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Effects of CeO_2/ Water Nanofluid on the Efficiency of Flat Plate Solar Collector

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Keywords： Flat plate, Solar water heater, Nanofluid, CeO_2, Heat exchanger

ABSTRACT

In the present work the effect of CeO_2/water nanofluid on the performance of a flat plate solar collector was investigated experimentally. Two units of flat plate solar water heating systems, one for conventional mode and another for heat exchanger mode, with 100 liters per day capacity were fabricated with the collector area of $2m^2$. Ladder type heat exchanger was used in the heat exchanger mode to transfer heat energy from collector to the water. The average particle size of 25nm and lower volume fraction of 0.05% were considered for the experimental study. Experiments were performed with and without polyvinyl pyrrolidine (PVP) used as the surfactant. The flow rate of nanofluid was varied from 1 lpm to 3 lpm and the efficiency was calculated as per ASHRAE standard. The experimental result revealed that the utilization of CeO_2/water nanofluid with flow rate of 1.5 lpm in heat exchanger mode increases the collector efficiency by 24.2% than conventional mode and the CeO_2/water nanofluid is suitable for improving the performance of flat plate solar water heating system.

INTRODUCTION

Solar energy is one of the renewable energies which are unlimited free source of energy that can be harnessed in the future energy needs without affecting the atmosphere (Matheswaran, M et al.2019). The crucial drawback for solar thermal usage is a way to enhance the performance of solar collector. It is conceivable that the effectiveness can be enhanced by optimizing the structure of solar collector or building up another sort of operating liquid. At present, more researchers have been involved to enrich the performance of solar water heaters by using the different type of nanofluids as working medium (Ferrouillat, S et al.2013). Generally, the thermal conductivity of the metals when they are in solid phase is higher than that of fluid phase (Kaufui, V et al.2010). For increasing the outlet temperature and better efficiency, nanoparticles having superior thermal property are blended with the essential working liquid to form nanofluids thereby enhancing the thermal conductivity of the operating liquid (Peyghambarzadeh, S et al.2013; Kole, M et al.2013). The use of nanoparticle results in higher thermal efficiency due to the efficient absorption of thermal energy and enhanced radioactive properties of nanofluids (Mu, L et al.2010). The effect of copper nanoparticle on a flat-plate solar collector with various volume flow rates and weight fractions were studied by Zamzamian, A et al.(2014) have observed that maximum efficiency has been achieved at 0.3 wt% Cu nanofluid at 1.5 lpm. In another investigation, it was seen that the performance enhancement of solar water heater using CuO/water nanofluid prepared with low volume fixation of 0.05% has improved to the tune of 6.3% (Michael, J et al.2015). Moghadam, A et al.(2014) have analyzed experimentally to study the performance of CuO/water nanofluid having 40 nm particle size and found that nanofluid having 0.4 % volume fraction with 1kg/min has improved the collector performance up to 21.8% when compared with its base fluid. He,Q et al. (2015) have studied the effect of Cu-H_2O nanofluids having 25 nm particle size with 0.1 wt% and 0.2 wt% respectively as the absorbing medium and revealed that the efficiency of solar collector was enhanced by 23.83% for 0.1 wt%. Menbari, A et al. (2016) have studied, both analytically and experimentally, the effect of CuO/water nanofluid on the performance of a direct absorption parabolic collector. The results have shown that the thermal efficiency of the system could be improved from 18% to 52% by increasing volume fraction of nanoparticle from 0.002% to 0.008%. The effect of Al_2O_3/water nanofluids have studied with lower volume fraction of 0.01% with average particle size of 25 nm with and without Triton X-100 sur-factant and varying the

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flow rate from 1 L per minute to 3 L per minute, as per ASHRAE standard. The experimental results show that utilizing Al_2O_3/water nanofluid with mass flow rate at 2 L per minute increases the collector efficiency by 14.3% when compared to distilled water as the working medium (Prakasam, M et al.2017).

Yousefi, T et al. (2012) have studied the performance of flat plate solar water heater experimentally using 15 nm size nanoparticles with 0.2 % weight fraction of Al_2O_3/water nanofluid with the help of Triton X100 surfactant and observed that 28.3% enhancement in thermal efficiency. In another experiment carried out by Gangadevi, R et al. (2013), they found that low volume fraction nanofluids have shown better results when experimented with Al_2O_3 and TiO_2 nanofluids. In the same manner, Omid Mahian, O et al. (2014) conducted a systematic analytical report on the general execution of Al_2O_3/water nanofluid in a flat plate solar collector for different molecule sizes and volume concentration. Stalin, P et al. (2019) have used the CeO_2 nano particles of 0.01% low volume fraction with water in a flat plate solar water heater to improve the heat transfer rate. The investigation was carried out both experimentally and theoretically. They concluded that the nano particles improved the collector efficiency 21.5% more than the case, without nano particles. Verma, S et al. (2016) have studied the impact of mass flow rate and particle volume fraction using MgO nanofluid on the efficiency of the collector experimentally and observed an efficiency enhancement of about 9.34% in comparison with water as working fluid for 0.75% particle volume fraction at 1.5 lpm volume flow rate. Vincely, D et al.(2016) have observed that for GO nanofluid with mass concentration 0.02 and a flow rate of 0.0167 kg/s, the improvement in the collector efficiency was 7.3% over that of the distilled water.

Even though many research works have been done with various nanofluids in the past, no research work has been carried out with CeO_2 / water nanofluid, as working fluid in flat plate solar water heating system. CeO_2/water is an chemically inert nanofluid with copper material and has higher values of thermal conductivity and heat transfer coefficient including better dispersion stability. The CeO_2 is an economically feasible nanoparticle when compared to the cost of CuO, TiO_2, SiO_2 etc. The main objective of this study is to find the effect surfactant addition and volume flow rate of CeO_2/water nanofluid on the performance of solar water heating systems.

SOLAR WATER HEATING SYSTEM

Development of Experimental Setup

The photographic view shown in Figure.1 (a) describes the two experimental setups that are constructed for this study. The setup consists of flat plate solar collector, storage tank and ladder type heat exchanger. The solar collector contains a copper absorber plate with a surface area of 2×1 m^2 and thickness of 0.45mm. The absorber plate is coated with black paint to increase the absorption rate of thermal radiation. The side and bottom heat losses are reduced by using a wool insulation of thickness 25mm and 50mm respectively. The ladder type heat exchanger is attached inside the secondary tank and this tank is covered by the primary tank with a clearance of 0.1m. The tank assemblies are well insulated to avoid the heat loss from the water. The ladder type heat exchanger is made up of copper with an area of 0.12m^2 which is used to transfer the heat from the nanofluid to the water to be used. The top and bottom header of the collector is connected by equally placed nine parallel risers with 10mm diameter. Each riser is placed on the posterior of absorber plate in order to get regular flow distribution and static pressure at inlet and outlet sections. The schematic layout of the experimental setup with measuring instruments is shown in Figure.1(b). The nanofluid which is circulated in the solar collector absorbs heat from solar energy and transfers it to the water to be used. An electrical pump is used to maintain a constant flow rate in the flow circuit. The required flow rate can be achieved by using flow control valve and rotameter. During the experimentation, temperatures are measured by using K type thermocouple having an accuracy of ±0.5°C at solar collector, storage tank, inlet and outlet water tubes and different locations in the heat exchanger. The thermocouples are connected with eight channel digital temperature indicator having a precision of ±0.1°C. Solar power meter (Make-TES Electrical electronics, Model-1333) with the Range-1 to 2000 W/m^2 is used to measure solar intensity. The experimentation was conducted from 9:00 to 16:00 hrs at Coimbatore Institute of Engineering and Technology, Coimbatore in the month of April to May 2016. The average solar radiation and ambient temperature are taken for minimizing the deviations due to varying climate conditions at different days of experimentation. The detailed specifications with respect to the solar collector and is listed in Table 1.

Fig 1.(a) The experimental setups

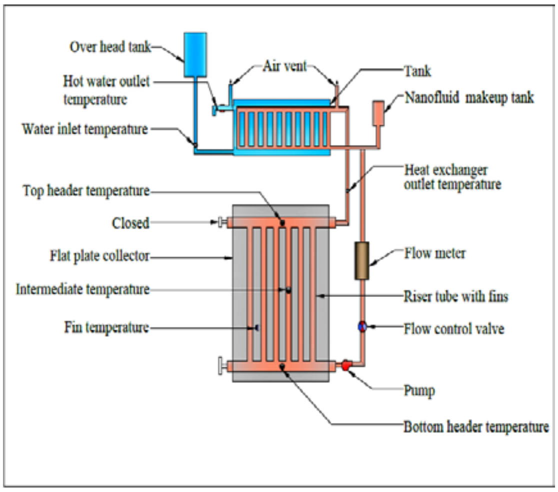

Fig.1(b). Schematic diagram of the experimental setup

Table 1 Specifications of flat plate solar collector for the experimental study

Sl.No	Description	Dimension
1	Length of the collector	2000 mm
2	Width of the collector	1000 mm
3	Collector tilt angle	15°
4	Thickness of back insulation	50 mm
5	Thickness of edge insulation	25 mm
6	Absorber plate thickness	0.454mm
7	Thermal conductivity of the absorber plate	386 Wm^{-1} K^{-1}
8	Emissivity of absorber plate	0.95
9	Thickness of the glass cover	4mm
12	Effective transmittance - absorptance product	0.82
10	Tube spacing between risers (9 Nos)	95mm
11	Inner diameter of the riser pipe	9.5mm
12	Outer diameter of the riser pipe	10mm
13	Header pipe diameter	25mm

Preparation of nanofluid

Business accessible spherical molded cerium oxide powders having 99.5% of virtue and a mean diameter of 25nm has been utilized as a part of this experimental study. Furthermore, polyvinyl pyrolidine (PVP), a characteristic surfactant scattering of cerium oxide and distilled water has been utilized as an operating liquid in this investigation. The flat plate solar water heater having 8.5 liters capacity for working fluid was fabricated for experimental investigation. For preparing 0.05% volume fraction of CeO_2/water nanofluid, the quantity of nanoparticles was estimated to be 3.825 g. For avoiding the settling down of the CeO_2 nanoparticles because of its higher density, 10% weight of PVP surfactant was dispersed in distilled water, initially, with the help of a magnetic stirrer and then the required amount of CeO_2 nanoparticles was slowly added while maintaining constant stirring for about half an hour. For obtaining a homogeneous mixture, once again the prepared solution was sonicated continuously using ultrasonic vibrator for another 30 minutes approximately with a frequency range from 15 Hz to 100 Hz thereby breaking down the agglomeration of CeO_2 nanoparticles and water. The ultrasonic vibrator used for preparing nanofluid solution is shown in Figure.2. The properties of nanoparticle, base fluid and CeO_2/water nanofluid are indicated in Table 2.

Fig.2. Ultrasonic vibrator

Table 2 Properties of the base fluid, Cerium oxide nanoparticle and CeO_2/water nanofluid

Sl. No	Material	Thermal conductivity (W/mK)	Specific heat (J/kg K)	Viscosity (kg/m s)	Density (kg/m)
1	Water	0.61	4187	0.000620	1000
2	CeO_2	12	460	-	7132
3	CeO_2/ water nanofluid (0.05%)	0.697	4152	0.000690	1010

Measurement of thermo physical properties

Thermal properties analyser (KD2 Pro,

Decagon Devices) shown in Figure.3 was used to measure thermal conductivity of CeO_2/water nanofluid, which may be defined as the property of the material to conduct heat by the transient hotwire method. It was found a value of 0.697 W/mK for the CeO_2/water nanofluid having 25 nm average diameters with lower volume fraction of 0.05% at nanofluid temperature of 31.45^{0}C. Moreover, in primary theories, the parameters such as thermal conductivity of the base fluid, thermal conductivity of nanoparticles, particle size of the nanoparticle and the volume fraction of the nanoparticles were being counted to measure the effective thermal conductivity of nanofluid. In addition, the enhancement of heat transfer along with the possible increase in effective thermal conductivity is due to the reduced thickness of the thermal boundary layer, thermal characteristics of the working fluidand the role of Brownian motion of nanoparticles, which took place due to the larger surface area of nanoparticles for molecular collisions.

The density data obtained is compared with the values obtained using the density correlation equation (1)) for nanofluids, which is given below (Stalin, P et al. 2017):

$$\rho_{nf} = \varphi\rho_{np} + (1-\varphi)\rho_{bf} \tag{1}$$

Some of the viscosity models have been developed by few researchers from which experimental results have been compared. In the present study, a correlation equation (2) has been used for predicting the viscosity in terms of nanoparticle volume concentration when it is lower than 5%, in the base fluid and it is given below(Stalin, P et al. 2017):

$$\mu_{nf} = \mu_{bf}\left(\frac{1}{(1-\varphi^{2.5})}\right) \tag{2}$$

The specific heat of working nanofluids were estimated for all the volume concentrations considered in the present work, using the equation (3) denoted by (Stalin, P et al.2017):

$$C_{p,nf} = \frac{\rho_{bf} C_{pf}(1-\phi) + \rho_{np} C_{np,p}\phi}{\rho_{nf}} \tag{3}$$

Determination of efficiency

In order to evaluate the thermal performance of the solar collector, it is necessary to estimate the energy transferred to the working fluid through radiation by the collector. The energy transferred to the fluid has been stated as instantaneous power and it can be determined by using the Eq. (4) (Stalin, P et al.(2017):

$$Q_u = \dot{m}\, C_p (T_o - T_i) \tag{4}$$

where and C_p represent mass flow rate and specific heat capacity of the working fluid respectively. In the above equation, T_o and T_i denote the outlet and inlet temperatures of the working fluid respectively. The instantaneous thermal efficiency of the collector (η) is calculated with the help of instantaneous power (Q_u) and the radiation (I) coming to gross area of the collector (Stalin, P et al. 2017) :

$$\eta = \frac{Q_u}{I} \tag{5}$$

For calculating the incoming radiation, Eq. (5) is modified by considering the total area of collector and the amount of radiation coming on the unit surface. It is given as:

$$\eta = \frac{Q_u}{A_C G_T} \tag{6}$$

The instantaneous thermal performance of the collector (η) using nanofluid as heat transfer fluid can be expressed as given below:

$$\eta = \frac{\dot{m}_{nf}\, C_{nf}(T_o - T_i)}{A_C G_T} \tag{7}$$

Fig.3. Thermal properties analyzer

RESULTS AND DISCUSSION

The experiments were conducted several days from 9:00 to 16:00 hrs for evaluating the performance of flat plate solar water heating system. The flat plate solar collector's performance was experimented with lower volume fraction of 0.05% and by varying flow rates from 1lpm to 3 lpm. Figure.4. represents the solar intensity, the collector inlet, outlet fluid temperatures and the ambient temperature versus time for CeO_2/water nanofluid at 1.5 lpm. The experimental data were selected based on the solar radiation similarity pattern and represented in the study to get concurrent results. In the morning up to a certain time, the experimental curves are scattered due to the weak morning sunshine and hence the temperature rise in the collector will be minimum. Then during the peak sunny period, the scatter reduces gradually with time when the incident heat flux increases thereby increasing the outlet collector temperature and ambient temperature. There is no further enhancement observed thereafter because of increasing radiation losses, as difference between average collector temperature and ambient temperature increases.

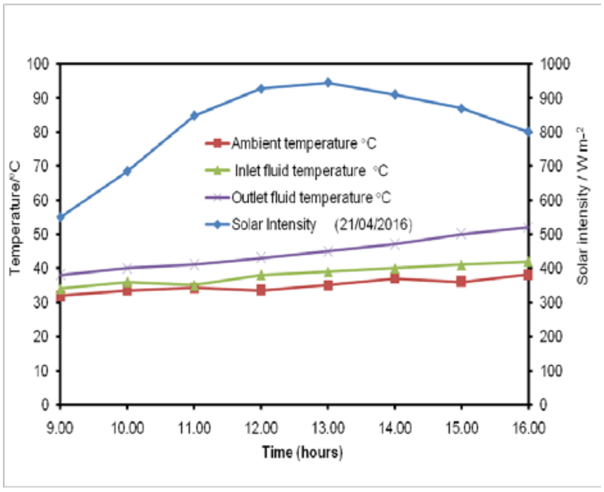

Fig.4. Variation of different Temperatures considered in this analysis and solar Radiation

Thermal absorber fin temperature

Tests have been conducted in different flow rates for lower volume concentration and the Figure.5 shows to the trail information of the solar collector thermal absorber fin temperature. Initially low temperature was absorbed in the copper fins at the inlet side. However, as the liquid in the riser tube gets warmed up, the temperature rises upward. In this way the temperature distinction between the nanofluid and the fins gets diminished. The higher temperature of CeO_2/water nanofluid coupled with the heat exchanger creates the specified temperature distinction between the CeO_2/water nanofluid and collector absorber fins. In the case of heat exchanger mode, at 1.5 lpm rate of flow, the thermal absorber fin temperature is low thereby retaining more heat from the operating liquids owing to that the heat exchanged to the water is higher and fin temperature increases when the flow rate is changed from 2 lpm to 3 lpm. It is also observed that at low flow rate, nanofluid gets more opportunity to gather the heat from thermal absorber plate and therefore lower fin temperature. Nanofluid couldn't gather more heat at higher flow rates because of lessened contact time and better fin temperature. However, fin temperature is marginally higher with in the case of conventional mode solar water heater as appeared in Fig.5 on account of poor thermal characteristics of water because of which it couldn't collect lot of heat from the absorber plate.

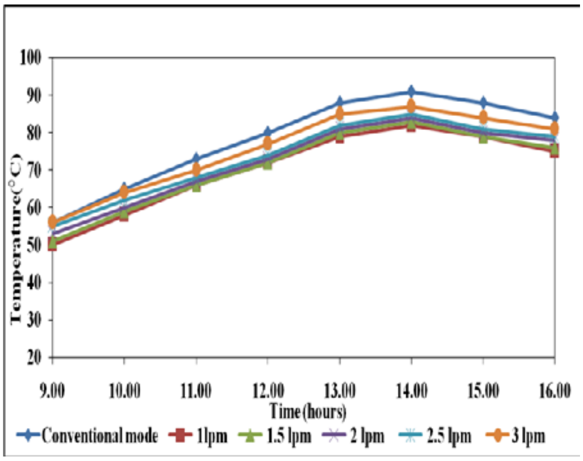

Fig.5. Influence of various flow rate on absorber fin temperature

Thermal Storage tank temperature

The temperature of the thermal storage tank water mainly depends upon the temperature difference of the working fluid at inlet and outlet of heat exchanger. The CeO_2/water nanofluid in heat exchanger mode at 1.5 lpm produced the maximum solar heat intensity of 945 $W/m^2$and the highest storage tank temperature of 89.4^{0}C at around 13.30 hrs while the lowest temperature of 75.2^{0}C was attained at around 16.00 hrs as shown in Figure.6. In contrast, the highest temperature reached in conventional mode is 77.2^{0}C which is less than that of the temperature achieved by the CeO_2/water nanofluid. It is seen that the CeO_2/water nanofluid at 1.5 lpm and 0.05 % volume fraction with surfactant produces 12.2^{0}C more than that of the conventional system. The outlet temperature of the fluid from the solar collector mainly depends on ambient temperature, the volume flow rate of nanofluid, solar intensity, and the thermal characteristics of nanofluid. The storage tank water temperature rises as the heat is transferred effectively from the CeO_2/water nanofluid in heat exchanger mode. Because of lesser contact time with the heat exchanger, the nanofluid produces the lowest temperatures in the thermal storage tank at higher flow rates. Hence CeO_2/water nanofluid has increased the storage tank temperature by 15.8% in comparison with conventional mode when using with 0.05% volume fraction. From the above results, it is clear that the addition of nanoparticles improves the absorption capacity of the base fluid thereby increasing thermal storage tank temperature in heat exchanger mode.

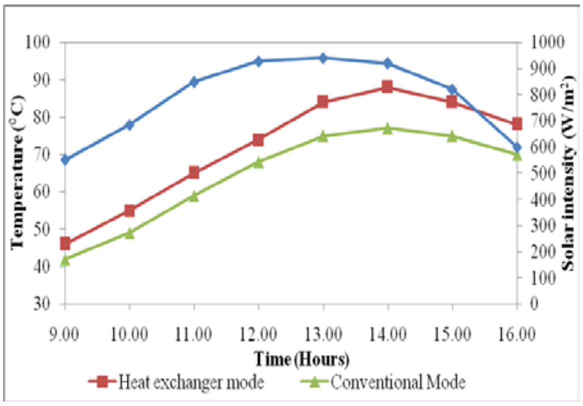

Fig.6. Influence of mode of operation on Thermal storage tank temperature

Effect of working nanofluid without surfactant for different flow rates

The CeO_2/water nanofluid was prepared with lower volume fractions of 0.05% without surfactant. The experimental tests were performed for CeO_2/water nanofluid and the readings recorded for 0.05% lower volume fractions by varying flow rates (1 lpm to 3 lpm) for several days. Figure.7 shows the variation of instantaneous collector efficiency versus reduced temperature parameter $(T_i–T_a)/G_T$ for CeO_2/water nanofluid volume flow rates with 0.05% volume fraction. The experimental data which has all the flow rate are fitted with linear trend line equations for describing characteristic parameters of flat plate solar collector.

In the following Table 3, the collector efficiency parameters F_R $(\tau\alpha)$ and F_RU_L have been tabulated for all volume flow rates of working nanofluid including conventional mode. It is seen that the instantaneous collector efficiency for nanofluid CeO_2/water having 1.5 lpm is higher than the efficiencies of all other flow rates while evaluating without surfactant. This can be deduced by comparing energy removal factor F_RU_L and absorbed energy factor F_R $(\tau\alpha)$ of all the flow rates of nanofluids and conventional mode from Table 3.It is observed that the efficiency of CeO_2/water nanofluid is 20.7 % higher than that of conventional mode while it is 3.7 % higher than that of 1 lpm flow rates of nanofluid. It is interesting to see that when the flow rate is changed from 1.5 to 3 lpm, there is a gradual decrease in the efficiencies of the collector as given in the Table 3. It is also observed from Eq. (4) that the removed energy factor F_RU_L is pre-dominant when the temperature difference is higher and the absorbed energy factor F_R $(\tau\alpha)$ is pre-dominant when the temperature difference is lower.

Table 3. Values of F_R $(\tau\alpha)$ and F_RU_L of the flat plate collector are given below.

Base fluid type	F_RU_L	F_R $(\tau\alpha)$	R^2
CeO_2/water nanofluid (0.05% & 1 lpm)	9.076	0.614	0.985
CeO_2/water nanofluid (0.05% & 1.5 lpm)	9.786	0.651	0.988
CeO_2/water nanofluid (0.05% & 2 lpm)	8.811	0.622	0.993
CeO_2/water nanofluid (0.05% & 2.5 lpm)	8.741	0.605	0.992
CeO_2/water nanofluid (0.05% & 3 lpm)	8.568	0.578	0.985
Conventional mode	9.892	0.444	0.987

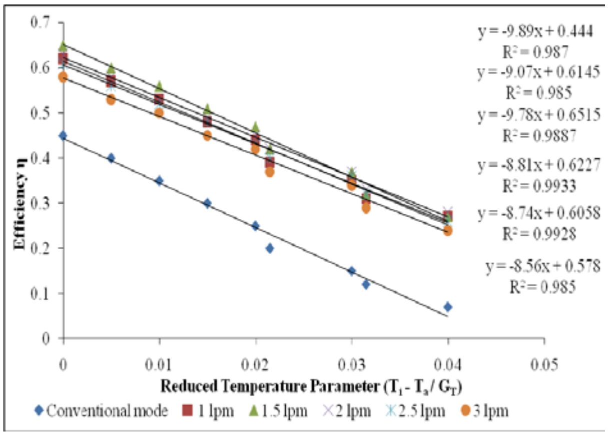

Fig.7. Efficiency of CeO_2/water nanofluid with 0.05% volume fraction and without surfactant

Effect of the presence of surfactant in working nanofluid for different flow rates

Use of surfactant is an economic and effective way to improve the stability of nanofluids which act as a bridge between nanoparticles and base fluids for creating continuity between nanoparticles and base fluids. In this section, analysis is done in order to judge the impact of the presence of surfactant polyvinyl pyrolidine (PVP) in working fluids. The efficiency of the flat plate solar collector versus reduced temperature parameter $(T_i – T_a)/ G_T$ have been plotted as shown in the Figure.8. In the following Table 4, the collector efficiency parameters F_R $(\tau\alpha)$ and F_RU_L have been tabulated for all the flow rates of working nanofluid. It can be observed that the efficiency of flat plate collector with CeO_2/water as nanofluid for1.5 lpm flow rate is higher when compared with all other flow rates while evaluating with surfactant. This can be deduced by comparing energy removal factor F_RU_L and absorbed energy factor F_R (τα) of the nanofluid from Table 4. As per Eq. 4, the energy absorbed parameter F_R (τα) is dominant in the region of lower temperature differences and the removed energy parameter F_RU_L is dominant in the region of higher temperature differences. It is seen that the efficiency of CeO_2/water nanofluid is 24.2 % higher than that of conventional mode while it is 3 % higher than that of 1 lpm low rates of nanofluid. It is interesting to see that when the flow rate is changed from 1.5 to 3 lpm, there is a gradual decrease in the efficiencies of the collector as given in the Table 4.

Table 4. Values of F_R (τα) and F_RU_L of the flat plate collector at various flow rates

Base fluid type	F_RU_L	F_R (τα)	R^2
CeO_2/water nanofluid (0.05% & 1 lpm)	9.377	0.651	0.994
CeO_2/water nanofluid (0.05% & 1.5 lpm)	9.601	0.686	0.988
CeO_2/water nanofluid (0.05% & 2 lpm)	9.184	0.662	0.985
CeO_2/water nanofluid (0.05% & 2.5 lpm)	8.934	0.649	0.986
CeO_2/water nanofluid (0.05% & 3 lpm)	8.914	0.627	0.989
Conventional mode	9.89	0.444	0.987

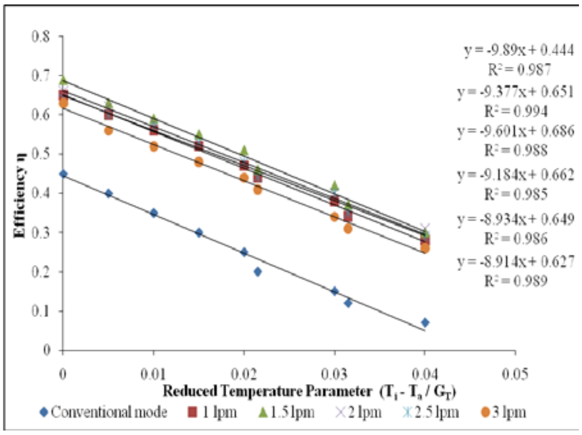

Fig.8. Efficiency of CeO_2/water nanofluid with 0.05% volume fraction with surfactant

The effect of volume flow rate

The energy absorbed parameter F_R(τα) and the removed energy parameter F_RU_L for the working fluid for all the flow rates have been shown in Fig. 7 and Fig. 8 along with Tables 3 and 4. It is observed that highest enhancement of 24.2% in solar collector efficiency has been achieved for flow rate at 1.5 lpm and 0.05% particle volume concentration compared to conventional mode solar water heating systems and 3.5% enhancement when compared with same working fluid with higher flow rate (3 lpm). At the flow rate of 1.5 lpm, the time of circulation of the nanofluids in the collector is higher and hence greater absorption of solar energy which leads to more temperature rise thereby higher heat transfer rate. At higher flow rates, the temperature rise in the fluid itself is small due to lesser residence time of nanofluids and hence lower heat transfer rate. It is also seen that collector efficiency increases with the increase in flow rate up to certain limit after which it shows negative results. The primary reason is Reynolds number increased with the increase in flow rate thereby increasing the velocity and improvement in heat transfer coefficient. Beyond the certain limit, increased flow rate causes reduction in bulk temperature of the nanofluids and hence the reduced enhancement in thermal conductivity in the working fluids.

Validation of Experimental work

To validate the present work at conventional mode of operation the results are compared with experimental results given by Gupta, H et.al.(2015) at identical operating conditions is shown in Figure.9. The average absolute deviation between the results is 7.24%. This shows the reliability of the present work and the system can be used for further evaluation.

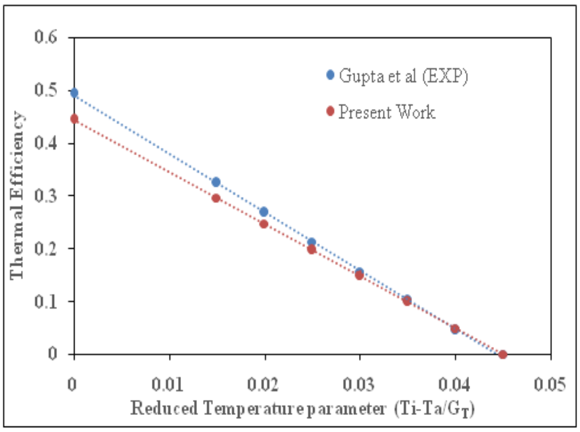

Fig.9. Validation of Experimental work at conventional mode of operation at 1.5 lpm

CONCLUSION

The performance of heat exchanger mode flat plate solar water heating system was experimentally analysed with CeO_2/water nanofluid as working fluid for lower volume concentration of 0.05% and by varying flow rate from 1 lpm to 3 lpm, with and without surfactant. The results have been compared with the performance of conventional mode solar water heating system simultaneously in similar climatic conditions. The effect of flow rate on the performance of the heat exchanger mode was studied by varying the flow rate. The enhancement in the efficiency of solar collector at 1.5 lpm with surfactant was found to be 24.2% higher than that of conventional mode. When the flow rate is increased further, the efficiency of the system was found to be decreasing due to drop in the temperature difference between outlet and inlet points. It is also seen that the efficiency of collector decreases to about 5.9% when the flow rate is changed from 1.5 lpm to 3 lpm. Hence the CeO_2 /water nanofluid can also be considered as working fluid in flat plate solar water heating systems for improving the thermal performance.

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NOMENCLATURE

A -surface area of solar collector (m^2)

C_p -Heat capacity (J/kg °K)

G_T -Global solar radiation (W/m^2)

$\dot{m}$ -Mass flow rate of fluid flow (kg/sec)

T_a-Ambient Temperature (°C)

T_i -Outlet fluid temperature of solar collector (°C)

Q_u-Useful energy gain (W)

F_R-Heat removal factor

U_l -Total loss coefficient (W/m^2K)

η -Efficiency

Lpm-Volume flow rate in Liters per minute

α-Transmittance of glass cover

τ-Absorptance of plate