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Nanofluid Based Concentrating Parabolic Solar Collector (NBCPSC): A New Alternative

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Abstract
Performance of solar collectors depends upon various factors like collector & receiver material, solar intensity, nature of working fluid etc. Above all, nature & the properties of the working fluid which flows through the collectors, greatly effects its performance. Here, an attempt has been made to improve the performance of a parabolic solar collector by using nanofluids instead of conventional fluid like water as working fluid. The present investigation mainly focuses on the nanofluid based concentrating parabolic solar collector (NBCPSC). Nanofluids are the suspensions of metallic or non-metallic nanoparticles like aluminium, aluminium oxide, copper oxide etc. in base fluids like water, ethylene glycol, oil etc. The performance of a parabolic solar collector is investigated experimentally by studying the effect of alumina (Al_2O_3) & copper oxide (CuO) nanoparticles in water, as working fluids. Three mass flow rates (20, 40 & 60) l/hr and particles volume concentrations of 0.01% have been examined. The average size of nanoparticle is 20-30 nm. Comparison of water based alumina nanofluid is done with copper oxide nanofluid and it is observed that by using CuO nanofluid as a working fluid the value for maximum instantaneous & thermal efficiency has been improved. Therefore, from the results it can be concluded that the performance of solar collector is remarkably enhanced by using nanofluids as working fluid in the solar collector.

Keywords
Parabolic Solar Collector, Efficiency, Nanofluid, Mass Flow Rate, Concentration

I. Introduction

A. Solar Energy
Solar energy is promising to be the best option for renewable source. The proper or efficient utilization of this source i.e. solar energy is increasingly being considered to be the suitable solution to solve the global warming like issues. By the usage of solar energy we can also achieve the concept of sustainable development.

In today's world economy Renewable energies are gaining a lead role because they are sustainable and safe. Renewable energies are expected to grow at higher rate because of the following reasons [1].

1. World energy demand is expected to rise in future with a corresponding decline in oil production.
2. Due to changing climatic conditions.

Solar thermal energy is a very suitable source of heating and it is a technology that does not depend on scarce, finite energy resources. Solar collector transforms solar radiation into heat and transfer the heat to a medium. The main application of solar energy is that it is used for heating or cooling systems [2]. Solar thermal collector devices are used to convert solar radiation energy to internal energy of the transport medium. These are also known as heat exchangers. On the other hand, non-concentrating solar collectors are used if a big quantity of solar radiation coming from the sun is concentrated on a relatively small collecting area [3]. In last 10–15 years innovation in concentrated solar energy has plays an important role or has a major contribution to increase the number of experimental and commercial thermal systems [4].

B. Nanofluids in Solar Energy
The use of nanofluids for the devices like solar collectors as a working medium is a relatively an innovative idea. In order to improve the physical properties for enhancing direct solar collectors, various studies have to be carried out. As solar power is readily available, researchers are developing the various means to make efficient use of this energy [3].

Nanofluids are potential heat transfer fluids with improved thermophysical properties and heat transfer performance can be applied in many devices for better performances (i.e. energy, heat transfer and other performances) [5]. Nanoparticles provide the following possible advantages in solar power plants [4].

1. The very small size of the particles preferably lets them to pass through pumps without adverse effects.
2. Nanofluids can absorb energy directly--- skipping intermediate heat transfer steps.
3. The nanofluids have high absorption in the solar range and low emittance in the infrared).
4. A more uniform receiver temperature can be attained inside the collector.
5. Enhanced heat transfer via greater convection and thermal conductivity which may enhance the performance of a receiver, and
6. Absorption efficiency may be improved by modifying the nanoparticle size and shape to the application.

One of the most effective methods to increase the solar collector efficiency, is to replace the working fluid, water, by high thermal conductivity fluids. At present nanofluids are expected to excellent heat transfer properties as compare to the conventional heat transfer fluids [2].

Nanofluids are suspensions of metallic or nonmetallic nanoparticles like copper, aluminum silicon, alumina (Al_2O_3) in a base fluid such as water, ethylene glycol [6].

Common fluids such as water, ethylene glycol, and heat transfer oil plays a vital role in various industrial processes such as generation of power, heating or cooling processes, chemical processes, and microelectronics. However, the thermal conductivity of these fluids is comparatively low and thus cannot able to reach high heat exchange rates in thermal engineering devices. A way to solve this obstacle is using excessive fine solid particles suspended in common fluids so that their thermal conductivity will be improved. Experiments have shown that nanofluids have substantial higher thermal conductivities compared to the base fluids. These suspended nanoparticles can change the transport and thermal properties of the base [7]. Nanofluids show better stability, rheological properties, and considerably higher thermal conductivity.

For various industrial and automotive applications nanofluids are the novel generation heat transfer fluids because they exhibit excellent thermal performance [8]. Recently, many researchers have investigated the effects of nanofluids on the improvement of heat transfer in thermal engineering devices, both experimentally and theoretically [9]. The exceptional features of nanofluids are increase in liquid thermal conductivity, liquid viscosity, and heat transfer coefficient.

Using nanofluids as a (Direct Absorption Solar Collector) DASC leads to following advantages [10]

1. Variability of the shape, size, material, and volume fraction of the nanoparticles allows for tuning to maximize spectral absorption of solar energy during the fluid volume.
2. Enhancement in the thermal conductivity can lead to efficiency improvements, although small, by more effective fluid heat transfer; and, finally.
3. Huge improvements in surface area due to the very small particle size, which makes nanofluid-based solar systems attractive for thermo chemical and photo-catalytic processes.

Khullar et al. [11] carried out theoretical & numerical investigation regarding the application of nanofluids as the working fluid in concentrating parabolic solar collectors. The results also showed that the addition of aluminium nanoparticles into the base fluid (water) significantly improves its absorption characteristics. Taylor et al. [4] carried out theoretical & experimental investigations regarding the applicability of nanofluids in high flux solar collectors and to compare the performance of nanofluid-based concentrating solar thermal system with a conventional system. The results indicated that the usage of a nanofluid as the working fluid in the receiver enhance the efficiency by 10%. It was seen that Collector efficiency enhancement of 5%–10% is possible with a nanofluid used as the working fluid in the receiver. It was concluded that using graphite/therminol VP-1 nanofluid for 10–100 MWe power plants, with volume fractions approximately up to 0.001% or less could be advantageous. De Risi et al. [12] did mathematically modelling and optimization of transparent parabolic trough collector based on gas-phase nanofluids as a working fluids. To directly absorb the solar energy a new concept of solar Transparent Parabolic trough Collector (TPTC) working with gas-based nanofluid as heat transfer fluid was suggested and examined. The model of the geometrical, thermal and fluid dynamic aspects of the TPTC was developed mathematically in order to attain global performance and to describe the main geometrical and operational parameters of the TPTC. Simulation of the gas based nanofluids absorption showed that a complete absorption of the solar spectrum within the diameter of the receiver tube is attained by a correct mixture (0.25% CuO and 0.05% Ni). The results also indicated that the maximum TPTC solar to thermal efficiency is 62.5% for a nanofluid outlet temperature of 650°C and a nanoparticles volume concentration of 0.3%.

II. Methodology

A. Experimental Setup

The experimental setup for testing the performance of collector consists of the parabolic shaped collector, parabolic reflector, receiver tube, glass cover tube, 10 litre storage tank, supporting structure, tracking mechanism, piping system and ball valve as a throttling valve. The storage tank is fixed below the receiver's pipe level to allow the heating fluid to flow in a forced manner with pumping system. The storage tank is filled with water/nanofluid and flow takes place in a closed system. The complete set-up of Parabolic Trough Solar Collector (PTSC) is shown in the fig. 1.

Fig. 1: Parabolic Trough Solar Collector (PTSC) set-up

The Parabolic trough collector system consists of following parts:

A Stainless steel sheet having dimensions (1.20 m × 0.91 m) is used to form the parabolic shape. Parabolic shaped mirrors are used as reflectors with a reflectivity of 96%. A receiver Tube: The receiver tube is composed an outer glass cover tube, a vacuum type enclosure or annular space & an inner black painted tube made of copper material. In receiver tube the flowing heat transfer fluid (HTF) such as water or nanofluid gains heat from the solar radiation coming from the reflector part. A black painted copper tube which has higher thermal conductivity is used as a receiver tube and is covered by a glass cover tube. A receiver tube has 4ft length with inside and outside diameter of 27 mm & 28 mm. glass cover tube has 3ft length with inside and outside diameter of 64 mm & 66 mm. The support structure for the parabolic solar collector is made of cast iron. The selection of cast iron material for the support structure is because of its greater rigidity, hardness and more flexibility. Mainly two types of tracking systems are used namely, manual tracking system and automatic tracking system. In this experiment manual tracking is used because it is inexpensive as compared to automatic tracking as, automatic tracking requires a motor and a gear mechanism. The entire piping system is insulated with SUPERLON insulation. Pump is used to circulate water or nanofluid from the storage tank to the inlet of the receiver tube at some appreciable height. In this experiment submersible pump is used with a maximum height of 5 ft., 1100 l/hr output and 18 W power.

1. Measuring Devices and Instruments

The inlet & outlet temperature of receiver tube is measured with the help of mercury-in-glass thermometer. The solar intensity is measured during the day using a solar power meter (model No.: TM-207).

In the present experiment the air flow velocity is measured with the help of digital anemometer (model no. AM-4201) in m/sec or in km/hr. The magnetic base angular measuring instrument is used to vary the angle of parabolic collector in accordance with sun's direction.

2. System Operation

The parabolic trough collector is manually tracked on each day with the help of mechanism consisting of clutch wire and bicycle hub before the reading starts so that the solar radiations coming from the sun fall perpendicular to the plane of aperture area. When the solar radiations fall on the aperture area of the parabolic trough collector, these radiations are concentrated on the receiver tube. This causes the heat transfer from the surface of the receiver tube to the water/nanofluid flowing inside the receiver tube and fluid gets heated up.

B. Preparation of Nanofluids

In order to carry out experimental studies with nanofluids, their preparation is the first main step. Nanofluids are prepared by dispersing nano sized solid particles like alumina (Al_2O_3), silicon oxide (SiO_2), copper oxide (CuO) into base liquids such as water, ethylene glycol therminol-VP-1 etc. There are mainly two techniques used to produce nanofluids: the single-step and the two-step method. In the present experimental work two-step method is used as this method is widely used for the preparation of nanofluids.

In this method, first the nanoparticles are obtained by different methods and then are dispersed in an appropriate base fluid like water, oil, ethylene glycol, therminol-VP 1 [7].

C. Sonication of Nanoparticles

1. Sonication of Alumina (Al_2O_3) Nanoparticles

Sonication is a technique for dispersing the aggregated nanoparticle. The alumina (Al_2O_3) nanofluid & copper oxide (CuO) is prepared by using two step method. Al_2O_3 & CuO nanoparticle is mixed with double distilled water. Firstly weight of nanoparticles (Al_2O_3 & CuO) in grams by using weighing machine is determined. Then make the volume concentrations of 0.01% & 0.05% by stirring 0.397 gm, 1.985 gm & 0.64 gm, 3.20 gm of nanoparticles for 30 - 35 minutes in 1000 ml of double distilled water are prepared using a device called magnetic stirrer hot plate as shown in the fig. 2.

Fig. 2: Magnetic Stirrer Hot Plate

This test is repeated 10 times in order to prepare 10 litres of aluminium oxide & copper oxide nanofluid for both concentrations. To make the nanoparticles more stable and remain more dispersed in water, ultra bath sonicator is used. Sonication of aluminium oxide & copper oxide nanoparticles is necessary before testing any thermo physical property of the nanofluids like viscosity, thermal conductivity, and electrical conductivity. In this experiment sonication is done for 2 hours in an ultra-bath sonicator. By this aluminium oxide & copper oxide nanoparticles become more evenly dispersed in distilled water. After sonication the obtained nanofluid solution is ready for the application. Fig. 3 shows the Bransonic ultra-bath sonicator (CPXH series) used to carry out sonication process.

Fig. 3: Bransonic Ultra-Bath Sonicator (CPXH Series)

The prepared samples for 0.01% volume concentration of alumina (Al_2O_3) shown in the fig. 4 & of copper oxide (CuO) shown in the fig. 5.

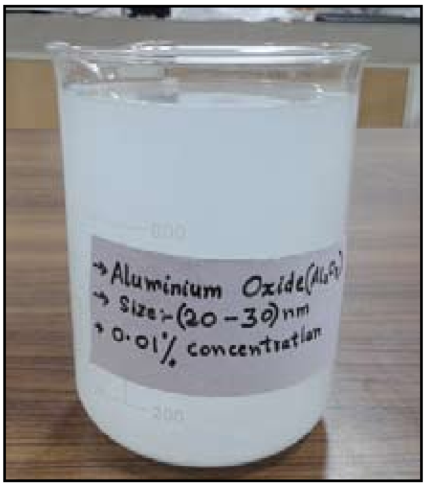

Fig. 4: Prepared Al_2O_3 Nanofluid Solution

Fig. 5: Prepared CuO Nanofluid Solution

III. Experimental Results & Discussions

This chapter mainly deals with the results in form of plots/graphs which are obtained by the experimental work on nanofluid based concentrating parabolic solar collector (NCPSC) by using water based alumina (Al_2O_3) & copper oxide (CuO) nanofluids as working fluid. This section mainly deals with the comparisons of instantaneous & thermal efficiency w.r.t. time for water & water based alumina & copper oxide nanofluids in the form of graphs/plots. The following relations are used to determine the instantaneous & thermal efficiencies.

For instantaneous efficiency, ηi

$$\frac{\dot{m}\, c_p\, (T_{out} - T_{in})}{G_T R_b\, W\, L}$$

For thermal efficiency, ηth

$$\frac{m\, c_p\, (T_{out} - T_{in})}{A_{aper.}\, G_T\, t}$$

where $\dot{m}$ is the mass flow rate in kg/sec, c_p is the specific heat in J/kg K of water or nanofluid respectively, T_{out} & T_{in} are the outlet & inlet temperatures, G_T is solar intensity in W/m², R_b is bond resistance, W is the width of collector, L is the length of collector, m is the mass of water or nanofluid in kg taken as 10 kg, $A_{aper.}$ is the aperture area taken as 1.0188 m², t is the time respectively.

A. Calculations for Nanofluids

1. Density of Nanofluids [13]

$$\rho_{nf} = f_v\, \rho_{np} + (1 - f_v)\, \rho_{bf}$$

where f_v is the volume fraction of the nanoparticles, ρ_{nf}, ρ_{np}, ρ_{bf} are the densities of the nanofluid in kg/m³, nanoparticles and the base fluids, respectively.

2. Specific Heat of Nanofluids [2]

$$c_{pnf} = \frac{[(1 - f_v)\, \rho_{bf}\, c_{bf} + f_v\, \rho_{np}\, c_{np}]}{\rho_{nf}}$$

where c_{pnf}, c_{bf}, c_{np} are the specific heats of nanofluid, base fluids and nanoparticles, respectively.

3. Thermal Conductivity of Nanofluids [14]

$$k_{nf} = \left[\frac{k_{np} + 2k_{bf} + 2f_v\,(k_{np} - k_{bf})}{k_{np} + 2k_{bf} - f_v(k_{np} - k_{bf})}\right] k_{bf}$$

where k_{nf}, k_{bf}, k_{np}, are the thermal conductivities of nanofluid, base fluids and nanoparticles in W/m-K, respectively, & f_v is the volume fraction of the nanoparticles.

IV. Dynamic Viscosity of Nanofluids [14]

$$\mu_{nf} = \frac{1}{(1 - f_v)^{2.5}}\, \mu_{bf}$$

where μ_{nf}, μ_{bf} are the dynamic viscosities of nanofluids and base fluids in m²/s, & f_v is the volume fraction of the nanoparticles respectively.

V. Thermal Conductivity Ratio for Nanofluids [15]

$$\frac{k_{nf}}{k_{bf}} = y$$

where k_{nf}, k_{bf}, are the thermal conductivities of nanofluid, base fluids in W/m-K, respectively

B. Experimental Results

Fig. 6 shows the comparison of instantaneous efficiency w.r.t. time for water & water based alumina and CuO nanofluid with 0.01% volume concentration at 20 l/hr mass flow rate. From the graph it is observed that the copper oxide nanofluid shows higher efficiency from 9:30-11:30 AM & from 12:00-3:00 PM in comparison with alumina nanofluid & water.

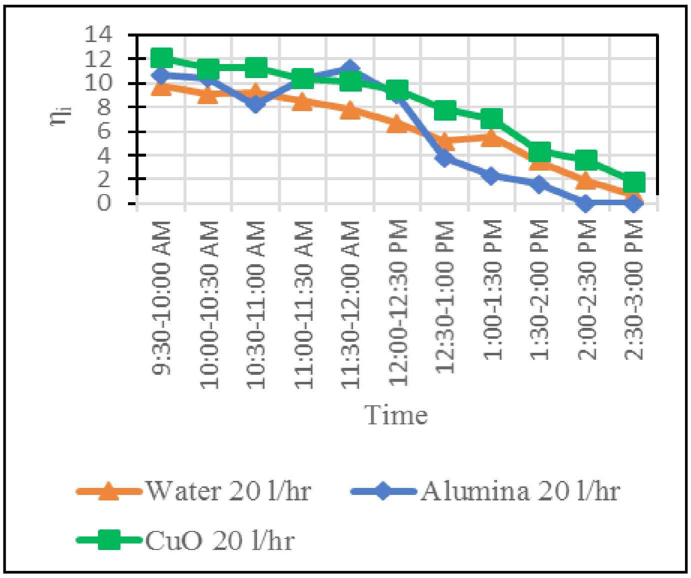

Fig. 6: Comparison of Instantaneous Efficiency w.r.t. Time for Water & Water Based Alumina and CuO Nanofluid With (0.01%) at 20 l/hr Mass Flow Rate

If we talk about alumina nanofluid, it shows higher efficiency than water from 9:30 to 10:30 AM & from 11:00 AM to 12:30 PM because of higher temperature difference & lower intensity of radiations. But there is sudden drop also observes in the thermal efficiency of alumina at 10:30-11:00 AM than water because of the higher specific heat of water, as instantaneous efficiency directly depends upon specific heat. If specific heat increases efficiency increases. From 12:30-3:00 PM water has higher efficiency because of the higher specific heat & faster variation in temperature difference as compare to alumina nanofluid.

Fig. 7 shows the comparison of instantaneous efficiency w.r.t. time for water & water based alumina and CuO nanofluid with 0.01% volume concentration at 40 l/hr mass flow rate. From the graph it is observed that the copper oxide nanofluid shows the higher efficiency at the time interval from 9:30 AM to 3:00 PM in comparison with water & alumina nanofluid.

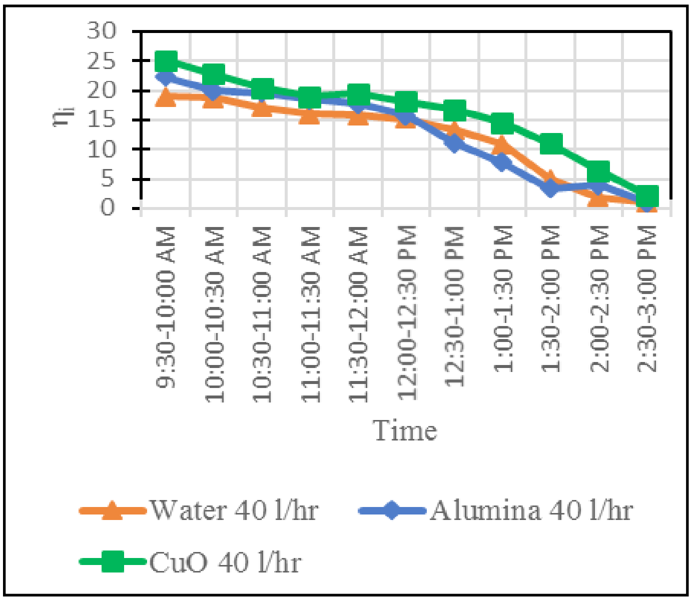

Fig. 7: Comparison of Instantaneous Efficiency w.r.t. Time for Water & Water Based Alumina and CuO (0.01%) Nanofluid at 40 l/hr Mass Flow Rate

On the other hand, alumina nanofluid shows higher efficiency from 9:30 to 12:30 PM & at 2:00 to 3:00 PM in comparison with water because of higher temperature difference & lower intensity of radiations. Water shows higher efficiency as compare to alumina nanofluid from 12:30 to 2:00 PM because of its higher specific heat value. The overall maximum value of instantaneous efficiency for CuO is 25.17%, for alumina is 22.35% & for water is 18.91% at 9:30-10:00 AM.

Figure 8 shows the comparison of instantaneous efficiency w.r.t. time for water & water based alumina and CuO nanofluid with 0.01% concentration at 60 l/hr mass flow rate. From the graph it is observed that copper oxide nanofluid shows the higher efficiency at the time interval from 9:30 AM to 3:00 PM because of faster variation in temperature difference.

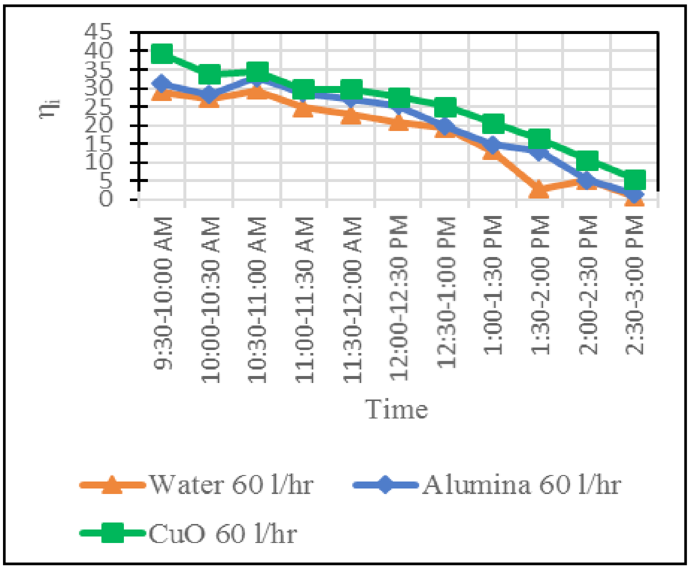

Figure 8: Comparison of instantaneous efficiency w.r.t. time for water & water based alumina and CuO (0.01%) nanofluid at 60 l/hr mass flow rate

The overall maximum value of instantaneous efficiency for CuO is 39.39% at 9:30-10:00 AM, for alumina is 32.9% at 10:30-11:00 AM & for water is 29.34% at 10:30-11:00 AM.

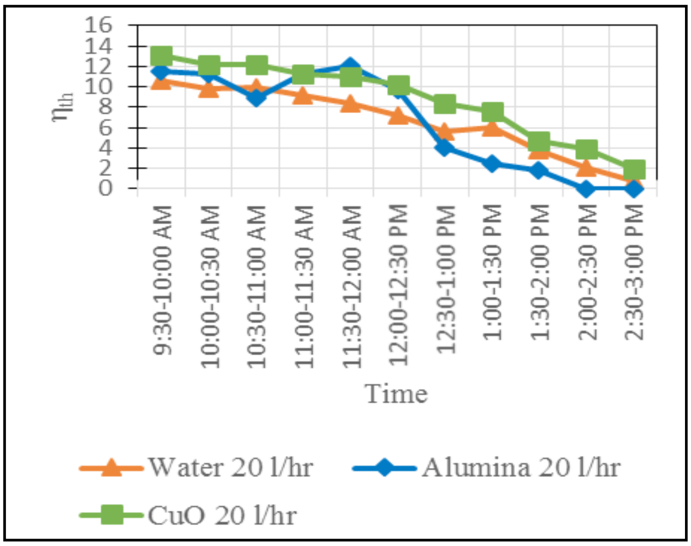

Fig. 9: Comparison of Thermal Efficiency w.r.t. Time for Water & Water Based Alumina and CuO (0.01%) Nanofluid at 20 l/hr Mass Flow Rate

Fig. 9 shows the comparison of thermal efficiency w.r.t. time for water & water based alumina and CuO nanofluid with 0.01% volume concentration at 20 l/hr mass flow rate. From the graph it is analysed that the CuO nanofluid shows the higher efficiency from 9:30-11:30 AM & from 12:00-3:00 PM because of the faster variation in the temperature difference in comparison with water & alumina nanofluid. On the other hand, alumina nanofluid shows the higher efficiency from 9:30-10:30 AM & from 11:00-12:30 PM in comparison with water because of faster variation in the temperature difference and lower intensity of radiation. From the graph it is also noted that the alumina nanofluid shows the higher peak value of efficiency at 11:30-12:00 PM in as compare to CuO nanofluid because of higher value of specific heat by the amount 90.02 J/kgK and higher temperature difference. The overall maximum value of instantaneous efficiency for CuO is 13.05% and for water is 10.56% at 9:30-10:00 AM & for alumina is 11.99% at 11:30-12:00 PM.

Fig. 10 shows the comparison of thermal efficiency w.r.t. time for water & water based alumina and CuO nanofluid with 0.01% volume concentration at 40 l/hr mass flow rate. From the graph it is observed that the

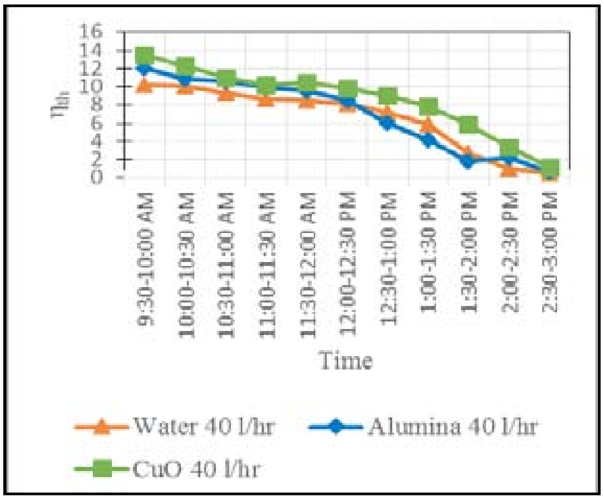

Fig. 10: Comparison of Thermal Efficiency w.r.t. Time for Water & Water Based Alumina and CuO (0.01%) Nanofluid at 40 l/hr mass flow rate

CuO nanofluid shows the higher efficiency continuously from 9:30 AM to 3:00 PM in comparison water & alumina naniofluid because of higher temperature difference. It is also observed that the alumina nanofluid shows the higher efficiency from 9:30-12:30 PM & from 2:00-3:00 PM as compare to water because of lower solar intensity and faster variation in temperature difference while on the other hand, water shows higher efficiency from 12:30-2:00 PM as compare to alumina nanofluid because of higher specific heat value & higher temperature difference at these time periods. The overall maximum value of instantaneous efficiency for CuO is 13.56%, for alumina is 12.06% &.for water is 10.20% at the same interval of 9:30-10:00 AM.

Fig. 11 shows the comparison of thermal efficiency w.r.t. time for water & water based alumina and CuO nanofluid with 0.01% volume concentration at 60 l/hr mass flow rate. From the graph it is observed that the CuO nanofluid shows the higher efficiency at regular intervals from 9:30 AM to 3:00 PM because of faster variation in temperature difference in comparison water & alumina nanofluid. On the other hand it is also observed that the alumina nanofluid shows higher efficiency from 9:30-3:00 PM as compare to water because of lower solar intensity & higher temperature difference.

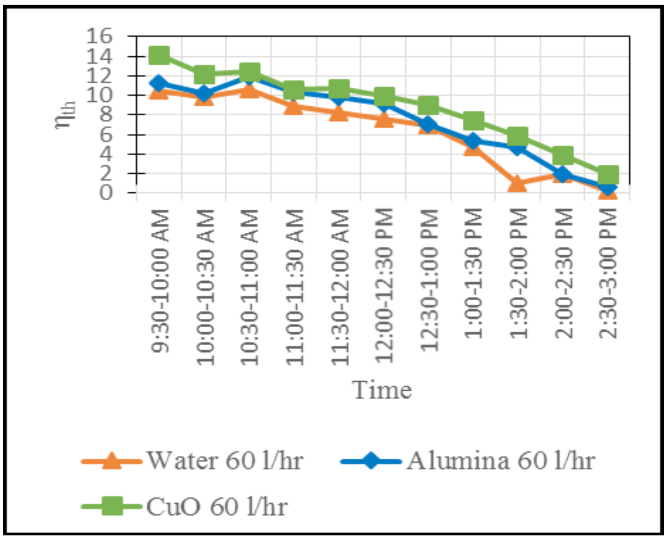

Fig. 11: Comparison of Thermal Efficiency w.r.t. Time for water & water based alumina and CuO (0.01%) nanofluid at 60 l/hr mass flow rate

The overall maximum value of instantaneous efficiency for CuO is 14.15% at 9:30-10:00 AM, for alumina is 11.87% &.for water is 10.58% at the same interval of 10:30-11:00AM.

IV. Conclusion

The purpose of this experimental work is to check the performance of parabolic concentrating solar collector by using water, water based aluminium oxide (Al_2O_3) & copper oxide (CuO) nanofluid as the working fluids. Following are the conclusions drawn.

1. By using copper oxide (CuO) nanofluid as a working fluid with 0.01% concentration, collector's instantaneous efficiency has been found to be improved from 0.88 to 2.83%, 1.24 to 6.26%, and 4.74 to 13.57% for 20, 40 & 60 l/hr mass flow rates. Whereas, Collector's thermal efficiency is improved from 0.95 to 3.05%, 0.66 to 3.36%, and 1.7 to 4.87% for 20, 40 & 60 l/hr mass flow rates.
2. By using copper oxide (CuO) nanofluid as a working fluid with 0.01% concentration, collector's instantaneous efficiency is improved from 0.02 to 4.77%, 0.45 to 7.71%, and 1.1 to 8.16% for 20, 40 & 60 l/hr mass flow rates. Collector's thermal efficiency is improved from 0.5 to 5.14%, 0.21 to 4.15%, and 0.33 to 2.88% for 20, 40 & 60 l/hr mass flow rates.
3. By using alumina (Al_2O_3) nanofluid as a working fluid with 0.01% concentration, collector's instantaneous efficiency is enhanced from 0.92 to 3.39%, 0.1 to 3.44%, and 0.02 to 10.1% for 20, 40 & 60 l/hr mass flow rates. Collector's thermal efficiency is enhanced from 1 to 2.55%, 0.05 to 1.86%, and 0.01 to 3.67% for 20, 40 & 60 l/hr mass flow rates.

V. Future Scope

There is a lot of scope in the field of solar energy harvesting using nanofluid-based concentrating parabolic solar collector (NCPSC) system. In the present experimental work we took fixed dimensions & same material of receiver tube, glass cover tube, and parabolic collector & take only one size of nanoparticles. In addition, thermophysical properties (density, specific heat, viscosity & thermal conductivity) are taken at standard temperature.

In the future various investigations will be carried out to check out the performance of parabolic collectors are given as follows:-

1. By varying the dimensions (length, diameter) of the receiver tube and glass cover tube.
2. By varying the dimensions (length, height) of parabolic collector.
3. By changing the material of receiver tube & glass cover tube such as quartz or Pyrex glass.
4. By changing the material of reflector such as stainless steel sheet, aluminium sheet or aluminium sheet.
5. By changing the size of nanoparticle and try with different concentrations with different base fluids other than water like with ethanol or therminol-VP1.
6. Calculate thermophysical properties (density, specific heat, viscosity & thermal conductivity of nanofluid at varying temperatures.
7. By using air as a working medium instead of using nanofluids with the help of blower.
8. By using automatic tracking system in place of manual tracking system.

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