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Analysis of thermal efficiency of solar flat plate collector working with hybrid nanofluids: An experimental study

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Abstract. Thermal efficiency of solar flat-plate collector (SFPC) was analyzed experimentally through water -based mono Al_2O, CuO, and hybrid Al_2O_3-CuO nanofluids. The particle loadings used for the analysis are 0.048%, 0.096%, 0.144%, 0.192% and 0.24%, respectively. The experiments were conducted at a flow rate of 0.008 kg/s of mono, and hybrid nanofluids. The experimental outcomes indicate, the thermal efficiency of mono and hybrid nanofluids raised under the larger volume loadings in comparison with water. Results show, that the Al_2O_3-CuO hybrid nanofluid offered higher thermal efficiency values than mono Al_2O_3 and CuO nanofluids. Thermal efficiency of SFPC was found to get enhanced by 57.66%, 66.58% and 73.75% at 0.24 vol.% Al_2O_3, CuO, and Al_2O_3-CuO hybrid nanofluids, over the water data, respectively, at solar noon time of 12:00 P.M.

Introduction

The depletion of fossil resources has resulted in a global energy shortage. In the current situation, energy is critical to industrial and economic development, hence efforts must be necessary to fix the problem of using fossil fuels with alternative fuels. The ongoing movement in development toward sustainability and better environmental responsibility connected with future development, emphasizes the need for renewable energy.

Renewable energy is a rapidly growing industry, with numerous innovations and applications emerging. The concept of localized renewable energy systems has been recognized as a solution to industries and residential energy demands. The depletion of natural resources and the growing demand for traditional energy have prompted planners and decision-makers to look into other sources. As the cost of conventional energy sources rises, there is a growing interest in renewable energy sources. Recently, there has been a great deal of effort in the field of renewable energy source engineering, particularly in the generation of solar energy. Unfortunately, the spectrum of feasible applications is limited to large-output arrays, prohibitively expensive technology, and massive assemblies requiring large parcels of land and expenses because a significant portion of the development of said renewable energy generation has not been for utilities.

The sun emits solar energy into space, but only 1367 W/m^2 penetrates Earth's atmosphere [1]. The energy received from the solar mean in a certain time interval of time on a 1 m^2 area can be estimated that, the radiation during that particular time period, which is known as solar radiation or insulation. This is called as direct and diffuse solar radiation [2]. Three major criteria influencing the performance of solar energy systems in converting direct and diffuse sunlight into useable energy are a given location's geographical coordinates, topography, and climatic conditions [3].

Thermal converters capture thermal energy, which is then transferred to a fluid that circulates through the panel. The solar radiation concentrators are non-concentrator type, i.e. flat plate or vacuum tubes, and concentrated type collectors. Flat non-concentrated heat collectors (which require pipes to connect the two components) are made up of numerous parts: a transparent glass cover, pipes, absorbers, and a thermal insulting layer. In contrast, the vacuum tubes' solar thermal collector is made up of absorbers, glass tubes, heat pipes, and an insulated casing [4]. In both systems, the absorber is critical to the heat transfer process, which requires high thermal conductivity. To limit the heat losses, the insulation between absorber and collector housing must be adjusted. Such factors necessitate to use of high price materials, raising the initial cost of collectors [5].

Literature review

Solar flat plate collectors (SFPC) consist of a heat-absorbing plate, serpentine tube, insulation and a heat transmitting cover. Solar energy falls on the absorber plate, and which is transmit into the working fluid in a tube based on the convection mode of heat transfer. The absorber is made from high thermal conductivity aluminum metal sheet. Even though these SFPC are used commonly, further larger in thermal efficiency of these collectors is necessary, because they are still under low thermal efficiencies [6]. Studies to improve the thermal efficiency of SFPC have included the redesigning of riser's channels [7], re-designing the top glazing in the collector and changing the heat-transfer fluid.

One of the most convenient and successful methods for increasing the improvement of SFPC is to introduce the nanofluids into the collector's tubes instead of standard heat transfer fluids such as water. Choi and Eastman introduced the term "nanofluid" for the first time [8]. The nanofluid is a colloidal dispersion of nanoparticles in base fluids (size less than 100 nm). Dispersing solid nanoparticles into the base fluid improved thermal conductivity. Nanofluids can dramatically increase thermal conductivity and heat transfer coefficient [9]. Nanofluids have a larger density and a lower specific heat, which leads to increased thermal efficiency. As a result, it minimizes the solar collector's area, weight, energy, and manufacturing costs.

Nanofluids are classified into mono and hybrid nanofluids [10]. The hybrid nanofluids are new generation and homogeneous mixture fluids which can be prepared by suspending different types (two or more than two) of nanoparticles in base fluid with developed physical and chemical bonds. Due to synergistic effect, the thermal conductivity and heat transfer of hybrid nanofluids are higher than individual nanofluids [11], Lee and Sharma [12]. Experimental results show that ethylene glycol as heat transfer fluid (HTF) in active solar flat plate heat (SFPH) system is good for cold climate countries due to its antifreeze properties.

Geovo et al. [13] considered experimental data of water diluted MgO nanofluids in SFPC for the purpose of comparison with the MATLAB software. They noticed maximum relative error of 5.36% and minimum relative error of 0.20% between experimental and software data. Choudhary et al. [14] obtained thermal efficiency increase of 16.7% for MgO-ethylene glycol/distilled water nanofluids in a FPSC under 0.2 vol% at a flow rate of 1.5 L/min. Verma et al. [15] used different nanofluids in a FPSC and analyzed energetic and exergetic parameters and obtained 23.47% increase of thermal efficiency at 0.75 vol% and at a flow rate of 0.025 kg/s for MNCNT/water as the working fluid. Moghadam et al. [16] considered water mixed CuO nanofluids in a FPSC and seen 21.8% of increase of thermal efficiency at vol. of 0.4 and at 3 kg/min. Yousefi et al. [17] found 28.3% increase of collector thermal efficiency by using Al_2O_3/water nanofluids in a FPSC. In another analysis, Yousefi et al. [18] analyzed the collector thermal efficiency by changing the nanofluids pH value, and they mentioned that, nanofluid pH also one of the influencing parameters for the collector efficiency. Belkassmi et al. [19] obtained efficiencies of 4.45%, 4.28%, and 4.22% at 2.0 lit/min, based on the experimental data of water dispersed Cu, CuO, and Al_2O_3 nanofluids in FPSC, respectively.

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With the utilization of mono nanofluids, the collector thermal efficiency is enhanced. Similarly, researchers have concentrated the use of hybrid nanofluids in FPC. Elshazly et al. [20] seen an enhanced thermal efficiency of 26% by using hybrid nanofluids of MWCNT/Al_2O_3 (50:50%) in a FPSC at 1.5 lit/min.

This work is to estimate experimentally the thermal efficiency of water diluted Al_2O_3-CuO nanofluids flow in a FPSC with various volumetric concentrations. In addition to the above, the study is also focused on to investigation of efficiency of water-based copper oxide (CuO) and aluminum oxide (Al_2O_3) nanofluids alone and compare with the Al_2O_3-CuO water based nanofluid at constant mass flow rate to get the required amount of heat for water heating applications.

Experimental study

Preparation of nanofluids

The nanofluids are prepared by mixing the nanoparticles with water. Table 1 is the physical properties of Al_2O_3, CuO and water, and Table 2 is the weights of CuO and Al_2O_3 nanoparticles used for water for developement of various nanofluids. Step-by-step procedure of nanofluids preparation is mentioned in Fig. 1.

Table 1: The physical properties of Al_2O_3, CuO and water.

Nanoparticle/ base fluid	ρ, kg/m^3	C_p, (J/kgK)	k, (W/mK)	Color	Diameter, (nm)
Al_2O_3	3900	785.2	30	White	50
CuO	6510	540	33	Black	27
Water	1000	4179	0.613	---	---

Table 2: Weights of CuO, and Al_2O_3 nanoparticles used for water for the preparation of various nanofluids.

Mass of nanoparticles (g)	Particle volume loading (%)				
	ϕ = 0.048%	ϕ = 0.096%	ϕ = 0.144%	ϕ = 0.192%	ϕ = 0.24%
CuO (g)	25	50	75	100	125
Al_2O_3 (g)	15	30	45	60	75
Al_2O_3-CuO, (g)	20	40	60	80	100
Water (lit)	8	8	8	8	8

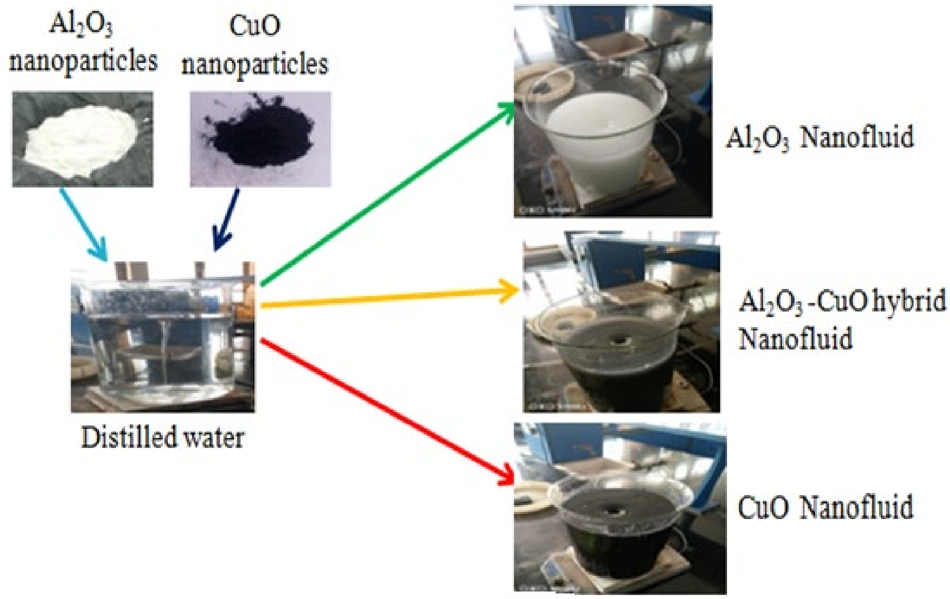

Fig. 1: Preparation of water-based mono and hybrid nanofluids.

Flat plate collector

The experimental set-up of flat plate collector is shown in Fig. 2, and which is used for water, mono, and hybrid nanofluids and its thermal efficiency is estimated. The solar collector was placed in the Gondar town, Ethiopia, which is located on 12.6˚ N latitude and 37.47˚ E longitude in the northern hemisphere with an elevation of 2133 meters above sea level. For maximum captured radiation, the flat plate solar collector was installed at 27.6˚ tilt angle. The set-up mainly consists of an absorber plate to absorb incident solar radiation, a single glass cover to protect collector heat loss, serpentine tube for fluid passage through the solar collector, storage tank to store working fluids for experimentation and used as heat exchanger, a pump capable to deliver the fluid to the serpentine pips, by-pass valve for returning of fluids after adjusting the control valve, adjustable valves to control flow rate one at the main flow loop and the other at the by-bass line, flow meter to measure the fluid flow rate, cold water storage tank, table to support water tank, and collector support to carry the flat plate solar collector. During the experimental test, the glass temperature, plate temperature, inlet and outlet temperatures and mass flow rates of the working fluids are measured to obtain the thermal efficiency of the flat plate solar collector.

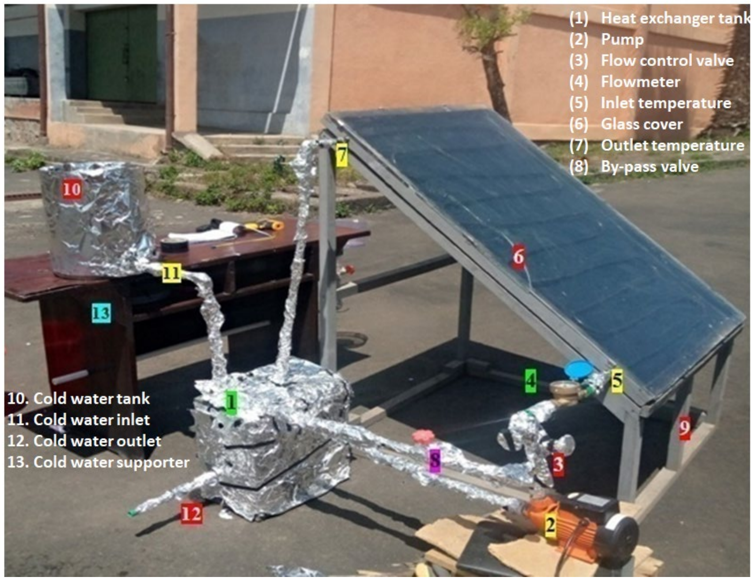

Fig. 2: Photograph of flat plate collector.

Data analysis

Collector thermal efficiency analysis

Thermal performance of solar collector is evalauted through the instantaneous collector efficiency, which requires the amount of solar radition attracted by the collector. The useful heat energy of the working fluid is determined by the following equations.

$$Q_u = \dot{m}C_{pf}(T_o - T_i) \tag{1}$$

$$\eta_{th} = \frac{Q_u}{A_C I_T} \tag{2}$$

$$\eta_{th} = \frac{\dot{m}C_{pf}(T_o - T_i)}{A_C I_T} \tag{3}$$

Where, C_p is specific heat (KJ/kgK), T_o is outlet temperature (K), T_i is inlet temperature (K), η_{th} is the thermal efficiency, and Q_u useful heat energy or the incident solar energy, A_c is absorber area (m^2), and I_T is the incident solar energy (W/m^2).

Results and discussion

Temperature distribution

In Fig. 3, it is seen that the highest outlet temperature at solar noon for 0.24% volumetric concentrations of Al_2O_3, CuO and Al_2O_3-CuO hybrid water based nanofluids are 62.4 ºC, 69 ºC, and 86.7 ºC, respectively. From the above experimental readings it is noticed that the Al_2O_3-CuO hybrid nanofluids outlet temperatures of flat plate solar water heating is higher than individual nanofluids and CuO nanofluid outlet temperatures is also higher than Al_2O_3 and base fluid. Due to larger random collisions of nanoparticles in base fluid, the outlet temperature of the nanofluid is raised. Therefore, increasing the volume particle concentrations of nanofluids and hybridizing the nanoparticles raises the exit temperature of the fluid by increasing the absorptivity of SFPC.

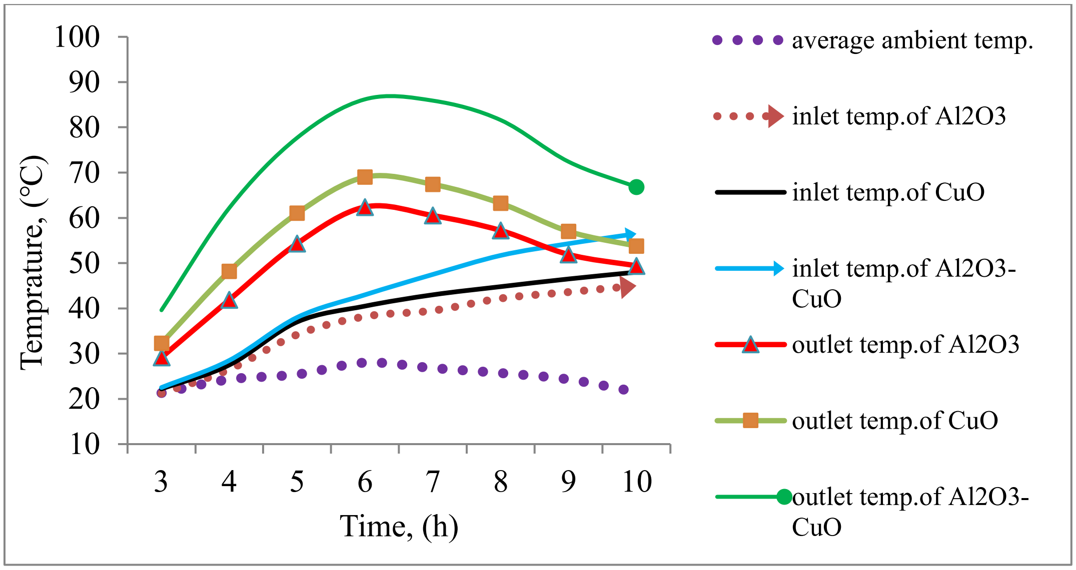

Fig. 3: Temperature records at ϕ = 0.24% particle concentration nanofluids with time.

Heat gain in the collector

Fig. 4 gives compression of useful heat gained by the distilled water and 0.048% nanoparticle concentration of single and hybrid water-based nanofluids at constant mass flow rate of 0.008 kg/s. Maximum useful energy of distilled water and 0.048% particle volume concentration of Al_2O_3, CuO and Al_2O_3-CuO hybrid water based nanofluids are 574.15 W/m^2, 627.76 W/m^2, 691.82 W/m^2, and 799.72 W/m^2 respectively. This shows that useful heat energy of distilled water was less with the same mass flow rate compared to 0.048% Al_2O_3/water nanofluid and the useful heat energy of CuO nanofluid is greater over Al_2O_3 nanofluid under a fixed particle volume loading and fluid flow rate, also, useful heat energy of Al_2O_3-CuO/water hybrid nanofluid was very high with the same mass flow rate and particle volume concentration compare to CuO/water nanofluid.

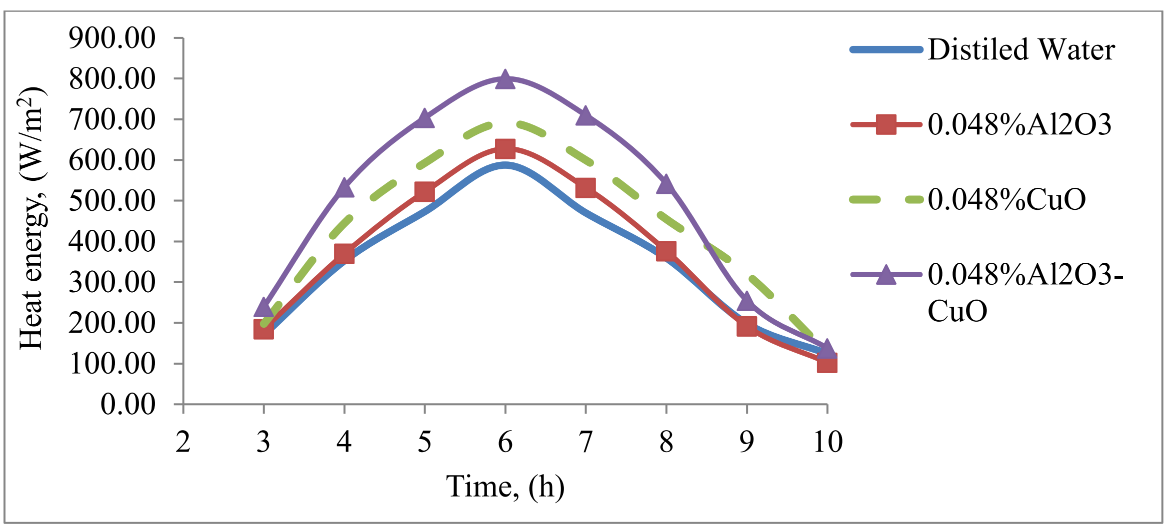

Fig. 4: Hourly variation of heat energy of water and nanofluids (ϕ = 0.048%) with time.

From Fig. 5 it is seen that the maximum useful heat energy with 0.096% particle volume concentration and constant mass flow rate of Al_2O_3, CuO and Al_2O_3-CuO hybrid water based nanofluids were 650.28 W/m^2, 738.58 W/m^2 and 834.73 W/m^2, respectively.

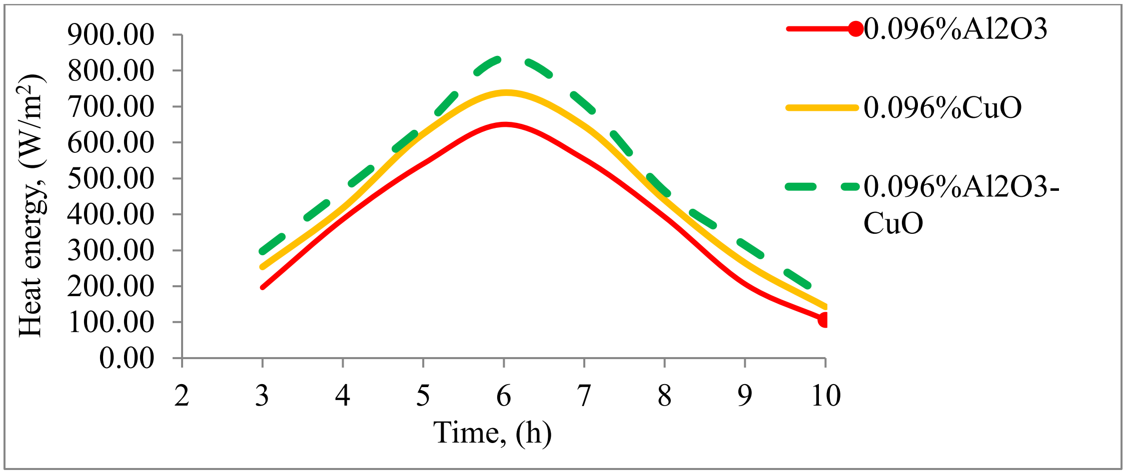

*Fig. 5: Hourly variation of heat energy for (**ϕ** = 0.096%) nanofluids with time.*

From Fig. 6, it can be seen that the maximum thermal efficiency of flat plate solar collector was 57.66%, 66.58% and 73.75% for 0.24% particle concentration of Al_2O_3, CuO and Al_2O_3-CuO hybrid water based nanofluids respectively at fixed 0.008kg/s mass flow rate. The experimental results indicated that due to the increased interactions of nanoparticles in base fluid, the efficiency of flat plate solar collector increased with percentage volume concentration of all nanofluids. Furthermore, because of the rise in internal energy between particles and reduction in agglomeration, hybrid nanofluid has higher collector efficiency than the isolations. The result is also understood that CuO/water nanofluid has greater collector efficiency than Al_2O_3/water nanofluid due to the higher thermal conductivity properties of copper oxide nanoparticles.

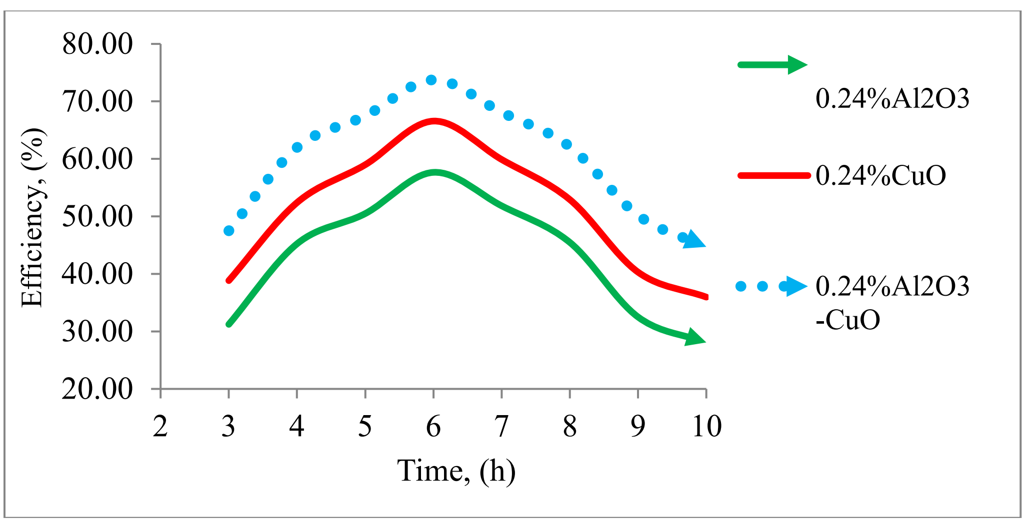

*Fig. 6: Hourly variation thermal efficiency comparisons of nanofluids at (**ϕ** = 0.24%).*

Figure 7 gives the data related to the thermal eficiency of mono, and hybrid nanofluids in a FPSC. Experimental results showed that at constant flow rate, the efficiency of flat plate solar collector was improved in all nanofluids with the increase in volumetric concentrations of nanoparticles in base fluids. The lowest thermal efficiency of the solar collector was observed about 48.32% for distilled water. The maximum thermal efficiency improvements of flat plate solar collector with 0.24 percentage nanoparticle concentration of Al_2O_3, CuO, and Al_2O_3-CuO hybrid nanofluids were 9.34%, 18.26% and 25.43% respectively compared to base fluid i.e., distilled water. Moreover, from the results it is noticed that hybrid nanofluid is more efficient than the individual nanofluids. The results are also shown that, the thermal efficiency of CuO nanofluid is higher than Al_2O_3 nanofluid and base fluid. Therefore, hybridizing nanoparticles and increasing nanoparticle concentrations from 0.048 to 0.24% improved the thermal efficiency of SPFC.

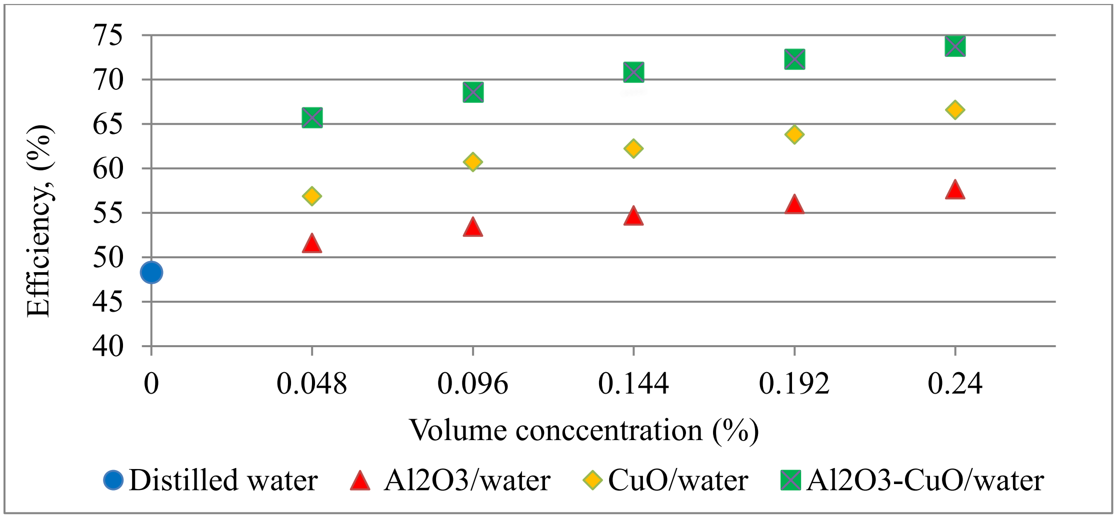

Fig. 7: Thermal efficiencies of working fluids as function of nanoparticle concentration.

Conclusions

In this research the thermal efficiency of flat plate solar collector with Al_2O_3/water, CuO/water and Al_2O_3-CuO/water hybrid nanofluid, the effect of particle volume concentrations and the two-step preparation methods were studied. Efficiencies of FPSC with each working fluid at various nanoparticle concentrations and constant flow rate 0.008kg/s were compared. The thermal efficiency of flat plate solar collectors is show to increase with the increase in nanoparticle concentration of the nanofluids. The maximum thermal efficiency of the flat plate solar collector for water and 0.24% Al_2O_3, CuO and Al_2O_3-CuO hybrid nanofluids was 48.32%, 57.66%, 66.58% and 73.75% respectively at constant flow rate 0.008 kg/s. From this, mixing of Al_2O_3 nanoparticles in water enhances the collecor efficiecy by 9.34% as compared to pure water. The SFPC with CuO nanofluid is better than Al_2O_3 nanofluid by 8.92%. Thermal efficiency SPFC wokirng with Al_2O_3-CuO hybrid nanofluid is higher than CuO/water nanofluid by 7.17%. Therefore from the 0.24 vol. % data, volume concentration of Al_2O_3-CuO/water hybrid nanofluid and 0.008kg/s, the thermal efficiency of SPFC raises upto 73.75%, which was 25.43% higher than the pure water.

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