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Performance Evaluation Of Flat Plate Solar Water Heater Using Ceo_2/Water And Al_2O_3/Water Nanofluids: Experimental And Thermophysical Analysis

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Abstract
The depletion of fossil fuels and the growing demand for sustainable energy necessitate the advancement of renewable energy systems. Solar water heating systems, being cost-effective and eco-friendly, have attracted significant attention for residential and industrial applications. In this study, CeO_2*/water and* Al_2O_3*/water nanofluids at different volume concentrations (0.01%, 0.05%, and 0.1%) were prepared using a two-step method and characterized for thermophysical properties such as thermal conductivity, viscosity, density, and specific heat. Experimental investigations were conducted on a flat plate solar water heater equipped with a ladder-type heat exchanger under the climatic conditions of Coimbatore, India, following ASHRAE standards. Results demonstrated that nanofluids exhibited superior heat transfer performance compared to conventional water, with* CeO_2*/water nanofluid at 0.01% concentration and 2 L/min flow rate achieving a maximum instantaneous efficiency of 78.2%. Energy and exergy analyses further confirmed the enhanced thermal performance, while economic evaluation highlighted the feasibility of nanofluid-based solar heaters for practical applications. The findings emphasize the potential of nanofluids in advancing solar thermal technologies and optimizing operating conditions for improved efficiency and sustainability.*
Keywords: *Solar water heater; Flat plate collector; Nanofluids;* CeO_2*;* Al_2O_3*; Thermal performance; Energy efficiency; Exergy analysis; Economic evaluation*

1. INTRODUCTION

Energy is most important thing required for the basic as well as advanced development of any country. By the end of the 21st century, crude oil will become a history while considering the major sources of energy. The global requirement for energy will increase in many fields in the next 20 years due to continuous population growth and improvements in modernization. Technologies that can be used to harvest energy from direct and indirect effects on the Earth from the Sun's energy, gravitational effects and the high temperature of the Earth's core (geothermal) are experienced as renewable desired technologies. Solar energy is sustainable and unlimited free source of energy that can be harnessed in the future energy needs without affecting the atmosphere. For achieving goals of a country and its economic growth, energy security is critical and it plays an important role thereby alleviating poverty and eradicating unemployment.

A country's growth is generally based on its energy consumption and per capita income. The United States of America occupies the first position in terms of energy consumption and per capita income. At present India's energy consumption is 3.56 times lesser than that of world average energy consumption which is 1852 kg of oil equivalent. Similarly, India's per capita income is 5.64 times smaller than that of world average per capita income which stands at US Dollars 14890. Hence it is the need of the hour to increase the per capita energy consumption and income so that India can compete globally in all walks of life. The energy consumption in a country mainly depends on the use of energy efficient technologies and number of manufacturing facilities. The following Figure 1.1 and Figure 1.2 represent the amount of energy consumed and the amount of energy generated from various countries.

2. LITERATURE REVIEW

The usage of solar energy is receiving greater attention now a day because of the depletion of fossil fuels and environmental degradation. The existing reviews show that the numerous studies have been carried out in the area of solar water heating systems, especially, in natural and forced circulation modes of operation in the past and the present. Most of the preceding research work has been focused on the performance improvement of flat plate solar collector. In addition to that, the absorber plate performance, use of selective coatings, impact of absorber plate and its design, various thermal losses, effectiveness of insulation materials and impact of tilt perspective have also been analyzed. As a gift, the nanofluids have the outstanding potential in the heat transfer enhancement and many research works have been done on nanofluid properties and its overall heat transfer performances.

One of the most promising renewable energy inventions is the solar water heater, which helps saving considerable amount of electrical energy consumption in low temperature residential applications and small- s c a l e industries. Because of its promising and wide spread commercial use, considerable numbers of optimization and performance enhancement studies have been carried out by various researchers in order to optimize various components of the system for better overall performance. The thermal performance of a flat plate solar water heater is generally characterized by its various parameters like transmittance, absorption and conduction of solar energy including the conductivity of the working fluid. The design and thermal properties of the absorber plate play an important role in deciding the performance of collector in addition to the optical efficiency of glass cover. In the sections below, a variety of SWH systems are reviewed and classified in terms of circulation methods and applications, with a discussion on the designs and modifications in recent years. In the due course, the effects of various designs of absorber plate on the performance of a solar water heating system have been investigated.

Kemp CM (1891) developed the first commercial solar water heater which consists of a metal tank immersed in a glass covered wooden box. It is used to produce hot water to the tune of 38.8°C. The first commercial solar water heater of Japan was invented in the year of 1947 by Yamamoto (Butti & Perlin, 1979) is shown in Figure 2.1. Commercial solar water heaters were introduced on a wider scale in the early 1960s by many researchers.

For the design of thermosyphon system, various assumptions have been proposed by Duffie and Beckman (1980) regarding mass flow rate of collector like neglecting the headers area, uniform distance between riser tubes, laminar flow and uniform distribution of flow in the tubes which are proved to be very useful in the analysis of solar water heater. The radiation losses and the maximum energy conversion of absorber plate with the use of selective coatings have been analyzed by Stanley and Moore (1985). The effect of insulation thickness on the temperature profiles of the storage tank material has been studied experimentally by Eldighidy Shawki (1991). For improving the efficiency of the system and guiding the water, baffles plate was used in the triangular ICS system by Kaushik et al (1995) as shown in Figure 2.2. It was found that the thickness and material of the baffle had no effect on the performance of the system. Shariah and Lof (1996) have analyzed the thermosyphon type solar water heating system for the operating range of 50° to 80°C and found that the optimum values for storage tank height and volume. Zerrouki *et al.* (2002) have found that the flow rate of solar water heaters can be increased by increasing the relative height between the collector and storage tank in case of thermosyphon solar water heater without affecting the system efficiency. Hussein (2003) has predicted that storage tank volume to collector area ratio and storage tank dimensions ratios have significant effects on the heater performance in the two-phase natural circulation thermosyphon flat plate solar water heater. Also, it was revealed that the height between the storage tank and collector has little effect and optimum values were suggested for the same. Thermal performance of active and passive solar water heating system with ethylene glycol as heat transfer fluid was studied by Lee and Sharma (2007). The experiment was conducted by fitting a pump between the collector and storage tank in active system and no pump is used in passive system for one year and the results depicted that active hot water system is suitable for that region due to the cold climate. To get higher performance of the system, water should be drawn off only once in the evening. Similarly, Chien *et al.* (2011) investigated a two-phase thermosyphon solar water heater at different solar radiation intensities with various tilt angles and proposed two different methods for enhancing the performance of the solar collector. Results show that the best charge efficiency of the system is 82% which is higher than the conventional solar water heaters by 4%. The thermal performance of a thermosyphon solar water heater was theoretically and experimentally analyzed by Paul Magloire Koffi *et al.* (2014) and its performance depends upon the storage tank capacity, the thermal capacity of the flat plate collector and the hot water withdrawal pattern.

Huang *et al.* (2010) designed a mantle heat exchanger used in the flat-plate solar water heating system which has a primary advantage that it has low frictional resistance to thermosyphon circulation and maintains the simplicity of the thermosyphon system. A mantle heat exchanger contains the inner tank wall which provides large heat transfer area and thermal stratification in the storage tank can be promoted with appropriate design. Hussein *et al.* (1999) investigated and developed the governing equations of the different components of the collector in terms of dimensionless forms for the thermosyphon flat plate solar collector under transient conditions. Using Transient Simulation System, the effect of thermal conductivity of the absorber plate has been studied by Shariah *et al.* (1999) which revealed that the characteristic factors like fin efficiency, collector efficiency and heat removal are influenced by the thermal conductivity of absorber plate. Chuawittayawuth and Kumar (2002) compared the theoretical models with experimental model to predict the temperature and flow distribution in a natural circulation solar water heating system. Holck *et al.* (2003) found that humidity inside collector leads to the decrease the service life time of solar collector and emphasized on the design of collectors to solve the moisture problems. The authors have also developed a simulation program to take care of micro climatic condition existing inside the collector by considering various configuration of the collector like location and size of the ventilation hole, etc. This model gives an idea about design optimization of the collector based on the micro climatic conditions. Ammari and Nimir (2003) have developed the tar solar water heater and tested its performance. Its performance was compared with that of the conventional solar water heater and revealed that tar collector had better conservation of energy in late evening; as a result, warmer water outlet is possible late in the day. Cadafalch (2009) has described the fundamentals of a model for the design and optimization of flat plate collectors by devising a one-dimensional transient numerical model for the solar thermal devices. It can be utilized to analyze different components such as multiple glazing, transparent insulation, air-gaps, surface coatings, opaque insulation and energy accumulation in water. In corrugated solar water heater, more solar energy is converted into useful heat but this modification reduces the efficiency of the system marginally. The thermal performance of corrugated solar water heater depends significantly on the amount of solar radiation incident on the absorber surface in addition to the heat transfer rate between the absorber surface and water. For enhancing the heat transfer rate in solar collector, Lambert *et al.* (2006) have demonstrated a new concept of oscillatory flow. For producing oscillatory motion of the fluid, a reciprocating pump is used to conduct the experiment using Newtonian and visco elastic fluids. Since the thermal diffusivity of fluid in oscillatory motion has several orders of magnitude higher than the fluid molecular diffusivity, this type of flow enhances the heat transfer rate in comparison with the conventional forced circulation mode with unidirectional flow.

Effects of different discharging and charging strategies and their effects on the performance of a combined solar thermal system were studied by Glembin and Rockendorf (2012) and results show that a good thermal stratification within the storage lead to higher energy saving and it can be reached by both a stratified charging and discharging. A stationary V trough solar water heating system with simulated solar concentration has been proposed by Chong *et al.* (2012) and it increases the optical efficiency up to 70.54%. This analysis is very much useful in the construction of low cost, efficient solar water heating systems for domestic and commercial applications. Bellamy (2012) conducted experimental measurements to evaluate the energy performance of a solar heated stratified concrete wall panel which consists of an interior layer of high thermal mass concrete and an exterior layer of insulating concrete which is embedded with a solar thermal collector covering 10% of the panel‘s face. It was observed that the collector improves the energy performance of stratified concrete panels by more than 15% and it could be used by architects while designing the roof of the building which may serve as a low cost solar collector to provide hot water at moderate temperature for meeting various purposes during daytime. Travis Sarver *et al.* (2013) in their research work, they reported that collector efficiency is generally associated with a variety of environmental and climatic factors including the sun‘s available irradiance and spectral content. Results also show that the absorption coefficient decreases when the insulation thickness increases. To provide a long term storage unit for hot water from solar collectors with minimal losses, Nwosu *et al.* (2013) developed a low cost fiber-reinforced plastic hot water storage tank in which it was found that ambient and geometric parameters along with the tank insulation material properties can significantly impact the storage performance. Hobbi and Siddique (2009) have derived the optimal design of a forced circulation solar water heating system for a residential unit in cold climate using TRNSYS in which a flat plate solar collector has been modelled for domestic hot water requirements of a single family in Canada. All the design parameters like collector area, fluid type, collector mass flow rate, storage tank volume and height, etc. are studied and optimum values are obtained using TRNSYS. The result shows that the designed systems can meet up to 97% and 62% of hot water requirements in summer and winter seasons respectively. The thermal behavior of the stratified tank system subjected to constant temperature charging has been analyzed by Dickinson *et al.* (2013) using TRNSYS simulation environment. The heat transfer behavior of a two phase thermosyphon in the supercritical region using CO2 as a working fluid has been investigated by Lin Chen *et al.* (2013) and results indicated that the natural circulation loop flow will change from unstable sub-critical two-phase flow to stable liquid flow before attaining stable super critical circulation with the increase of system initial pressure. Bur it was seen that the two-phase flow or single-phase flow at sub-critical region leads to instability of the system.

3. METHODOLOGY

3.1 Nanofluid preparation

The cerium oxide nanopowder having purity of 99.5% for the experimental study was purchased from Alfa Aesar, Thermo Fisher Scientific India Private Limited, and which is also available in Sigma-Aldrich, Bengaluru, Karnataka 560099. The crystallographic structure of CeO_2 nanoparticle is cubic. The average spherical diameter of all the nanoparticles is approximately 25 nm. In the present work, water based CeO_2 nanofluid was prepared using two-step method. Initially, CeO_2 nanoparticles were weighed precisely based on their volume concentrations namely 0.01%, 0.05% and 0.1% calculated. The quantity of nanoparticles required to prepare a various volume concentration of the nanofluid was calculated. Preparation of nanofluids was done for the flat plate solar water heater with ladder type heat exchanger having 8.5-liter intake capacity of working fluids. For preparing a CeO_2/water nanofluid with 0.01% volume concentration, the quantity of nanoparticles was estimated to be 0.7132g. Initially, the required amount of CeO_2 nanoparticles was slowly added in the water using a magnetic stirrer and maintaining constant stirring for about half an hour. For obtaining a homogeneous mixture, once again the prepared solution was sonicated continuously using ultrasonicator for another 30 minutes approximately with a frequency range from 15 Hz to 100 Hz thereby breaking down the agglomeration of CeO_2 nanoparticles with water. Similarly, CeO_2/water nanofluid for other volume concentrations was prepared following the same procedure. In the same way, Al_2O_3 nanofluids were prepared for three different volume concentrations following the above-mentioned procedure. The prepared nanofluid solutions are depicted in Figure 1. The intensities and position of peaks in XRD image of CeO_2 nanoparticle are shown in Figure 2.

Figure 1 Nanofluid preparations using Ultrasonicator

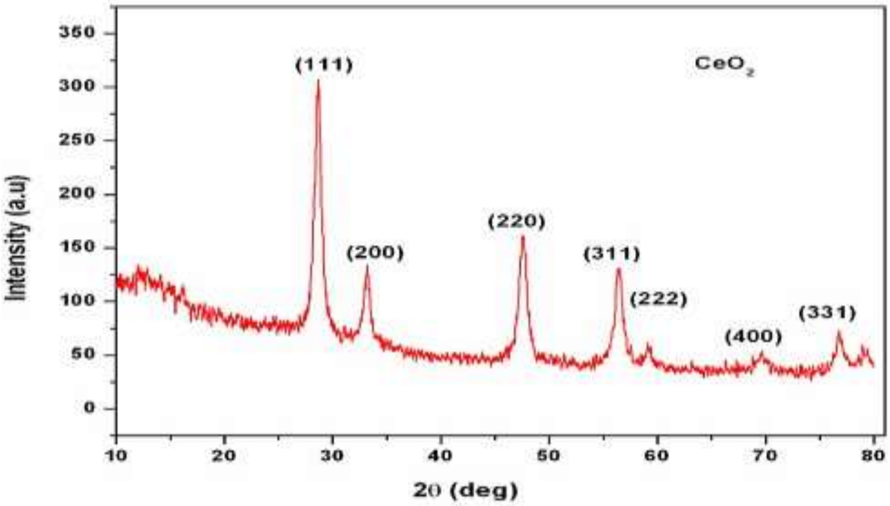

Figure 2 XRD analysis of CeO_2 nanoparticles

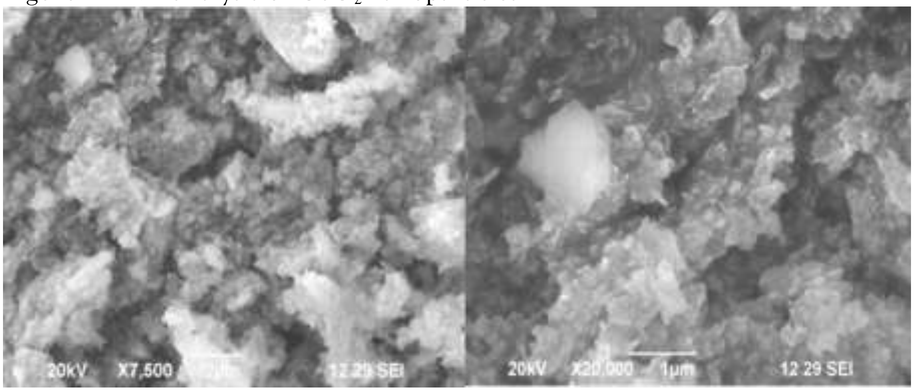

Figure 3 SEM images of CeO_2 nanoparticle

Scanning Electron Microscope (SEM) is a powerful method used for studying the shape of nanoparticle and suspension uniformity. Morphology test was carried out by passing a fine beam of high energy electrons on the surface of the sample of the nanoparticle for viewing the shape and size of the CeO_2 nanoparticles. The images of the nanoparticles with two magnifications have been shown in Figure 3. The synthesized nanoparticles are spherical in shape due to the scattered electron beam and sample interaction as the image shows that the highly agglomerated particles in the size range of micrometer under atmospheric condition.

Table 1 Properties of the CeO_2 /water and Al_2O_3 /water nanofluids

Properties	**Nanofluids**					
	CeO_2/water			**Al_2O_3/water**		
	0.01	**0.05**	**0.1**	**0.01**	**0.05**	**0.1**
Thermal conductivity (W/mK)	0.681	0.697	0.714	0.626	0.639	0.658
Specific heat (J/kg K)	4164	4152	4139	4169	4158	4143
Viscosity (mPa-s)	0.66	0.68	0.71	0.65	0.67	0.69
Density (kg/m^3)	1004	1010	1018	1001	1007	1013

The values of the thermo-physical properties of the CeO_2/water and Al_2O_3/water nanofluids at various volume concentrations are presented in Table 1.

3.2 Experimental Procedure

The experimental investigations were performed under the meteorological conditions of Coimbatore, India (latitude of 11.0183° N; longitude of 76.9725° E) during the months of March to May 2016. Initially

CeO_2/water and Al_2O_3/water nanofluids each of which 8.5 liters capacity were prepared before conducting the experimental investigation. First, water was filled into heat exchanger circuit with the help of makeup tank before conducting the experiments. The water enters the collector from the heat exchanger through the header and is evenly distributed in the riser tubes arranged in parallel. The storage tank was filled with water so that heat can be absorbed from the heat exchanger in forced circulation. The flow rate of working fluid was monitored by a flow meter, and its circulation was maintained by a flow circulation pump. The heat is transferred by convection from the riser tube wall to the fluid flowing inside the tubes and the fluid gets heated up. The hot absorber fluid exchanges heat with the utility water in the storage tank and the cold working fluid is circulated back to the collector. The heat is exchanged continuously to water so that the water temperature is continuously increased. Once the water reaches the desired temperature of its intended end use, it will be taken out from the storage tank through the outlet pipe.

The same procedure was repeated for CeO_2 /water nanofluid and Al_2O_3 /nanofluid readings were recorded for experimental analysis. The experiments were conducted as per ASHRAE standards and the analysis was performed based on real and consistent meteorological data recorded every 30 minutes of interval from the period of 9:00 AM to 05:00 PM during the investigation. The details of test periods with different volume concentrations and volume flow rates are given in the Table 2.

Table 2 Details of test periods

Volume concentration (υ)	**Flow rate**
0.01 %	1 Lit/min
	2 Lit/min
	3 Lit/min
0.05%	1 Lit/min
	2 Lit/min
	3 Lit/min
0.1%	1 Lit/min
	2 Lit/min
	3 Lit/min

4. RESULTS AND DISCUSSIONS

4.1. Performance of Solar Collector using CeO_2/Water as Working Fluid

The experiments were conducted number of days and based on the solar radiation similarity pattern, the data were selected and presented in this study to get concurrent results. All the data recorded were divided into several test runs in the interval of 30 minutes in order to obtain a quasi-steady state condition. The experimental results are exhibited in the figures and equations that describe the collector efficiency against a reduced temperature parameter $(T_i-T_a)/G_T$ for each volume flow rates. The experimental data are fitted with linear trend line equations for describing the characteristic parameters of the flat plate solar water heater. The experimental data is used to analyze solar water heater performance in order to find out the optimum values of operating parameters under similar climatic conditions.

Experiments were performed initially on forced circulation mode flat plate solar water heating system using CeO_2/water nanofluid as the working fluid from 9:00 AM to 5:00 PM for different lower volume concentrations of 0.01%, 0.05% and 0.1% by varying volume flow rates from 1 to 3 Lit/min. The details of the analysis are given below.

4.2. Absorber Fin Temperature

Fin efficiency defined as the ratio of the rate of heat transfer in the working fluid running in the tube from the absorber plate fin to the highest rate of heat transfer that is possible and it is basically the difference between the absorbed solar energy and energy lost by the absorber plate fin.

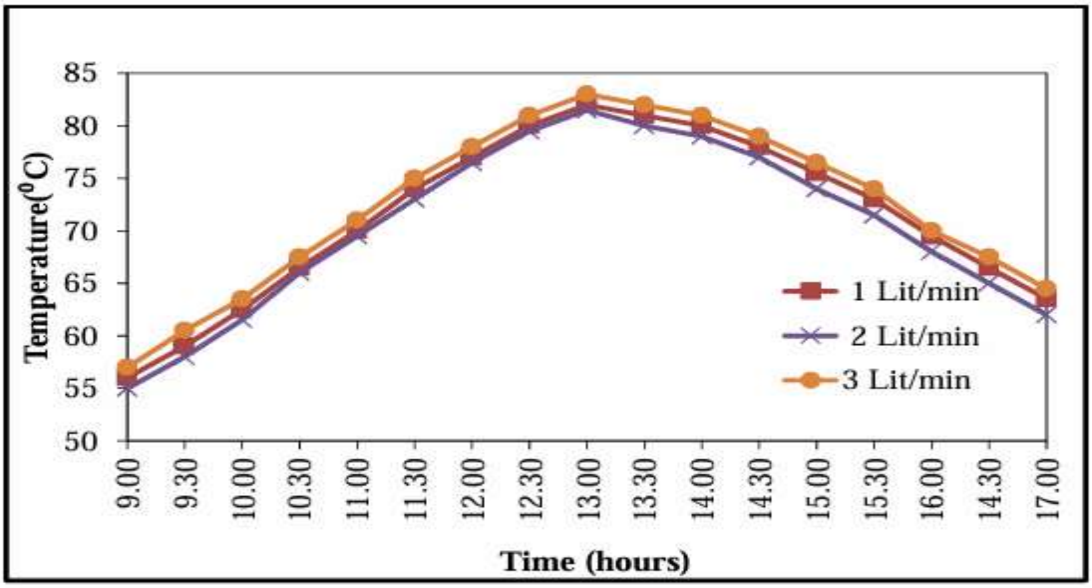

Figure 4 Absorber fin temperature

The heat transfer rate and fin efficiency do not depend on size of the absorber plate but they are dependent of thermal conductivity of fin material and overall loss coefficient. The thermal absorber fin temperature for various volume flow rates of CeO_2/water nanofluid is shown in the Figure 1. In the current study, when the volume flow rate of CeO_2/water nanofluid was increased from 1 to 2 Lit/min, the thermal absorber fin temperature was low because more heat is absorbed from the working fluid through the thermal absorber fins. It is also observed that working nanofluid gets more opportunity to collect the heat from thermal absorber fin and therefore lower fin temperature. When the volume flow rate is changed from 2 to 3 Lit/min, thermal absorber fin temperature increases due to less contact time of the working nanofluid with thermal absorber fins.

4.3. Inlet and Outlet Temperature of Solar Collector

Figure 2 represents the ambient, inlet, outlet temperature of solar collector and intensity of solar radiation recorded with respect to time period.

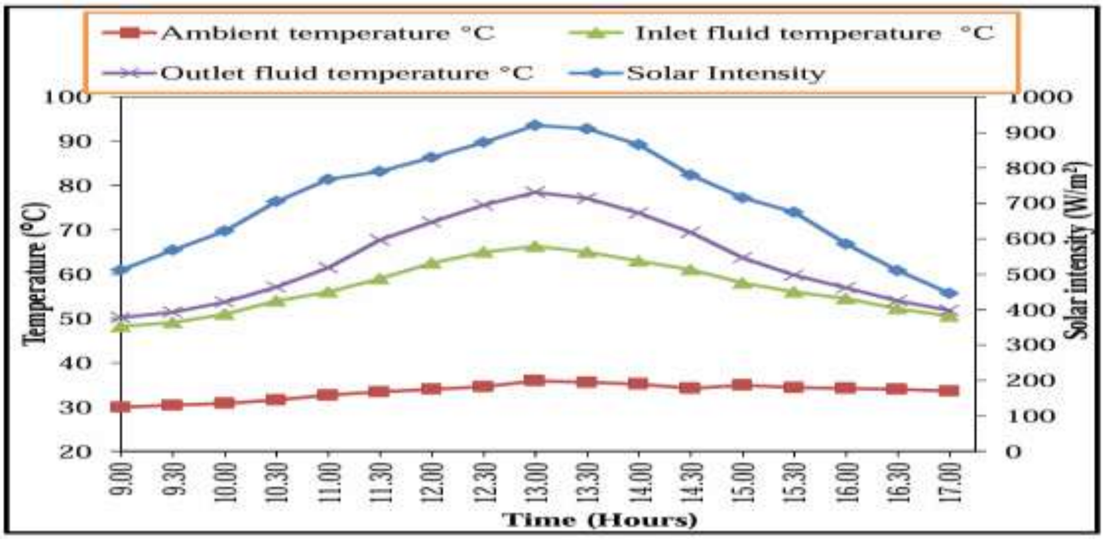

Figure 5 Experimental data for CeO_2/water as working fluid

The temperature difference between the outlet and inlet fluid increases with the increase in the intensity of solar radiation. The maximum temperature difference between the outlet and inlet fluid was 12.2°C observed at 13.00 hrs, at an ambient temperature of 35.9°C. The maximum temperatures reached by the outlet and inlet of the solar collector were 78.5°C and 66.3°C respectively which were attained at the time of 13.00 hrs. The inlet working fluid reached the maximum temperature gradually because of the thermal stratification of the storage tank temperature and effectiveness of the heat exchanger. It is also observed that the inlet working fluid and outlet working fluid attained almost equal temperature in the absence of solar radiation.

4.4. Effect of Volume Concentrations and Volume Flow Rates of CeO_2/water Nanofluid on Efficiency

For a flat plate solar water heating system, the efficiency may be defined as the ratio of the output energy given by the solar collector to the input energy supplied by solar radiation which is one of the most important deciding parameters. The efficiency is also determined by various other parameters like intensity of solar radiation falling on the solar collector, type of working nanofluid, particle size of the nanoparticle, volume concentration, inlet temperature of nanofluid and ambient temperature. Figure 6.3 shows the variation of instantaneous collector efficiency versus reduced temperature parameter $(T_i - T_a)/G_T$ for CeO_2/water nanofluid with the volume concentration of 0.01% by varying the volume flow rates from 1 to 3 Lit/min representing experimental analysis. The experimental data which has all the volume flow rates are fitted with linear trend line equations for describing characteristic parameters of flat plate solar water heater. It is seen that CeO_2/water nanofluid with the volume concentration of 0.01% at the volume flow rate of 2 Lit/min gives maximum efficiency of 78.2% for experimental analysis. It is also observed that the trend lines with respect to 1 Lit/min and 3 Lit/min volume flow rates intersect at reduced temperature parameter $(T_i - T_a)/G_T$ having a value of 0.018. It is due to the operating of solar collector which will not be that much effective when the reduced temperature parameter $(T_i - T_a)/G_T$ is greater than 0.018 in case of 3 Lit/min. After which the efficiency of flat plate solar water heater gets reduced when compared to 1 Lit/min volume flow rate. In the following Table 7.1, the flat plate solar water heater efficiency parameters such as energy absorbed parameter $F_R(\tau\alpha)$ and removed energy parameter of F_RU_L have been tabulated for all the volume flow rates of working nanofluid. It is seen that the instantaneous solar water heater efficiency for CeO_2/water nanofluid operating at 2 Lit/min is 78.2% which is higher when compared with the efficiency of the collector operating at other two volume flow rates. When the collector is operated by varying the volume flow rate from 1 to 2 Lit/min, the efficiency of solar water heater get improved by about 10.86% while it is reduced by about 5.62% when the solar water heater is operated with volume flow rate of 3 Lit/min. At higher volume flow rates, the temperature rise in the working fluid itself is small due to lesser residence time of nanofluids in the heat exchanger thereby less heat transfer rate. It is also seen that collector efficiency increases with the increase in volume flow rate up to 2 Lit/min after which it shows negative results.

5. CONCLUSION

The experimental and analytical investigations confirm that incorporating nanofluids as working fluids in solar water heating systems significantly improves their thermal efficiency. CeO_2/water and Al_2O_3/water nanofluids demonstrated enhanced thermophysical properties, with CeO_2/water at 0.01% concentration and 2 L/min flow rate delivering the best performance, achieving a maximum instantaneous efficiency of 78.2%. The efficiency trends revealed that increasing flow rates initially improved performance due to greater heat absorption but declined beyond the optimum due to reduced residence time. Exergy analysis provided deeper insights into system irreversibility, supporting the thermodynamic superiority of nanofluid-based systems. Additionally, economic analysis indicated that despite the initial preparation cost of nanofluids, long-term energy savings make them a viable solution for sustainable hot water generation. Overall, nanofluids hold considerable promise in improving the performance of flat plate solar water heaters and can contribute to wider adoption of renewable energy technologies for domestic and industrial use.

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