Applied Energy 116 (2014) 159–166

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

Influence of the receiver's back surface radiative characteristics on the performance of a heat-pipe evacuated-tube solar collector

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HIGHLIGHTS

- A model for describing the heat transfer characteristics of the ETSC is derived.
- A method by performing roughness treatment is proposed to change the emissivity.
- Increasing the receiver's back surface emissivity can greatly affect the heat loss.
- Real weather test verifies the proposed method in controlling overheat phenomenon.

ARTICLE INFO

Article history:
Received 18 July 2013
Received in revised form 26 September 2013
Accepted 22 November 2013
Available online 13 December 2013

Keywords:
Evacuated-tube solar collector (ETSC)
Receiver's back surface
Roughness treatment
Emissivity
Heat loss

ABSTRACT

The receiver's back surface radiative characteristics of a heat-pipe evacuated-tube solar collector (ETSC) may have a significant influence on its performance. This influence is generally related to the back surface emissivity and temperature; however it has been not studied previously. This paper firstly presents a heat transfer model for the ETSC, which is then derived to characterize the relationship between the heat loss and the back surface emissivity of the ETSC. A steady state experiment has been also performed to measure the heat loss of ETSC with different back surface emissivity values. The experimental results indicate that the heat loss of the ETSC increases with the increase of the back surface emissivity, but the rate of increase differs for different operation temperatures. When the back surface emissivity increases from 0.03 to 0.12, the heat loss of ETSC only increases by 31% when the operation temperature is below 100 °C, but the heat loss will increase to 96% when the operation temperature is over 200 °C. This means that the change of back surface emissivity can significantly affect the performance of the ETSC at higher temperature but affect little at lower temperature. Based on this, a novel method by performing roughness treatment on the receiver's back surface is proposed to solve the overheating problem of ETSC in summer. Two solar water heaters including 6 ETSCs with standard and roughness-treated tubes were tested under real weather condition. Experiment reveals that when the water temperature in tank is below 60 °C, the two solar water heaters own similar temperature change. But when the temperature is over 80 °C, the solar water heater with roughness-treated tube shows obviously lower temperature increase than that with standard tube. Therefore, it is very effective to prevent overheating of some solar water heaters used in high latitudes in summer by increasing the receiver's back surface roughness.

1. Introduction

Solar energy collection has been studied for many years and many solar collector designs have been presented [1–3]. Heat-pipe evacuated-tube solar collectors (ETSCs) have been getting popular, due to its advantages of high collection efficiency, pressure-bearing and anti-freezing [4]. For an ETSC, the solar receiver plate is coated with a membrane with high absorptivity and low emissivity, which can greatly reduce the heat loss of the receiver. In addition, solar heat is transferred to the water tank by heat pipes with their evaporation section placed inside the evacuated tube to minimize heat loss by convection and conduction, thus the ETSC generally owns excellent performance, even in the cold weather zone in winter [5–7]. However, for some high latitudes in summer, the daytime is very long and solar radiation is very intensive, but the heat requirement is relatively limited, which will cause the problems of high water temperature in tank and high pressure of working medium in the heat pipe. These problems will further affect the service life of the ETSC, or even result in some serious issues, e.g., water tank break [8]. Therefore, on one hand, it is important to investigate how to increase the efficiency and reduce heat loss in the ETSC. On the other hand, in order to maintain high efficiencies

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0306-2619/$ - see front matter
http://dx.doi.org/10.1016/j.apenergy.2013.11.051

Nomenclature

A_b area of the receiver (m^2)
$A_{g,o}$ area of the outer surface of the glass tube (m^2)
P_{heater} heating power of the resistance heater (W)
$Q_{cond,gf}$, $Q_{cond,gb}$ conduction heat transfer rate through the front and back of the glass tube, respectively (W)
$Q_{conv,gf\text{-}a}$, $Q_{conv,gb\text{-}a}$ convective heat transfer rate from the front and back outer surfaces of the glass tube to the environment, respectively (W)
$Q_{h\text{-}end\text{-}a}$ heat loss through the end (W)
$Q_{h\text{-}g\text{-}a}$ heat loss through the glass tube (W)
Q_{loss} total heat loss of the ETSC (W)
$Q_{r,bf\text{-}g}$, $Q_{r,bb\text{-}g}$ radiative heat transfer rate of the front and back surfaces of the receiver to the inner surface of the glass tube, respectively (W)
$Q_{r,gf\text{-}sky}$, $Q_{r,gb\text{-}sky}$ radiative heat transfer rate of the front and back outer surfaces of the glass tube to the sky, respectively (W)
$Q_{r,p\text{-}g}$ radiative heat transfer rate of the copper tube of the evaporation section to the inner surface of the glass tube (W)
T_1, T_2, T_3 temperature of the inner surface of the copper tube located at 1.6 m, 0.95 m and 0.4 m distance to the end of the heater, respectively (K)
T_b temperature of the receiver (K)
$T_{gf,o}$, $T_{gb,o}$ temperature of the front and back outer surfaces of the glass tube, respectively (K)

Greek
ε_{bf}, ε_{bb} emissivity of the front and back surfaces of the receiver, respectively
ε_g emissivity of the glass tube
σ_i ($i = 2 \sim 7$) receiver's back surface roughness of tubes i
ε_i (i=2 $\sim$ 7) receiver's back surface emissivity of tubes i

in the low temperature range, it is necessary to avoid overheating in the high temperature range under some special conditions. This becomes very important especially when the ETSC is used for heat water production in high latitudes. For example, to satisfy the heating requirement in winter, more collection area is needed, which will generate too much and too hot water in summer. This not only increases the burden to users, but also increases the potential safety hazard. So, for the ETSC, it is also urgently needed to decrease the heat efficiency by increasing heat loss when the working temperature goes too high [9].

To prevent the overheating problem of an ETSC, some measures have been proposed, i.e., increasing the water tank volume, adding sunshade or heat dissipation equipments, draining recycling medium [8,10,11]. However, these measures have some problems, e.g., high cost, low water temperature in winter, inconvenient operation, which limits the application of these methods.

Considering those disadvantages, this paper proposes a novel method to solve the overheating problem of an ETSC. That is to perform roughness treatment on the receiver's back surface of the ETSC to increase the emissivity of the back surface, hence increasing heat loss under overheating condition. Moreover, the presented method can effectively control the stagnation temperature in the situation without a water flow, so as to prolong the service life and reduce the manufacturing cost of an ETSC.

This paper focuses on studying the methods of increasing or decreasing the heat loss of ETSC by changing the receiver's back surface emissivity, and validates that it can effectively and selectively increase the emissivity by performing roughness treatment on the receiver's back surface, while the radiative heat loss can be reduced by adding sunshade plate. This paper firstly develops a heat transfer model to describe the heat loss of an ETSC to obtain the relationship between the heat loss and operation temperature for different back surface emissivity values. Then, the heat loss results from the model predictions and experiments are compared and analyzed. In addition, a real weather test for two solar water heaters comprising 6 ETSCs with the standard or roughness-treated receivers is performed to illustrate the role of the back surface emissivity to prevent the overheating problem of the ETSCs.

2. Heat transfer model of the ETSC

2.1. Structure and operation principle of the ETSC

The structure of an ETSC is schematically shown in Fig. 1. It is comprised of a heat pipe, a metal absorber plate or receiver (4), a glass tube (5), an end cover (2) and a spring holder (6). The heat pipe includes two sections, i.e., the condensation section (1) and the evaporation section (3). The metal receiver is fastened inside the glass tube by the spring holder.

When the ETSC works, solar radiation firstly penetrates through the glass tube and cast on the receiver. Then, the receiver absorbs the solar radiation and transforms it into heat, and subsequently transfers heat into the evaporation section in the middle of the receiver plate by conduction, making the liquid medium inside the evaporation section evaporate immediately. Following that, the vapor medium rises to the condensation section and releases heat to the other medium in the solar collector (water or oil), in the meantime the condensed medium inside the heat pipe flows back to the evaporation section by virtue of gravity. The above process repeats when the ETSC is used in practice. Vacuum condition is maintained inside the glass tube, so the heat loss due to conduction and convection can be regarded as negligible.

2.2. Heat transfer model of the ETSC under the steady state condition

To study the influence of the receiver's back surface emissivity on the performance of the ETSC, a simplified ETSC model was employed, in which the heat pipe was assumed to be a constant temperature heat source such as a resistance heater uniformly distributed along the axis of the receiver. When the temperature of the receiver is stable, i.e., the steady state is reached, the heat release by the receiver is equal to the heat loss of the ETSC [12,13]. The similar method is applied by the NREL (National Renewable Energy Laboratory) of America [14–16], thus being also adopted here.

Fig. 2 shows the heat transfer process when resistance heater is applied to heat the ETSC. For the heat transfer model in the present study, the assumptions made include: (1) the ETSC reaches steady

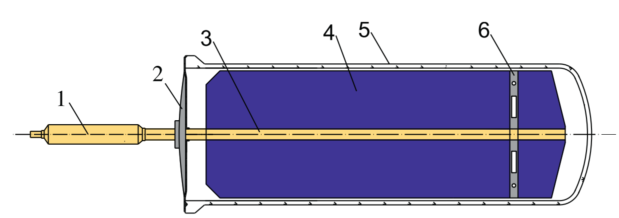

Fig. 1. Schematic structure of a heat-pipe evacuated-tube solar collector (ETSC).