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Analysis of thermal performance for parabolic trough solar collector

The heat transport process of parabolic trough solar collector is analyzed, and the mathematical model of heat transport is established. The contrast made our calculation of model with result of experiment of LS-2 collector, through contrast test and correction, temperature of fluid outlet had a maximum error of 0.56%. Meanwhile, some factors in account of influence fluid outlet temperature and thermal efficiency are analyzed, which including solar radiation intensity, fluid volume and the diameter of metal tube.There are three obvious relationships: with the increase of solar radiation intensity, outlet temperature increase continuously, but the change of thermal efficiency is insidious; with the increase of volume of fluid, outlet temperature keeps declining, efficiency continues to rise, but the increasement tend to be gentle; with the increase of the diameter of metal tube, both temperature and efficiency are decline, but the change of temperature are subtle.

Keywords: Parabolic trough solar collector, instantaneous efficiency, fluid outlet temperature, heat transport

1. Introduction

Parabolic trough solar collector is a kind of high efficiency solar thermal collector, which is used widely in the area of solar thermal-generated electricity, material drying and desalination. As a core part of the process of photo thermal conversion, its performance will influence whole system directly[1]. The research and analysis of heat transfer is the key technology of parabolic trough solar collector, we could improve the thermal efficiency of it by study the regulation of heat transfer and the performance of component of it, which also provide us the theoretical basis of design and manufacture of the collector.

Currently, research of parabolic trough solar collector mainly concentrated in the aspect of overall heat loss. The heat losses are analyzed by testing the thermal performance of collector in document[2]. The effect of heat losses caused by air velocity, temperature, selective coating and annular space are researched with different types of collector tube in document[3-4]. And many researchers contribute papers in the thermal efficiency of collector, but most of them probably cannot take all factors in account[5,6] or cannot establish a relatively easy model[7].

This paper analyzes the heat transport process and establish the mathematical model of parabolic trough solar collector, and study the effect of temperature of fluid outlet and thermal efficiency caused by the factor that including solar radiation intensity, air velocity, the diameter of heat-absorbed pipe and the split distance of solar concentrator, which provide us a theoretical reference for optimization and practicability of collector.

2. Heat transport model of parabolic trough solar collector

2.1. Structure and principle

The collector is composed of four parts, they are parabolic mirror, vacuum tube system, metal supporting mechanism and drive mechanism. Vacuum tube system is an important part of the process of photo thermal conversion, which consists of two parts: the metal absorption tube that is coated with selective absorption coating in surface and the glass tube that is coated with an anti-reflection coating that enables sun light through it. The annular space between glass and metal is pumped into vacuum. The vacuum tube is right in focal line of mirror, absorbing the light reflected from mirror.

The sun light passes through the opening of mirror, with reflected by mirror, gathering in the tube on focal line. Most light reaches metal tube by glass, the temperature of tube will be increasing with solar radiation is absorbed by metal, meanwhile, the metal makes convection heat transfer to working fluid by heat transport of metal pipe wall, and finally, the power of solar radiation is turned to thermal energy of working fluid.

2.2. Model of heat transport

With the heat transfer between the metal tube and bracket is ignored, establishes the equation of heat balance of each parts according to the first law of thermodynamics.

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(1) Heat balance equation of working fluid

$$\rho_f q_v c_p (T_o - T_i) = \pi D_2 L h_{21} (T_2 - T_1)$$

Among them, ρ_f is the density of working fluid; q_v is the flow mass on working fluid; c_p is the specific heat at constant pressure; T_0 is the outlet temperature of fluid; h_{21} is the coefficient of convection heat transfer; D_2 is the inside diameter of metal tube; L is the length of thermal-collecting tube; T_1 is the average temperature of working fluid; T_2 is the inner wall temperature of metal tube.

(2) Heat balance equation of metal inner wall

Internal wall of metal absorbs the thermal energy from external by heat conduction, then transmitted the energy to working fluid by heat convection.

$$\pi D_2 h_{21} (T_2 - T_1) = \frac{2\pi k_{32} (T_3 - T_2)}{\ln \frac{D_3}{D_2}}$$

Among them, k_{32} is the thermal conductivity of metal tube; T_3 is the external wall temperature of metal tube; D_3 is the outside diameter of metal tube.

(3) Heat balance equation of metal outer wall

Part power of solar radiation absorbed in metal tube passes to the inner wall of the metal tube by heat conduction, and another part makes heat transfer with internal wall of glass tube by the way of convection and radiation.

$$IA_m \eta_{opt} = \frac{2\pi k_{32} (T_3 - T_2)}{\ln \frac{D_3}{D_2}} + \pi D_4 h_{34} (T_3 - T_4) + \frac{\sigma \pi D_3 (T_3^{\ 4} - T_4^{\ 4})}{\frac{1}{\varepsilon_2} + \frac{D_3}{D_4} (\frac{1}{\varepsilon_4} - 1)}$$

Among them, I is the direct radiation; A_m is the opening width of the parabolic trough; η_{opt} is the optical efficiency of concentrator; h_{34} is the is the coefficient of convection heat transfer between metal and glass; T_4 is the inner wall temperature of glass tube; D_4 is the is the inside diameter of glass tube; ε_2 is the emissivity of metal tube; ε_4 is the emissivity of glass tube.

(4) Heat balance equation of glass inner wall

The internal wall of glass transmitted thermal energy to external by heat conduction.

$$\frac{2\pi k_{45} (T_4 - T_5)}{\ln \frac{D_5}{D_4}} = \pi D_4 h_{34} (T_3 - T_4) + \frac{\sigma \pi D_3 (T_3^{\ 4} - T_4^{\ 4})}{\frac{1}{\varepsilon_2} + \frac{D_3}{D_4} (\frac{1}{\varepsilon_4} - 1)}$$

Among them, k_{45} is the thermal conductivity of glass tube; T_5 is the external wall temperature of glass tube; D_5 is the outside diameter of glass tube.

(5) Heat balance equation of glass outer wall

There are two way of heat transfer between outer wall of glass tube and outside air, respectively, convective and radiative transfer.

$$\frac{2\pi k_{45} (T_4 - T_5)}{\ln \frac{D_5}{D_4}} = \pi D_5 h_{56} (T_5 - T_a) + \sigma \pi D_5 \varepsilon_4 (T_5^{\ 4} - T_{sky}^{\ 4})$$

Among them, h_{56} is the coefficient of convection heat transfer between air and glass tube; T_a is temperature of environment; T_{sky} is the temperature of sky.

(6) Instantaneous thermal efficiency

The definition of instantaneous thermal efficiency of collector is the ratio of useful energy of fluid to the solar radiation absorbed by collector[8].

$$\eta = \frac{\rho_f q_v c_p (T_o - T_i)}{IA_m L}$$

3. Process of solve and verify of heat transport model

The six parameters need to be solved in the mathematical models of collector, respectively, the outlet temperature of fluid, the external and inner wall temperature of glass tube, instantaneous thermal efficiency, the external and inner wall temperature of metal tube. Fsolve of MATLAB can be used to solve that six non-linear algebraic equation. With the least-square method, Fsolve have the characteristic of fast convergence speed and small error, which can provide us a more accurate solution.

3.1. Parameter of model

We verify the correctness of MATLAB solution with LS-2 collector, and the parameter of LS-2 collector are as indicated in Table 1.

Table 1. Main parameter of model

Name	Value	Name	Value
I.D of Heat pipe	66mm	Length of Heat pipe	7.8m
O.D of Heat pipe	70mm	Width of collector	5m
I.D of glass tube	111mm	Optical efficiency for collector	0.75
O.D of glass tube	115mm	glass emissivity of external wall	0.9

3.2. Comparation between calculated results and measured results

With measured results compared to calculated results, the result of comparision is in Table 2.

With a high similarity between measured results and calculated by Fsolve, we can draw conclusion that our model is accurate, which can achieve a higher precision requirements.

Table 2. Comparation results between calculated and measured

Radiation intensity (w/m²)	Wind speed (m/s)	Temperature of air (°c)	Volume of fluid (l/min)	Imported temperature (°c)	Outlet temperature (°c)		Relative error (%)
					Measured	Calculated	
933.7	2.6	21.2	47.7	102.2	124.0	124.7	0.56
968.2	3.7	22.4	47.8	151.0	173.3	174.1	0.46
982.3	2.5	24.3	49.1	197.5	219.5	220.1	0.27
909.5	3.3	26.2	54.7	250.7	269.4	269.2	0.07
937.9	1.0	28.8	55.5	297.8	316.9	316.3	0.19
880.6	2.9	27.5	55.6	299.0	317.2	316.3	0.28
920.9	2.6	29.5	56.8	379.5	398.0	396.5	0.38
903.2	4.2	31.1	56.3	355.9	374.0	372.9	0.29

4. Factor analysis of thermal properties for collector

4.1. Influence of solar radiation intensity to properties of collector

Fig. 1 shows that the variation curve of outlet temperature of fluid and thermal efficiency when solar radiation intensity is changing. We can draw conclusion from Fig. 1 that: with the increase of solar radiation intensity, both outlet temperature and thermal efficiency increase continuously, but the rising extent of thermal efficiency tend to be gentle with the increase of solar radiation intensity, although the energy of fluid absorbed are rising, both the radiation intensity of external glass wall and loss caused by heat transfer are increasing with rising temperature of glass wall, which account for the gentle change of thermal efficiency.

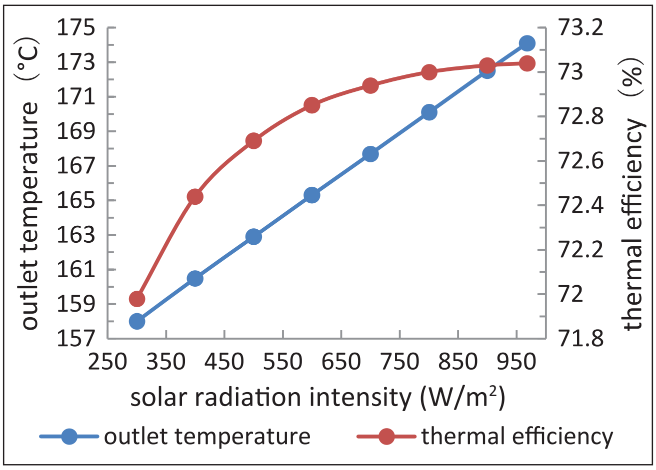

Fig. 1: Influence of solar radiation intensity to properties of collector

4.2. Influence of fluid volume to properties of collector

Fig. 2 shows that the variation curve of outlet temperature of fluid and thermal efficiency when fluid volume is changing. We can draw conclusion from Fig. 2 that with the rising of fluid volume (flow velocities), outlet temperature of fluid is decreasing. At the beginning of the increasing of the flow velocities, the range of temperature between the inlet and outlet is obvious, efficiency of collector increases dramatically. With the outlet temperature decreasing, that range of temperature diminishes, which account for the gentle change of the average temperature of fluid in tube, meanwhile, diminishes the loss of convection heat transfer and the thermal efficiency of collector tends to be stable.

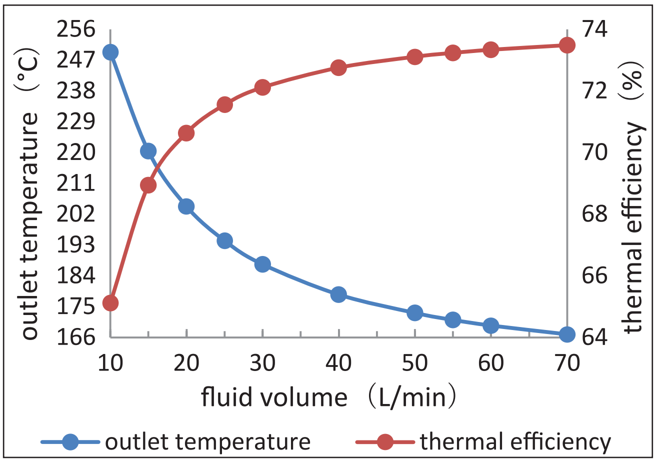

Fig. 2: Influence of fluid volume to properties of collector

4.3 Influence of inside diameter of metal tube to properties of collector

Fig. 3 shows that the variation curve of outlet temperature of fluid and thermal efficiency when inside diameter of metal tube is changing. We can draw conclusion from Fig. 3 that: with the increase of inside diameter, outlet temperature of fluid is slightly decreasing. The flow velocities will decrease and the temperature of metal tube will increase. While we enlarge the inside diameter and stabilize volume of fluid, which accounts for a sufficient heat transfer between metal and glass, meanwhile, more loss of thermal energy, lower thermal efficiency.

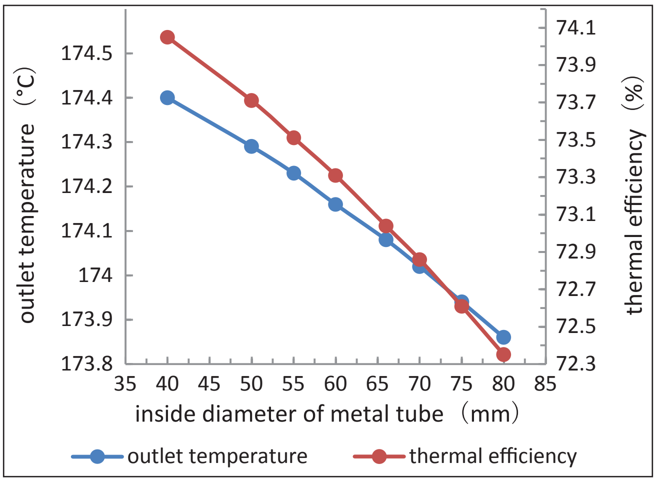

Fig. 3: Influence of inside diameter of metal tube to properties of collector

5. Conclusions

This paper analyzes the heat transport process and establish the mathematical model of parabolic trough solar collector, and we solve the model by Fsolve function of MATLAB, our conclusions are as follows.

(1) By making contrast of result between calculated MATLAB and the measured, temperature of fluid outlet had a maximum error of 0.56%. That means our model is accurate. Fsolve have the characteristic of fast convergence speed and small error, which can achieve a higher precision requirements in performance simulation.

(2) When the other parameters are constant, with the increase of solar radiation intensity, outlet temperature increases continuously, but the change of thermal efficiency is insidious; with the increase of volume of fluid, outlet temperature keeps declining, efficiency continues to rise, but the increasement tend to be gentle; with the increase of the diameter of metal tube, both temperature and efficiency are declining, but the change of temperature are subtle.

Acknowledgements

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RELATIONSHIP BETWEEN FRACTAL DIMENSION AND SHEAR STRENGTH OF VERTISOLS AND RED EARTH

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