t} + \frac{\partial v}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial v}{\partial z}) = -\frac{\partial p}{\partial x} + \mu \ (\frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2} + \frac{\partial^2 v}{\partial z^2}) + Fy \tag{10}$$

Z-direction:

$$\rho \ (\frac{\partial \omega}{\partial t} + u\frac{\partial \omega}{\partial x} + v\frac{\partial \omega}{\partial y} + \omega\frac{\partial \omega}{\partial z}) = -\frac{\partial p}{\partial x} + \mu \ (\frac{\partial^2 \omega}{\partial x^2} + \frac{\partial^2 \omega}{\partial y^2} + \frac{\partial^2 \omega}{\partial z^2}) + Fz \tag{11}$$

Vector form:

$$\rho \frac{dv}{dt} = F - \nabla p + \mu \nabla 2V \tag{12}$$

In the above formulas, μ—dynamic viscosity; p—pressure on a fluid element; $\frac{\partial p}{\partial x}, \frac{\partial p}{\partial y}, \frac{\partial p}{\partial z}$ —pressure gradient term; F_x, F_y, F_z —volume force terms; $\rho\left(\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} + \omega\frac{\partial u}{\partial z}\right), \rho\left(\frac{\partial v}{\partial t} + u\frac{\partial v}{\partial x} + v\frac{\partial v}{\partial y} + \omega\frac{\partial v}{\partial z}\right), \rho\left(\frac{\partial \omega}{\partial t} + u\frac{\partial \omega}{\partial x} + v\frac{\partial \omega}{\partial y} + \omega\frac{\partial \omega}{\partial z}\right)$ —inertial force term; $\mu\left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} + \frac{\partial^2 u}{\partial z^2}\right), \mu\left(\frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2} + \frac{\partial^2 v}{\partial z^2}\right), \mu\left(\frac{\partial^2 \omega}{\partial x^2} + \frac{\partial^2 \omega}{\partial y^2} + \frac{\partial^2 \omega}{\partial z^2}\right)$ —viscous

force term.

Energy conservation equation: According to energy conservation equation, the increase of energy in the fluid microelement is the same as the net heat flux absorbed by the microelement plus the work done by physical force and surface force to infinitesimal bodies.

$$\frac{\partial t}{\partial \tau} + u\frac{\partial t}{\partial x} + v\frac{\partial t}{\partial y} + \omega\frac{\partial t}{\partial z}) = a \quad (\frac{\partial^2 t}{\partial x^2} + \frac{\partial^2 t}{\partial y^2} + \frac{\partial^2 t}{\partial z^2}) \tag{13}$$

$$\frac{dt}{d\tau} = a \cdot \nabla 2t \tag{14}$$

a—coefficient of temperature conductivity，a =λ/Cpφ.

2.3.2. Establishment of flow equation for single tube vacuum tube. In the vacuum tube to take an infinitesimal section dl, force analysis on dl. When DL flows in the pipe, it is affected by buoyancy, gravity, viscous force and the resistance along the tube wall [5]. Because the relative velocity of fluid flow in the pipe is not large, the viscous force can be neglected. Since the fluid is flowing at the microscopic conceptual, according to Newton's second law, it is known that the component of the buoyancy of dl along the tube axis is equal to the loss due to frictional resistance, and the flow of fluid can be solved mc [5]. Then:

$$F_\theta \sin\beta = \Delta P_f \tag{15}$$

ΔP_f—The resistance along a fluid flow.

$$\Delta P_f = \lambda L \rho U_c^2/(4r) \tag{16}$$

λ—Resistance coefficient.

The flow state of the fluid in the vacuum tube is treated as a laminar flow; the coefficient of resistance λ is expressed as:

$$\lambda = 64/R_e \tag{17}$$

$$\Delta P_f = 2\mu L \tag{18}$$

μ— Dynamic viscosity.

The buoyancy force along the pipe axis of the infinitesimal section is [5]:

$$dF_\theta = (\rho_c - p_w)g(dv)\sin\beta \tag{19}$$

p_w—thermal fluid density of the infinitesimal sections,kg/m^3; ρ_c—Cold fluid density of the infinitesimal sections, kg/m^3; g—acceleration of gravity, m/s^2; β—Collector installation angle.

The relationship between density difference ($\rho_c - p_w$) and temperature difference ($t_w - t_c$) is [5]:

$$(\rho_c - p_w) = \rho\gamma(t_w - t_c) \tag{20}$$

ρ— the average density of the fluid infinitesimal sections, kg/m^3;

γ— coefficient of thermal expansion, 1/k.

From the analysis of the energy conservation equation for a single vacuum tube, the heat absorbed by the fluid in the vacuum tube is $m_c c(t_w - t_c)$, which is equal to the radiant energy absorbed by the heat fluid section [5]: $I_{eff}(\tau\alpha)_\theta \pi r L\cos\theta$. The flow of the fluid $m_c c$ can be expressed as $\varepsilon\rho U_c\pi r^2$.

When the infinitesimal section is small enough, the half of the heat absorption of a vacuum tube can be regarded as a rectangle. The absorption of solar radiation energy is: ($2I_{eff} \cdot r \cdot dr$）

$(\tau\alpha)_\theta$—The effective product of the transmittance ratio and absorption ratio. This paper selected the vacuum tube for τ is 0.93, α is 0.96.

$$\cos\theta = sin\delta sin\phi\cos\beta - sin\delta\cos\phi\sin\beta\cos\gamma + \cos\delta\cos\phi\cos\beta\cos\omega \tag{21}$$

$$I_{eff}(\tau\alpha)_\theta \pi r L \cos\theta = m_c C_{pc}(tw-tc) = \varepsilon\rho U_c \pi r^2 C_{pc}(tw-tc) \qquad (22)$$

U_c—Natural convection velocity of hot fluid, m/s.

ε: The ratio of the hot fluid flow cross-section to the vacuum tube cross-sectional area in the vacuum tube

$\varepsilon=0.5$ and according to formula (22) have:

$$t_w - t_c = 2 I_{eff}(\tau\tau)_\theta L\cos\theta\cos_c r C_{pc} \qquad (23)$$

$$dF_\theta = 2\gamma g I_{eff}(\tau\alpha)_\theta L(dv)\cos\theta(in\beta/(U_c r C_{pc})) \qquad (24)$$

Formula (9) integral from 0 to L, the buoyancy of the internal heat in the vacuum tube is:

$$F_\theta = \int_0^L dF_\theta = \gamma g I_{eff}(\tau\alpha)_\theta \pi r L^2 \cos\theta os\theta\beta/(U_c C_{pc}) \qquad (25)$$

The natural convection velocity of the hot fluid can be obtained according to equation (15):

$$U_c = \sqrt{\gamma g I_{eff}(\tau\alpha)_\theta r L^2 \cos\theta\sin\beta/(2\mu C_{pc})} \qquad (26)$$

The mass flow rate of the hot fluid in the vacuum tube is:

$$m_c = 0.5\pi.5\rho\sqrt{\gamma g I_{eff}(\tau\alpha)_\theta r L^2 \cos\theta\sin\beta/(2\mu C_{pc})} \qquad (27)$$

3. Experimental operation

3.1. Laboratory apparatus
Four vacuum tubes numbered A, B, C, and D; Four 4.5L water tanks; 12 temperature probes, 12 temperature transmitters; An information acquisition card; Irradiation instrument; Some wires; Support; Computer; Each one of the flat plate, T type, and the Y type guide plate.

3.2. The experimental process
This paper mainly studies the convective improvement of standard vacuum tubes. Three kinds of deflector are installed in the tube; they are a flat plate, a T-plate, and a Y-plate. The width of the flat plate is equal to the diameter of the inner tube of the vacuum tube; T-plate width 38 mm and high 34 mm; Y-plate three sides and the vacuum tube radius equal. Three types of deflector thickness are 2 mm, length is 1600 mm; Vacuum tube length is 1800 mm, outside diameter of the glass tube is 58 mm, and the internal diameter is 47 mm. Single tube glass tube placed south, tilt angle 35°. In the experiment, it is assumed that the vacuum tube is uniformly heated without considering the influence of air parameters (wind speed, ambient temperature, etc.).

In a vacuum tube, because the heat loss caused by heat conduction is smaller than the radiant heat loss, and the vacuum tube collector with a deflector has little effect on the loss due to heat conduction. Therefore, heat conduction losses can be neglected.

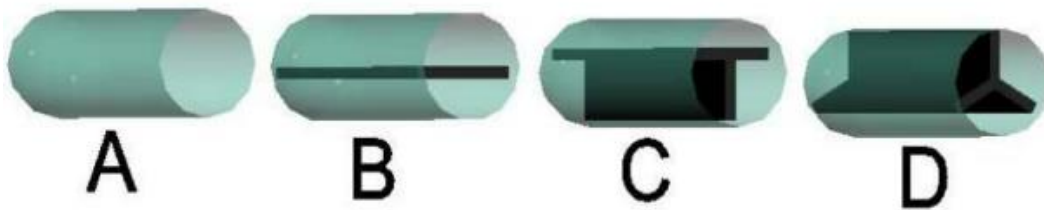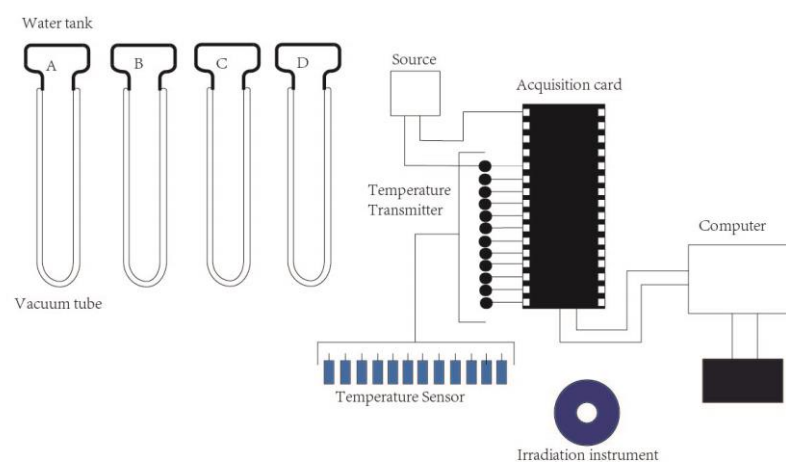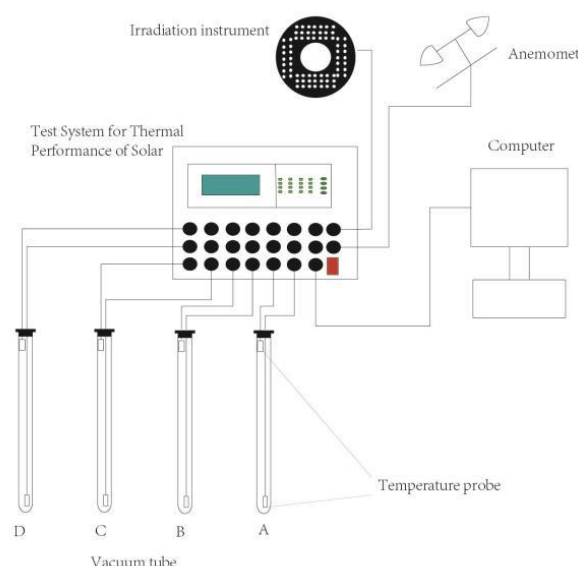The deflector provided in the vacuum tube is shown as figure 1:

Figure 1. Schematic diagram of the design of the baffle.

3.2.1. Major experimental content. As shown in figure 2, to build a solar energy test platform, the first system test, A, B, C, D four vacuum tube on the bracket, A tube without the baffle, B tube plus plate baffle, C tube plus T-type baffle, D tube plus Y-type baffle. And at the top of each vacuum tube and the bottom of the water tank put a temperature probe, numbered respectively A1, A2, A3; B1, B2, B3; C1, C2, C3; D1, D2, D3. Then connect the temperature probe to the temperature sensor, the temperature sensor and then connected to the information acquisition card, the information acquisition card connected to the computer, and finally began to test.

And then the single tube boring test is done, the other steps are the same as the above steps apart from the temperature probe in the tank and the tank. The system test is on May 4, and the single tube boring test is on May 2.

Figure 2. System test diagram.

Figure 3. Schematic diagram of single tube boring test.

3.2.2. Problems encountered in the experiment and debugging
- Existing problems

1. The temperature difference between the 12 temperature probes is not significant.

2. The temperature measured by B1 is higher than that of B2.

● Debugging

1. As can be seen in figure 3, considering the influence of the position of the temperature probe, the temperature of the 12 temperature probes is approximately the same. Because the temperature probe is too light, the temperature probe at the bottom of the vacuum tube may float in the vacuum tube hot water layer. This problem is solved by adding a weight to the A1, B1, C1, D1 four temperature probes, and each temperature probe may have some error, so it is corrected by the thermometer.

2. First, check the connection; if the connection is right, there is something wrong with the temperature transmitter, and then the transmitter need to be replaced until make it coincide with the measured data.

3.3. Vacuum tube heat exchanger set characteristic analysis

3.3.1. Characteristic analysis of vacuum tube for system test. It can be seen from figures 4 and 5 that the temperature of the bottom of the four tubes and the temperature of the nozzle are increasing with the increase of time. At about 4:15, the temperature tends to stabilize and then gradually decreases. The reason why the temperature change is due to the change of the solar radiation intensity first enhanced and then weakened with the change of time. When the solar radiation intensity is strong, the energy absorbed by the fluid in the vacuum tube is higher and the temperature of the fluid in the tube is higher. As shown in figure 6, the solar radiation intensity is strong at 11 o'clock to 3 o'clock, and the temperature of the water in the vacuum tube is the highest at about 4 o'clock. This is because the temperature of the fluid in the tube needs a constant heat absorption process. And the collector itself has a certain heat capacity, which is consistent with the theory.
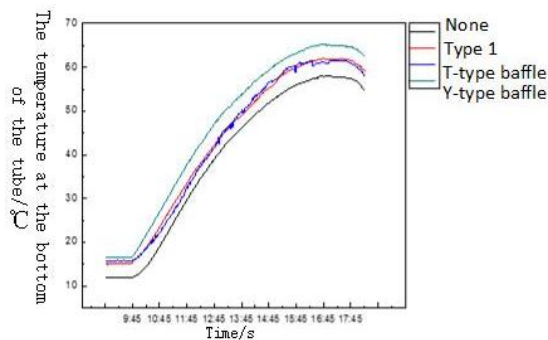

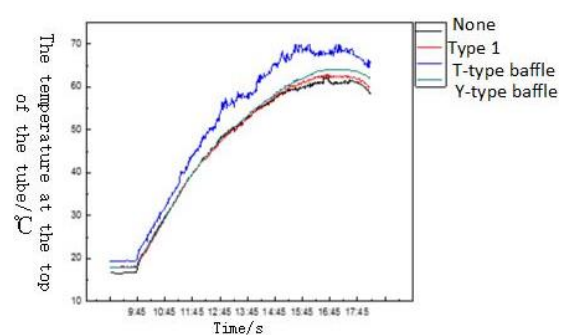**Figure 4.** The temperature at the bottom of the system change with time.

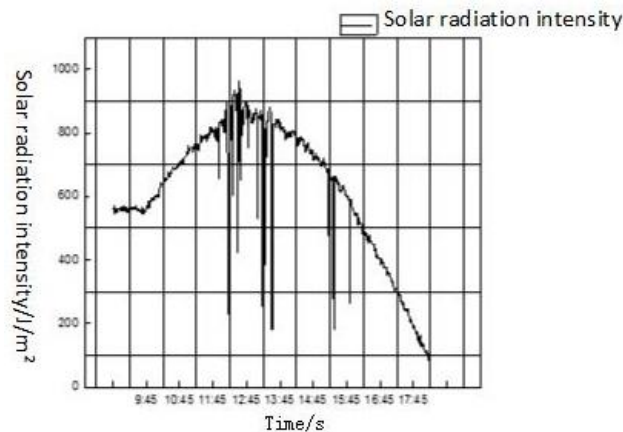**Figure 5.** The temperature at the top of the system change with time.

Figure 6. Solar radiation intensity and time diagram of the system.

As can be seen from figure 4, there is no deflector of the bottom temperature is the lowest, followed by the flat plate and T-plate, Y-plate has the highest temperature. The highest temperature of Y-plate reaches is 63℃, while the temperature without plate increases to 57℃, and the temperature of T-plate are similar to that of a flat plate, which is about 61℃. The plate type deflector is similar to the temperature of the T-type guide plate because the plate baffle plate divides the fluid in the vacuum tube into two channels to suppress lateral convection; However, the addition of a T plate divides the fluid in the vacuum tube into 3 channels, but the channel above the T deflector is the same as the flat plate. And the bottom of the two channels are divided by the cold fluid, so the lower part of the channel even if the separation of the cold fluid temperature is not large, it makes the two kinds of baffle temperature is similar. The Y-plate has the highest temperature because the Y-type guide plate divides the vacuum tube into 3 channels, and the channel occupied by the cold and hot fluid is more accurately separated, so the temperature is highest.

As can be seen from figure 5, the T-plate has the highest temperature, followed by the Y-plate and the flat plate, with the lowest without board. T-plate highest temperature up to 68℃; the maximum temperature is 62℃ without plate; the temperature of the plate and the Y-plate was 62℃ and 65℃, respectively. According to figure 4 analysis we can see that adding guide plates in a vacuum tube, to suppress transverse convection to improve the collector efficiency have a certain effect, the effect of T-plate on the suppression of lateral convection is best, Y-plate second, plate type weakest.

The detailed data are shown in tables 1 and 2:

Table 1. Temperature rise at the bottom of the vacuum tube (℃).

Parameter	A_1	B_1	C_1	D_1
Bottom initial temperature	12.0115	14.995	15.785	16.604
Bottom equilibrium temperature	57.8265	61.635	61.014	63.882
T_C	45.815	46.64	45.229	47.278

Table 2. Temperature rise at the top of the vacuum tube (℃).

Parameter	A_1	B_1	C_1	D_1
Top initial temperature	16.573	18.005	19.435	17.948
Top equilibrium temperature	62.53	62.566	68.538	65.018
T_C	45.957	44.561	49.103	47.07

The velocity of the fluid in the vacuum tube is inversely proportional to the temperature difference between the cold and hot fluid, and is proportional to the temperature at which the fluid rises at the inlet and outlet (Tc), the temperature at the inlet and outlet is approximately the temperature at the

nozzle and the temperature at the bottom of the tube. It can be seen from tables 1 and 2 that the rising temperature of the fluid at the inlet and outlet of B, C, and D is higher than that of A, and the temperature difference between hot and cold fluid, B and D tubes, is lower than that of a tube. Although the C tube temperature is higher than that of the A tube, the temperature at which the fluid rises is much higher than that of the A tube at the inlet and outlet of the C tube, so the flow velocity of the B, C and D tubes is greater than that of the A tube in general. By type (2-21) can see greater velocity, more heat fluid absorption, which indicates that adding guide plates have the effect on inhibiting radial convection of vacuum tube, the water temperature in the water tank was stratified, improving heat transfer efficiency.

3.3.2. Characteristic analysis of single tube boring test. It can be seen from figure 7 that the temperature of the bottom of the four vacuum tubes gradually increases with time, and the maximum is about 4 o'clock, and it will gradually decrease after a certain period of time. Four reasons for temperature changes in the tube: First, because the vacuum tube collector continues to absorb solar radiation energy, and with the increase in light intensity, the more heat absorbed by the tube fluid, the temperature gradually increased, and later the intensity of solar radiation weakened, the temperature will be reduced, 11 o'clock to 2:30 between the strongest, and the temperature is about 4 o'clock when the highest, this is because the collector has a certain heat capacity.
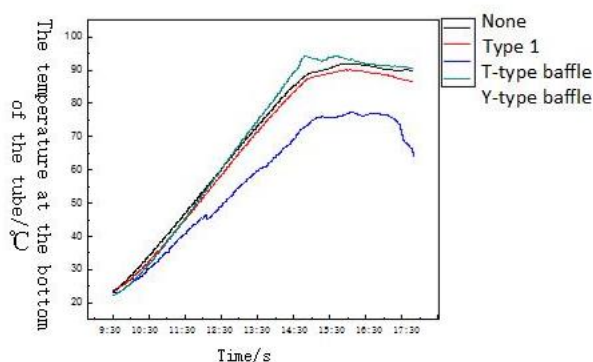

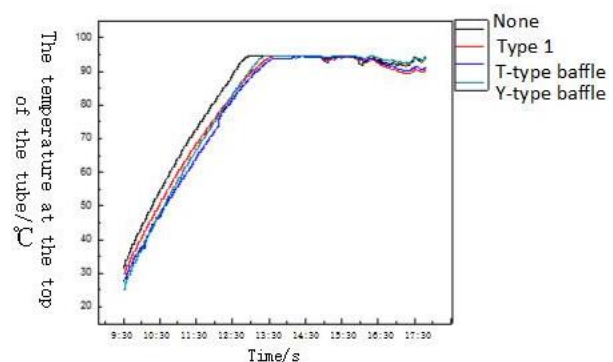**Figure 7.** Bottom temperature change with time of single tube boring test.

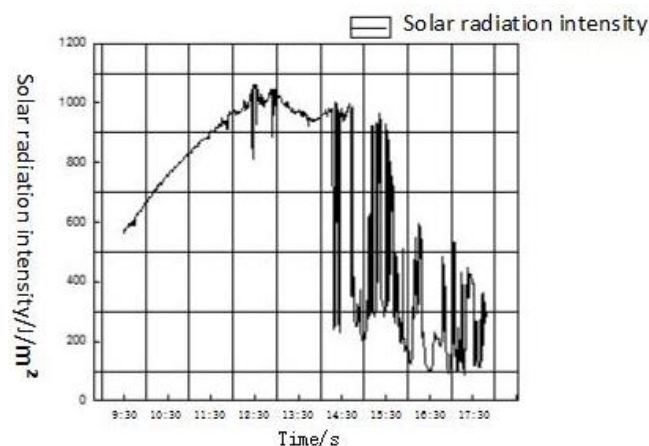**Figure 8.** Top temperature change with time of single tube boring test.

Figure 9. Solar radiation changes over time.

Figure 7 shows clearly that the Y-plate has the highest temperature; without the board and the plate is second; the lowest is T-plate. The maximum temperature of the Y plate reaches 93℃; the

temperature without a plate and the temperature of the flat plate were 91.9℃ and 90℃, respectively; plus T-plate reaches a maximum of 77℃.

As can be seen in figure 8, the temperature at the top of the four pipes gradually increases with time, rises to a certain extent, remains stable, and then decreases gradually. The tube without deflector reaches the highest at 1 o'clock, and the highest is 94.5℃. Three kinds of a vacuum tube with guide plate reached the highest in 1:30, the highest is 94.5℃. After 1:30, the temperature of the four tubes was almost equal, and there was a slight decrease after 4:30 o'clock. The reason for this phenomenon is that: As shown in figure 9, the vacuum tube collector absorbs the solar radiation energy continuously during the heat collection process so that the temperature of the fluid in the pipe increases continuously. When the fluid temperature is much higher than the ambient temperature, the solar collector's insulation performance deficiencies, bound outward by thermal radiation and convection heat transfer through the surface of the solar collector mode give off lots of heat, and after 3:00 solar radiation intensity also decreased. Tube fluid temperature in the 1:00 to 4:00 change is not more than 2℃. It is because, at 1 o'clock, the temperature of the fluid in the tube has reached the boring temperature, the temperature inside the tube will not be significantly increased.

According to the efficiency formula of the collector, the thermal efficiency of the system test and the single tube boring test are as follows:

Table 3. Maximum thermal efficiency of system and single tube.

Project	Standard vacuum tube	vacuum tube with a flat plate	vacuum tube with T-plate	vacuum tube with Y-plat
Single tube boring test	55%	55.4%	49%	57.6%
System test	29.1%	31.1%	32.2%	32%

From table 3 it can be concluded that single tube boring test plus Y-plate is the most efficient, plus flat plate is the next, and without adding plate is lower, plus T-plate is the minimum. The thermal efficiency of the Y-plate is 2.6% higher than that without the baffle, and the thermal efficiency of the T-plate is 6% lower than that without the baffle. Theoretically, the heat efficiency of a vacuum tube collector with a draft plate should be enhanced, which has a certain effect on suppressing radial convection and enhancing axial convection. But in the single tube stuffy test, the data added to the T plate decreased. The reason that may lead to this conclusion is that: Without the water tank, the water in the vacuum tube has no circulation; It is also possible that the heating time of the collector has not reached the maximum since the irradiation time of the T plate vacuum tube collector is not high enough, and the T plate has not reached the highest efficiency at the time of calculation.

In the system test, the efficiency of adding T-type plate is the highest, and the efficiency of adding y-type plate is next, plus the flat plate is lower, without the deflector is minimum.

4. Conclusion

In order to improve the convective heat transfer of the fluid in the standard all-glass vacuum tube collector, the guide plate that can inhibit the radial convection and enhance the axial natural convection were designed. The theoretical model was established. The thermal properties of various conditions were tested. The results show that:

The heat efficiency of the vacuum collector with the guide plate is improved due to the improvement of the internal flow field. For the system test, T-type guide plate, the effect of restraining the radial convection and enhancing the axial convection is better than Y-type guide plate, and the Y-type is better than the plate type. Vacuum tubes with guide plates are better than vacuum tubes without guide plates.

The efficiency of the vacuum tube collector with T, Y and plate type plate is increased by 3.1%, 2.9%, and 2% respectively compared with that without flow guide plate. The heat transfer efficiency of the vacuum tube with guide plate is 2.6% higher than that of the standard vacuum tube without

modification.

The installation of the guide plate can restrain radial convection and enhance axial convection for both single tube and the system, improve the efficiency of the collector to improve the performance of the entire water heater, and it is more effective for the system.

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