Experimental Evaluation of Using Nanofluid in Direct Absorption Solar Collector

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Abstract: Conventional tube in plate type solar collectors suffer from high heat losses due to surface based solar absorption and indirect transfer of heat from black painted or selective absorption surface to heat transfer fluid flowing in tubes resulting with low collection and conversion efficiency. To improve the efficiency, direct absorption solar collectors using base fluid mixed with nanoparticles called nanofluid as heat transfer media flowing as a thin film over the plate under gravity have been proposed. Direct absorption of solar radiation and using nanofluid improves the optical and thermo physical properties of the liquids, resulting to an increase in the efficiency of direct absorption solar collectors. In the present work the effect of alumina-water nanofluid, as heat transfer fluid, flowing as a thin film, on the efficiency of a direct absorption flat-plate solar collector was investigated experimentally. The volume fraction of alumina nanoparticles was 0.001%, 0.005%, 0.01% and 0.02% and the particles dimension was 20 nm. The ASHRAE standard was used to calculate the instantaneous efficiency. The results show that, in comparison with water as direct solar absorption medium using nanofluid as working fluid increases the efficiency. For 0.001 vol% the increased efficiency was 12.8%. Results also show that by increasing the volume fraction from 0.001% to 0.01%, there is a continuous increase in the efficiency and beyond that increase in volume fraction values, the solar collector efficiency gets a reverse trend and becomes constant.

1. INTRODUCTION

The limitation with the use of solar energy is poor collection and conversion efficiency of solar systems. Solar thermal collector is one of the most common types of solar system for conversion of solar energy into thermal energy. Among the different types of solar collectors, the conventional 'tube in plate' type flat plate collector absorbs incident solar radiation through a black surface, and transfers heat to working fluid flowing in tubes. Due to surface absorption and indirect transfer of heat to working fluid, the conversion of sunlight into thermal energy suffers from relatively low efficiencies [1].

In order to improve the efficiency of solar thermal collector, researchers proposed the concept of directly absorbing the solar energy within the fluid volume in the 1970s called Direct Absorption Solar Collector (DASC) [2-3]. However, the efficiency of such systems is limited due to the absorption and heat transfer properties of the conventional working fluid, which is very poor over the range of wavelength in solar spectrum [4]. This necessitates the mixing of the conventional working fluid with some sort of solid particle to enhance the absorption of solar energy and improved heat transfer properties. In the beginning, black liquids containing millimeter to micrometer sized particles were used as heat transfer fluid in direct absorption solar collectors that had showed efficiency improvement. The applications of micron-sized particles into the base fluid for DASCs led to pipe blockage, erosion, abrasion and poor stability. Particle sedimentation from the suspensions resulted in clogged channels [2].

Recent development in material synthesis technologies provide us an opportunity to produce the nano size materials called nanoparticles. The mixing of nanoparticles in a base fluid (nanofluid) has effective improvement on the liquid thermo physical properties such as thermal conductivity.

Masuda et al. [5] dispersed Al_2O_3 and TiO_2 nanoparticles in water and found thermal conductivity improvement by 32% and 11%, respectively. Natarajan and Sathish [6] investigated the thermal conductivity enhancement of base fluids using carbon nanotube (CNT) and suggested efficiency enhancement of the conventional solar water heater by using CNT based nanofluids as a heat transport medium. Nanoparticles also offer the potential of improving the radiative properties of liquids, leading enhanced efficiency of direct absorption solar collectors [7].

Yousefi et al. [8] reported the experimental results on a tube in plate type conventional solar collector (size 2 m^2) using Al_2O_3-H_2O nanofluid of 0.2 wt % and 0.4 wt % concentrations for three different mass flow rates and found 28.3% improvement in efficiency with 0.2 wt % of nanofluid in comparison to water. Yousefi et al. [9] also examined the effects of multi wall carbon nanotubes–water nanofluid and observed remarkable efficiency increase with 0.4 wt % nanofluid.

Tyagi et al. [10] numerically studied a direct absorption solar collector using aluminum nanoparticles in water for performance evaluation and reported efficiency improvement up to 10% than that of a flat-plate collector. Otanicar et al.

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[11] experimentally studied the role of different nanofluids as the absorption medium on the efficiency of horizontal micro size (3 cm x 5 cm) direct absorption collector in indoor environment and reported efficiency improvement up to 5%.

Very few studies for the effect of concentration of nanofluid on thermal performance of flat plate solar collector are available. As such no study on full size (1.4 m^2) tilted DASC under actual outdoor condition is available. An attempt has been made in the present paper, to experimentally study the effect of volume fraction of Al_2O_3-H_2O nanofluid flowing over the glass base plate as a direct absorbing medium on the efficiency of a tilted direct absorption solar collector under outdoor condition. Effect of four different nanoparticle volume concentrations i.e. 0.001%, 0.005%, 0.01% and 0.02% were considered on the DASC efficiency and the collector performance was also compared with base fluid distilled water.

2. DIRECT ABSORPTION SOLAR COLLECTOR

Schematic diagram explaining the working principle of direct absorption collector is shown in Figure 1.

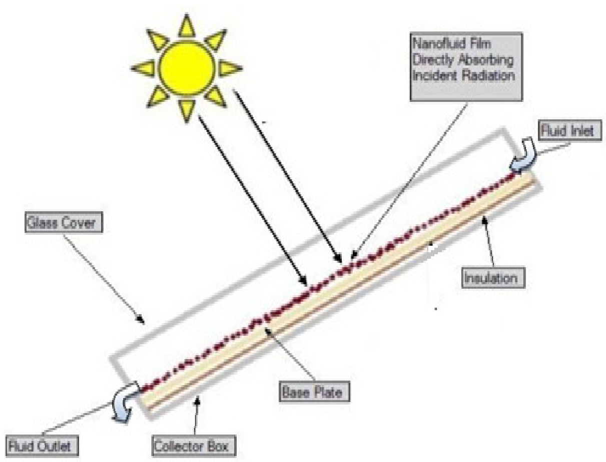

Fig. 1. The schematic of direct absorption solar collector.

The Direct Absorption Solar Collector (DASC) works on the principle of directly absorbing the incident solar radiations by the thin fluid film flowing over the back plate and thin film volumetrically absorbs the insolation.

From design point of view DASC closely resembles a conventional flat plate solar collector design except that in the case of the DASC, there is no absorber tube and instead there is a flow of fluid volume as a thin film over the base plate. The sun's rays directly strike the flowing fluid film volume. This is then employed for raising the temperature of pure water via a heat exchanger.

3. NANOFLUID PREPARATION

Preparation of stable nanofluid with uniform dispersion is an important requirement for improving heat transfer performance of conventional fluids and nanofluid needs to be prepared in a systematic and careful manner. Three methods available for preparation of stable nanofluids are [12].

i. Surfactant addition to the base fluid

ii. Acid treatment of base fluid

iii. Ultrasonic mixing of nano powder in base liquid

Thermo physical properties of nanofluids are affected with the use of surfactants and acid treatment may cause material degradation after some days of continuous usage of nanofluids in practical applications. The sonication is an approved technique for dispersing the aggregated nanoparticles [13-14]. In the present study ultrasonic vibration mixer is used for preparation of nanofluid with minimum aggregation of nanoparticles and improved dispersion behavior. Dry Al_2O_3 nanoparticles of 99.99% purity and average size of 20-30 nm are used with distilled water as base fluid in nanofluid preparation. Properties of the Al_2O_3 nanoparticles used are tabulated in the Table 1.

Table 1. Physical properties of Alumina (Al_2O_3) nanoparticles.

Size of particles	20-30 nm
Shape of particles	Spherical particles
Density	3700 kg/m^3
Surface area per unit weight	15-20 m^2/g
Crystal Form	Gamma
Al_2O_3 Content	99.99%

The quantity of Al_2O_3 nanoparticles required for preparation of nanofluid of different volume concentrations is calculated using formula in Eq. (1).

$$m_{np} - V_t \,.VF_{np}.\rho_{np} \quad (1)$$

Where m_{np} is the mass of nanoparticles (kg), V_t is the total volume of nanofluid (m^3), VF_{np} is the volume fraction of nanoparticles and ρ_{np} is the density of nanoparticles (kg/m^3).

Ultrasonication was applied for 6–7 hours to mix calculated amount of Al_2O_3 nanoparticles in distilled water using ultrasonic vibration mixer.

The Al_2O_3 nanofluid thus prepared was kept for observation and no particle settlement was observed at the bottom of the flask even after twenty four hours. During the experimentation, the time taken to complete the experiment is less than the time required for first sedimentation to take place and hence surfactants are not mixed in the Al_2O_3 nanofluids.

Four different volume concentrations of 0.001, 0.005, 0.01, and 0.02 % were used in the study.

4. TESTING METHOD AND EFFICIENCY CALCULATION

Thermal performance of solar collectors is commonly evaluated using ASHRAE Standard 93-86 [15]. Collector thermal performance is calculated by determining collector instantaneous efficiency for different incident solar radiations, ambient temperatures, and inlet fluid temperatures. Intensity of incident solar radiations as well as useful heat gain by the working fluid is measured under steady state conditions.

As per ASHRAE Standard 93-86 steady-state conditions should be maintained during the data period and also during a specified time interval prior to the data period, called the pre-data period. For attaining steady state conditions the mass flow rate must be within ± 1%, irradiation must be within ± 50 W/m^2, the outdoor ambient temperature must not vary more than ±1.5 K, and the inlet temperature must be within ± 0.1 K for the entire test period.

The experiments were performed at different inlet temperatures of working fluid according to ASHRAE Standard. The measurements were taken for ambient, inlet & outlet temperature, global solar intensity and the mass flow rate of working fluid. The useful heat gain by the fluid can be calculated using Eq. (2).

$$Q_u = \dot{m}\, C_p\,(T_o - T_i) = A_c F_R[I_T(\tau\alpha) - U_L(T_i - T_a)] \qquad (2)$$

where Q_u is the useful heat gain (W), $\dot{m}$ is the mass flow rate of fluid (kg/min), C_p is the heat capacity of water or nanofluid (J/kg K), T_o is the outlet fluid temperature of solar collector (K), A_c is the surface area of solar collector (m^2), F_R is the heat removal factor, ($\tau\alpha$) is absorptance–transmittance product, I_T is the global solar radiation (W/m^2), U_L is the overall loss coefficient of solar collector, and T_a is the ambient temperature (K).

The heat capacity of nanofluid is calculated with the help of Eq. 3 [16].

$$C_{p,nf} = C_{p,np}(\phi) + C_{p,bf}(1-\phi) \qquad (3)$$

where ϕ indicates the volume fraction of nanoparticles, and $C_{p,np}$ and $C_{p,bf}$ are heat capacities of nanoparticles (773 J/kg K) and base fluid (4180 J/kg K) respectively. Instantaneous collector efficiency relates the useful heat gain to the incident solar energy by Eq. (4) and (5).

$$\eta_i = \frac{Q_u}{A_c\, I_T} = \frac{\dot{m}\, C_p\,(T_o - T_i)}{I_T} \qquad (4)$$

$$\eta_i = F_R(\tau\alpha) - F_R U_L \frac{(T_i - T_a)}{I_T} \qquad (5)$$

If the thermal efficiency test is performed at the normal incidence conditions then $F_R(\tau\alpha)$, and $F_R U_L$ is constant for the temperature range of the collector. When the efficiency values obtained from averaged data is plotted against $\frac{(T_i - T_a)}{I_T}$ a straight line will result according to Eq. (5). Intersection of the line with the vertical efficiency axis equals to absorbed energy parameter, $F_R(\tau\alpha)$. At this point the temperature of the fluid entering the collector equals the ambient temperature and collector efficiency is at its maximum. Slope of the line indicates energy loss from the collector that is nominated as energy loss parameter $F_R U_L$. At the intersection of the line with the horizontal axis collector efficiency is zero and designated as stagnation point, usually occurs when no fluid flows in the collector.

5. RESULTS AND DISCUSSIONS

Experimental tests were performed with distilled water and prepared Al_2O_3-water nanofluid of four different concentrations of 0.001 vol%, 0.005 vol%, 0.01 vol% and 0.02 vol% on direct absorption solar collector from 10 AM to the time at which stagnation point is reached at the flow rate of 2 lpm on consecutive days. Each test was performed several times and the best data satisfying conditions of ASHRAE standard have been taken. The experimental results for water and four concentrations of nanofluids are plotted in the form of efficiency curves as shown in Figure 2. The experimental data are best fitted with linear equations to provide the performance characteristic parameters of the collector. These efficiency parameters, $F_R U_L$ and $F_R(\tau\alpha)$, are presented in the Table 2.

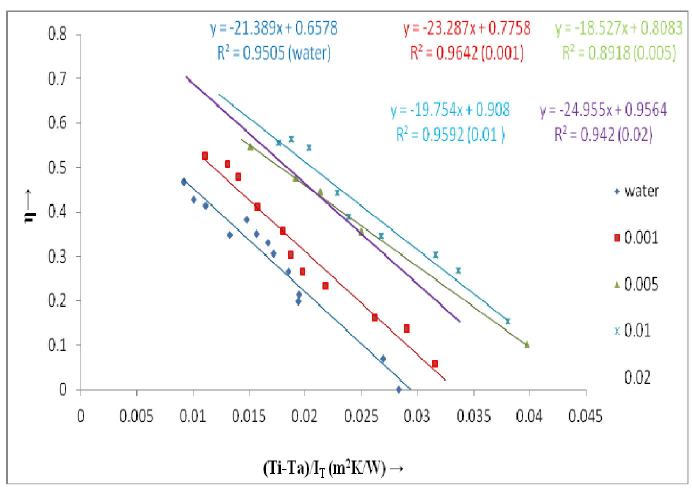

Fig. 2. Efficiency plots for Al_2O_3-water nanofluid at different concentrations

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It is observed from Figure 2 that collector efficiency with all the four concentrations of Al_2O_3 nanofluid is higher than with water as heat transfer fluid. This is mainly due to higher values of absorbed energy parameter $F_R(\tau\alpha)$ for Al_2O_3 nanofluids as compared to water as can be noticed from Table 2. It is also clear that the absorbed energy parameter, $F_R(\tau\alpha)$, value for 0.001 vol % of nanofluid is higher than water by 18 % but higher value of heat loss parameter, F_RU_L, the resultant collector efficiency with 0.001 vol% nanofluid is greater than water by 12.8 %.

Table 2 Collector efficiency parameters for Al_2O_3-water nanofluid.

S. No.	Working fluid type	Volume fraction (%)	F_RU_L	F_R $(\tau\alpha)$	R^2
1	Water	0	21.389	0.6578	0.9505
2	Al_2O_3 nanofluid	0.001	23.287	0.7758	0.9642
3		0.005	18.527	0.8083	0.8918
4		0.01	19.754	0.908	0.9592
5		0.02	24.955	0.9564	0.942

Collector efficiency increased with increase in nanoparticle concentration from 0.001 to 0.01 vol% due to increase in absorbed energy parameter by 38 % and heat loss parameter decrease by 7.6 % as observed from Table 2. Further increase of nanoparticles concentration from 0.01 vol% to 0.02 vol%, resulted collector efficiency decrease due to high increase of loss parameter (26%) in comparison to less increase (5.3%) in absorbed energy parameter.

The main reason for this result in Collector efficiency is that at lower volume fraction, some of the incident solar radiations were absorbed by the nanofluid film and remaining portion absorbed by the bottom base plate or reflected back into the nanofluid film. This raised the nanofluid temperature near the bottom plate causing extra emissive losses hence lower collector efficiency. At certain nanofluid volume fraction when peak collector efficiency is obtained, even temperature distribution within nanofluid volume is observed. For higher volume fraction, top layers of nanofluid absorbed most of the incident radiation and allowing little or no radiation to penetrate the lower fluid layer and reach the bottom plate. This results in uneven temperature distribution within nanofluid film and higher top layer temperature causes excessive emissive losses and drop in collector efficiency.

6. CONCLUSION

Thermal performance study of direct absorption solar collector using nanofluid of four different concentrations 0.001%, 0.005%, 0.01% and 0.02% with 20 nm alumina nanoparticles in distilled water is carried out. The main outcomes of the study are:

I. The collector efficiency increased for all four concentrations of nanofluid than pure water.

II. Collector efficiency enhancement of 32.3% and 12.8 % is noticed for 0.01 vol% and 0.001 vol% respectively.

III. Collector efficiency with nanoparticles concentrations beyond 0.01 vol% is found to be lower.

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