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A Semi-Instantaneous Heat Exchanger for Mobile Solar Collectors Test System

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Abstract

A semi-instantaneous heat exchanger which can solve low efficiency and space shortage of mobil test system for thermal performance of solar collectors is proposed in this paper, In this paper, the structure parameters of heat exchanger and the power of heat resistance are designed based on the method of mean temperature difference. The experiment results show the performance of test system has been optimized. The efficiency of collectors test can be increased 50% and the total weight of the primary heater and working medium is reduced to 13.8%.The load of the test vehicle and occupancy volume have been decreased.

Keywords: *semi-instantaneous heat exchanger, temperature control, mean temperature difference method, thermal performance test of collectors*

1. Introduction

Thermal performance test of solar collectors is to determine the steady state and dynamic efficiency, time constant, incidence angle correction coefficient and differential pressure between its two ends [1] according to GB/T 4271-2007 “Test methods for the thermal performance of solar collectors”. The mobile test system for thermal performance of solar thermal utilization products in this paper is vehicular test system. This test system is installed in a vehicle its 17 seats were removed and can wehiclery out thermal performance test of solar collectors and domestic solar water heating systems at any place. Limited by interior volume and weight of the vehicle, to reduce the volume and weight of every part of the test system is one of design keys of the mobile test system. A semi-instantaneous heat exchanger is presented in this paper, which can increase the test efficiency of solar collectors and reduce the whole weight and occupied volume of the test system.

2. The Working Principle and Requirements of Mobile Test System for Thermal Performance of Solar Thermal Utilization Products

The mobile test system for thermal performance of solar thermal utilization products consist of four parts: vehicle body, automatic tracking system of sun, closed piping system, measurement and control system of temperature and flow. Before test ,drive the test wehicle to the assigned place ,move the automatic double-shaft tracking system of sun with installation frame for thermal collectors, install the thermal collectors, set up test parameters, then the test can be started .And after test ,move the tracking system into the vehicle [4].

The principle diagram of closed water circulation pipeline of the testing system is shown in figure 1. The test system is composed of primary heat tank, secondary heating water tank, solar collectors, cold water machine, flow pump, flow frequency converter, concrete pump, expansion tank and thermal insulation materials, etc. In this system, the temperature control includes two stage [10]. The primary keeps the change of temperature among the ±1℃ about preset condition temperature by a large capacity heat storage tank (250L) and a mix water cycling pump. By using a mixed water pump and PID control algorithm, the second makes temperature change stable among ±0.1℃ about preset condition temperature.

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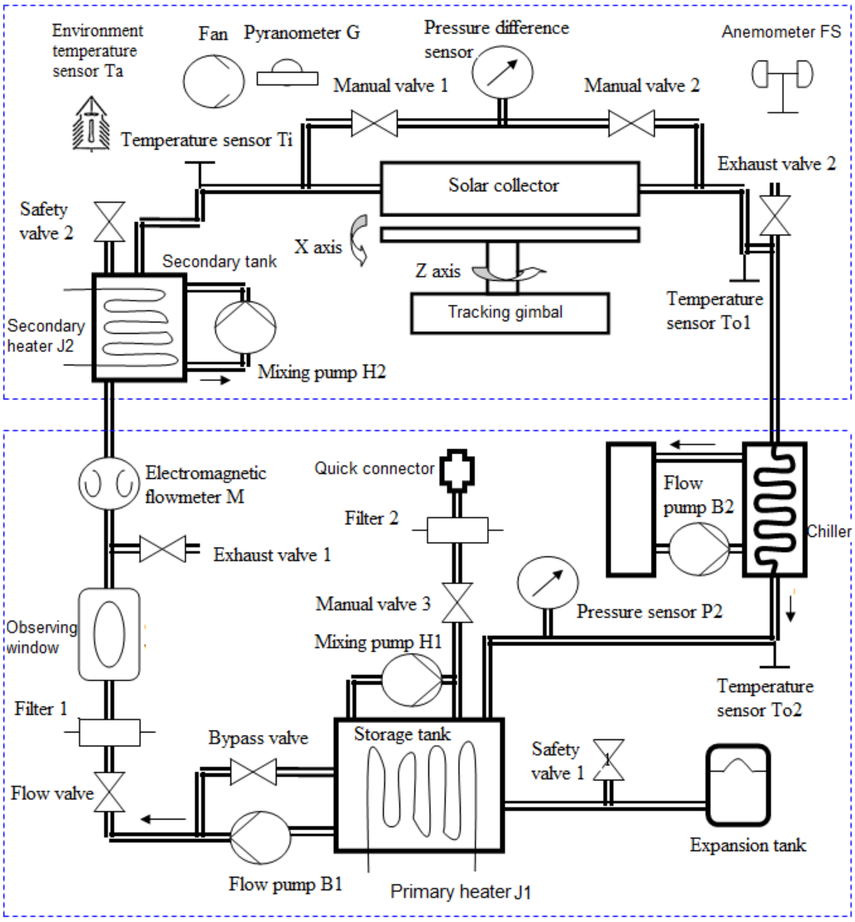


Figure 1. Principle diagram of closed water circulation pipeline of the testing system

GB/T4271 requires collectors import flow keep in $0.02kg/m^2{\cdot}s$ and temperature stable in ±0.1 ℃ of preset condition temperature while testing, complete four condition test. The testing time distributions of current test system in every condition is shown in table 1.

Table 1.The testing time distributions of current test system in every condition

Condition	Preset conditon temperature（℃)	Period of steady state preparation: required time for outlet temperature of primary heating water tank stable among the ±1℃ about preset condition temperature（min）	Period of steady state preparation: required time for outlet temperature of secondary heating water tank stable among ±0.1℃ about preset condition temperature.(min)	Period of steady state measurement (min)
1	Environmental temperature +3℃	6	9	15
2	Environmental temperature +16℃	36	10	15
3	Environmental temperature +29℃	37	10	15
4	Environmental temperature +42℃	41	11	15

From the above table, we can find the preparation time of the No. 2 to No. 4 working condition is much longer than the steady-state measuring time in addition to the first working condition. Especially the heating time of the primary heat tank is very long, and the main reason is the primary water tank has big volume. Its heating method is heat accumulation type. In order to shorten the adjustment time, a semi-instantaneous heat exchanger proposed in the paper is used to replace the primary water tank which has large heat capacity and mixing pump. The semi-instantaneous heat exchanger has the function to heat water rapidly. This can make outlet temperature of primary heating system stable among the ±1℃ about preset condition temperature. As a result, the efficiency of collectors test can be greatly improved.

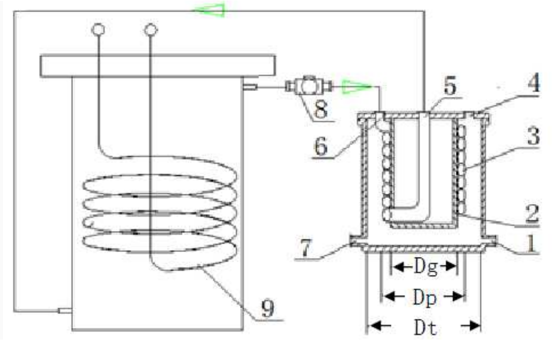
The semi-instantaneous heat exchanger proposed in this paper has smaller heat accumulation regulation function and rapid heating ability. It can replace the primary water tank and mix water pump in the figure 1 and realize dynamic control of flow and temperature.

The main working principle and working process of the test system is as follows. (1) Heating process for heat medium. Output 0～220V voltage for adjusting the heat medium heater ($7.3KW$ heating resistance wire) heating by using PID algorithm to control Silicon Controlled Rectifier [7] [9] make the outlet temperature of the heating medium stable at 95℃. (2) Adjusting process for inlet temperature of collectors. Firstly, working medium is heat-exchanged by semi-instantaneous heat exchanger and temperature is increased to preset conditions temperature range. For example, if preset conditions temperature is 23℃, temperature range is 22℃ to 23℃. Then water flow into the secondary heating water tank and outlet temperature of water tank is adjusted to stabling in ±0.1℃ about preset conditions temperature by PID controlling Silicon Controlled Rectifier to output $0 \sim 220V$ voltage and mix water pump adjusting the secondary heating water tank ($2KW$ heating resistance wire) heating [6]. (3) Automatic tracking frame makes sunlight always irradiate vertically on the tested solar collectors. Water temperature in the collectors tube is increased by heat collectors absorbed. Instantaneous thermal efficiency of the collectors can be calculated by measuring temperature difference between inlet and outlet of collectors. (4)Inlet temperature of collectors is increased from one condition to another condition by two-stage heating. For example, Inlet temperature is increased from 26℃ rise to 39℃. If outlet temperature of collectors is higher than 39℃, water coming from collectors should be cold exchanged by a cold water machine and water temperature is made down to 37℃~ 38℃.Finally inlet temperature of collectors working medium is controlled in ±0.1℃ range about preset conditions temperature by secondary heating.

3. Design of Semi-Instantaneous Heat Exchanger

The semi-instantaneous heat exchanger used in this paper has a structure of floating spiral coil type as shown in Figure 2. The heat exchanger consists of heat medium heat components and heat exchange components. Because of the effect of centrifugal force, the water can achieve the turbulence under a lower Reynolds during the process of heating. Because the suspension of particles in the moving fluid are difficult to deposit, the heat exchanger is hardly to scale and clog. The shell of heat exchanger is made of stainless steel with corrosion resistance and the heat exchange tube is made of thin-wall copper tube with bigger thermal conductivity. The isolate cylinder is placed in the center of the heat exchanger and spiral coil is winded from top to bottom [2].

Because the heat exchanger has smaller volume, the detention time working medium stay in the heat exchanger is too short to keep the outlet temperature constant. Therefore, sensitive and reliable temperature control is necessary [8]. In this new design, a temperature sensor $To2$ is fitted in the outlet of working medium, and an electromagnetic flux valve is fixed in the inlet of heat medium. The inlet and outlet temperature of working medium are measured by the temperature sensors. The flow rate of heat medium is calculated by the flow rate of inlet working medium. When the temperature of inlet working medium becomes lower, the control valve should be turned up to increase the supply of heat medium. In contrast, it should be turned down to decrease the supply to ensure the temperature of hot water steadily.



1:working medium outlet;2: isolate cylinder;3:heat exchange tube;4:working medium inlet;5:heat medium outlet;6:heat medium inlet;7: cooling water inlet;8:electromagnetic flux valve;9:heating resistance wire.

Figure 2. The structure of semi-instantaneous heat exchanger

According to the given conditions and requirements, the type, area and structure parameter of heat exchanger can be determined. The design calculation of heat exchanger is based on Logarithmic Mean Temperature Difference method (*LMTD* method). (1) Determine part parameters of heat exchanger Assume that the inner diameter of cylinder is set to D_t, the outside diameter of inside isolate cylinder of heat exchanger is D_g. Assume that the outside and inside diameter of heat exchanger copper tube d_w and d_n respectively. Then:

The distance from the outer edge of tube to the inside wall of cylinder:

$$(D_t - D_g - 2 d_w) /2 \quad (1)$$

The outer edge diameter of helical coiled tubes:

$$D_p = D_g + 2 d_w \quad (2)$$

According to the structure and installation characters of test system of mobile solar collectors test system, the main structure parameters of the floating helix coil tube type of semi-instantaneous heat exchanger are determined as follows. The inside diameter of the cylinder of heat exchanger D_t=200mm, the outside diameter of the inside isolate cylinder of heat exchanger D_g=160mm; the outside diameter of heat exchanger copper tube Φ16mm, the wall thickness is 1mm; The distance from the outer edge of tube to the inside wall of cylinder is 4mm, and the outer edge diameter of helical coiled tube is 192mm.

(2) The logarithmic mean temperature difference of hot and cold water mixing

A countercurrent way is taken in exchange for working medium and heat medium. Suppose that the flux of working medium is G_w, the inlet temperature of working medium T_{wi}, the inlet temperature of heat medium (Water) T_{mi}, outlet after heat exchange T_{mo}.

The logarithmic mean temperature difference

$$\Delta t'_m = [(T_{mi} - T_{wo}) - (T_{mo} - T_{wi})] / \ln \frac{(T_{mi} - T_{wo})}{(T_{mo} - T_{wi})} \quad (3)$$

Mean temperature difference correction factor $\varepsilon_{\Delta t'}$ is a function of *P* and *R*, here

$$P = (T_{wo} - T_{wi}) / (T_{mi} - T_{wi}) \quad (4)$$

$$R = (T_{mi} - T_{mo}) / (T_{wo} - T_{wi}) \quad (5)$$

The mean temperature difference correction factor $\varepsilon_{\Delta t'}$ can be check from table [3].

The logarithmic mean temperature difference of hot and cold water upstream is

$$\Delta t_m = \varepsilon_{\Delta t'} \cdot \Delta t'_m \tag{6}$$

(3) Determination of convection heat transfer coefficient of heat medium and tube inner wall

The arithmetic mean temperature of heat medium

$$T_m = (T_{mi} + T_{mo})/2 \tag{7}$$

The arithmetic mean temperature of working medium

$$T_w = (T_{wi} + T_{wo})/2 \tag{8}$$

Average value

$$T = (T_m + T_w)/2 \tag{9}$$

The mean temperature of tube wall is close to T. Suppose that mean temperature of tube wall is T_b.Logarithmic mean temperature difference between working medium and the tube wall is

$$\Delta t_{mm} = [(T_{mi} - T_b) - (T_{mo} - T_b)]/\ln\frac{(T_{mi} - T_b)}{(T_{mo} - T_b)} \tag{10}$$

The mean temperature of heat medium, or the qualitative temperature of convection heat transfer inside the tube

$$t_{mf} = T_b + \Delta t_{mm} \tag{11}$$

When temperature of water is t_{mf}, water's density is ρ_{mf}, and thermal conductivity is λ_{mf}, kinematic viscosity coefficient is γ_{mf} and Brand coefficient is P_{mf}.

The inside diameter of heat transfer tube is d_n, the flow sectional area of heat transfer tube

$$A = \pi(d_n/2)^2 \tag{12}$$

Suppose heat loss coefficient of system is 1.1 and heat for heating working medium from one working condition to another is Q_w.Then the flux of heat medium is

$$G_m = 1.1Q_w / c(T_{mi} - T_{mo}) \tag{13}$$

Mean rate of working medium flow is

$$v_m = G_m / \rho_{mf} A \tag{14}$$

Reynolds number [3] is

$$\mathrm{Re}_m = v_m d_m / r_{mf} \tag{15}$$

Nusselt number of helical coiled tubes inside [3] is

$$Nu_m = 0.023 \mathrm{Re}_m{}^{0.8} P_{mf}{}^{0.3}\left[1+10.3\left(2d_w / D_p\right)^3\right] \quad (16)$$

Flow heat transfer coefficient of tube inside is

$$h_m = Nu_m \lambda_{mf} / d_m \quad (17)$$

(4) Determination of the convection heat transfer coefficient of working medium and tube outer wall

Logarithmic mean temperature difference of working medium and tube wall is

$$\Delta t_{wm} = \left[\left(T_b - T_{wi}\right) - \left(T_b - T_{wo}\right)\right] / \ln \frac{\left(T_b - T_{wi}\right)}{\left(T_b - T_{wo}\right)} \quad (18)$$

Mean temperature of working medium, or the qualitative temperature of convection heat transfer outside the tube is

$$t_{wf} = T_b - \Delta t_{wm} \quad (19)$$

Under temperature t_{wf} of water, water's density is ρ_{wf}, and thermal conductivity is λ_{wf}, kinematic viscosity coefficient is γ_{wf} and Brand coefficient is P_{wf}.

Outside diameter of heat transfer tube is d_w, flow sectional area of working medium is

$$A = \pi\left(D_t / 2\right)^2 - \pi\left(D_p / 2\right)^2 \quad (20)$$

Set the flux of working medium to G_w, then mean rate of working medium flow is

$$v_w = G_w / \rho_{wf} A \quad (21)$$

Reynolds number is

$$\mathrm{Re}_w = v_w d_w / r_{wf} \quad (22)$$

Nusselt number of helical coiled tubes outside is

$$Nu_w = 0.26 \mathrm{Re}_w{}^{0.6} P_{wf}{}^{0.3} \quad (23)$$

Flow heat transfer coefficient of tube outside is

$$h_w = Nu_w \lambda_{wf} / d_w \quad (24)$$

(5) Determination of heat transfer coefficients *K*

$$K = 1/\left(\frac{1}{h_m} + \frac{\delta}{\lambda} + R_f + \frac{1}{h_w}\right) \quad (25)$$

In above equation, R_f is heat resistance of fouling of heat exchanger's sides, mainly scale, its thermal resistance $R_f = 1.8\times10^{-4} m^2 \cdot {}^{o}C / w$. δ / λ is thermal conductive resistance of heat transfer tube, it can be neglected because the thickness of heat transfer tube's wall δ is small and the thermal conductivity of copper tube is big.

$$K = 1/(\frac{1}{h_m} + R_f + \frac{1}{h_w}) \quad (26)$$

(6) Determination of heat exchange area

$$F = Q_m / K \cdot \Delta t_m \quad (27)$$

(7) Determination of heat transfer tube's length

Mean diameter of heat transfer tube is

$$d = (d_m + d_w)/2 \quad (28)$$

Desired length of heat transfer tube is

$$l = F / \pi \cdot d \quad (29)$$

(8) Determination of the number of helical coiled tube's turns

$$n = l / \pi \cdot (D_g + d_w) \quad (30)$$

According to the formula (30), coil turns n of heat exchange tube heat is 6.

(9) Estimation of heat medium heater power

When manufacturing factory of collectors hasn't special statements, working medium flow rate specified in GB/T4271 can be set at 0.02 $kg/m^2 \cdot s$ [1] according to the collectors area. Generally, testing area of most common collectors is less than 6 m^2. Temperature difference between two adjacent working condition can be set in 10 ~15 according to various season. Heat formula isas follows.

$$Q = Cm\Delta T = C\rho V\Delta T = \eta Pt \quad (31)$$

In above formula, Q is heat the working medium absorbed (J), C is working medium specific heat capacity (J / kg), ρ is working medium density (kg/m^3), V is the working medium volume (m^3), ΔT is working medium temperature change (℃), P is heater power of the heat medium (W), η is efficiency of the heat medium heater.

Heating power P of heat medium heater can be calculated by formula (31), $P = 7.3KW$ 。

If volume of the heat medium heater is very small, the temperature easily occur overshoot. If volume of the heat medium heater is very big, heating time is very long and water temperature is difficult to reduce when water temperature occurs overshoot. Therefore, volume of the heater is determined as 18L through comprehensive consideration. Considering heat loss coefficient of heat exchanger is 1.1, the necessary time heating heat medium from $20^o C$ to $95^o C$ is $t = 13\text{min}$ by calculation. By means of above equations, total test time and total weight of primary heating test system adopt primary water and semi-instantaneous heat exchanger can be calculated in table 2.

Table 2.Contrast of heater

main technical characteristics	Insulation heating water tank (250L)	Semi-instantaneous heat exchanger
Four working condition test total time	12min	113min
Total weight	Total weight of heater,mixing pump and working medium is 290kg	Total weight of heater and working medium is 40kg

4. Conclusion

The semi-instantaneous heat exchanger for mobile solar collectors test system can improve the test efficiency of 50%. At the same time, the small volume (30*L*) of the semi-instantaneous heat exchanger can solve the problem of lacking of space of the mobile solar test system. Floating spiral coil type semi-instantaneous heat exchanger that designed based on the logarithmic mean temperature difference method needs less coil turns of heat exchange tube. It only needs 6 laps.

References

[1] GB/T 4271-2007. Test methods for the thermal performance of solar collectors. Beijing: General Administration of Quality Supervision. Inspection and Quarantine of the People's Republic of China. 2007.
[2] Hongwei Wang. *The theoretical and experimental research new hot water supply system in cold region based on coupleed with the heating system*. Tianjin: Tianjin University of College of environmental science and engineering. 2011.
[3] Huasheng Zou, Li Zhong, Qin Wu. *Fluid Mechanics and heat transfer*. Guangzhou: The publisher of South China University of Technology. 2004; 8.
[4] He Tao, You Jun and Xu Li Xiang. Control system for a mobile platform in a test system of solar collectors based on state machine. *Applied Mechanics and Materials*.
[5] Xiaonian zheng, Qiaoyan Huang, Xiaoli Zhang, Li Xin. Solar heat collectors performance test system. *Acta Energiae Solaris Sinica*. 2004; 25(3): 278-282.
[6] Mingyun Li Yuning Zhong, Jiabao Cheng .A Closed-loop Temperature Control System for the Solar Energy Heat Collectors. *Advanced Materials Research Vols*. 2013; 608-609: 22-26.
[7] Hou Tao, Hong-xia Niu, Fan Duo-wang. Simulation and experiment study of optimizational PID control with changing integration rate. Indonesia *Journal of Electrical Engineering*. 2012; 11(1).
[8] Meizhong Shi, Zhongzheng Wang. The design and principle of heat exchanger. Nanjing: Southeast University Press.1996.
[9] Fan Liping, Zhang Jun, Huang Xing, Huang Dong. The design of the MISO Model Predictive Controller for Bioreactor. *Indonesia Journal of Electrical Engineering*. 2012; 10(6).
[10] Ruifang Duan: Thermal performance testing system about solar collector. Wuhan: Huazhong University of Science and Technology, 2003.