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Performance analysis of a new-design filled-type solar collector with double U-tubes

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ABSTRACT

In order to eliminate the influence of thermal resistance between the absorber tube and the copper fin of the conventional evacuated solar collector, which would decrease the thermal performance of the evacuated tube collector, a filled-typed evacuated tube with single U-tube (SUFET) was presented in our previous work, in which the filled layer was used to transfer energy absorbed by the working fluid flowing in the U-tube. In this paper an improved filled-type evacuated tube with double U-tubes (DUFET) was presented by means of theoretical analysis and experimental study to increase the heat transfer area and then improve the heat transfer efficiency of collectors. The structure of filled-type evacuated tube with double U-tubes was given first, and then the thermal performance of filled-type evacuated tube with double U-tubes was studied in both theory and experiment. The experimental results showed the feasibility and validity of this design. Finally, a comparative study between SUFET and DUFET was given at the same working conditions.

1. Introduction

The thermal efficiency of solar collectors is one of the most vital parameters of the solar collectors, and then the thermal performance of the solar collectors is the foundation for further spread of the solar thermal utilization. At present, the flat-plate solar collectors and the evacuated tube solar collectors are the main two kinds of solar collectors, which have been used in architectural field widely. However, evacuated tube solar collectors exhibit better performance than the flat-plate solar collectors, in particular for under high temperature operation. Furthermore, heat extraction manifold designs of single-ended evacuated tubes include simple fluid-in-glass and fluid-in-metal designs, such as heat pipes and a U-tube inserted into the tube.

Several studies on the thermal performance of heat pipe solar collectors were presented in the literatures [1–11]. The thermal performance of the heat-pipe solar collectors was studied in both theory and experiment [1–3], in which the evaporator section of collector was consisted of heat pipes with two layers of 100-mesh stainless steel screen fitted. Furthermore, the optimum ratio of the heated length-cooled length of the pipe was also discussed. A new closed-loop, oscillating, heat pipe evacuated tube solar collector had been designed by Rittidech et al. [4,5], which had the advantages of corrosion-free operation and the elimination of the winter icing problem. Nkwetta et al. presented a combined low-concentrator augmented solar collector in an array of evacuated tube heat pipe solar collectors, and the optical performance evaluation of internal concentrated evacuated tube heat pipe collectors was reported. And then the performance of an evacuated tube heat pipe solar collector compared to a concentrated evacuated tube single-sided coated heat pipe absorber for medium temperature applications had been studied [6–8]. In paper [9,10], the thermal performance of a thin membrane heat pipe solar collector and hybrid heat pipe solar collector/CHP system were studied to provide electricity and heating for a building.

Vacuum environment was a crucial requirement in the heat pipe to obtain higher thermal efficiency [11]. In fact, maintaining a vacuum environment was very difficult due to the production of non-condensable gases in the heat pipe, especially, when the system was operating. However, the U-tube evacuated tube solar collectors could overcome the flaw, which was caused by the structure of heat pipe evacuated tube solar collector. Furthermore, the heat transfer of the U-tube evacuated tube was more effective due to the U-tube evacuated tube overcame the drawback that the thermal efficiency decreased with the increase of cycle numbers of working fluid [12].

The researches of the U-tube evacuated tube solar collectors were currently available. The thermal performance model of the evacuated tube solar collector with a U-shaped fluid channel was established in paper [13], besides that, the temperature distribution of fluid in the U-tube and the effect of the maximum shift of temperature from the central line of the U-tube are studied.

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Nomenclature

A_c	the outer surface area of the absorber tube, m^2
C	thermal resistance, m K/W
C_{pf}	water specific heat at constant pressure, J/kg K
F'	efficiency factor
I_T	incident solar irradiance, W/m^2
L_u	the length of the U-tube
M	mass flow rate of working fluid, kg/s
Q_L	thermal loss, W
Q_u	net heat energy absorbed by the working fluid, W
T	temperature, K
U_t	the heat loss coefficient of the evacuated tube, $W/(m^2 K)$
U_L	the overall loss coefficient, $W/(m^2 K)$
Greek	
$(\tau\alpha)_e$	transmittance-absorbance product
η_i	solar collector efficiency
λ_c	conductivity of the heat transmission component
Subscripts	
i	location at the U-tube inlet
o	location at the U-tube outlet
a	ambient
f	working fluid
g	the surface of the outer glass tube
p	the outer surface of the absorber tube
c	the inner surface of the absorber tube
u	U-tube

The researchers gave a series of experiments in quasi-dynamic conditions to test the efficiency of the U-tube evacuated tubular collector following the standard EN 12975-2 [14]. Solar collector performance was studied numerically by Kim and Seo to find out the best shape for the absorber tube [15], the results showed that the U-tube collector is presenting better performance compared to other three signal-type collectors taking into account the influence of diffuse radiation and sunshade between the adjacent collectors. In order to enhance heat transfer from the absorber tube to the working fluid and reduce the heat loss of evacuated tube, Diaz developed mini-channel-based evacuated tube solar collectors. The results showed that the efficiency of the mini-channel tube can be improved approximately 5% compared to the standard U-tube collector [16]. The effect of the air gap between the absorber tube and copper tube on the thermal performance of the U-tube evacuated tube solar collector was studied by Ma et al. [17]. Furthermore, Liang et al. had studied the thermal performance of the filled-type evacuated tube with U-tube and the copper fin evacuated tube with U-tube by theoretical and experimental methods based on paper. The results showed that the thermal performance of the filled-type evacuated tube is 12% higher than that of the copper fin evacuated tube [18].

During the research, the authors found that the heat transfer area was a key factor for the efficiency of filled-type evacuated tube with U-tube (UFET). The thermal performance of UFET became higher along with the increment of heat transfer area under the same condition of quantity of flow. Therefore, a filled-type evacuated tube with double U-tubes (DUFET) is presented in this paper to improve the heat transfer efficiency of collectors. The rest of this paper is organized as follows. In Section 2, the description of theoretical modeling of the collector is given. In this part, the heat transfer model and analytic solution of dimensionless model are given after designing of the structure of DUFET. Section 3 constructs the experimental platform for thermal performance of evacuated tube. The test results and further discussion are presented in Section 4. Finally, Section 5 concludes the paper.

2. Theoretical modeling of the collector

2.1. Description of DUFET

Fig. 1 illustrates the structure of the filled-type solar collector vacuum tube with double U-tubes. The U-tubes in the vacuum tube are communicated with the delivery pipe and the collector pipe, as is shown in Fig. 1. The pipes of the U-tube are centrosymmetric distribution, where tubes numbered 1 and 3 are connected with delivery pipe, 2 and 4 are connected with collector pipe. At this context, the working fluid flows into the U-tube firstly though connector pipe which is shown as left side in Fig. 1(b), and then dividing one into two by the delivery pipe enters into 1 and 3 pipes. The working fluid mixes two into one from pipes 2 and 4 after absorbing solar energy and changing into thermal energy, and gathers together into connector pipe, finally.

The physical model and the thermal network of the DUFET are as shown in Fig. 2. Where T_a is ambient temperature, T_g is the surface temperature of the outer glass tube, T_p is the outer surface temperature of the absorber tube, T_c is the inner surface temperature of the absorber tube, T_{fi} and T_{ui} are the fluid temperature and the surface temperature of the U-tube, respectively. The heat transfer process of the DUFET is that, the incident solar irradiance is absorbed by the selective absorbing coating after passing through the outer glass tube. During this transfer process, some energy absorbed by the absorber is lost, owing to the radiation, convection and conduction between the absorber and ambient environment, which is called Q_L. On the other hand, the energy conducted by the filled layer and U-tube to the working fluid is the real obtained energy, which is called Q_u. Specifically, the contact thermal resistance between the filled layer and U-tube can be negligible because the gap between layer and the surface of the absorber tube is filled with conduction oil.

2.2. Heat transfer model

According to the energy balance equations, the net heat gain absorbed by the working fluid is equal to the difference between the energy absorbed by the absorbing coating and the energy lost to the environment.

$$Q_u = A_c[I_T(\tau\alpha)_e - U_L(T_p - T_a)] = MC_{pf}(T_o - T_i) \quad (1)$$

where I_T is the incident solar irradiance, A_c is the outer surface area of the absorber tube, M is the mass flow rate of working fluid, C_{pf} is the water specific heat at constant pressure, T_i and T_o are the inlet and outlet temperature of the U-tube, respectively.

The pipes numbered 1 and 3 of the U-tube are the inlet pipes of the DUFET, and the corresponding pipes numbered 2 and 4 are the outlet pipes. According to the symmetry and the law of energy conservation, the energy balance equation of the pipes can be written in the following form:

$$\begin{cases} q_{u1} = q_{u3} = MC_{pf}(T_{mid} - T_i) \\ q_{u2} = q_{u4} = MC_{pf}(T_o - T_{mid}) \end{cases} \quad (2)$$

where q_{ui} ($i = 1, 2, 3, 4$) are the heat gain absorbed from the working fluid in the pipes, T_{mid} is the working fluid temperature in the center of U-tube.

The steady-state energy balance equation is established to calculate the temperature variation of the working fluid in the flow direction. Fig. 3 shows the energy balance relationship of each part.