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Energy performance of an evacuated tube solar collector using single walled carbon nanotubes nanofluids

M.A. Sabiha [a], R. Saidur [b], S. Hassani [a], Z. Said [c], Saad Mekhilef [d,*]

[a] Department of Mechanical Engineering, Faculty of Engineering, University of Malaya, 50603 Kuala Lumpur, Malaysia
[b] Centre of Research Excellence in Renewable Energy (CoRE-RE), King Fahd University of Petroleum and Minerals (KFUPM), Dhahran 31261, Saudi Arabia
[c] Department of Engineering Systems and Management, Masdar Institute of Science and Technology, PO Box 54224, Abu Dhabi, United Arab Emirates
[d] Power Electronics and Renewable Energy Research Laboratory (PEARL), Department of Electrical Engineering, University of Malaya, 50603 Kuala Lumpur, Malaysia

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ABSTRACT

An experimental study was performed to determine the thermal efficiency of an Evacuated Tube Solar Collector (ETSC) using water based Single Walled Carbon Nanotubes (SWCNTs) nanofluids. Experiments were carried out using SWCNTs nanofluids having volume concentrations of 0.05, 0.1, and 0.2 vol.%. The performance of the collector was compared with SWCNTs nanofluid and water using the flow rates of 0.008, 0.017, and 0.025 kg/s. The experiments were undertaken according to ASHRAE standard 93-2003. The results show that, the collector efficiency improved with SWCNTs nanofluids compared to water as a working fluid. The maximum efficiency found to be 93.43% for 0.2 vol.% SWCNTs nanofluids at a mass flow rate of 0.025 kg/s. The collector efficiency shows greater enhancement with the increasing volume fractions of SWCNT nanoparticles and flow rate. In conclusions, results suggest that SWCNTs nanofluids can be used as the working fluids in an ETSC to absorb heat from solar radiation and to convert solar energy into thermal energy efficiently.

1. Introduction

Renewable energy can be considered as an alternative energy source to meet the growing energy demand due to the scarcity and continuous depletion of conventional fuels. The most available source of renewable energy on earth is solar energy as the earth receives abundance of energy coming from the sun. Solar thermal collectors capture solar radiation which is then turned to thermal energy and transferred to a working fluid subsequently. Compared to other stationary collector such as flat plate solar collector (FPC), ETSCs have outstanding thermal performance due to lower heat loss, easy transportability, and quick installation. In addition, ETSCs are suitable for unfavorable climates [1–4]. The vacuum between the glass tubes in an ETSC reduces conduction and convection losses and allow the collector to operate at high temperatures [5–7]. The conventional fluids which are used as the heat transfer medium in solar collectors suffer from poor thermal and heat absorption properties. It has been found that these conventional fluids have a limited capacity to carry heat up, which in turn limits the collector performance. From literature, it has been observed that nanoparticles dispersed in conventional fluids (Nanofluids), have improved thermal properties [8,9]. Thus, nanofluids can be a good substitute of the conventional fluids in solar collectors [10–12]. Several researchers have already used different types of nanofluids to investigate the performance of an ETSC.

A recent study regarding the performance of an ETSC by using nanofluids have been conducted by Hussain et al. [13]. Silver (Ag – 30 nm) and zirconium oxide (ZrO_2 – 50 nm) nanoparticles were dispersed in distilled water at 0, 1, 3, and 5 vol.% and two step method was applied to prepare the nanofluids. The efficiency of an ETSC was investigated as functions of mass flow rate (30 and 90 l/h m^2) of Ag and ZrO_2 nanofluids as well as the volume concentrations of nanoparticles. The efficiency of the ETSC was higher for 5 vol.% Ag nanofluids compared to ZrO_2 nanofluids due to the higher thermal conductivity of Ag nanoparticles. The thermal conductivity of Ag and ZrO_2 nanoparticles are 429 W/m K and 22.7 W/m K respectively. In comparison with distilled water, higher thermal performances have been observed for both Ag and ZrO_2 nanofluids.

Al-Mashat and Hasan [14] investigated the efficiency of a well instrumented ETSC consists of 16 evacuated tubes using Al_2O_3/water nanofluid. The performance of an ETSC is found to be proportional to volume concentration. The efficiency enhanced 28.4% with 1 vol.% of Al_2O_3 and 6.8% with 0.6 vol.% of Al_2O_3. In addition, the efficiency increased by 7.08% using flat plate reflector, and 16.9% using curved plate reflector.

* Corresponding author. Tel.: +603 7967 6851; fax: +603 7967 5316.
E-mail addresses: sabiha.akter89@gmail.com (M.A. Sabiha), saad@um.edu.my (S. Mekhilef).

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Nomenclature

ETSC	Evacuated Tube Solar Collector
SWCNT	Single Walled Carbon Nanotube
Q_u	useful energy, W
A_c	collector absorbance area
C_p	specific heat, J/kg °C
τ	transmittance
α	absorptance
G	solar irradiance, W/m^2
U	uncertainty
a	sensitivity
N	number of measurements
S	standard deviation
η	efficiency of the collector
T_i	inlet temperature of the working fluid, °C
T_o	outlet temperature of the working fluid, °C
T_a	ambient temperature, °C
φ	nanoparticles volume fraction, %
$\dot{m}$	mass flow rate of working fluid, kg/s
k_n	thermal conductivity of nanofluid
k_{bf}	thermal conductivity of base fluid

Subscript

1	at the flow rate of 0.008 kg/s
2	at the flow rate of 0.017 kg/s
3	at the flow rate of 0.025 kg/s

Water based CuO nanofluid were used by Liu et al. [15] to investigate the efficiency of special open thermosyphon and evacuated tubular solar air collector combined with compound parabolic concentrator (CPC). Using nanofluid, the maximum value of collecting efficiency of open thermosyphon has an increment of 6.6% and the mean value of collecting efficiency has an increment of 12.4%.

Gao et al. [16] compared the thermal efficiency between water in glass (WGETSC) & U pipe ETSC (UPETSC) using antifreeze fluid (40% glycol by volume) as a working fluid. From the experimental study, the average thermal efficiency of WGETSC is found less than UPETSC.

Mahendran and Sharma [17] conducted experiment on an ETSC using TiO_2 nanofluids and reported that 2.0 vol.% TiO_2 nanofluids increases the efficiency by 42.5% compared to water. The efficiency of collector shows greater enhancement at low volume flow rate of nanofluids compared to water as a base fluid.

Deionized water and water based CuO nanofluids were used by Lu et al. [18] on an evacuated tube solar air collector. The CuO nanoparticles have the potential to increase evaporation heat transfer coefficient by about 30%. The wall temperature of the open thermosyphon decreases due to the use of the CuO nanofluid. However, in this paper SWCNTs nanofluid is considered as the working fluid which has been used by some researchers for other types of solar collector.

Karami et al. [19] introduced CNT nanofluid as an excellent working fluid for direct absorption solar collector (DASC) due to its high thermal conductivity, good optical properties, and dispersion stability. Functionalized CNT (f-CNT) nanoparticles were dispersed in water and the thermal conductivity, optical property and stability were observed for six different volume concentrations (5, 10, 25, 50, 100, 150 ppm) of f-CNT particle. The extinction coefficient of nanofluid having 150 ppm CNT increased by 4.1 cm^{-1} and thermal conductivity increased by 32.2% compared to water. They also found that the thermal conductivity is mainly dependent on temperature than the volume concentration for solar collector applications. Consequently, they reported CNT nanofluid as a very suitable working fluid for increasing overall efficiency of DASC.

To enhance the heat transfer efficiency of a heat pipe in a solar collector Park and Kim [20] proposed a new method where the hydroxyl radicals were combined with oxidized MWCNTs to be used as the working fluid. The oxidized MWCNT nanofluids performed better than MWCNT nanofluids in increasing the operating temperature range and the total heat. From the experiment, at 90 °C, the thermal conductivity of the nanofluid of 0.1 vol.% is 12.6% higher than that of the base fluid (distilled water). Hence, they proposed that the oxidized MWCNT nanofluid will show outstanding effects as working fluid of a heat pipe of solar collector.

Quarter circular solar collector is a novel model for solar thermal system which was proposed by Rahman et al. [21]. The enhanced performance was achieved using CNT/water nanofluid by compromising between two parameters which were the volume fraction of nanoparticles and tilt angle of the collector.

Chougule et al. [22] conducted a study on an FPC consists of heat pipe and compared the performance using water and CNT nanofluid. The performance of collector using nanofluid is better. The average collector efficiencies at tilt angle 31.5° are 25% and 45%, at 50° are 36% and 61% for water and nanofluid respectively. The maximum instantaneous efficiency obtained by using nanofluid is 69% for 50° tilt angle. From their experimental results, it was furthermore reported that the FPC consists of heat pipe (overall efficiency 25–69%) gives better performance over conventional FPC (overall efficiency 12–20%).

According to literature study summarized in Table 1, it can be observed that no experimental study has been conducted using SWCNT nanofluid as the working fluid in a heat pipe ETSC. The objective of this study is to investigate the thermal performance enhancement of heat pipe ETSC using SWCNTs nanofluids as the nanofluids are capable to absorb solar thermal energy at all available solar radiations. Due to the hydrophobic nature of CNT nanoparticles, Sodium Dodecyl Sulfates (SDS) have been used to prepare the nanofluid with the base fluid (distilled water).

2. Heat pipe solar collector

A heat pipe ETSC consists of a heat pipe inside the vacuum sealed tube, containing a temperature sensitive medium such as methanol. There are condensation and evaporation sections in the heat pipe. Solar radiation heats up and vaporizes the heat pipe fluid in the evaporation section, and the vapor then rises to the condenser where the vapor emits the heat and condensed back. The working fluid flowing through a manifold absorbs the emitted heat. The condensed fluid flows back to the bottom of the heat pipe where the solar radiation begins heating it up again. To work properly, the pipes must have a minimum tilt angle in order for vapor to rise and the fluid to flow back.

This collector uses the copper heat pipe and the structure is illustrated in Fig. 1. The external diameter of the evaporator section for this heat pipe is 8 mm and the length is 1630 mm. The external diameter of the condensation section for this heat pipe is 14 mm and the length is 70 mm. An aluminum fin covers the outside of the heat pipe evaporation section. There is Cu-SS-N/AL absorbent coating on the fins; the absorptivity is more than 0.93. The heat pipe is inside a vacuum sealed glass tube made of a borosilicate