ICEAIST-24
International Conference on Exploring AI, IOT, Science & Technology-24
ESP Journal of Engineering Technology Advancements / ISSN: 2583-2646

Original Article

Design & Modification of a Solar Thermal Collector to Evacuated Tube Solar Thermal Absorber

Abstract: *Evacuated-tube solar collector (ETSC) is developed to achieve high heating medium temperature. Heat transfer fluid contained inside a copper heat pipe directly affects the heating medium temperature. A 10 mol% of ethylene-glycol in water is the heat transfer fluid in this system. The purpose of this study is to modify inner structure of the evacuated tube for promoting heat transfer through aluminum fin to the copper heat pipe by inserting stainless-steel scrubbers in the evacuated tube to increase heat conduction surface area. The experiment is set up to measure the temperature of heat transfer fluid at a heat pipe tip which is a heat exchange area between heat transfer fluid and heating medium. The vapor/ liquid equilibrium (VLE) theory is applied to investigate phase change behavior of the heat transfer fluid. Mathematical model validated with 6 experimental results is set up to investigate the performance of ETSC system and evaluate the feasibility of applying the modified ETSC in small-scale industries. The results indicate that the average temperature of heat transfer fluid in a modified tube increased to 160.32 ◦C which is higher than a standard tube by approximately 22 ◦C leading to the increase in its efficiency by 34.96%. Keywords: evacuated tube; heat pipe tip; heat transfer fluid; stainless-steel scrubber*

Keywords: *Evacuated Tube; Heat Pipe Tip; Heat Transfer Fluid; Stainless-Steel Scrubber.*

INTRODUCTION

At present, pollution released from combustion in industries is one of main causes of environmental problems. To reduce the pollutant emission from the production of thermal energy, solar energy receives an increasing attention as a clean and abundant renewable source [1]. The evacuated-tube solar collector (ETSC) is a system used to absorb solar energy from radiation of the sun and convert into thermal energy. There have been several studies on the improvement of thermal performance of ETSC and the applications of the ETSC in industries. Ma et al. [2] studied the thermal performance of evacuated-tube solar collector with U-tube by analyzing a network of thermal resistances. They found that the efficiency of evacuated-tube solar collector with U-tube and exit fluid temperature would increase by 10% and 16%, respectively, if the thermal conductivity increased from 5 to 40 W/m·K. Some researchers tried to modify the inner structure of evacuated tube to reduce thermal resistance. Abd-Elhady et al. [3] improved performance of evacuated tube heat pipes by filling the gap between the heat pipe and inner wall of an evacuated tube with oil and foamed copper

The oil was added to store thermal energy supplied to the heat pipe after the sun set, and the foamed copper was used to enhance heat conduction. They found that the evacuated tube filled with oil and foamed copper could improve heat transfer rate causing the increase in its efficiency by 55.6%. Heyhat et al. [4] studied the effect of CuO/water nanofluid and copper metal foam as a solar absorber on the performance of direct absorption parabolic trough solar collector (DAPTSC). They Appl. Sci. 2021,11,4100. https://doi.org/10.3390/app11094100 https://www.mdpi.com/journal/applsci concluded that the combination of 0.1 vol% of CuO/water nanofluid and copper metal foam in solar collector tube provided the maximum temperature difference of working fluid by 16.3 ◦C. The thermal efficiency increased by 42.48%. Using of the combination of nanofluid and foam copper was better than using each one alone. Sarafraz et al. [5] used carbon nanoparticles dispersed in acetone as heat transfer fluid inside the evacuated tube to increase thermal performance of solar absorption cooling system

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The solar collector working with nanofluid achieved 91% of maximum thermal efficiency compared with conventional working fluid. Olia et al. [6] reviewed the influence of nanoparticles and base fluid type on the thermal efficiency, entropy generation and pressure drop of parabolic trough collectors (PTC). They found that copper nanoparticle and MWCNT nanoparticle that were metallic nanofluid and non-metallic nanofluid, respectively, could provide the highest enhancement of thermal efficiency. The addition of nanoparticle in nanofluid could provide higher thermal efficiency and exergy efficiency. Sarafraz et al. [7] evaluated the heat transfer coefficient of the gravity-assisted heat pipe containing graphene nanoplateletspentane nanofluid inside.

The graphene nanoplatelets-pentane nanofluid would promote the Brownian motion and thermophoresis effect which had a positive effect on heat transfer coefficient. The heat transfer coefficient of the system was improved to 5300 W/m2 ·K at 0.3 Wt.% of nanoparticles in base fluid.

Other studies about the improvement of evacuatedtube solar collector by using the nanofluid and metal foam for thermal absorber had shown similar associations [8–10]. In addition, Papadimitratos et al. [11] represented the improvement of evacuated-tube solar collectors performance by using phase change materials (PCM). Paraffin, their chosen PCM, was added in the tubes for storing the thermal energy supplied to heat pipe. The efficiency of the improved solar collectors increased by 26% compared with the standard one. Selvakumar et al. [12] filled the therminol D-12 oil as a heat transfer fluid in the evacuated-tube solar collector with parabolic trough. This design could increase hot water temperature from 40 ◦C to 68 ◦C under the low solar intensity condition and increase the thermal efficiency by 30%. Kim et al. [13] compared the effect of shape of absorber (fin), angle of tubes and arrangement of tubes on the performance of 4 models of evacuated-tube solar collector. They concluded that the shape of absorber was the most influential for the performance of the tube. U-tube welded inside a circular fin (model II) provided the best performance.

However, the incidence direction of solar radiation should be considered in the design of evacuated tube [14]. In the industry application part, Luu et al. [15] reported that the use of the evacuatedtube solar collector with 9 tubes to produce a 45 ◦C, 120 L of hot water per day in a domestic service could save 81.7% of fossil fuel compared with non-solar energy system. Al-Falahi et al. [16] found that the evacuated tube solar collector integrated with a gas boiler in an absorption cooling system could generate 57% of total thermal energy. Ghoneim [17] designed the 110 m2 of the evacuated-tube solar collector system to produce 4000 kg of hot water per day at 80 ◦C for the syrup preparation process in the soft drink industry. The annual lifetime saving was estimated as USD 900 per year. Isafiade et al. [18] reported that the integration of the evacuated-tube solar collector with the continuous multi-period heat exchanger in a chemical industry could reduce the total annual operating cost around USD 650,000 per year. Picón-Núñez et al. [19] evaluated the design of the evacuated-tube solar collector network in industry and reported that the number of tubes in series and parallel lines was defined by the target temperature and total mass flow rate, respectively.

Kotb et al. [20] introduced the optimal number of evacuated tube chart used to match the rise of hot water temperature at different water mass flow rate, inlet water temperature, and solar irradiance for facilitating solar absorption chillers. However, the effect of storage volume on storage temperature, the development of a predictive model aimed for industrial applications, and the combination of experimental and modeling works have been rarely investigated. The main objective of this work is to evaluate the effect of modifying the inner structure of commercial grade evacuated tubes to improve the ability to transfer heat absorbed from the sun radiation to heat the heat transfer fluid stored in the heat pipe using a cheap and readily available material like stainless-steel scrubbers In this study, the mechanistic ordinary differential equation model was set up and validated with the experimental results conducted from the 20-ETSC set at different heating medium volumes. This model was then used to predict the performance of the modified ETSC system and evaluate the feasibility of applying the modified ETSC in a small-scale industry in terms of payback period and economic worthiness.

METHODOLOGY

System Configuration The principle of the ETSC is described in Figure 1. A conventional evacuated tube consists of concentric glass tubes, an aluminum fin, and a copper heat pipe. The space between inner and outer glass walls is vacuumed for preventing the heat loss.

The inner glass wall is coated by the selective absorber coating for absorbing the solar radiation. The solar radiation transforms to thermal energy to heat the heat transfer fluid stored inside the copper heat pipe. The aluminum fin is placed inside the space to make a contact between the concentric glass tube and heat pipe wall and, therefore, increase thermal conduction surface area. The heat transfer fluid is responsible for receiving thermal energy from the outside, then evaporating to the heat pipe tip, exchanging heat with heating medium flowing through the manifold. After transferring its latent heat to the heating medium, the heat transfer fluid vapor is condensed and flows down to the bottom of copper heat pipe to receive heat again. Eventually, the heating medium will be used for such a thermally applications.

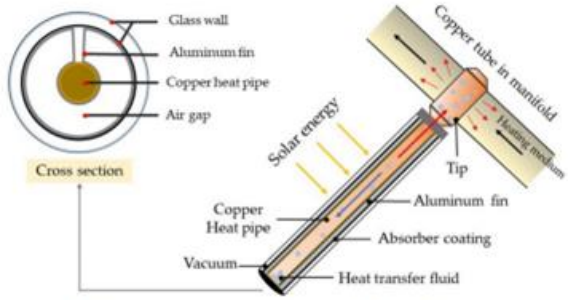

Figure 1. Principle of an evacuated-tube solar collector.

CALCULATION

Mechanistic ordinary differential equation model has been developed to predict the performance of the ETSC. The model is validated with the experimental data, then applied to study the feasibility of adapting the ETSC with a small-scale industry. The evacuated tubes and a storage tank are modelled separately.

Energy Transfer in the Evacuated-Tube Solar Collector SystemThe solar radiation absorbed by evacuated tubes absorber can be calculated by using Equation (1).$Q_{rad} = IA_{ETC}$ (1)The heat transfer rate from the tubes' tips in the manifold to the heating medium canbe calculated by Equation (2).**Q_{ETC} =**$mc_p(T_{man} - T_{St}) = hA_s\Delta T_{lm}$ (2)

EXPERIMENTAL SETUP

A set of ETSC was installed at King Mongkut's Institute of Technology Ladkrabang,Bangkok (13◦43′ N, 100◦46′ E), as shown in Figure 3. The experimental set included 20 evacuated-tubes containing 10 mol% of ethylene-glycol in water as a heat transfer fluid; palm oil was used as heating medium receiving thermal energy from the tips of the evacuated tubes placed inside the manifold, then transferring to store in the storage tank. The characteristic of the ETSC system is shown in Table 1. The ETSC was operated by turning on the pump to allow for the palm oil to circulate throughout the system between 9.00 a.m. to 4.00 p.m. daily during the observation period. The palm oil circulation rate was fixed at 0.032 kg/s with varying the volumes of 50, 80, 100, 120, 140, and 160 L stored inside the storage tank. The inlet and outlet temperatures of the palm oil, the storage tank temperature and the solar intensity were recorded every hour. The system was shut down between 4.00 p.m. to 0.00 a.m. and temperature change during this period was recorded for evaluating heat loss from the storage tank. Type-k thermocouples (±0.4% error) and a solar intensity meter (TM-206, ±5% error, TENMARS ELECTRONICS, Taiwan) were used to measure temperatures and solar intensity, respectively. The experiments were carried out on 6 consecutive days with similar solar intensity and ambient temperature in November 2020. The average solar intensities of these days were approximately 828.36–870.93 W/m2 The experimental data are used to validate the mathematical model

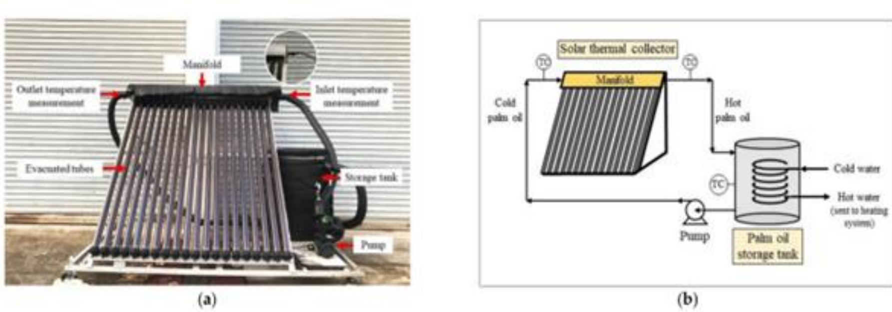

Figure 3. **(a)** A set of evacuated-tube solar collector system in the experiment; **(b)** Schematic of evacuated-tube solar collector.

RESULTS AND DISCUSSION

Experimental Results he mathematical model was developed to facilitate the study of operating and climatic condition effects on the performance of ETSC. Furthermore, the validated model could be applied to study the feasibility of adapting the ETSC with thermally application in a small-scale industry. In this work, the palm oil was used as a heating medium in the 20-ETSC system. Figure 5a–f show the manifold and storage temperatures with different storage volumes of palm oil experimentally and theoretically and the solar intensity. The storage volume was one of the parameters affecting the performance of the ETSC

Table 1. Computational parameters of evacuated-tube solar collector system.

Evacuated Tube			**Heat Transfer Fluid**		
Inner diameter	0.047	m	Component	10 mol% of ethylene-glycol (EG) in water	
Outer diameter	0.058	m			
Length	1.80	m	Volume	5	mL
Surface area	0.15	m^2	MW of EG	62.07	g/mol
Number of tubes	20	tubes	Density of EG	1.11	kg/m^3
Copper heat pipe			**Air layer**		
Thermal conductivity	401	W/m·K	Thermal conductivity	0.03	W/m·K
Inner diameter	0.012	m	Heat transfer coefficient	10	$W/m^2 \cdot K$
Outer diameter	0.014	m	Thickness	0.016	m
Aluminum fin			**Stainless-steel scrubber**		
Thermal conductivity	237	W/m·K	Thermal conductivity	15.1	W/m·K
Thickness	0.5	mm	Void fraction	0.02	
Heating medium storage tank			**Copper heating medium tube**		
Heating medium	Palm oil		Inner diameter	0.019	m
Tank diameter	0.58	m	Outer diameter	0.022	m
Tank height	0.76	m			
Overall heat transfer coefficient, U	0.72	$W/m^2 \cdot K$			

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