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STUDY ON HEAT LOSS OF ALL GLASS VACUUM TUBE SOLAR WATER HEATER AT NIGHT

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ABSTRACT

For all-glass vacuum tube solar water heater, which integrates heat collection and storage, night heat loss affects its continuous and stable energy supply for users. For this reason, taking a set of 30 all-glass vacuum tube solar water heaters with specifications of Φ58 mm×1800 mm as the research object, the temperature changes of 20:00-07:00 water heater storage tank and vacuum tube within 10 days were experimentally studied, and the night heat loss of each part of the water heater was analyzed. In addition, a three-dimensional unsteady numerical model of all-glass vacuum tube solar water heater was established, and the flow and heat transfer characteristics of the water heater during night heat dissipation were analyzed. The results show that among all kinds of heat loss of water heater, the radiation heat loss of vacuum tube is the largest, accounting for 57.8% of the total heat loss of water heater. The convective heat loss of hot water storage tank accounts for 32.1%, that of vacuum tube accounts for 3.7%, and that of other heat loss accounts for 6.4%. With the development of heat dissipation, temperature stratification in water heater becomes more and more obvious, fluid flow becomes slower and slower, and the static stagnation area in vacuum tube expands gradually from bottom to top.

Keywords: all-glass vacuum tube solar water heater, nocturnal heat loss, internal flow characteristics

NONMENCLATURE

Q^t_{loss}	Theoretical nighttime heat loss of water heater
$Q^t_{\text{loss-tank}}$	Theoretical nighttime heat loss of tank
$Q^t_{\text{loss-tube}}$	Theoretical nighttime heat loss of tube
$Q^t_{\text{tube-conv}}$	Theoretical convective nighttime heat loss of tube
$Q^t_{\text{tube-rad}}$	Theoretical radiative nighttime heat loss of tube
$q_{\text{1a-conv}}$	Convection heat transfer between cylindrical surface of water tank and surrounding environment in unit time
$q_{\text{1'a-conv}}$	Convection heat transfer between side wall of water tank and surrounding environment in unit time
$q_{\text{2a-conv}}$	Convection heat transfer between vacuum tube and surrounding environment in unit time
$q_{\text{2sky-rad}}$	Radiative heat transfer between vacuum tube and sky in unit time
Δt	Time interval
Q^a_{loss}	Actual nighttime heat loss of water heater
$Q^a_{\text{loss-tank}}$	Actual nighttime heat loss of tank
$Q^a_{\text{loss-tube}}$	Actual nighttime heat loss of tube
c_1	Specific heat capacity of water in tank
c_2	Specific heat capacity of water in

	tube
m_1	Quality of water in tank
m_2	Quality of water in tube
t_{b1}	Initial temperature of water in tank
t_{e1}	Final temperature of water in tank
t_{b2}	Initial temperature of water in tube
t_{e2}	Final temperature of water in tube
t_1	Temperature of water in tank
t_2	Temperature of water in tube

1. INTRODUCTION

Under the dual pressures of environmental problems and energy demand, the use of solar energy instead of traditional energy has become an important means to promote sustainable economic development and solve the energy crisis [1,2]. In the process of utilizing solar energy, all glass vacuum tube solar water heater is the most rapidly developed and widely used solar energy product [3,4]. Whether the water heater can operate efficiently and steadily is an important basis for evaluating its performance. The nighttime heat loss and flow of all glass vacuum tube solar water heater directly affect the stability of its energy supply for users. Scholars at home and abroad have done a lot of research in this area. In terms of night heat loss, Smyth M, Michaelides I and Ma F [5-7]calculate the night heat loss coefficient of the water heater by calculating the heat loss coefficient of the water heater, so as to compare the thermal performance of different specifications of water heater. Liu Huifang et al. [8]measured and calculated the average heat loss coefficient of solar collector under the static condition at night, combined with the initial temperature at night to predict the change of liquid temperature, so as to prevent the freezing of the collector loop according to the lowest temperature. Li Jinping [9]obtained the relationship between the thermal loss coefficient of all-glass vacuum tube solar water heater hot water tank and the average ambient temperature, the range of ambient temperature change and the average wind speed under the actual working conditions at night by the method of multiple linear fitting, and then estimated the thermal loss coefficient of the hot water storage tank at any period of time. Li Tong [10] numerically simulated the flow and heat transfer in the vacuum tube solar water heater from 10:00 to 14:00. The influence of climate and technical parameters on the performance of the vacuum tube solar water heater was studied. It was found that the increase of the length of the collector tube would lead to the decrease of the efficiency of the water heater. It was also found that the radiation loss was the main heat loss mode of the whole glass vacuum tube solar water heater. In terms of internal flow of water heater, Tang R et al. [11] studied the thermal performance of all-glass vacuum tube solar water heater at night through experiments. It was found that the water temperature in the vacuum tube was always lower than that in the water tank, but higher than the predicted water temperature in the case of natural cooling and no reverse flow, which indicated that the solar water heater had counter current at night.

To sum up, there are many studies on calculating the night heat loss of solar water heaters by using the heat loss coefficient, but few studies have been done on the heat loss of each part of the water heater at night, and on the internal flow and heat transfer characteristics of the water heater at night. Therefore, this paper studies the heat loss of each part of the water heater at night and their proportion to the total heat loss of the water heater. In addition, based on the three-dimensional unsteady numerical model of all-glass vacuum tube solar water heater, the temperature and velocity characteristics of the water heater during the night heat dissipation process are analyzed.

2. TESTING DEVICES AND TESTING PROCESS

2.1 Testing devices

In this paper, a set of 30-branch vertical-tube all-glass vacuum tube solar water heater in Lanzhou City, Gansu Province is taken as the test object. The water heater is positioned to the South with an angle of 45 degrees between the collector surface and the ground. The installation of test bench components meets the requirements of GB/T 18708-2002 "Test Method for Thermal Performance of Household Solar Hot Water Systems"[12]. The parameters of the components are detailed in Table 1.

Table 1 Geometric parameters of all-glass vacuum tube solar water heater

Parts		Parameters
Tank	Internal diameter: 360	The inner liner material is SUS304-2B stainless steel, the thickness is 0.4

	mm, External diameter : 460 mm, Total length: 2540 mm, Volume: 250 L	mm, its thermal conductivity is 16.3 W·m^{-1}·K^{-1} Insulation material is polyurethane, its thermal conductivity is 0.035 W·m^{-1}·K^{-1} Shell material is galvanized sheet, the thickness is 0.4 mm, its thermal conductivity is 121 W·m^{-1}·K^{-1}
Vacuum tube	Internal diameter: 47 mm, External diameter: 58 mm, Total length: 1800 mm, Pipe spacing: 80 mm	The glass material is borosilicate 3.3, the thickness is 2 mm, its thermal conductivity is 1.2 W·m^{-1}·K^{-1} Selective absorption coating is Al-N/Al coating, its emissivity is 0.06

2.2 Testing process

The test time was from March 29, 2018 to April 12, 2018, totaling 14 days. During the whole test period, the water in the water heater does not circulate. The temperature sensor arrangement in the water heater is as follows: One Pt100 is installed at the center of the water tank axis, 120 mm above the center and 120 mm below the center to measure the water temperature of the middle, upper and lower layers of the water tank. Three Pt100 sensors is fixed at the central position of the vacuum tube (left 15) at 300, 900 and 1500 mm from the pipe orifice to measure the water temperature of the upper, middle and lower layers of the vacuum tube.

Clean the solar water heater before the experiment starts, then fill it with water. The calculation time of night heat loss is from 20:00 p.m. to 07:00 a.m. the next day.

Table 2 Test Bench Components and Technical Parameters

Name	Type and Specification	Quantity	Accuracy range
Temperature sensor	Pt100 thermal resistance	7	Range: -50~100 ℃; accuracy: class A, ±0.15 ℃
Wind speed sensor	FC-2A3	1	Range: 0~30 m·s^{-1}; accuracy: ±5%
Solar Radiometer	TBQ-2-B	1	Range: 0~2000 W·m^{-2}; sensitivity: 11.710 μV·W^{-1}·m^{2}
Data Acquisition Instrument	Agilent34970A	1	

3. ANALYSIS OF HEAT DISSIPATION PROCESS OF ALL GLASS VACUUM TUBE SOLAR WATER HEATER

All-glass vacuum tube solar water heater is in the state of natural heat dissipation when it is in the static state at night. It radiates heat to the surrounding environment through the hot water tank and all-glass vacuum tube. Its heat dissipation process is a transient heat transfer process, including heat conduction, convection and radiation.

3.1 Theoretical value of heat loss

The *theoretical* nighttime heat loss of all-glass vacuum tube solar water heater during the whole night is as follows.

$$Q^{t}_{\text{loss}} = Q^{t}_{\text{loss-tank}} + Q^{t}_{\text{loss-tube}} \tag{1}$$

$$Q^{t}_{\text{loss-tube}} = Q^{t}_{\text{tube-conv}} + Q^{t}_{\text{tube-rad}} \tag{2}$$

The convective heat loss of the hot water tank is the sum of the convective heat transfer between the cylindrical wall and the two side walls and the surrounding environment.

$$Q^{t}_{\text{loss-tank}} = \left(q_{1a-conv} + 2q_{1'a-conv}\right)\Delta t \tag{3}$$

The heat loss of all glass vacuum tubes is the sum of convective and radiative heat transfer between 30 tubes and the surrounding environment.

$$Q^{t}_{\text{tube-conv}} = 30 q_{\text{2a-conv}} \Delta t \tag{4}$$

$$Q^{t}_{\text{tube-rad}} = 30 q_{\text{2sky-rad}} \Delta t \tag{5}$$

3.2 Actual value of heat loss

In the course of analyzing the test results, considering the obvious stratification of temperature in all-glass vacuum tube and hot water tank at night, the temperature from top to bottom decreases in turn, and the natural convection is weak, assuming that the water in solar water heater is stationary. The actual heat loss of all glass vacuum tube solar water heater at night is as follows:

$$Q_{\text{loss}}^{a} = Q_{\text{loss-tank}}^{a} + Q_{\text{loss-tube}}^{a} \quad (6)$$

The actual heat loss of a hot water tank at night can be expressed as

$$Q_{\text{loss-tank}}^{a} = c_1 m_1 \left(t_{\text{b1}} - t_{\text{e1}} \right) \quad (7)$$

The actual heat loss of all glass vacuum tubes at night can be expressed as

$$Q_{\text{loss-tube}}^{a} = 30 c_2 m_2 \left(t_{\text{b2}} - t_{\text{e2}} \right) \quad (8)$$

The temperature of water heater water tank and vacuum tube is calculated by volume weighting method from the upper, middle and lower layers respectively.

3.3 Heat Loss Analysis of Night Water Heater

According to the test data, the actual heat loss and the calculated heat loss of the night water tank, vacuum tube and water heater are obtained. The results are shown in Table 3.

Table 3 Theoretical and actual value of heat loss at night for water heaters

Date	Actual value			Theoretical value			Deviation		
	$Q^{a}_{\text{loss-tank}}$/MJ	$Q^{a}_{\text{loss-tube}}$/MJ	Q^{a}_{loss}/MJ	$Q^{t}_{\text{loss-tank}}$/MJ	$Q^{t}_{\text{loss-tube}}$/MJ	Q^{t}_{loss}/MJ	($Q^{a}_{\text{loss-tank}}$-$Q^{t}_{\text{loss-tank}}$)/MJ	($Q^{a}_{\text{loss-tube}}$-$Q^{t}_{\text{loss-tube}}$)/MJ	(Q^{a}_{loss}-Q^{t}_{loss})/MJ
03-29	10.42	13.09	23.51	7.50	14.26	21.76	2.92	-1.17	1.75
03-30	7.67	8.65	16.32	5.90	9.80	15.70	1.77	-1.15	0.62
03-31	6.75	8.88	15.63	5.31	9.85	15.16	1.44	-0.97	0.47
04-01	9.39	12.57	21.96	6.77	13.77	20.54	2.62	-1.20	1.42
04-02	10.76	13.34	24.10	7.16	14.47	21.63	3.60	-1.13	2.47
04-03	10.30	13.54	23.84	7.36	14.91	22.26	2.94	-1.37	1.57
04-04	9.49	11.28	20.77	7.35	13.16	20.51	2.14	-1.88	0.26
04-05	9.02	10.55	19.57	7.48	11.62	19.10	1.54	-1.07	0.47
04-06	10.64	13.98	24.62	7.89	15.51	23.40	2.75	-1.53	1.22
04-07	10.88	13.92	24.80	7.66	15.20	22.86	3.22	-1.28	1.94
04-08	10.99	13.63	24.62	7.19	14.87	22.06	3.80	-1.24	2.56
04-09	11.29	13.51	24.80	7.33	14.75	22.07	3.96	-1.24	2.72
04-10	8.82	10.62	19.44	6.14	12.42	18.57	2.68	-1.80	0.88
04-11	8.88	10.50	19.38	5.69	11.85	17.55	3.19	-1.35	1.84

As can be seen from the table above, the actual heat loss of the hot water tank at night is always greater than the calculated heat loss, while the actual heat loss of the vacuum tube is always smaller than the calculated heat loss. This is because besides convective heat transfer with the surrounding environment, the water tank of the water heater transfers heat to the vacuum tube on the one hand, and dissipates heat through the connection of the water tank and the vacuum tube on the other hand. For the vacuum tube, the heat dissipated to the surrounding environment through convection and radiation comes from the internal energy of the water in its own tube on the one hand, and the heat transferred to it by the water in the tank on the other hand.

Figure 3 shows the proportion of the heat loss of each part of the all glass vacuum tube solar water heater to the actual total heat loss of the water heater during the test period. As can be seen from the figure, among all kinds of heat loss of water heater, the

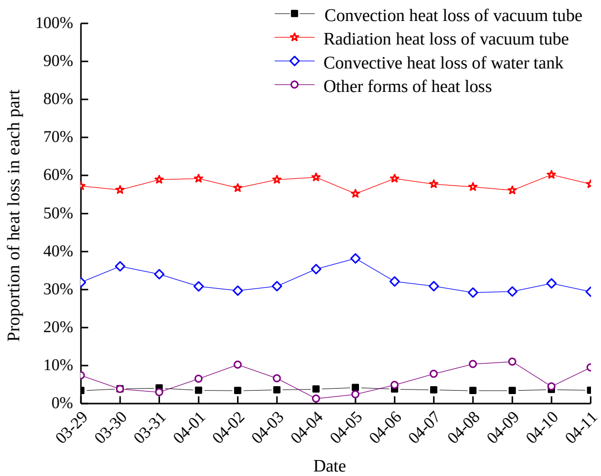


Figure 3 The proportion of heat loss of each part of solar water heater to the actual total heat loss

radiation heat loss of vacuum tube is the largest, accounting for 55.2%~60.2% of the total heat loss of water heater, with an average of 57.8%. The second is the convective heat loss of the hot water tank, accounting for 29.2%~38.2%, with an average of 32.1%. Finally, the convective heat loss of the vacuum tube is stable, accounting for 3.4%~4.2%, with an average of about 3.7%. Other heat loss of water heater includes heat loss at the connection of water tank and vacuum pipe and heat loss caused by neglecting other factors, which accounts for about 6.4% of the total actual heat loss of water heater on average.

As the most important part of the night heat loss of water heater, the radiation heat loss of vacuum tube can be reduced by taking corresponding measures, such as selecting low emissivity coating, improving the vacuum degree of vacuum interlayer and reducing the temperature of the tube.

4 ANALYSIS OF FLOW AND HEAT TRANSFER IN WATER HEATER AT NIGHT

4.1 Model validation

In this paper, the finite volume method is used to solve the flow and heat transfer in all-glass vacuum tube solar water heater. The SIMPLE algorithm is used to couple the velocity and pressure, the first-order implicit scheme is used for the transient term, and the second-order upwind scheme is used for the energy and momentum equation. The total simulation time is 12 hours and the time step is 60 seconds. Each step is iterated 20 times.

In order to verify the feasibility of the water heater model, the experimental results obtained under the same conditions are compared with the numerical results, as shown in Figure 4. From the figure, it can be seen that the simulated temperature is always higher than the measured temperature, whether it is the water tank or the vacuum tube of the water heater. This is because the heat dissipation at the junction of the water tank and the vacuum tube is not taken into account in the numerical calculation. After calculation, the simulation results of temperature in water tank and vacuum tube are in good agreement with the measured results, and the relative error is less than 4.0%. Therefore, it is considered that the water heater model is feasible and the simulation results are reliable.

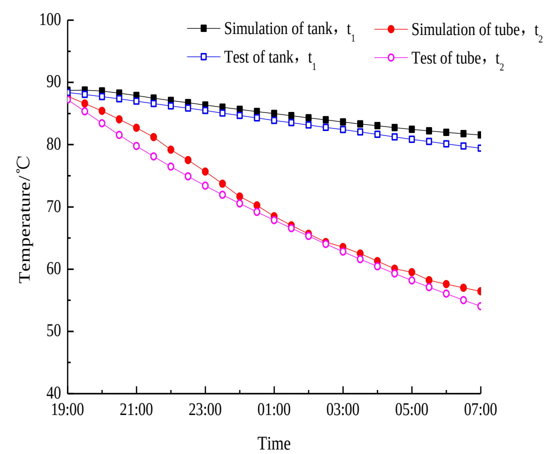
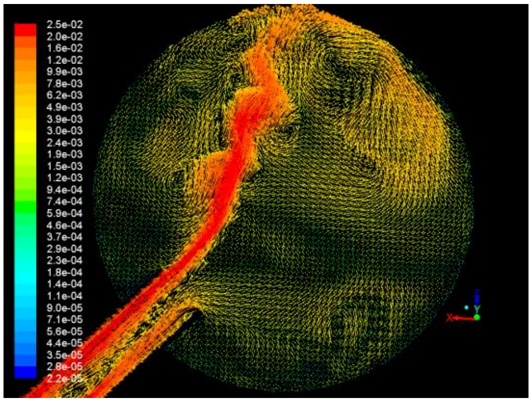


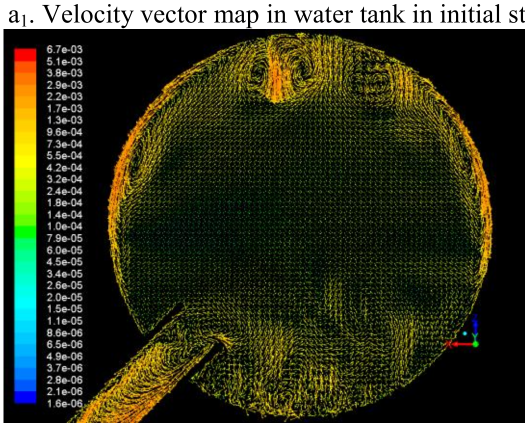
Fig.4 Comparison of the temperature of water heater by simulation and test

4.2 Analysis of flow and heat transfer in water heater

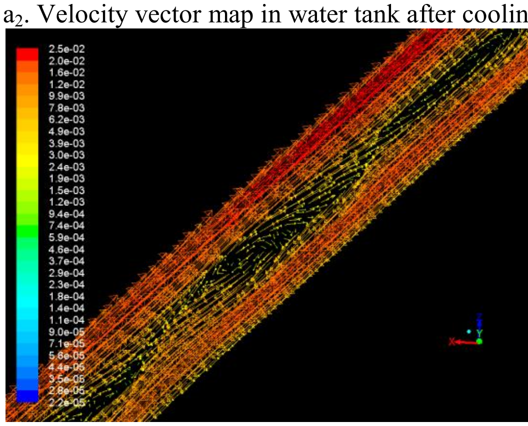
Figure 5 is the velocity vector diagram of the water heater in the process of heat dissipation. It can be seen from the figure that the temperature in the vacuum tube is higher than that in the water tank at the initial state (the end of the heat collection). Under the action of natural convection, the hot fluid in the tube flows into the water tank close to the upper wall of the vacuum tube, and the cold fluid in the water tank flows into the tube along the lower wall of the vacuum tube. The mixing of hot and cold fluids in vacuum tube is serious, and the bottom fluids also have a certain flow velocity. When the water heater is cooling for 2 hours, the temperature of the fluid near the wall of the water tank first decreases, the density increases, and it begins to flow downward along the wall. The velocity of the fluid in the other parts of the water tank is very small. Similarly, the fluid near the wall of the vacuum tube flows downward. Under the action of buoyancy, the higher temperature fluid in the vacuum tube flows upward, which forces a part of the cold fluid not reaching the bottom of the vacuum tube to flow back to the water tank. At this time, the velocity of the fluid at the bottom of the vacuum tube is very small, and there is a random eddy at the junction of the water tank and the vacuum tube.



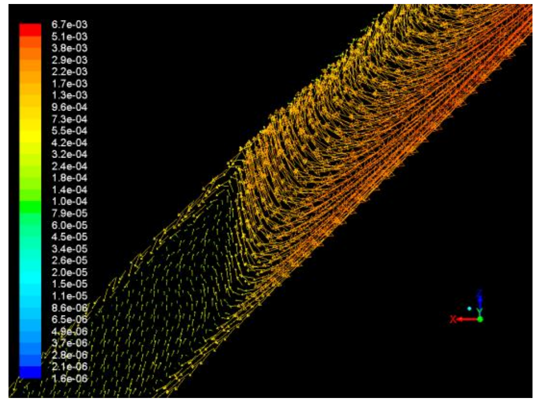
a_1. Velocity vector map in water tank in initial state



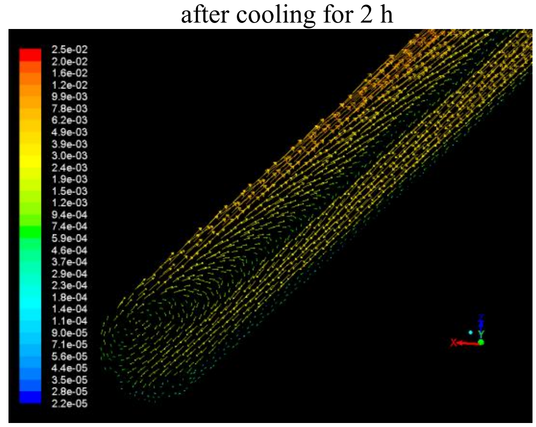
a_2. Velocity vector map in water tank after cooling for 2 h



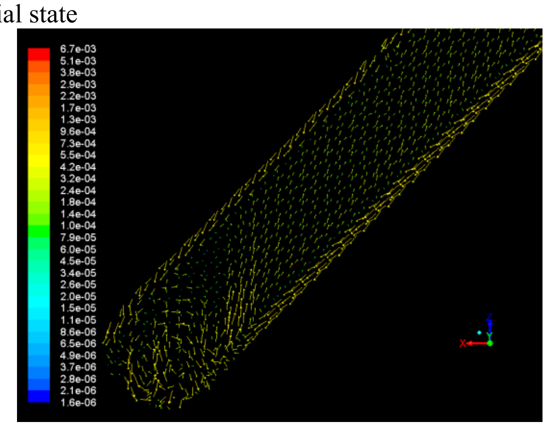
b_1. Velocity vector map in the middle of vacuum tube in initial state



b_2. Velocity vector map in the middle of vacuum tube after cooling for 2 h



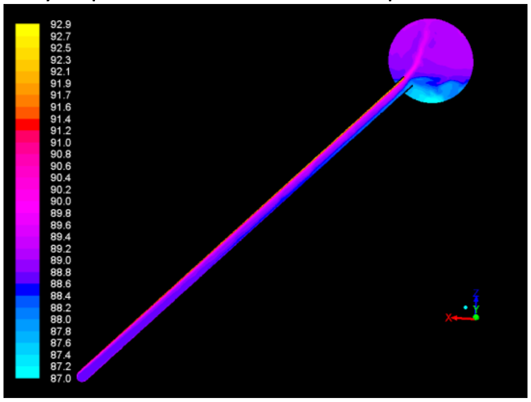
c_1.Velocity vector map at the bottom of vacuum tube in initial state



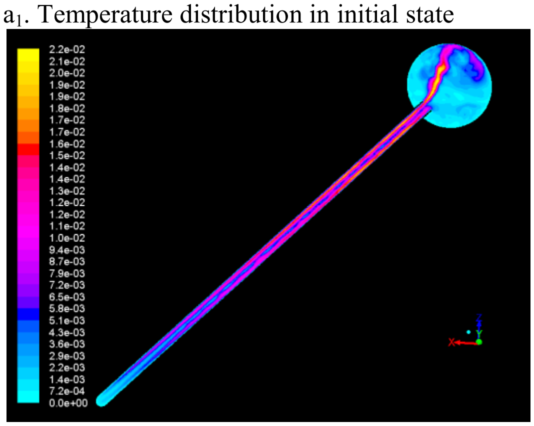
c_2. Velocity vector map at the bottom of vacuum tube

Fig.5 Velocity vector diagram in solar water heater

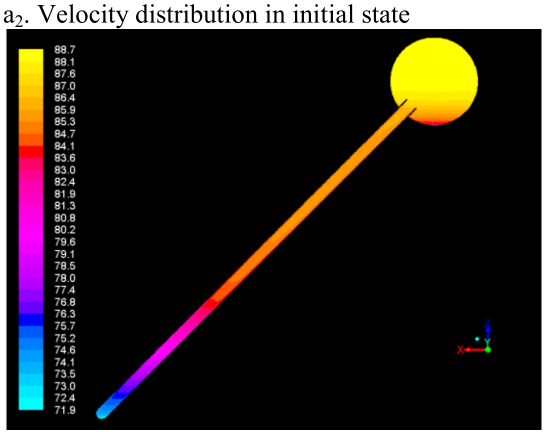
Figure 6 shows the temperature and velocity distribution of the water heater in the process of heat dissipation. It can be seen from the figure that the temperature in the vacuum tube decreases faster than that in the water tank. There is little difference between the upper and middle temperature of water tank, and the lower temperature is obviously low. With the progress of heat dissipation, the temperature stratification in the whole water heater becomes more and more obvious, the fluid flow is slower and slower, and the static stagnation area in the vacuum tube gradually expands from bottom to top.



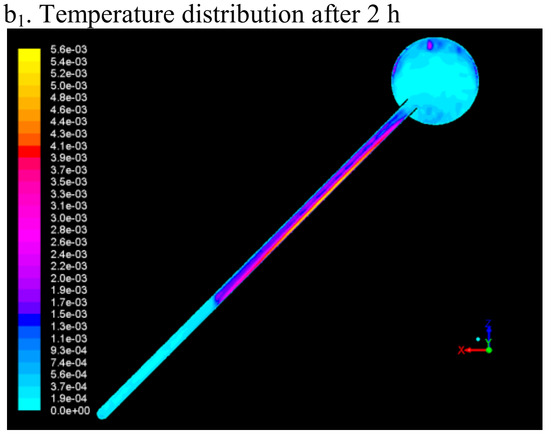
a_1. Temperature distribution in initial state



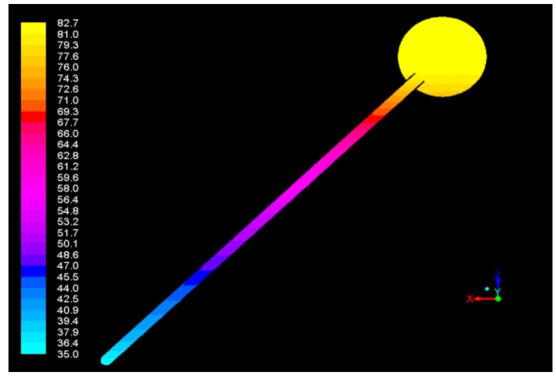
a_2. Velocity distribution in initial state



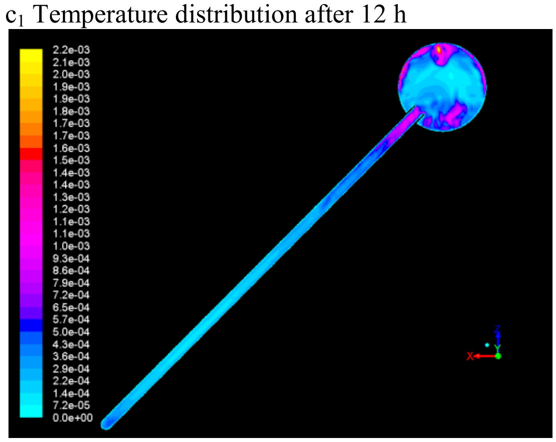
b_1. Temperature distribution after 2 h



b_2. Velocity distribution after 2 h



c_1 Temperature distribution after 12 h



c_2. Velocity distribution after 12 h

Fig.6 Temperature and velocity distribution during heat dissipation in the water heater

5 CONCLUSIONS

Through the experimental study and numerical simulation of all glass vacuum tube solar water heater at night, some conclusions are drawn as follows:

(1) Among all kinds of heat loss of water heater, the radiation heat loss of vacuum tube is the largest, accounting for 57.8% on average. The second is the convective heat loss of the hot water tank, accounting for 32.1% on average. Finally, the convective heat loss of the vacuum tube averages about 3.7%. The remaining heat loss is the heat loss at the junction of water tank and vacuum tube and the heat loss caused by neglecting other factors.

(2) At night, there are random eddies at the junction of the water tank and the vacuum tube. The decreasing speed of temperature in vacuum tube is faster than that in water tank. There is little difference between the upper and middle temperature of water tank, and the lower temperature is obviously low. With the progress of heat dissipation, the temperature stratification in the whole water heater becomes more and more obvious, the fluid flow is slower and slower,

and the static stagnation area in the vacuum tube gradually expands from bottom to top.

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