AN EXPERIMENTAL STUDY OF THE MASS FLOW RATES EFFECT ON FLAT-PLATE SOLAR WATER HEATER PERFORMANCE USING AL_2O_3/WATER NANOFLUID

by

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Original scientific paper
https://doi.org/10.2298/TSCI17S2379P

In the present work, flat plate solar water heating system has been designed and fabricated accommodating 2 m^2 *area of solar collector and 0.12 m*^{2} *surface area of the heat exchanger using* Al_2O_3*/water nanofluid as the working fluid in order to evaluate the performance efficiency in the forced circulation mode. The instantaneous efficiency of solar collector is calculated by taking lower volume fraction of 0.01% with average particle size of 25 nm with and without Triton X-100 surfactant and varying the 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.*

Key words: *heat exchanger, nanofluid, flat plate solar collector, surfactant*

Introduction

Solar water heater is a clean alternative to fire wood and electricity used for heating the water required for domestic and industrial needs in both urban and rural areas. Solar collector converts the incoming radiations at the absorbing surface into thermal energy and transfers this energy to the working fluid. With the use of nanofluids in solar water heater, the temperature range can be improved. Several researchers around the world have analyzed theoretically and experimentally the effects of nanofluids in various industrial and domestic applications of solar heating systems and they observed that the thermal efficiency using nanofluids depends on different thermo-physical properties of nanoparticles such as shape, particle diameter, viscosity pH value, thermal conductivity, and specific heat of nanofluids. Advanced material synthesis technology, provides an opportunity to manufacture the nanosize materials suspended in the conventional fluids, which are known as nanofluids [1]. The unique characteristics of these nanofluids are that they have substantial increase in liquid thermal conductivity, liquid viscosity, and heat transfer coefficient. It is also observed that the metals in solid phase have higher thermal conductivities than those of fluids [2]. The use of nanofluids has shown very good improvement on the liquid thermophysical properties such as thermal conductivity [3, 4]. Natarajan and Sathish [5] have investigated that the uses of nanoparticles and carbon nanotube have improved the efficiency of solar water heater because of the enhanced

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absorption of solar energy. It is also observed that the use of nanoparticles, improves the thermal efficiency due to effective absorption of thermal energy and enhanced radioactive properties of nanofluids [6]. Li *et al.* [7] observed that the use of nanoparticles of Al_2O_3, MgO, and ZnO with distilled water in a forced convective solar collector has increased the temperature by 3 °C during the peak hour of solar radiation as compared with the use of base fluids. The nanoparticles with higher thermal properties were mixed with the primary fluid which resulted in increasing the effective thermal conductivity of the primary solution.

Many theories were developed to understand the actual behaviour of nanoparticles under temperature, pH, sonication, *etc.* Theoretical analysis on the heat transfer coefficient based on the effect of nanoparticle size, extinction coefficient [8], Brownian motion and thermophoresis were developed to understand the behaviour of nanoparticle [9]. Different thermo physical properties of Al_2O_3 and TiO_2 nanofluids were measured for various temperatures and volume fractions and it was observed that, nanofluid performed better than water as base fluids [10]. The CuO/water nanofluid prepared for a low volume concentration of 0.05%, enhanced the thermal performance of the solar water heater up to 6.3% [11]. The performance, size, cost, savings, payback period, and environmental impact of a solar collectors were estimated for different nanofluids [12] and, also it was calculated that nanofluids reduces the embodied energy and carbon emission by approximately 9% and 3%, respectively [13]. Saleh *et al.* [14] investigated experimentally the effect of SiO_2/water nanofluid on the thermal efficiency of flat plate solar collector with volume fractions up to 1% and revealed that SiO_2 nanoparticles improved the performance of solar collectors despite its low thermal conductivity when compared to other usual nanoparticles. It is observed from the literature review that only limited work has been done on the performance of flat-plate solar collector using Al_2O_3/water as the working fluid. The aim of the study is to find the effect of the mass flow rate for lower volume fraction concentration of Al_2O_3/water nanofluid with and without surfactant on the collector efficiency.

Figure 1. Experimental set-up

Solar water heating system

Development of experimental set-up

The experimental set-up shown in fig. 1, consists of flat plate solar collector, storage tank and ladder type heat exchanger. The dimensions of the solar collector are 2 m length, 1 m width and 0.15 m height, and the area of the collector is 2 m^2. A copper sheet of 0.45 mm thick is used as the absorber plate and a transparent glass of 4 mm thick is used to cover the collector in order to reduce the loss of radiation. The gap between the glass cover and absorber plate is 0.03 m. The collector bottom and side are insulated using glass wool with a thickness of 50 mm and 25 mm, respectively, to reduce the heat loss due to convection. The storage tank consists of inner tank and outer tank, in which the inner tank is placed inside the outer tank. The 0.1 m gap is maintained between two tanks, which are filled by glass wool in order to reduce the heat losses from hot water. The solar collector which consists of nine parallel tubes (risers) of 10 mm diameter on the backside of the absorber plate is connected at the top and bottom by headers to provide homogenize flow distribution and static pressure at inlet and outlet section. The schematic diagram of the solar water heating system is shown in fig. 2. A ladder type heat exchanger (fig. 3) made up of copper tubes having 25.4 mm diameter, with the surface area of 0.12 m^2 is placed inside the storage tank that transmits the heat load of the solar cycle to the consumable water.

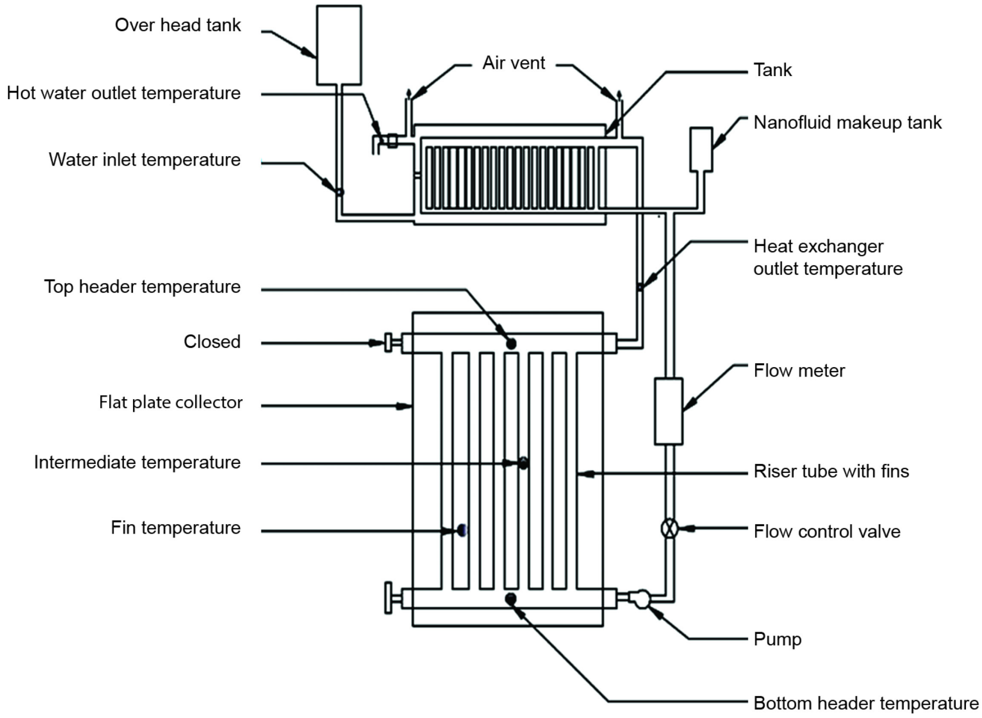

Figure 2. Schematic diagram of the experimental set-up

The experimental set-up is equipped with suitable measuring instruments for the performance study of solar water heating system. Eight thermocouples of K type with an accuracy of ±0.5 °C were fixed at various locations of the solar collector, storage tank and heat exchanger to measure the temperatures of water passing through the experimental set-up and they were connected with an 8 channel digital indicator with a resolution of 0.1 °C. Solar intensity was measured using a solar power meter. A flow control valve and rotameter were used to control the flow rate and measure the volume flow rate of working fluid, respectively. An electrical pump was employed for the circulation of nanofluids.

Figure 3. Ladder type heat exchanger

Preparation of the working nanofluids

Commercial spherical shape aluminum oxide powders with 99.5% of purity and an average diameter of 25 nm was used in this study. In addition, Triton X-100, as natural sur-

Figure 4. Ultrasonic agitator

Figure 5. Prepared Al_2O_3 nanofluid solution

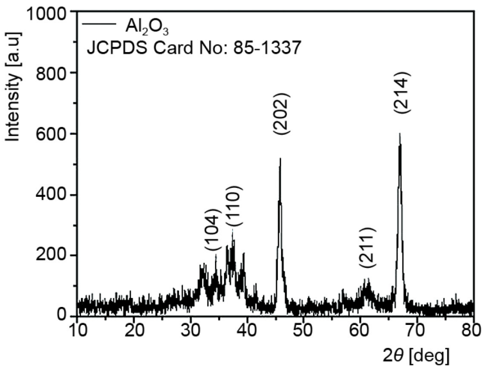

Figure 6. The XRD image of Al_2O_3 nanoparticle

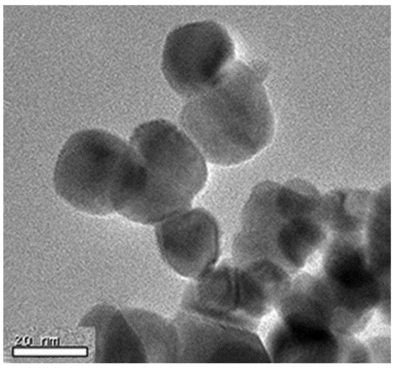

Figure 7. The TEM image of Al_2O_3 nanoparticle

factant for dispersion of Al_2O_3, and distilled water, as a base fluid, were used in this study. Due to density (3700 kg/m^3) of the Al_2O_3 nanoparticles compared to the base fluid, water (1000 kg/m^3), settlement of the Al_2O_3 nanoparticles takes place at the bottom end of the beaker. To prevent the settlement, a compatible amphiphilic surfactant, namely, Triton X-100 of 10% weight of the amount of nanoparticles was first dispersed completely in double distilled water and then Al_2O_3 nanoparticles of the required quantity were slowly added with constant stirring for 60 minutes using a magnetic stirrer. The prepared solution is further sonicated using an ultrasonic agitator for one hour to break the agglomerated particles in order to produce a homogeneous mixture of the Al_2O_3 nanoparticles and water, called Al_2O_3/water nanofluid. The ultrasonic agitator used for preparing nanofluid solution is shown in figs. 4 and 5. The transmission electron microscopy (TEM) and X-ray diffraction (XRD) images of Al_2O_3 nanoparticle is shown in figs. 6 and 7, respectively.

Experiments and calculation

The experiments were carried out during March-May 2016 at Coimbatore Institute of Engineering & Technology. The experiments were conducted several days from 9:00 to 16:00 hour 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 0.01% Al_2O_3/water nanofluid and varying flow rates from 1 to 3 L per minute. While conducting experiment, the global solar radiation (G_T) was measured every half an hour using the solar power meter (Make-TES Electrical electronics, Model-1333, Range-1 to 2000 W/m^2). Based on the energy absorbed by the absorber and the energy lost from the absorber, the useful energy gain (Q_u) was determined by eqs. (1) and (2):

$$Q_u = \dot{m}\, C_p (T_o - T_i) \tag{1}$$

where $\dot{m}$ and C_p denote mass flow rate and heat capacity of fluid and T_o and T_i are the outlet and inlet fluid temperatures of solar collector, respectively.

$$Q_u = F_R \left[G_T(\tau\alpha)A - U_L A(T_i - T_a) \right] \tag{2}$$

where F_R is heat removal factor, which can be conveniently expressed by eq. (3).

$$F_R = \frac{\dot{m}C_p(T_i - T_a)}{G_T(\tau\alpha)A - U_L A(T_i - T_a)} \tag{3}$$

where A is the surface area of the collector, $\tau\alpha$ – the absorptance and transmittance product, G_T – the global solar radiation, U_L – the overall loss coefficient of solar collector, and T_a – the ambient temperature. In eq. (3), actual gain of the collector has been related to the usefull energy gain by the collector by considering the collector surface temperature as same as that of the fluid inlet temperature. A measure of flat plate collector performance is the collector efficiency, η, which is defined as the ratio of the useful energy gain, Q_u, to the incident solar energy over a particular time period. Moreover, the thermal efficiency, η, can be obtained by dividing by the energy input, AG_T, as in eq. (4):

$$\eta = \frac{F_R[G_T(\tau\alpha)A - U_L A(T_i - T_a)]}{AG_T} \tag{4}$$

Results and discussion

Figure 8 represents the solar intensity, the collector outlet fluid temperature, the inlet fluid temperature of solar collector, and the ambient temperature *vs.* time for Al_2O_3/water nanofluid at 1 L per minute during one of the test days. Each test was performed in several days and consistent experimental data has been chosen for the calculations.

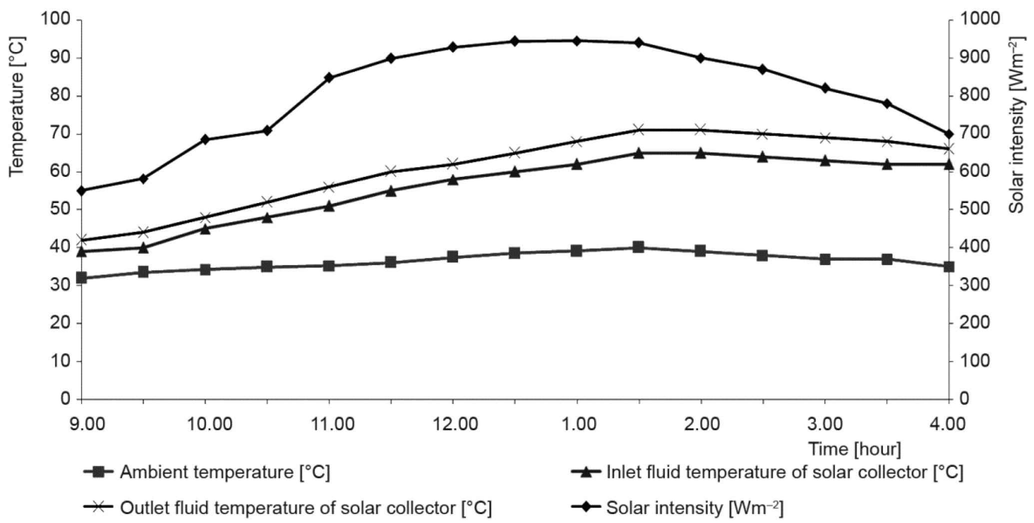

Figure 8. Solar intensity and various temperatures of solar water heating system

Thermal absorber fin temperature

The heat transfer rate and fin efficiency are dependent on thermal conductivity of material and overall loss coefficient but independent of aspect ratio of absorber plate. Experimental tests have been performed in various flow rates with lower volume concentration and fig. 9 shows the experimental data of the thermal absorber fin temperature with time. The temperature of the copper fins at the inlet side is low during the initial period, but subsequently as the fluid in the riser tube gets heated up, it moves upward and the temperature difference between the fluid and the fin gets reduced. The higher temperature of Al_2O_3/water nanofluid combined with the heat exchanger causes the large temperature difference between the Al_2O_3/water nanofluid and absorber fins. At 2 L per minute flow rate, fin temperature is low thereby absorbing more heat from the working fluids due to which the heat transferred to the water is higher and fin temperature increases further when flow rate is varied from 2 to 3 L per minute. Because at lower flow rate, nanofluid gets more time to collect the heat from the absorber plate and hence fin temperature is low. At higher flow rates, nanofluid could not able to collect more heat due to lesser contact time and higher fin temperature. The fin temperature was observed to much higher in the case of distilled water as working medium as shown in fig. 9. Distilled water has poor thermal characteristics due to which it is not able to collect more heat from the absorber plate. The heat transfer rate from the absorber plate fin decreases with increase in fluid outlet temperature. But, heat transfer rate increases with increase in overall loss parameter and solar flux.

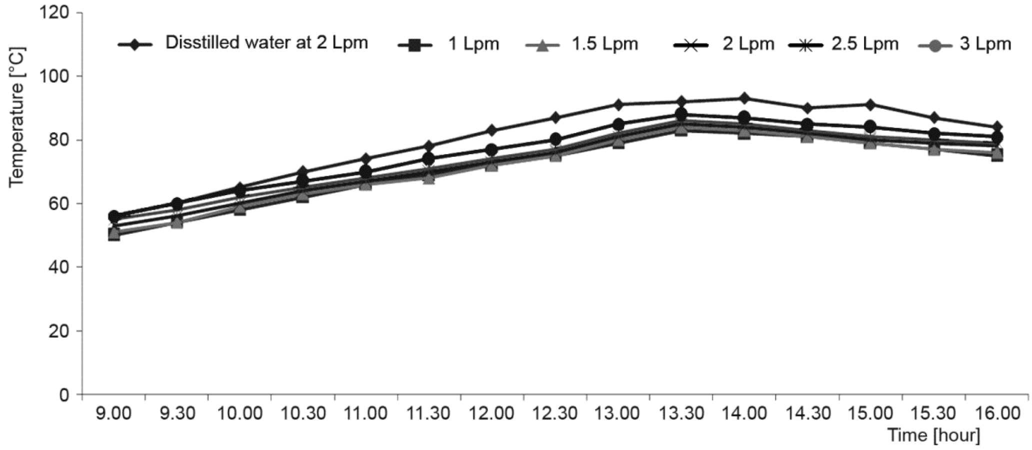

Figure 9. Thermal absorber fin temperature

Thermal storage tank temperature

The Al_2O_3/water nanofluid in forced circulation produced the highest storage tank temperature of 82.7 °C at 2 L per minute flow rate when compared with higher flow rates as shown in fig. 10. In contrast, the highest temperature reached using distilled water as the working fluid in the forced circulation is 70.6 °C, which is less than that of using Al_2O_3/water nanofluid as working fluid. The storage tank water temperature rises as the heat is transferred effectively from the Al_2O_3/water nanofluid gradually in distilled water in the forced circulation. Because of the very less contact time with the heat exchanger both fluids produce the lowest temperatures in the storage tank at higher flow rates.

Effect of working nanofluid without surfactant for different flow rates

Figure 11 shows the variation of collector efficiency *vs.* the reduced temperature parameters $(T_i - T_a)/G_T$ for each flow rate. The efficiency parameters, $F_R U_L$ and $F_R(\tau\alpha)$, at each flow rate with and without surfactant are presented in table 1.

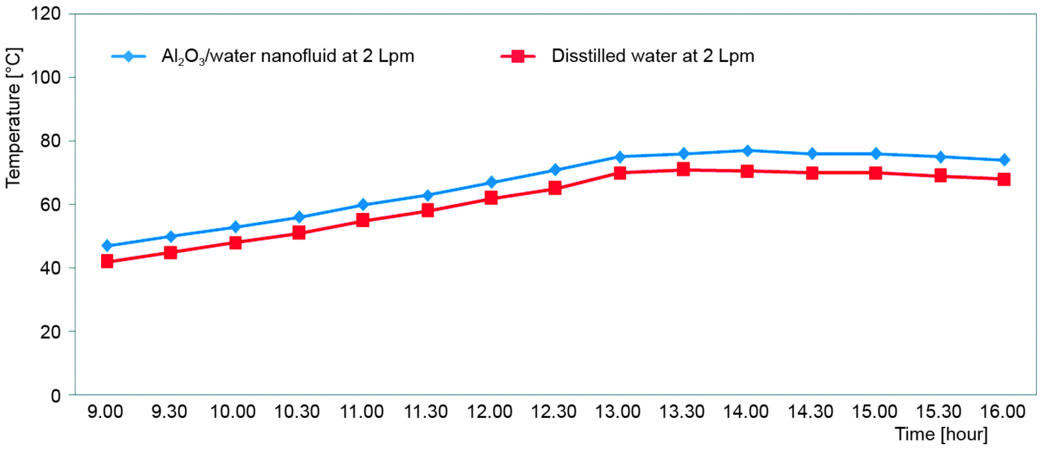

Figure 10. Thermal storage tank temperature

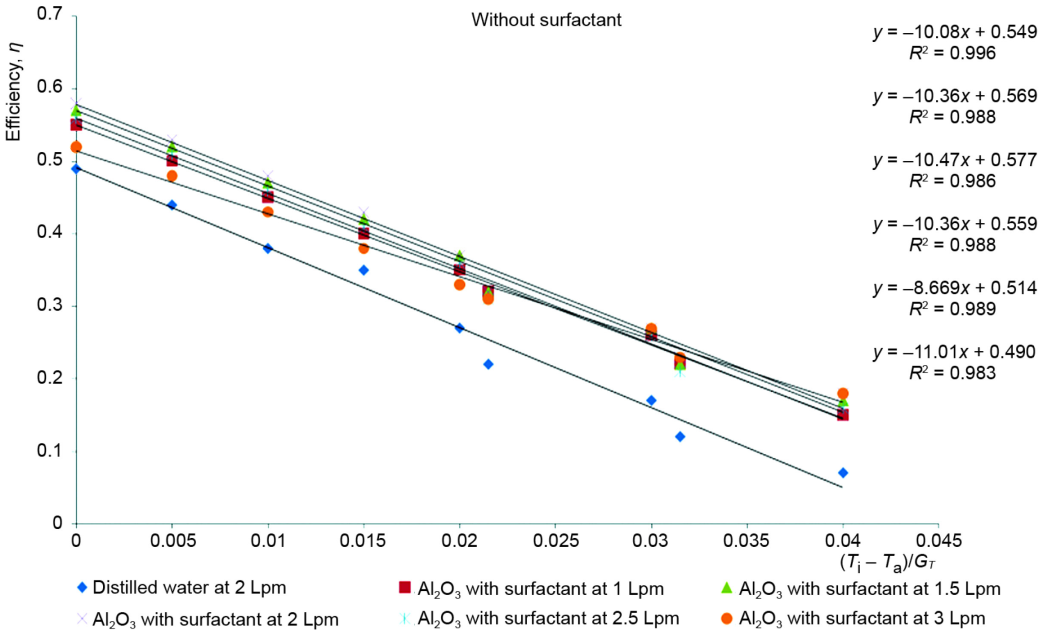

Figure 11. Efficiency of Al_2O_3/water nanofluid with 0.01% volume fraction and without surfactant

Figure 11 and tab. 1 show the efficiency of the collector in various mass flow rates with the distilled water and Al_2O_3/water nanofluid as the working fluid. When the mass flow rate of distilled water is increased from 1 to 2 L per minute, the maximum efficiency of 49% was observed at 2 L per minute flow rate. While increasing the flow rate from 2 to 3 L per minute, the efficiency started to decrease. Figure 11 shows the effect of the volume flow rate of the working nanofluid on the efficiency of the solar collector without surfactant. The volume flow rates of the working fluid were increased from 1 to 3 L per minute in steps of 0.5 L per minute. It is seen that the instantaneous collector efficiency for nanofluid Al_2O_3/water at 2 L per minute is higher than the efficiencies of all other flow rates. It is interesting to see that when the flow rate is increased from 2 to 3 L per minute, there is a gradual decrease in the ef-

Table 1. Values of $F_R(\tau\alpha)$ and F_RU_L of the flat plate collector are given below.

S. No.	Flow rate [L per minute]	F_RU_L (without surfactant)	F_RU_L (with surfactant)	$F_R(\tau\alpha)$ (without surfactant)	$F_R(\tau\alpha)$ (with surfactant)	R^2 (without surfactant)	R^2 (with surfactant)
1	1	10.08	10.12	0.549	0.592	0.996	0.987
2	1.5	10.36	10.50	0.569	0.607	0.988	0.991
3	2	10.47	11.36	0.577	0.633	0.986	0.991
4	2.5	10.36	10.36	0.559	0.603	0.988	0.990
5	3	8.67	9.48	0.514	0.560	0.989	0.993
6	Distilled water (2)	11.01	11.01	0.490	0.490	0.983	0.983

ficiencies of the collector as given in tab. 1. Figure 11 and tab. 1 show that the highest $F_R(\tau\alpha)$ value obtained for 2 L per minute is 0.577, and F_RU_L value for this volume flow rate was 10.47 without surfactant. Meanwhile, the F_RU_L value of the collector for 3 L per minute was the lowest. Based on the eq. (4), it is seen that the $F_R(\tau\alpha)$ is dominant parameter in small temperature differences whereas F_RU_L is dominant parameter in higher temperature differences.

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

In order to investigate the effect of surfactant on the efficiency of the solar collector, the nanofluid is prepared at 0.01% of Al_2O_3/water nanofluid with adding nanoparticle weight equal to 10% of Triton X-100 as surfactant. The efficiency of the flat plate solar collector *vs.* reduced temperature parameter $(T_i - T_a)/G_T$ have been plotted as shown in fig. 12. In tab. 1, collector efficiency parameters $F_R(\tau\alpha)$ and F_RU_L have been tabulated for all the flow rates of

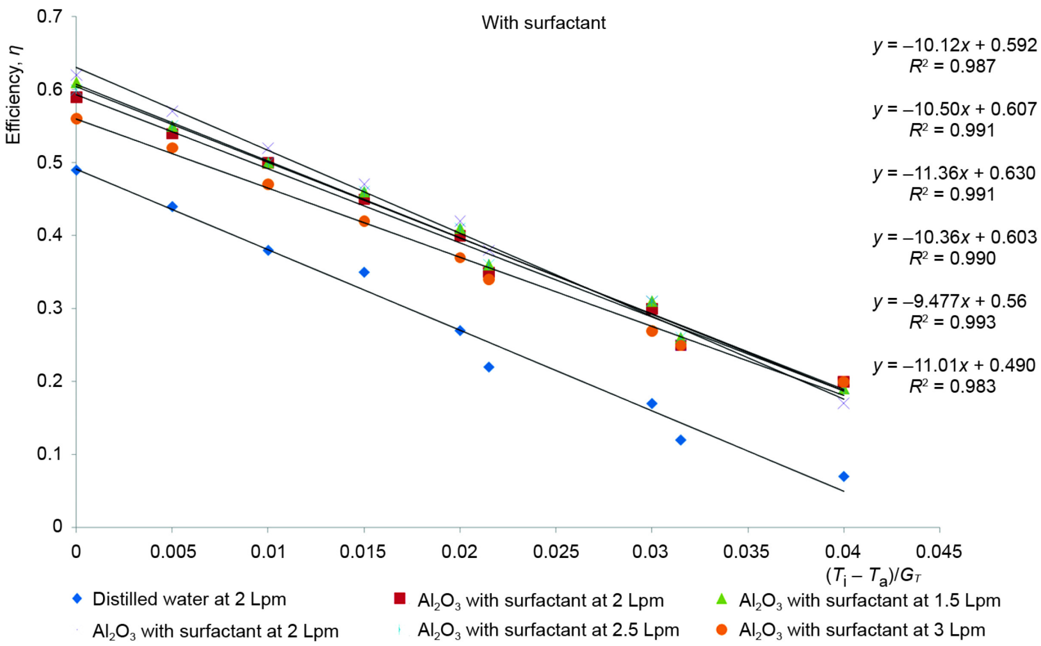

Figure 12. Efficiency of Al_2O_3/water nanofluid with 0.01% volume fraction with surfactant

working nanofluid. It can be seen that the efficiency of flat plate collector with Al_2O_3/water as nanofluid at 2 L per minute flow rate is higher when com-pared with all other flow rates while evaluating with the presence of surfactant. This can be deduced by comparing energy removal factor $F_R U_L$ and absorbed energy factor $F_R(\tau\alpha)$ of the nanofluid from tab. 1. As per eq. (4), the energy absorbed parameter $F_R(\tau\alpha)$ is dominant in the region of lower temperature differences and the removed energy parameter $F_R U_L$ is dominant in the region of higher temperature differences. It is seen that the efficiency of Al_2O_3/water nanofluid with surfactant is 14% higher than that of distilled water as base fluid at the flow rate of 2 L per minute. It is interesting to see that when the flow rate is increased from 2 to 3 L per minute, there is a gradual decrease in the efficiencies of the collector as given in tab. 1.

The absorbed energy parameter, $F_R(\tau\alpha)$, for nanofluid with and without surfactant are 0.630 and 0.577, whereas $F_R U_L$ values are 11.36 and 10.47, respectively. It is found that when Triton X-100 surfactant is added to the nanofluid $F_R(\tau\alpha)$ value increased about 5.6%. This is because the stability of the nanofluid is increased with the addition of surfactant and it has a positive effect on the maximum thermal performance of the collector.

Effect of mass flow rate

Al_2O_3/water nanofluids were prepared with 0.01% volume fraction for the investigation of the collector efficiency for various flow rates from 1 to 3 L per minute. Tests were carried out for all the flow rates with and without surfactant for several days. The efficiency of the flat plate solar collector in various mass flow rates with Al_2O_3/water nanofluid is compared with distilled water. The highest efficiency of the solar collector is achieved at the mass flow rate of 2 L per minute for both Al_2O_3/water nanofluid and distilled water as working fluids. The collector efficiency decreases with increase in mass flow rate from 2 L per minute. Therefore, it can be concluded that the optimum mass flow rate depends upon the working fluid's thermal characteristics. The highest instantaneous efficiency of 63.3% was obtained using Al_2O_3/water nanofluid as working fluid while it was 49% for distilled water at mass flow rate of 2 L per minute. It was observed that the enhanced performance using Al_2O_3/water nanofluid was significant at medium flow rate when compared to higher flow rates. When the mass flow rate is increased from 2 to 3 L per minute, experimental study shows negative trends.

Conclusion

The performance of heat exchanger mode flat plate solar water heating system was experimentally analysed with Al_2O_3/water nanofluid as working fluid for lower volume concentration of 0.01% and by varying flow rate from 1 to 3 L per minute, with and without surfactant. The results have been analysed to compare the performance of distilled water and Al_2O_3/water nanofluid in the solar water heating system in similar climatic conditions. The optimum flow rate for Al_2O_3/water nanofluid as working fluid was found to be 2 L per minute, which enhanced the efficiency of flat plate solar collector with surfactant by about 14.3% higher than compared to distilled water. Also, it is observed that, the performance of the collector decreases when the flow rate of working fluid increases above 2 L per minute.

Nomenclature

A – surface area of solar collector, [m^2]
C_p – heat capacity, [Jkg^{-1}K^{-1}]
F_R – heat removal factor, [–]
G_T – global solar radiation, [Wm^{-2}]
$\dot{m}$ – mass flow rate of fluid flow [kgs^{-1}]
Q_u – useful energy gain, [W]
T_a – ambient temperature, [°C]
T_i – inlet fluid temperature of solar collector, [°C]
T_o – outlet fluid temperature of solar collector, [°C]
U_L – overall heat loss coefficient, [Wm^{-2}K^{-1}]

Greek symbols

η – efficiency, [%]

$\tau\alpha$ – absorptance and transmittance product, [–]

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Paper submitted: March 16, 2017
Paper revised: August 30, 2017
Paper accepted: September 15, 2017