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Utilizing Hybrid Nanofluids to Analyze the Thermal Performance of a Solar Flat Plate Collector

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Effective utilization of solar energy in industrial application is a challenging task today. Solar energy is used in many applications such as water heating, drying of grains, room heating and cooling, process heating in industries, etc. Solar flat plate collector is one of the devices used as water heater in industrial applications.However, efficiency of the collector is limited while using conventional fluid as working medium since the efficiency of the collector depends on absorption properties of the working fluid. The efficiency of the collector can be enhanced by using nanofluid as working medium. As nanofluid is a colloidal suspension of ultrafine particle with base fluid, the pressure drop across the collector also increases which leads to high operational cost.Hence, an attempt was made in this work to find optimum value of heat transfer rate, collector efficiency and pumping power by mixing CuO and Al2O3 nanoparticle in base fluid, former possesses high thermal conductivity and later possesses moderate thermal conductivity but cheaper than former. Hybrid nanofluids were prepared with 0.1%, 0.2% and 0.3% by volume concentration with equal volume proportion of CuO and Al2O3 nanoparticle. Example, for 0.1% nanoparticle concentration, 0.05% CuO and 0.05% Al2O3 by volume is blended and mixed with distilled water and the same methodology is followed to prepare 0.2% and 0.3% nanoparticle concentration. Prepared nanofluid with different nanoparticle concentration were tested with three mass flow rates such as 0.016kg/s, 0.033kg/s and 0.05kg/s.Based on the experimental result, the outlet temperature, heat transfer rate, collector efficiency, pressure drop across the collector, pumping power, Nusselt number and friction factor were analyzed and compared with water.The current experimental work shows hybrid nanofluids provide optimum heat transfer characteristics, minimum pressure drop and less operational cost.

Keywords: Solar flat plate collector, Hybrid nanofluid, CuO- Al2O3 nanofluid, heat transfer, efficiency, pressure drop, friction factor.

1. Introduction

Sun emits approximately 1350W/m2 of solar energy out of it only 0.5% is being converted into useful energy [1]. Conversion of electrical energy is attained by solar power grid and thermal energy is obtained by solar collectors [2]. Solar collector is used to trap solar energy released by sun into useful thermal energy. The efficiency of the collector can be enhanced by altering absorber plate design, reduce heat loss, use of proper insulation, use of mini and micro channel or strips to create turbulence, use of phase change materials to store heat energy and use of nanofluids as heat transfer medium [3]. Initially, the collector was developed with black absorber plate of flat type with transparent cover, side and bottom insulation and heat transfer fluid [4-5]. The selective surfaces were used to enhance collector efficiency and optical concentration was used to generate high pressure steam [6]. Use of nanofluid as heat transfer medium is the latest technique used by the researchers to improve heat transfer rate and efficiency of the collector. Nanofluid consist of high thermal conductivity nano-sized particles mixed with conventional fluid such as water, vegetable oils, ethylene glycol, Therminol VP-1, propylene glycol, etc. The major problem associated while using nanofluid is agglomeration and sedimentation of nanoparticles and clogging in pipelines. Hence, Hordy N et al. [7] studied the stability of nanofluids under high temperature and long duration. From the result, it is observed that glycol based nanofluids having more stability nearly 8 months and some agglomeration found in water based nanofluids. Also, higher rate of degradation found in case of Therminol VP-1 based nanofluids. Formation of agglomerates were restricted upto 85OC and 170OC in case of water based and glycol based nanofluids respectively. Based on optical study, Multi Walled Carbon Nano Tubes (MWCNT) [8] absorbs almost 100% solar radiation even at low concentrations under a wide spectrum. Experimental analysis shows the efficiency of the collector increases with the increase of nanoparticle concentration upto 0.4% by weight fraction and addition of surfactant helps to increase stability of the nanofluid. CuO-H2O and Al2O3-H2O nanofluids were tested experimentally to find the influence of pH value [9]. The nanofluids prepared with 0.1wt% and 0.2wt% respectively by using sodium dodecyl sulfonate as surfactant. The test was carried out with solar collector with cylindrical glass tube having maximum transmissivity and minimum reflectivity and receiver is made of copper of black helical pipe. The difference between pH value and isoelectric point of nanofluid increases the efficiency of the collector increases. The efficiency of the collector can be enhanced by increasing the collector area but it will make the collector bulky and heavier [10]. Hence, the attempt was made to compact collector using nanofluids with same output. CuO, SiO2, TiO2 and Al2O3 nanofluids were used as heat transfer medium and the weight of the collector was reduced by 10239kg, 8625kg, 8857kg and 8618kg respectively for 1000 units of collector. Considering thermal performance, CuO nanofluid provides high thermal efficiency when compared with other three nanofluids. Also, nanofluid helps to make compact, cost effective and environmental friendly collector by saving energy and reducing CO2 emissions during manufacturing of collectors. SWCNT/H2O nanofluid was tested experimentally using evacuated tube solar collector [11]. Attempt was made to test the collector efficiency with different flow rate and nanoparticle concentration and the maximum efficiency of 93.4% was obtained at 0.025kg/s flow rate of nanofluid. An enclosed type evacuated type collector was tested by enhancing thermal resistance using air gap with MWCNTs as working fluid [12]. The efficiency of the collector was enhanced by 4% and CO2 and SO2 emission was reduced by 1600kg and 5.3kg respectively per annum per 50 collectors. The convective heat transfer coefficient of Al2O3 nanofluid containing 2.78% concentration of nanoparticle had been enhanced by 75% [13]. Thermal conductivity of base fluid was increased by the addition of carbon nanotubes [14]. Tyagi et al. [15] investigated the performance of direct absorption solar collector theoretically and compared the results with flat plate collector. Otanicar et al. [16] explained that nanofluids not only enhancing the efficiency of the solar collector but also it helps to reduce the effect on environment and improve economy. Godson et al. [17] mentioned in their review article that nanofluid helps to enhance thermal conductivity, heat transfer rate, Brownian motion and thermophoresis. Wang et al. [18] explained that the transport properties of base fluid changes adversely by homogeneous suspension of nanoparticles. Yu et al. [19] prepared AlN nanofluid using ethylene and propylene glycol as base fluids. AlN of 0.2% volume concentration was mixed with base fluids and found experimentally that thermal conductivity was increased predominantly. Yousefi et al. [20] said Al2O3-H2O nanofluid enhances collector efficiency by 28.3% and Tiwari et al. [21] found that collector efficiency improved by 31.64% while using Al2O3 nanofluid.

Many researchers focused on enhancing the performance of the collector using exergy analysis. Exergy analysis of solar flat plate collector helps to analyze useful work and losses in the system thermodynamically. Kar [22] carried out exergy analysis of solar flat plate collector to optimize the design of the collector by minimizing the pressure drop in consideration with flow rate of the fluid. Said et al. [23] carried out exergy and energy analysis of solar flat plate collector using SWCNT/H2O nanofluid. They obtained 95.12% and 26.25% of energy and exergy efficiency respectively when compared with water having 42% and 8.7%. Chen et al. [24] tested efficiency of the collector by considering concentration of nanoparticle, height of the collector and time of irradiation using silver and gold nanofluids as heat transfer medium. Also reported that Ag and Au nanofluids provides high photo thermal conversion efficiency than TiO2 nanofluid. The influence of nanoparticle shape, radiation parameter, velocity ratio and magnetic field was tested numerically on Cu, Al2O3 and SWCNTs nanofluids [25]. The result shows SWCNTs with sphere shape nanoparticles provide better heat transfer rate when compared with other two fluids and particle transport and heat transfer rate are greatly influenced by the shape of nanoparticles. R. Dharmalingam et al. [26] carried out experimental analysis and optimizing the performance of solar collector using silver-water nanofluid as heat transfer medium. The Design of Experiments (DoE) was done using Taguchi L9 orthogonal array and Reynolds number, nanoparticle concentration and incident solar radiation on inclined surface were taken as process parameter. Maximum collector efficiency obtained at 25000 Reynolds number, 0.03% nanoparticle concentration and 800W/m2 incident radiation. L. Syam Sundar [27] et al. used strip inserts of longitudinal type with aspect ratio equal to 1 to enhance the collector efficiency from 58% to 84% contains 0.3% volume fraction of nanoparticle at 13,500 Reynolds number. Karami et al. [28] prepared CuO nanofluid with 70% water and 30% ethylene glycol by volume and obtained collector efficiency upto 17% in comparison with base fluid. Chougule et al. [29] tested CNT/water based nanofluid with different tilt angle and shown that better effectiveness obtained at 50O tilt angle. H Chaji et al. [30] tested TiO2-H2O nanofluid using solar flat plate collector and observed that effectiveness improved from 3.5% to 10.5% while using 0.1% and 0.3% of nanoparticle concentration by weight respectively. T B Gorji et al. [31] tested graphite, magnetite and Ag nanofluids experimentally using direct absorption solar collector. From the result, magnetite nanofluids having greater potential of exergy and thermal efficiencies in comparison with other two fluids.

From the literature survey, many works have been carried out with nanofluids prepared with one or two base fluids and tested experimentally and numerically to enhance the performance of the solar flat plate collector. Almost all the analysis shows greater improvement in heat transfer rate and efficiency of the collector and at the same time higher pressure drop obtained which leads to more operational cost. Hence, it makes the authors to prepare hybrid nanofluid consist of CuO and Al2O3 nanoparticle mixed with distilled water to obtain optimum heat transfer rate, efficiency and pressure drop across the collector.

2. Experimental Analysis

The hybrid nanofluid is prepared with CuO and Al2O3 nanoparticle mixed with distilled water. Sodium dodecyl sulfonate of 0.2% by weight was used as surfactant to avoid settling and agglomeration of nanoparticle [32]. Initially, surfactant was thoroughly mixed with distilled water. Equal volume proportion of CuO and Al2O3 nanoparticle of 0.1%, 0.2% and 0.3% in total was mixed with water and surfactant solution. The volume concentration of nanoparticle was calculated by using equation 1. Then the mixture kept in ultrasonicator and mixed with the frequency of 20kHz. The ultrasonication process of nanofluid is shown in figure 1. The homogeneous mixture was used to test the heat transfer characteristics of solar flat plate collector [33]. The properties of the water and CuO and Al2O3 nanoparticle is given in table 1.

% Volume concentration of nanoparticle $$= \frac{\frac{w_{CuO}}{\rho_{CuO}} + \frac{w_{Al_2O_3}}{\rho_{Al_2O_3}}}{\left[\frac{w_{CuO}}{\rho_{CuO}} + \frac{w_{Al_2O_3}}{\rho_{Al_2O_3}} + \frac{w_w}{\rho_w}\right]} X100 \quad \text{……..(1)}$$

Table 1. Properties of water and CuO and Al_2O_3 nanoparticle.

Fluid/Nanoparticle	Thermal Conductivity (W/mk)	Density (kg/m^2)	Specific heat, J/kgK
Water	0.613	997.13	4180
CuO nanoparticle	18	6510	540
Al_2O_3 nanoparticle	39	3970	775

The Density (ρnf), viscosity (μnf), specific heat (Cp)nf and thermal conductivity (knf) of the nanofluids were calculated as follows.

$\rho nf = \varphi\ \rho p + (1-\varphi)\ \rho w$ …………………. (2)

$\mu nf = \mu w\ (1+2.5\varphi)$ ………………………(3)

$(Cp)\ nf = \varphi(Cp)\ p + (1-\varphi)(Cp)w$ ……………………… (4)

$$k_{nf} = k_w \left[\frac{k_p + 2k_w - 2\varphi(k_w - k_p)}{k_p + 2k_w + 2\varphi(k_w - k_p)} \right]$$ ………………………… (5)

Where represents nanoparticle concentration and w represents weight. In the equations, the suffix w represents water, p represents nanoparticle and nf represents nanofluid [34]. The properties of hybrid nanofluid was calculated using equation (2) to (5) using proportion ratio of CuO and Al2O3 nanoparticles and is given in table 2.

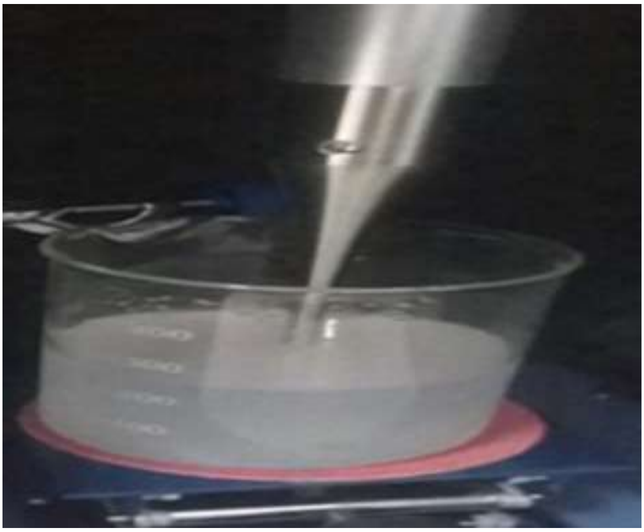

Figure 1 Ultrasonication of nanofluid.

The experimental setup consists of solar flat plate collector, heat exchanger, chiller, nanofluid tank and pump [35]. The length, width and thickness of the collector is 2m x 1m x0.1m respectively. The collector top cover is made of toughened glass with 4mm thickness and followed by corrugated absorber plate made of copper with the area of 1.9m2 and 2mm thickness. The absorber plate has the thermal conductivity of 350W/mK and convective heat transfer between the glass cover and absorber plate is 350W/m2K [36]. The bottom and side of the collector is covered with an insulating material made of glass wool to avoid heat loss. The experiments were conducted under forced circulation of fluid into the collector using 1HP pump. The fluid entering at the bottom of the collector through bottom header pipe, rises through nine riser tubes and collected at the top of the collector using top header pipe. The hot fluid collected from the collector is passed through shell and tube heat exchanger and chiller unit to cool to 25OC and stored in nanofluid tank for recirculation. There are two K type thermocouples of ±0.1OC accuracy and two pressure gauges of ±0.1% accuracy are connected at inlet and outlet of the collector to measure inlet and outlet temperature and pressure respectively. Two other thermocouples are connected with absorber plate and riser tube [37]. The mass flow rate of the fluid was measured using flow meter which is connected at the inlet. The solar flux incident on the surface was measured using pyranometer. The experimental setup of solar flat plate collector is shown in figure 2.

Before starting the experiment, the fall of solar radiation on 12O inclined surface throughout a day was observed and average of 3 days is shown in figure 3. As the variation of solar radiation was less during 12noon to 1pm. Hence the test was carried out during this time period [38].

Table 2 Properties of water and nanofluid

Nanoparticle concentration	Density (kg/m3)	Viscosity (Ns/m2)	Thermal conductivity (W/mK)	Specific heat (J/kgK)
Water (0%)	997.13	0.00089	0.613	4180
Al2O3 -0.05%, CuO-0.05% (0.1%)	1421.42	0.00116	0.665	3827.72
Al2O3-0.1%, CuO-0.1% (0.2%)	1845.7	0.00155	0.709	3475.44
Al2O3-0.15%, CuO-0.15% (0.3%)	2269.99	0.00217	0.747	3123.16

Figure 2. Experimental setup of solar flat plate collector.

The experiment was carried out at the location of 11°1'0.64''N latitude and 76°57'21''E longitude. Based on previous researches, the optimum tilt angle was identified as 12O south faced. The experiments were conducted according to the ASHRAE 93-86. The prepared nanofluid of 0.1%, 0.2% and 0.3% and water were circulated with 0.016kg/s, 0.033kg/s and 0.05kg/s flow rates and inlet and outlet temperature and pressure were measured. From the measured data, heat transfer rate, efficiency and pumping power, Nusselt number and friction factor were calculated using equation (6) - (10) respectively [39].

Heat transfer rate, Q=mCp(To-Ti) …………………. (6)

Collector efficiency, η=Qu/(ACIT) ……………………. (7)

Pumping power, $$P = \frac{m}{\rho}(\Delta p)$$ ……………………. (8)

Nusselt number, $$Nu = \frac{hD}{k}$$ …………………….. (9)

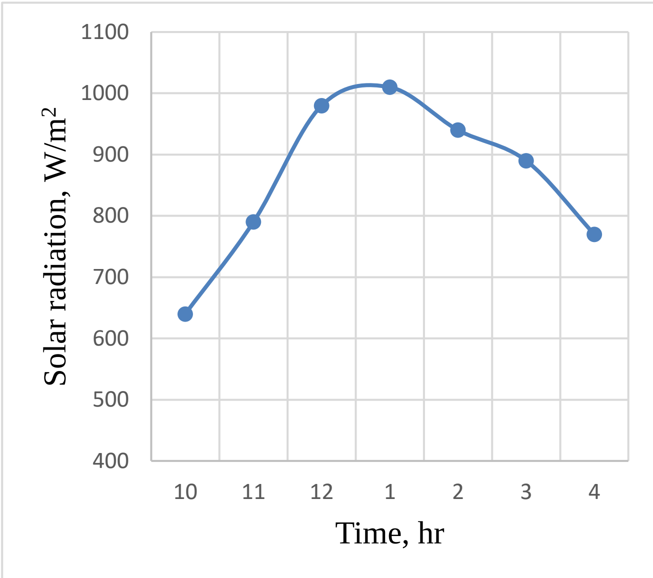

Figure 3 Solar radiation over a day on tilted surface.

Friction factor, $$f = \frac{\Delta p}{\frac{L}{D}\left(\frac{\rho v^2}{2}\right)}$$ ………………….. (10)

Where m is mass flow rate, TO is outlet temperature of the fluid, Ti is inlet temperature of the fluid, Qu is useful heat gain, AC is area of the collector, IT is total incident radiation on the inclined surface, Δp is pressure drop, L is length of the pipe, D is diameter of the pipe, v is velocity of the fluid and h is convective heat transfer coefficient.

3. Result and Discussion

The temperature and pressure of the collector at inlet and outlet were measured at different nanoparticle concentration with the mass flow rates of 0.016kg/s, 0.033kg/s and 0.05kg/s. Three readings were taken for each experimental run and values are averaged to minimize the error. The heat transfer rate, collector efficiency, pumping power, Nusselt number and friction factor were calculated using above mentioned equations [40]. Figure 4 shows the effect of hybrid nanofluid on outlet temperature of the collector at three different mass flow rates. The outlet temperature increases as the nanoparticle concentration increases. But outlet temperature decreases as mass flow rate increases. Due to availability of more retention time for nanofluid within the collector which helps to absorb more amount of solar radiation in the form of heat at lower mass flow rates.

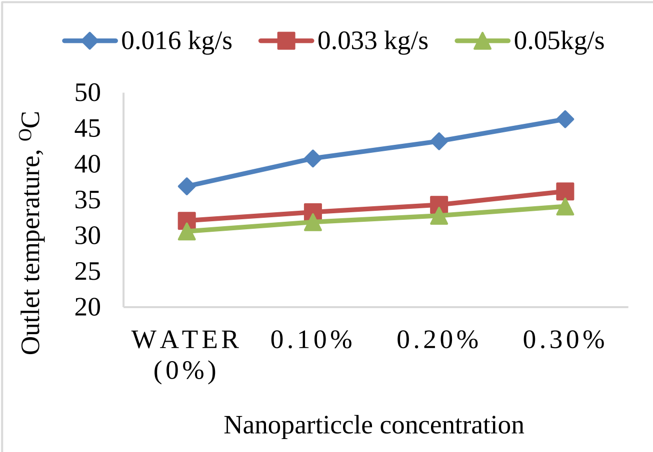

Figure 4 Outlet temperature of the collector against nanoparticle concentration.

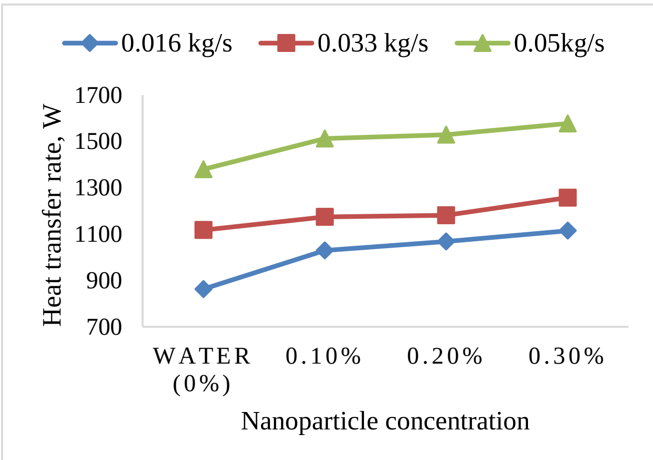

Figure 5 Heat transfer rate against nanoparticle concentration

The rate of heat transfer merely depends on difference between the fluid temperatures at inlet and outlet and mass flow rate of the fluid. Figure 5 shows that heat transfer rate increases with the addition of nanoparticle concentration, in contradiction with outlet temperature, maximum heat transfer rate obtained at higher mass flow rate. Addition of nanoparticle enhances the thermal conductivity of fluid and higher mass flow rate enhances heat transfer rate. It shows that dominance of mass flow is better when compared with nanoparticle concentration. The observation proves that in case of hybrid nanofluid made with CuO-Al2O3-H2O, the additional tests should be carried by increasing the nanoparticle concentration beyond 0.3% to obtain the saturation value. The percentage of enhancement of heat transfer is 14% at 0.05kg/s and at 0.3% nanoparticle concentration in comparison with base fluid.

Efficiency of the collector is directly proportional to useful heat gain of the collector and inversely proportional to collector area and solar flux incidence on the collector surface. From the figure 6, the efficiency of the collector increases as the nanoparticle concentration and mass flow rate increases. But, the enhancement of efficiency is not appreciable upto 0.2% and after that it increases linearly. Maximum efficiency of 75.4% is obtained at 0.3% nanoparticle concentration and 0.05kg/s mass flow rate. The percentage of enhancement of efficiency is 29.1% and 14.3% at 0.016kg/s and 0.05kg/s respectively at 0.3% nanoparticle concentration when compared with water.

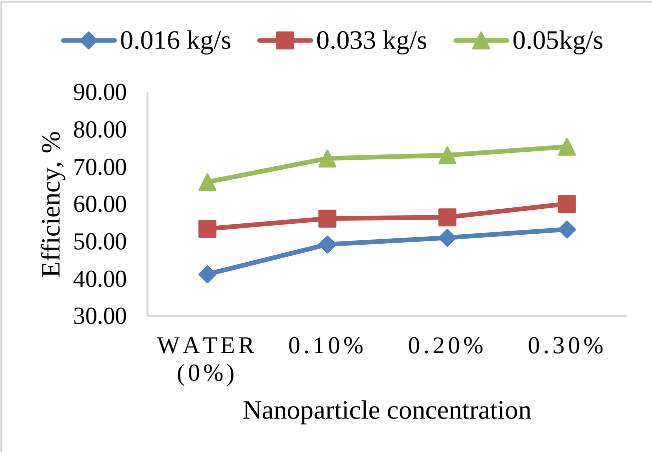

Figure 6 Efficiency of the collector against nanoparticle concentration.

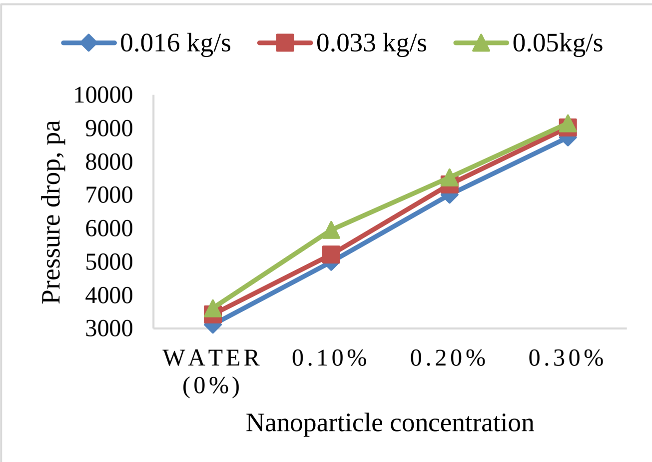

Figure 7 Pressure drop against nanoparticle concentration

It is important to note that addition of nanoparticle in the base fluid enhances outlet temperature, heat transfer rate and efficiency of the collector but it also adversely increases the pressure drop across the collector as shown in figure 7. As the nanoparticle concentration increases pressure drop increases. Also, higher mass flow rate leads to higher pressure drop.

Pumping power is the direct measure of operational cost of the system. From figure 8, the pumping power of the collector increases as the nanoparticle concentration and mass flow rate of the fluid increases. Observation shows that the addition of nanoparticle increases the density of the fluid which is inversely proportional to pumping power. At 0.3% nanoparticle concentration, the percentage of increase of pumping power is equal to 22%, 15.9% and 11% at 0.016kg/s, 0.033kg/s and 0.05kg/s respectively. Therefore, pressure drop dominating the mass flow rate on pumping power.

Figure 9 shows the value of Nusselt number at different mass flow rates. Nusselt number increases as mass flow rate and nanoparticle concentration increases. As the nanoparticle concentration increases, more amount of heat is absorbed by the fluid which leads to enhancement of convective heat transfer coefficient as well as Nusselt number. The Nusselt number is enhanced by 10.99% at 0.05Kg/s with 0.3% volume concentration of nanoparticle when compared with water at same flow rate.

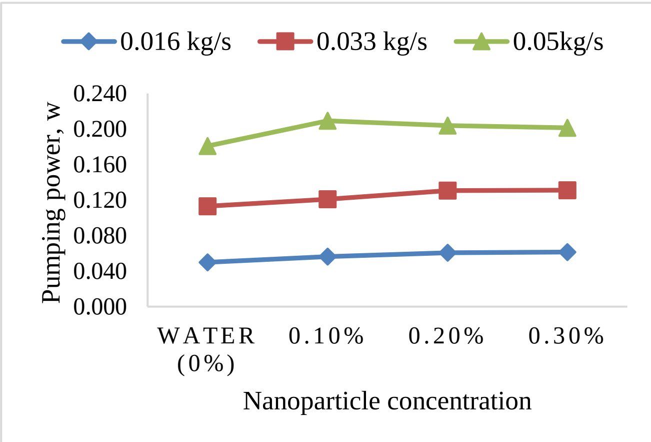

Figure 8 Pumping power against nanoparticle concentration

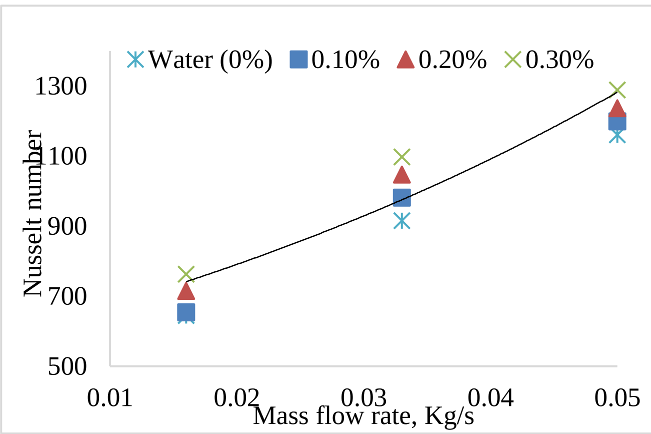

Figure 9 Nusselt number of water and nanofluids at different mass flow rates.

The friction factor represents loss of pressure when fluid interacts with the pipe surface. The friction factor of pure water and hybrid nanofluids are calculated using equation (10) [41].

From figure 10, friction factor decreases as mass flow rate increases. It doesn't mean that when friction factor decreases, head loss also decreases. As mass flow rate increases, the viscous force on the pipe wall decreases which increases Reynolds number largely. According to Darcy weisbach equation, friction factor is inversely proportional to Reynold's number or inversely proportional to square of velocity, it decreases as flow rate increases. Also, the friction factor increases with the addition of nanoparticle concentration. At 0.3% nanoparticle concentration and mass flow rate of 0.016Kg/s, the friction factor increased by 30.1%.

To confirm the feasibility and adoptability of hybrid nanofluid as heat transfer medium in solar flat plate collector, the heat transfer rate and pressure drop of hybrid nanofluid have been compared with published research article Published Al2O3 nanofluid [42] and CuO nanofluid is compared with hybrid nanofluid of current research work of same volume concentration and mass flow rate and it is shown in figure 11. The enhancement of heat transfer rate of hybrid nanofluid is 4.78% and 1.97% when compared with Al2O3 and CuO nanofluid respectively. Better heat transfer rate obtained when compared with Al2O3 and slight improvement obtained when compared with CuO nanofluid. At the same time, pressure drop of hybrid nanofluid is in between Al2O3 and CuOnanofluid. The result shows that hybrid nanofluid can be used in solar flat plate to obtain better thermal performance with minimum pressure drop.

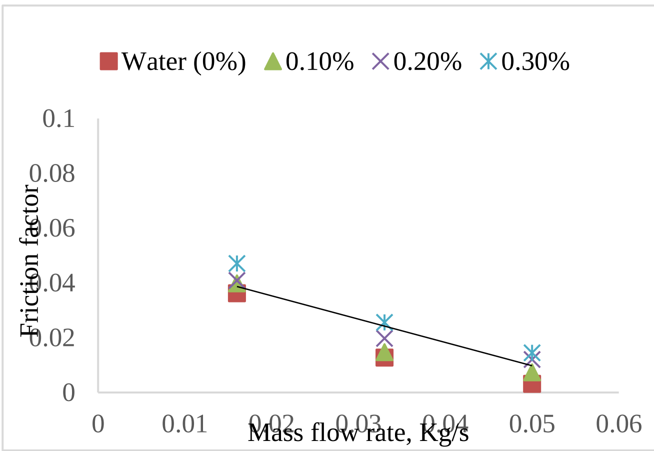

Figure 10 Friction factor of water and nanofluids with respect to different mass flow rates.

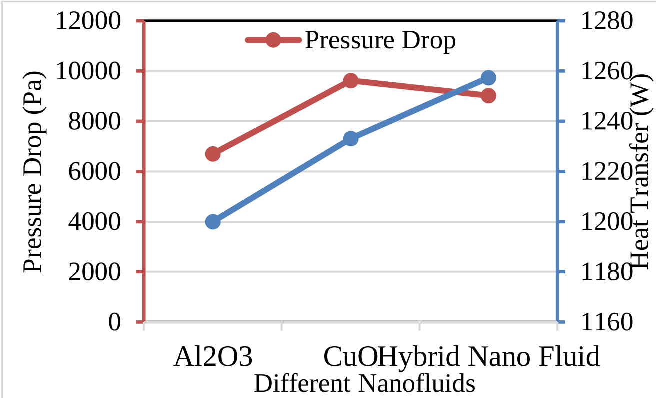

Figure 11 Comparison of heat transfer rate and Pressure drop of hybrid nanofluid with published research work

But optimum value of hybrid nanoparticle concentration should be identified by conducting more experimental tests to yield better heat transfer characteristics and minimum pressure drop.

4. Conclusion

The thermal performance of solar flat plate collector is tested using hybrid nanofluid consist of equal proportion of Al2O3 and CuO nanoparticles mixed with distilled water. The hybrid nanofluid consist of 0.1%, 0.2% and 0.3% nanoparticle concentration and in case of 0.1% of nanoparticle concentration, 0.05% of Al2O3 and 0.05% CuO by volume was blended and mixed with distilled water and the same methodology was followed to prepare 0.2% and 0.3% nanoparticle concentration. Each proportion was tested with three mass flow rates such as 0.016kg/s, 0.033kg/s and 0.05kg/s and result have been compared with water. From the experimental analysis, the following conclusions were made.

(i) The outlet temperature increases as the nanoparticle concentration increases and the maximum outlet temperature attained at 0.016kg/s mass flow rate.

(ii) The heat transfer rate increases with the addition nanoparticle concentration and maximum heat transfer rate obtained at higher mass flow rate with 0.05% nanoparticle concentration. The percentage of enhancement of heat transfer is 14% at 0.05kg/s and 0.3% nanoparticle concentration in comparison with base fluid.

(iii) The efficiency of the collector increases as the nanoparticle concentration and mass flow rate increases. Maximum efficiency of 75.4% is obtained at 0.3% nanoparticle concentration and 0.05kg/s mass flow rate. The percentage of enhancement of efficiency is 29.1% and 14.3% at 0.016kg/s and 0.05kg/s respectively when compared with water.

(iv) The pumping power of the collector increases as the nanoparticle concentration and mass flow rate of the fluid increases. At 0.3% nanoparticle concentration, the percentage of increase of pumping power is equal to 22%, 15.9% and 11% at 0.016kg/s, 0.033kg/s and 0.05kg/s respectively.

(v) Nusselt number increases as mass flow rate and nanoparticle concentration increases and the Nusselt number value is enhanced by 10.99% when flows at 0.05Kg/s with 0.3% volume concentration of nanoparticle when compared with water.

(vi) Friction factor of nanofluid decreases as mass flow rate increases and the friction factor increases with the addition of nanoparticle concentration

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