Available online at www.sciencedirect.com

ScienceDirect

Solar Energy 85 (2011) 1735–1744

Solar Energy

www.elsevier.com/locate/solener

Theoretical and experimental investigation of the filled-type evacuated tube solar collector with U tube

Ruobing Liang, Liangdong Ma, Jili Zhang *, Dan Zhao

Faculty of Infrastructure Engineering, Dalian University of Technology, Dalian 116024, China

Received 17 June 2010; received in revised form 8 March 2011; accepted 12 April 2011
Available online 26 May 2011

Communicated by: Associate Editor Brian Norton

Abstract

The filled-type evacuated tube with U-tube, in which the filled layer is used to transfer energy absorbed by the working fluid flowing in the U-tube, is proposed to eliminate the influence of thermal resistance between the absorber tube and the copper fin of the conventional evacuated solar collector. In this paper, the thermal performance of the filled-type evacuated tube with U-tube was researched by means of theoretical analysis and experimental study. The temperature of the working fluid in the flow direction was obtained, and the efficiency of the evacuated tube was also calculated, based on the energy balance equations for the working fluid in the U-tube. The effects of the heat loss coefficient and the thermal conductivity of the filled layer on the thermal performance of the evacuated tube were studied. In addition, the test setup of the thermal performance of the filled-type evacuated tube with U-tube was established. The evacuated tube considered in this study was a two-layered glass evacuated tube, and the absorber film was deposited in the outer surface of the absorber tube. The results show that the filled-type evacuated tube with U-tube has a favourable thermal performance. When the thermal conductivity of the heat transmission component is $\lambda_c = 100$, the efficiency of the filled-type evacuated tube with U-tube is 12% higher than that of the U-tube evacuated tube with a copper fin. The modelling predictions were validated using experimental data which show that there is a good concurrence between the measured and predicted results.

Keywords: Filled-type; Evacuated tube; U-tube; Theoretical analysis; Experimental study

1. Introduction

Evacuated tube solar collectors exhibit better performance than flat-plate solar collectors, in particular for high temperature operation. Therefore, the glass evacuated tube is gradually becoming the key component in solar thermal utilization such as the solar water heating system. Over the past several decades, different types of evacuated tube solar collectors have been discussed in many research papers (Rahman et al., 1984; Sawhney and Bansal, 1987; He et al., 1997; Morrison et al., 2005; Budihardjo and Morrison, 2009; Shah and Furbo, 2007; Kim et al., 2007; Han et al., 2008; Azad, 2008, 2009; Rittidech et al., 2009; Kim and Seo, 2007; Diaz et al., 2008; Badran et al., 2008; Ma et al., 2010). Optimal operating conditions, manifold designs, optical design, solar collector tubes array, heat transport in solar collector tubes and performance evaluations of solar collectors, etc., have been studied. And the major difficulty with the application of the evacuated tube solar collector is to extract heat from the evacuated tube (Morrison et al., 2005). At present, 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.

The low manufacturing cost and high thermal efficiency of the fluid-in-glass collector give it a wide market. In this system, the fluid in the tubes is heated by solar irradiance. Morrison et al. performed an experimental and numerical investigation to evaluate the rate of natural circulation in

* Corresponding author. Tel./fax: +86 411 87407753.
E-mail address: zhangjili@hit.edu.cn (J. Zhang).

0038-092X/$ - see front matter © 2011 Elsevier Ltd. All rights reserved.
doi:10.1016/j.solener.2011.04.012

Nomenclature

A_c	the outer surface area of the absorber tube, m^2
A_p	the sunshine area of the evacuated tube, m^2
C_p	water specific heat at constant pressure, J/kg K
D	half the distance of the two pipes of the U-tube, m
h	the heat transfer coefficient, W/(m K)
I_T	incident solar irradiance, W/m^2
L	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
r	radius, m
R	thermal resistance, m K/W
T	temperature, K
U_t	the heat loss coefficient of the evacuated tube, $W/(m^2 K)$
U_L	the overall loss coefficient, $W/(m^2 K)$
U_e	the heat loss coefficient of the header tube, $W/(m^2 K)$

Greek

ε_p	the emissivity of the selective absorbing coating
$(\tau\alpha)_e$	transmittance-absorbance product
η	solar collector efficiency
λ_c	conductivity of the heat transmission component
λ_u	conductivity of the copper tube
λ	conductivity of air layer
h_{ga}	the heat transfer coefficient
h_{pgr}	the radiation heat transfer coefficient
h_{pgc}	the convection heat transfer coefficient

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

fluid-in-glass evacuated tubes (Morrison et al., 2005). Subsequently, Budihardjo and Morrison simulated the long-term performance of fluid -in-glass evacuated tube solar water heaters using transient system modelling (Budihardjo and Morrison, 2009). One-dimensional and three-dimensional analytical models were used to investigate the thermal performance of all-glass evacuated tubes with a coaxial fluid conduit inserted in the tube (Kim et al., 2007; Han et al., 2008). However, owing to the low pressure bearing capacity, the application of the fluid-in-glass evacuated tube has been restricted in a high temperature system. Moreover, frequent impact of cold and hot fluid causes cracking in the fluid-in-glass evacuated tube.

Currently, metal-in-glass collectors have been developed for high temperature and high pressure systems. They are attracting increasing attention to heat-pipe evacuated tube solar collectors because of their anti-freezing systems, rapid start-up, and easy installation (He et al., 1997). The thermal behaviour of the heat-pipe solar collectors is investigated by means of theoretical and experimental methods, and the optimum ratio of the heated length–cooled length of the pipe is also discussed (Azad, 2008, 2009). Rittidech et al. designed a closed-loop, oscillating, heat-pipe evacuated tube solar collector with the advantages of corrosion-free operation and the elimination of the winter icing problem, and investigated its thermal performance with an efficiency of about 76% (Rittidech et al., 2009). A good vacuum environment is required in the heat pipe to obtain higher thermal efficiency (Han et al., 2008). In fact, maintaining a vacuum environment is very difficult because of the production of non-condensable gases in the heat pipe when the system is operating. As a result, the thermal performance of the heat pipe and the operating life of the heat-pipe evacuated tube will be seriously affected (Rittidech et al., 2009).

The U-tube evacuated tube solar collector appears to be a well-developed, new type of collector. It has the advantages of high-pressure-bearing ability and simpler structure, compared with the all-glass evacuated tube and heat-pipe evacuated tube. Fig. 1 illustrates the evacuated tube with a U-tube inserted in the tube, and its cross section view. Research reports on the thermal performance of the evacuated tube solar collector with U-tube are currently available. (Sawhney and Bansal, 1987; Kim and Seo, 2007; Diaz et al., 2008; Badran et al., 2008; Ma et al., 2010). Sawhney et al. established the thermal performance model of the evacuated tube solar collector with a U-shaped fluid channel embedded in a flat absorber. The temperature distribution of fluid in the U-tube was studied, and the effect of the maximum shift of temperature from the central line of the U-tube was analysed (Sawhney and Bansal, 1987). Solar collector performance was studied numerically by Kim and Seo to find the best shape for the absorber tube (Kim and Seo, 2007). Diaz developed mini-channel-based evacuated tube solar collectors to enhance heat transfer from the absorber tube to the working fluid and reduce the heat loss of evacuated tube. The mini-channel with the same free flow area as a round tube was used in place of the U-tube. The results show that the efficiency of the mini-channel tube can be improved approximately 5%