Experimental Evaluation on the Effect of Nan fluid Concentration on the Performance of Direct Absorption Solar Collector

Hemant Kumar Gupta, Ghanshyam Das Agrawal, Jyotirmay Mathur

Abstract- In this study, a direct absorption solar collector (DASC) working on volumetric absorption principle is developed to perform experimental study for evaluating the effects of different Al_2O_3-H_2O nanofluid concentration. Experimentation was carried using four different concentrations of 20 nm size Al_2O_3 nanoparticles, 10 ppm, 50 ppm and 100 ppm. ASHRAE standard 93-86 was followed for calculation of instantaneous efficiency of solar collector. Use of nanofluid as working fluid improves the optical and thermo physical properties that result into an increase in the performance of the collector. Improvement in efficiency of solar collector has been recorded in all three cases of using nanofluids in place of water. Optical efficiency enhancement of 22.1%, 39.6% and 24.6% has been observed for 10 ppm, 50 ppm and 100 ppm concentration respectively.

Keywords: Direct absorption solar collector; Al2O3-water nanofluid; Concentration, Collector testing; Performance enhancement

I. INTRODUCTION

Use of solar energy is popular renewable source of energy with least environmental impact and free availability for every human being all over the world. The major limitation with the use of solar energy is poor collection and conversion efficiency of solar conversion systems. Solar thermal collector is one of the most common type of solar system for collection and conversion of solar energy into thermal energy. Among these different types of solar collectors, the conventional 'tube in plate' type flat plate collector absorbs incident solar radiation through a black solid selective surface, and transfers heat to working fluid flowing in tubes called risers, brazed onto the surface of the absorber plate. The efficiency of a solar thermal collector relies on the effectiveness of absorbing incident solar radiant energy and heat transfer from the absorber to the carrier, which is normally fluid. Due to surface heat absorption and indirect transfer of heat to working fluid, the conversion of sunlight into thermal energy suffers from relatively low efficiencies and outlet temperatures (Pacheco, 2001).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) (Minardi and Chunag, 1975; Bertocchi et al., 2004).

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Hemant Kumar Gupta, Department of Mechanical Engineering, Malaviya National Institute of Technology Jaipur, India
Ghanshyam Das Agrawal, Department of Mechanical Engineering, Malaviya National Institute of Technology Jaipur, India
Jyotirmay Mathur, Department of Mechanical Engineering, Malaviya National Institute of Technology Jaipur, India

However, the efficiency of direct absorption collector is limited by the absorption properties of the conventional working fluid, which is very poor over the range of wavelength in solar spectrum (Otanicar et al., 2009). In the beginning, black liquids containing millimeter to micrometer sized particles were also used as working fluid in direct absorption solar collectors to enhance the absorption of solar radiation that had showed efficiency improvement. The applications of micron-sized particles into the base fluid for DASCs lead to pipe blockage, erosion, abrasion and poor stability. Particle sedimentation from the suspensions resulted in clogged channels (Minardi and Chunag, 1975). Advance 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 a dramatic effect on the liquid thermo physical properties such as thermal conductivity (Arai et al., 1984). Studies suggested the thermal conductivity enhancement due to dispersion of nanoparticles (Wang and Majumdar, 2007), intensification of turbulence (Pak and Cho, 1998), Brownian motion (Xuan and Li, 2000; Keblinski et al., 2002) and thermophoresis (Koo and Kleinstreuer, 2005).

Masuda et al. (1993) dispersed Al_2O_3 and TiO_2 nanoparticles in water and found thermal conductivity improvement by 32% and 11%, respectively. Grimm (1993) dispersed aluminum metal particles (1-80 nm) into water and claimed 100% increase in thermal conductivity of the nanofluid for 0.5-10 wt%. Natarajan and Sathish (2009) 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 (Mu et al., 2010). Yousefi et al. (2012a) 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. (2012b) also examined the effects of multi wall carbon nanotubes–water nanofluid and observed remarkable efficiency increase with 0.4 wt % nanofluid. Tyagi et al. (2009) 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. (2010) 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%.

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Very few studies on the thermal performance evaluation of flat plate solar collector with nanofluids are available. As such no study on DASC under actual outdoor condition is available. An attempt has been made in the present paper, to experimentally study the effect of Al_2O_3-H_2O nanofluid concentration as a direct absorbing medium on the efficiency of a tilted direct absorption solar collector under outdoor condition. Effect of three different nanofluid concentrations i.e. 10 ppm, 50 ppm and 100 ppm were considered on the DASC efficiency and the collector performance was also compared with distilled water.

II. DASC Experimental Set-up

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

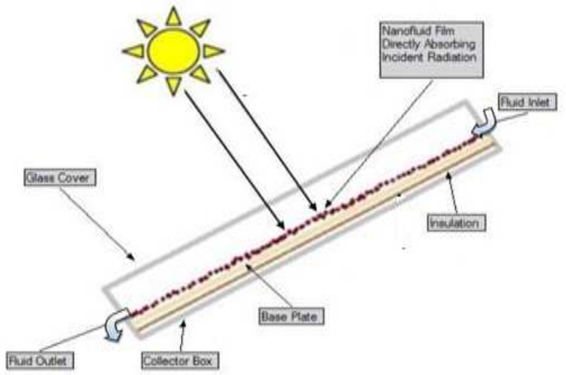

Fig.1. The schematic of direct absorption solar collector (DASC).

Table1 The Specifications of DASC components.

Component	Dimension	Remark
Collector	1.54 m x 0.9 m	Gross Area = 1.40 m^2
Absorber	1.44 m x 0.80 m	Effective Area = 1.15 m^2
Transparent cover	6 mm	Material- toughened glass
Base plate	6 mm thick	Material- toughened glass
Collector box inner glass wall	6 mm thick	Material -plain glass
Film formation system	¾" header pipe with 1 mm dia holes-106 no, pitch 1 mm	Aluminum pipe
Bottom insulation	50 mm thick	Glass wool
Side insulation	25 mm thick	Glass wool
Frame	200 mm height	Material- M.S.

2.1. Experimental Apparatus and procedure

For experimental study, a set up of DASC was developed and erected at the roof top of Mechanical Engineering Department, Malaviya National Institute of Technology, Jaipur (26.01° latitude and 75.52° longitudes). The collector was oriented due south with a tilt angle of 26^o. Specifications of the collector components used are shown in Table 1. It mainly consists of a glass base plate, mounted on a wooden box with inner glass wall on all four sides and equipped with a spray system for film formation over the glass base plate. In DASC no tubes are used for carrying fluid and nanofluid flows directly over the glass plate, which is used in place of black absorber plate. Experimental test set up consists of a solar collector, working fluid loop and data acquisition system. Flow rate is measured with the help of electromagnetic digital flow meter (Make-Electronet, range 0–5 lpm, accuracy ±1 %). A centrifugal pump circulates the collected fluid in the system. Three K-type thermocouples were installed to measure collector inlet and outlet fluid temperatures and the ambient temperature. These readings were collected and stored in a computer through a data logger (Make-Agilent, model-34970A, 16 channels). Intensity of total solar radiation was recorded using digital solar meter (Range-1to1300 W/m^2, accuracy ±5 % of measurement). The experiments were performed at different inlet temperatures of working fluid according to ASHRAE Standard 93-86 (1986).

2.2. 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 (Trisaksri and Wongwises, 2007).

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 (Liu et al., 1998; Li et al., 2007). 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 (procured from Nanoshel-Intelligent Materials Private Ltd, USA based company) are used with distilled water as base fluid in nanofluid preparation.

The quantity of Al_2O_3 nanoparticles required for preparation of nanofluid of different volume concentrations is calculated using formula in Eq. (1). A sensitive balance (make-citizen, model-CTG 602 resolution- 0.1mg) is used to weigh the Al_2O_3 nanoparticles very accurately.

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

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).

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Ultrasonication was applied for 6–7 hours to mix calculated amount of Al_2O_3 nanoparticles in distilled water using ultrasonic vibration mixer (Make-Toshniwal, model-UP-600S, power-600W, frequency-27±3 kHz,).

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 0.05 % were used in the study.

III. Data Reduction

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).

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

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 equation (Zhang et al. 2006).

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

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).

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

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

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.

IV. Results and discussions

4.1 Al_2O_3-water as working fluid

Al_2O_3 nanoparticles are mixed in base fluid distilled water to get nanofluid of 50 ppm concentration and investigations are performed to determine the effect of different flow rates at 1.5, 2 and 2.5 lit/min. At each flow rate experiments with several test periods at different inlet fluid temperature in quasi steady state conditions were conducted from 10.00 AM to time when stagnation temperature is achieved on a day. The experimental results are plotted as shown in Fig.2. The efficiency parameters $F_R(\tau\alpha)$ and $F_R U_L$ of collector for three flow rate of Al_2O_3 nanofluid are presented in Table 2.

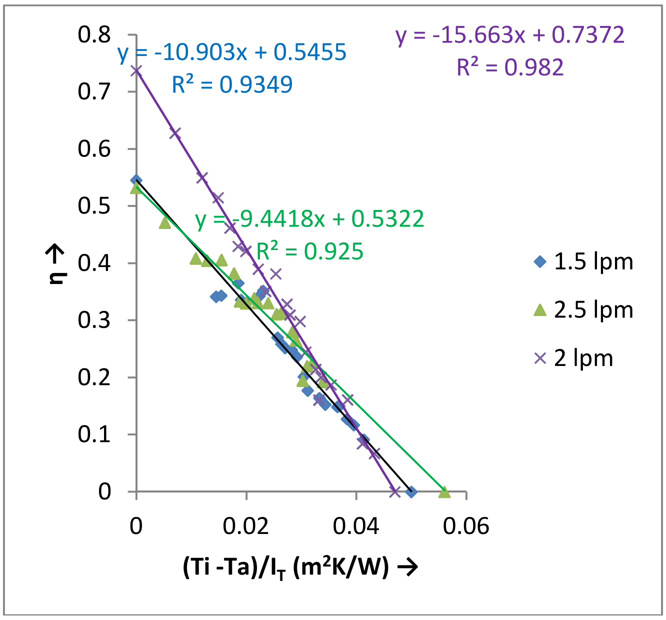

Fig.2. Efficiency curve at three flow rates for Al_2O_3 - water nanofluid.

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Table 2 Collector efficiency parameters for Al_2O_3-water nanofluid

S.No.	Flow rate (lit/min)	F_RU_L	F_R (τα)	R^2
1	1.5	10.903	0.5455	0.9349
2	2	15.663	0.7372	0.982
3	2.5	9.4418	0.5322	0.925

It is observed from Fig.2 that the collector efficiency lines for 2 and 2.5 lit/min intersect each other at reduced temperature value of 0.035. For low temperature range, $(T_i - T_a)/ I_T < 0.035$, the collector efficiency is greater at 2 lit/min due to higher value of absorbed energy parameter and reduced heat losses. However for high temperature range, $(T_i - T_a)/ I_T > 0.035$, the collector efficiency is greater at 2.5 lit/min. As collector is operated most of the time in the low temperature range hence, 2 lit/min flow rate is chosen for further experimental study.

4.2 Al_2O_3-water as working fluid- effect of volume fraction

Al_2O_3-water nanofluid of three different concentrations of 10 ppm, 50 ppm and 100 ppm were prepared and studies were performed at the flow rate of 2 lit/min. The experimental results for water and four concentrations of nanofluids are plotted in the form of efficiency curves as shown in Fig. 3.

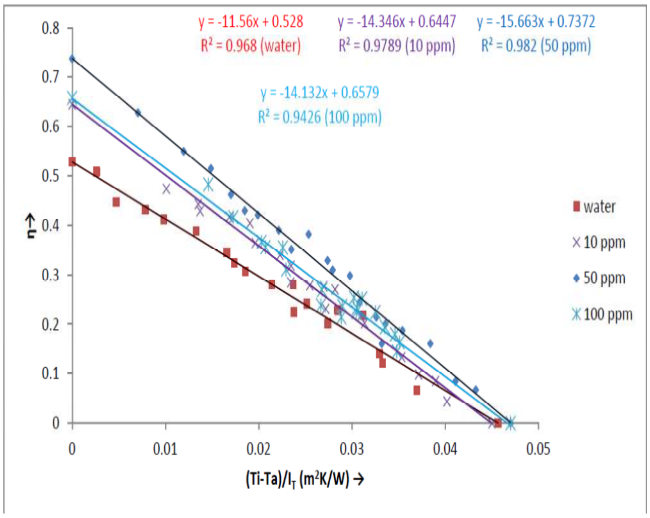

Fig.3. Efficiency curves for Al_2O_3-water nanofluid at different concentrations

It is observed from Fig.3 that collector efficiency with all the three concentrations of Al_2O_3 nanofluid is higher than with water as working fluid. This is due to higher values of absorbed energy parameter F_R(τα) and lower values of energy loss parameter F_RU_L for Al_2O_3 nanofluids as compared to water as can be noticed from Table 3. It is also clear that for wide temperature range, the absorbed energy parameter, F_R(τα), value for 10 ppm of nanofluid is higher than water by 22.1% and correspondingly optical efficiency with nanofluid is greater than water by 22.1% because in low temperature range absorbed energy parameter dominates over heat loss parameter. But higher value of heat loss parameter, F_RU_L, for 10 ppm of Al_2O_3 nanofluid than water, in high temperature range causes collector efficiency decrease and collector efficiency for the fluids become nearly equal towards higher temperature range.

Table 3 Collector efficiency parameters for Al_2O_3-water nanofluid.

S.No.	Working fluid type	Concentration	F_RU_L	F_R (τα)	R^2
1	Water	0	11.56	0.528	0.968
2	Al_2O_3 nanofluid	10	14.346	0.6447	0.9789
3		50	15.663	0.7372	0.982
4		100	14.132	0.6579	0.9426

Direct absorption collector efficiency increased with increase in nanoparticle concentration from 10 to 50 ppm due to increase in absorbed energy parameter by 14.35 % and heat loss parameter increase by 9.2 % as observed from Table 3. Further increase of nanoparticle concentration from 50 to 100 ppm, resulted collector efficiency decrease. The basic reason for this result is that the Collector efficiency peaked at certain volume fraction (ϕ), and decreased for lower and higher values of volume fraction. For lower volume fraction, some of the incident solar radiations were absorbed by the nanofluid film and remaining portion absorbed by the bottom base plate. 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.

V. Conclusion

Thermal performance study of direct absorption solar collector using nanofluid of three different concentrations 10 ppm, 50 ppm and 100 ppm with 20 nm alumina nanoparticles in distilled water is carried out. The collector efficiency increased for all three concentrations of nanofluid than pure water. Collector efficiency enhancement of 39.6% and 22.1% is noticed for 50 ppm and 10 ppm respectively. Enhancement in efficiency with nanoparticle concentrations beyond 50 ppm is found to be lower as compared to other concentrations.

REFERENCES

[1] J.E. Pacheco, Demonstration of solar-generated electricity on demand: the solar two project, J. Solar Energ. Eng. Trans. ASME 123 (1) (2001) 5.
[2] Minardi, J. E., and Chunag, H. N., 1975, "Performance of a Black Liquid Flat-Plate Solar Collector," Sol. Energy, 17, pp. 179–183.
[3] Bertocchi, R., Karni, J., and Kribus, A., 2004, "Experimental Evaluation of a Non-Isothermal High Temperature Solar Particle Receiver," Energy, 29, pp. 687–700.
[4] T.P. Otanicar, P.E. Phelan, J.S. Golden, Optical properties of liquids for direct absorption solar thermal energy systems, Solar Energ. 83 (7) (2009)

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969–977.

[5] X. Q. Wang and A. S. Majumdar, " Heat transfer characteristics of nanofluids, a review," Int. J. Therm. Sci. **46**, 1,2007.

[6] B.C. Pak, I.Y. Cho, Hydrodynamic and heat transfer study of dispersed fluids with sub-micron metallic oxide particles, Exp. Heat Transfer 11 (1998) 151–170.

[7] Y. Xuan, Q. Li, Heat transfer enhancement of nanofluids, Int. J. Heat Fluid Flow 21 (1) (2000) 58–64.

[8] P. Keblinski, S.R. Phillpot, S.U.S. Choi, J.A. Eastman, Mechanisms of heat flow in suspensions of nano-sized particles (nanofluids), Int. J. Heat Mass Transfer 45 (4) (2002) 855–863.

[9] J. Koo, C. Kleinstreuer, Impact analysis of nanoparticle motion mechanisms on the thermal conductivity of nanofluids, Int. Commun. Heat Mass Transfer 32 (9) (2005) 1111–1118.

[10] J. Buongiorno, Convective transport in nanofluids, J. Heat Transfer 128 (3) (2006) 240–251.

[11] Masuda H, Ebata A, Teramae K, Hishinuma N. Alteration of thermal conductivity and viscosity of liquid by dispersing ultra-fine particles (dispersion of g-Al2O3, SiO2 and TiO2 ultra-fine particles). Netsu Bussei (Japan) 1993;7:227-33.

[12] A. Grimm, Powdered aluminum-containing heat transfer fluids, German Patent DE 4131516 A1 (1993).

[13]. Mu LJ, Zhu QZ, Si LL: Radiative properties of nanofluids and performance of a direct solar absorber using nanofluids. 2nd ASME Micro/Nanoscale Heat & Mass Transfer International Conference 2010, 1:549-553.

[14] Natarajan E, Sathish R. Role of nanofluids in solar water heater. Int J Adv Manuf Technol; 2009. doi:10.1007/s00170-008-1876-8.

[15] H. Tyagi, P. Phelan, R. Prasher, Predicted efficiency of a low-temperature nanofluid-based direct absorption solar collector, J. Solar Energ. Eng. 131 (4) (2009) 1–7.

[16] T.P. Otanicar, P.E. Phelan, R.S. Prasher, G. Rosengarten, R.A. Taylor, Nanofluidbased direct absorption solar collector, J. Renew. Sust. Energ. 2 (033102) (2010) 1–13.

[17] Trisaksri V, Wongwises S (2007) Critical review of heat transfer characteristics of nanofluids. Renew Sustain Energy Rev11:512–523.

[18] Liu J, Rinzler AG, Dai HJ, Hafner JH, Bradley RK, Boul PJ, et al. Fullerene pipes. Science 1998;280:1253e6.

[19] Li XF, Zhu DS, Wang XJ. Evaluation on dispersion behavior of the aqueous copper nano suspensions. J Colloid Interface Sci 2007;310:456e63.

[20] ASHRAE Standard 86-93. Methods of testing to determine the thermal performance of solar collectors; 1986. Atlanta, GA, USA.

[21] Zhang X, Gu H, Fujii M. Effective thermal conductivity and thermal diffusivity of nanofluids containing spherical and cylindrical nanoparticles. J Appl Phys 2006;100:044325.

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