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Experimental investigation of flat plate solar collector using CeO_2-water nanofluid

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ABSTRACT

Using nanofluids in thermal energy devices, such as flat-plate solar collectors, is gradually making progress, and getting awareness in the scientific community. Experiments were performed to study the effect of using CeO_2-water on the efficiency of flat-plate solar collector by three different volume fractions of CeO_2 nanoparticles of 0.0167%, 0.0333% and 0.0666%, while the mean particle dimension was kept constant at 25 nm. An ultrasonic process was used for maintaining the stability of the CO_2-water nanofluid. The working fluid mass flux rates were 0.015, 0.018 and 0.019 kg/s m^2. The experiments were carried out in Budapest, Hungary on the latitude of 47°28′N and longitude of 19°03′E. Higher collector efficiency was achieved when using CeO_2-water nanofluid compared to results achieved with water application. Based on present data, the efficiency of the collector is directly proportional with the mass flux rate and with the volume fraction in the ranges of the present study. Experiments indicate that the highest rise in efficiency of the collector at zero value of $[(T_i - T_a)/G_T]$ is 10.74%, for volume fraction (φ) 0.066%, and for mass flux rate of 0.019 kg/s m^2 compared to water.

1. Introduction

In the past few years, scientists raised general attention to nanoparticles with less than 100 nm in size. It was found out that the tiny particles hold by fluids and make a remarkable change or even the properties of fluids. Based on this fact, it was observed that a lot of nano-scale materials added to fluids changed their thermal properties, as well as the performance of thermal devices. Solar collectors are one of these devices which take advantage of the observed properties of nanofluid. In this part, when getting a focus view on using nanofluid as the working fluid in flat-plate types of solar collectors, will be presented. Table 1 shows different experimental investigation of performance of flat plate solar collector when using nanofluid as a working fluid.

Although all above studies didn't modify the conventional solar collector design, other researchers made some modification in the design of solar collector such as Faizal et al. [24] who used numerical methods to design a smaller solar collector that can produce the same desired output temperature as the bigger one. From his study, it was found that by applying nanofluid the cost of solar collector, embodied energy and CO_2 emissions were reduced. Colangelo et al. [25] modified the design of the flat-plate collector by rearranging bottom and top headers to reduce the sedimentation of the clusters of nanoparticles, and, in this way, they were able to apply high nanoparticle concentration for the first time ever. Sekhar et al. [26] investigated convective heat transfer analysis for a horizontal circular pipe with Al_2O_3 nanofluids at different volume concentrations in mixed laminar flow range.

Based on Latest review studies [28–35] no research had been done to detect the effect of CeO_2-water nanofluid on the efficiency of a flat-plate collector although it had good thermal properties as Tiwari et al. [27] found. Also, CeO_2 nanoparticles has several benefits like:

- It has good availability and easy to prepare
- it's price isn't high so it has a good economic potential
- the stability of it with water is high comparing to other nanoparticles
- No toxicity or flammability was observed when it was using so it environmental friendly.

This paper is focusing on studying the performance of a flat-plate collector using CeO2-water nanofluid as working fluid instead of using distilled water. Also, making a stable CeO_2-water nanofluid using ultrasonic technique is an aim for this work. On other side, examine to what extent the thermal performance is affected by adding CeO_2 nanoparticles and using different mass flux rate is deeply studied in this

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Nomenclature

A_c	surface area of the solar collector (m^2)
C_p	heat capacity of (J/kg K)
C_{pbf}	heat capacity of base fluid (water) (J/kg K)
C_{pnp}	heat capacity of nanoparticles (J/kg K)
C_{pnf}	heat capacity of nanofluid (J/kg K)
F_R	heat removal factor
G_T	solar radiation normal to collector (W/m^2)
k_{nf}	thermal conductivity of nanofluid (W/m K)
k_{bf}	thermal conductivity of base fluid (W/m K)
k_{np}	thermal conductivity of nanoparticles (W/m K)
$\dot{m}$	mass flow rate of nanofluid (kg/s)
R^2	root Mean Square Error
T_a	ambient temperature (K)
T_i	collector inlet temperature (K)
T_o	collector outlet temperature (K)
Q_u	useful heat energy rate (W)
U_L	overall coefficient of heat loss (W/m^2 K)
$V^{\cdot}$	volume flow rate (L/h)

Greek symbols

$\tau\alpha$	absorption-transmittance product
η_i	instantaneous efficiency
ρ_{nf}	density of nanofluid (kg/m^3)
ρ_{np}	density of nanoparticles (kg/m^3)
ρ_{bf}	density of base fluid (kg/m^3)
φ	volume fraction of nanoparticles

Subscripts

bf	base fluid
nf	nanofluid
np	nanoparticles

paper. A detailed discussion about the effect of environmental parameters like ambient temperature and solar radiation is held in presented work by using the reduced temperature parameter, $[(T_i–T_a)/G_T]$, as independent variable in several figures.

2. Methodology

This section is presented in two parts. The first part deals with nanofluid preparation and the second part describes the set-up that has been used for experiments on the flat plate solar collector.

2.1. Preparation method and characterization

In this study, deionized water and water-based CeO_2 nanofluids were utilized as working fluids. Commercial spherical shape CeO_2 nanopowder (supplier: M K Impex, Canada) of 99.9% purity and 25 nm average diameter was used for the experimental investigation. Distilled water served as reference fluid. The CeO_2 nanoparticles, insoluble in water, had a density of 7.123 g/cm^3. The nanofluids were prepared by a two-step method where CeO_2 nanoparticles were dispersed into the base fluid directly first; later they were oscillated continuously for about 90 min, and 50% amplitude in an ultrasonic homogenizer (Bandelin, SONOPULS HD 2200, output power maximum 200 W).

2.2. Experimental procedure

Experimental apparatus diagram and picture is shown in Figs. 1 and 2, respectively.

The experiments were performed in Budapest (latitude 47°28′N longitude 19°03′E). The specifications of the collector are given in Table 2. The collector type is TS 300 from Naplopó Kft. in Hungary and the inclination was 45 degree.

An electrical pump was used to circulate the working fluid, while a heat exchanger transferred heat from the solar collector to the tank. The tank capacity was nearly 500 l. A flow meter was used to measure fluid flow rate. To control flow rate, a simple valve was also installed after the electric pump. Also, a series of Pt-100 resistance thermometers were fitted to the collector in order to measure the temperature of the working fluid in the collector both in- and outbound. The ambient temperature was measured by a thermometer, while the total solar radiation was measured by a LP PYRA 03 solar meter.

3. Testing method

In the current study, ASHRAE Standard 93-2003 [36] was the basis to investigate the thermal performance of the solar collector. The purpose of this standard is to introduce test methods to detect thermal performance of solar collectors that use single-phase fluids without significant internal energy storage. According to ASHRAE Standard 93-2003 [36] solar collector should examine at 0.02 kg/s m^2 or at recommended flow rate as manufacturer. Therefore, we use these mass flux rate of 0.015, 0.018, and 0.019 kg/s m^2 as it in the range of recommended by manufacturer and also it just below the standard mass flux of 0.02 kg/s m^2. The thermal performance of the solar collector is calculated by determining the values of instantaneous efficiency of different combinations of incident radiation, ambient temperature, and inlet fluid temperature. In addition, experiments must be done under steady-state conditions. The instantaneous efficiency is defined as the ratio of useful energy, Q_u, and the solar energy received by absorber plate of collector, A_cG_T and it is calculated by Eq. (1) below.

$$\eta_i = \frac{Q_u}{A_c G_T} \quad (1)$$

The useful heat energy rate is calculated by using Eq. (2), and can also be determined in terms of the energy absorbed by the absorber, and the energy lost from the absorber as given by Eq. (3).

$$Q_u = \dot{m}C_p(T_o - T_i) = \rho V^{\cdot} C_p(T_o - T_i) \quad (2)$$

The useful heat energy rate can be also described as the difference between energy absorbed by the absorber plate and the energy loss from the absorber as:

$$Q_u = A_c F_R[G_T(\tau\alpha) - U_L(T_i - T_a)] \quad (3)$$

So the instantaneous efficiency can be expressed by Eqs. (4) or (5)

$$\eta_i = \frac{\rho V^{\cdot} C_p(T_o - T_i)}{A_c G_T} \quad (4)$$

$$\eta_i = \frac{A_c F_R[G_T(\tau\alpha) - U_L(T_i - T_a)]}{A_c G_T} \quad (5)$$

$$\eta_i = F_R(\tau\alpha) - F_R U_L\left(\frac{T_i - T_a}{G_T}\right) \quad (6)$$

Eq. (6) which defines the instantaneous efficiency is known as the Hottel-Whillier equation. F_R is known as the collector heat removal factor and is expressed by Eq. (7),

$$F_R = \frac{\dot{m}C_p(T_o - T_i)}{A_c[G_T(\tau\alpha) - U_L(T_i - T_a)]} \quad (7)$$

where, $\dot{m}$ is the mass flow rate of the working fluid, T_i is the collector inlet temperature, T_o is the collector outlet temperature, T_a is the ambient temperature, G_T is the global solar radiation normal to the collector, A_c is the surface area of the solar collector, $\tau\alpha$ is the absorption-

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