PERFORMANCE EVALUATION OF A NANOFLUID BASED PARABOLIC SOLAR COLLECTOR – AN EXPERIMENTAL STUDY

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Abstract- An experimental study has been conducted to investigate the performance of a parabolic solar collector using SiO_2-H_2O based nanofluid. Volumetric concentration of 0.01% and 0.05% has been used in the experiment to prepare the nanofluid. The different volume flow rates employed in the experiment are 20 l/h, 40 l/h and 60 l/h. Surfactants are not used while preparing the nanofluids. Sonication is done by using ultra bath sonicator to enhance the stability and dispersion of nanoparticles in water. Magnetic stirrer with hot plate system has been used for stirring purpose to mix the nanoparticles in water before sonication. Manual tracking mechanism has been used for tracking the sun position during the day. From the results, it has been found that SiO_2-H_2O based nanofluid has comparatively higher efficiency at higher volume flow rates.

Keywords- Parabolic Solar Collector, Instantaneous Efficiency, Thermal Efficiency, Overall Thermal Efficiency, SiO_2 Nanofluid, Nanofluid Properties

I. INTRODUCTION

One of the important challenges which our society facing now a day's is sustainable energy generation. Electricity demand is growing at a faster rate but the shortage of fossil fuels and environmental considerations will constrain the use of fossil fuels in the future. Therefore, researchers are motivated to find alternative sources of energy. This has become even more popular as the price of fossil fuels continues to rise. Conventional energy sources are not in enough amount. The coal is of low quality and containing high amount of ash. The solar energy provides a solution to overcome from sustainable energy generation problem. Average of about 15 kWh spends on water heating per day for a particular household in a developed nation. Movement towards the use of solar energy is due to discontinuity in electricity supply, government losses by providing over-subsidised LPG and sharp increase in CO_2 emission. For electricity purpose, non concentrating collectors are not so good. So, instead of this, concentrating collectors are used. The use of conventional fluids in solar collectors have low efficiency as compared to nanofluids. This is due to its poor thermophysical properties compared to nanofluids.

II. NANOFLUID BASED SOLAR COLLECTORS

Now a day's use of nanofluid technology instead of conventional fluids is seen as potential area where performance of solar collectors can be improved. The selection of nanofluid is a big concern for using in solar collectors. Nanofluids have certain limitations like corrosion and erosion of components, pumping power problem, pressure drop, high cost, agglomeration of nanoparticles and instability etc. Pressure drop enhances by employing CuO-oil based nanofluid under laminar regime. Pressure drop enhances by enhancing volumetric concentration of TiO_2-water based nanofluid under turbulent regime. If the temperature gradient is high, the agglomeration problem of nanoparticles is more. ZrO_2 and TiO_2 nanoparticles provides higher corrosion compared to SiC nanoparticles. So, the proper selection of nanofluid is necessary for improving the performance of solar collectors. At the high volumetric concentration of nanofluids, viscosity is also high. Nanofluids can be used in parabolic trough systems, photovoltaic/thermal systems, solar ponds, solar thermoelectric cells, solar cooling systems, solar absorption refrigeration systems and combination of different solar devices. Different results are provided by different authors on solar collectors using water and nanofluid as working fluid. Enhanced average efficiency is 11% for nanofluid and 12% for water at 31.5° and 4% for nanofluid and 7% for water at 50° utilizing solar tracker device. Solar to thermal efficiency is 62.5% at the outlet temperature of nanofluid which is 650^0 C having volume fraction of 0.3%.

A maximum extinction coefficient of aluminium nanoparticles is at 0.3μm wavelength and after that it decreases sharply and the size of nanoparticles did not show a significant effect on optical properties. 5% improvement in efficiency can be obtained using nanofluid as working fluid in solar collector of direct absorption type. It is also found that efficiency increases with increase in the volumetric concentration of nanoparticles and the efficiency also increases when the size of silver nanoparticle is reduced from 40 to 20 nm because optical properties depended on nanoparticle size. Thermal conductivity of MWCNT-water based nanofluid increases with increase in the volumetric concentration of MWCNTs and if nanofluids are employed for heating purposes, then it enhances the performance of the conventional

solar water heater. Single wall carbon nanohorns-water based nanofluid in solar system is very helpful for improving the efficiency and for more efficient and incorporated designs.

III. THEORY

The performance of the parabolic solar collector is determined by calculating useful heat gain, thermal efficiency (per half an hour), instantaneous efficiency and overall thermal efficiency. Nanofluids properties are determined by using mathematical models. Following are the equations which are generally used to investigate the performance of solar collectors.

The density of the nanofluid is determined by using eq. (1).

$$\rho_{nf} = (1 - \varphi_p)\, \rho_f + \varphi_p\, \rho_{np} \qquad (1)$$

The specific heat of the nanofluid is determined by using eq. (2).

$$c_{nf} = \{(1 - \varphi_p)\, \rho_f\, c_f + \varphi_p\, \rho_{np}\, c_{np}\} / \rho_{nf} \qquad (2)$$

Thermal conductivity of the nanofluid is determined by using eq. (3).

$$k_{nf} = k_f\, [k_{np} + 2\, k_f + 2\, \varphi_p\, (k_{np} - k_f)] / [k_{np} + 2\, k_f - \varphi_p\, (k_{np} - k_f)] \qquad (3)$$

Viscosity of the nanofluid is determined by using eq. (4).

$$\mu_{nf} = \mu_f / (1 - \varphi_p)^{2.5} \qquad (4)$$

Useful heat gain of the system is determined by applying eq. (5).

$$q_u = \square\, c_{nf} (\, T_{0ut} - T_{in}\,) \qquad (5)$$

Thermal efficiency of the system is determined by applying eq. (6).

$$\eta_{th} = m\, c_{nf} (\, T_{0ut} - T_{in}\,) / A_{aper}\, G_T\, t \qquad (6)$$

Instantaneous efficiency of the system is determined by applying eq. (7).

$$\eta_i = q_u / G_T\, R_b\, W\, L \qquad (7)$$

Overall thermal efficiency of the system is determined by applying eq. (8).

$$\eta_{ot} = m\, c_{nf} (\, T_{max} - T_{min}\,) / A_{aper}\, G_{av}\, t \qquad (8)$$

Convective heat transfer coefficient is determined by applying eq. (9).

$$h_f = N_u \times k / D_i \qquad (9)$$

Collector heat removal factor is determined by applying eq. (10).

$$F_R = \square\, c_{nf} / \pi\, L\, D_o\, U_L\, [1 - \exp(\, -\pi\, D_o\, U_L\, L\, F' / \square\, c_{nf})] \qquad (10)$$

IV. MATERIAL AND NANOFLUID PREPARATION

The SiO_2 nanoparticles have been used in the experiment. The average size of the SiO_2 nanoparticles is 20-30 nm with purity 99%. The nanoparticles are mixed in base fluid to prepare the nanofluid and the base fluid used is distilled water. The XRD and TEM images of SiO_2 nanoparticles have been shown in figure 1(a) and 1(b). XRD has been used to characterize the SiO_2 material as a nanomaterial whereas, the TEM image of SiO_2 sample confirm the size and shape of the SiO_2 nanoparticles.

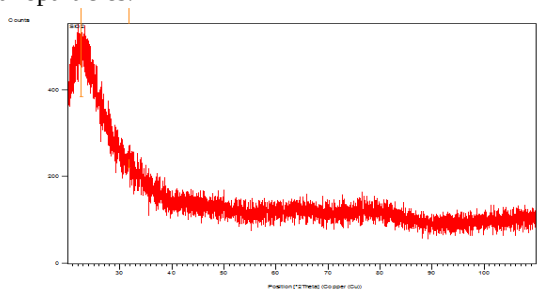

Fig. 1(a) XRD image of SiO_2 nanoparticles

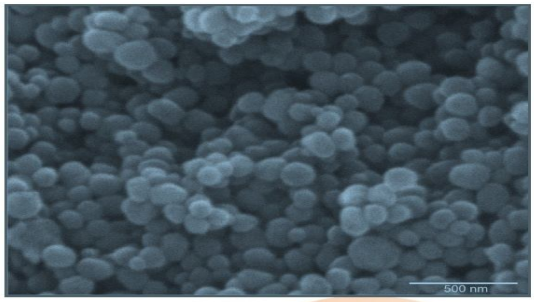

Fig. 1(b) TEM image of SiO_2 nanoparticles

Nanofluids are prepared by using either one step method or two step method. In one step method, nanoparticles are simultaneously making and dispersing in the base fluid. Where as in two step method, nanoparticles used are first produced as dry powder by using physical or chemical method. After that, in the second step, dry nanoparticles are dispersed into base fluid. Two step method is used in the experiment to prepare the nanofluid. The SiO_2-H_2O based nanofluid is prepared by dispersing nanoparticles in base fluid. Sonication is done for about two and a half hours but before this, stirring is done by using magnetic stirrer with hot plate system. The stirring is done for about half an hour for SiO_2-H_2O based nanofluid and are prepared without using any surfactant. Ultra bath sonicator is used for sonication purpose. The volumetric concentration of nanoparticles used is 0.01% and 0.05%. The nanofluids prepared is shown in figure 2(a) and 2(b) at volumetric concentration of 0.01% and 0.05%.

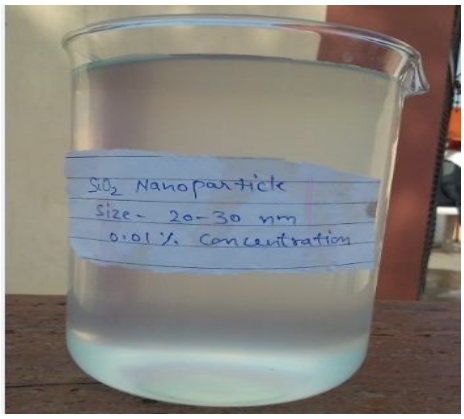

Fig. 2(a) SiO_2-H_2O based nanofluid at 0.01% vol. conc.

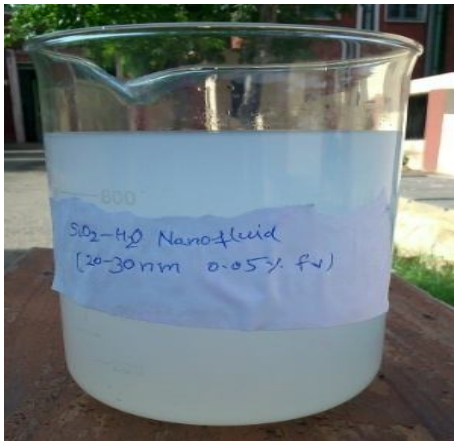

Fig. 2(b) SiO_2-H_2O based nanofluid at 0.05% vol. conc.

V. EXPERIMENTAL SET-UP

The experimental set up used during the experiment is shown in figure 3. This is a parabolic solar collector with manual tracking system and has been used to carry out the different experiments. A Stainless steel sheet is employed to develop the parabolic structure. The reason behind the use of stainless steel sheet is that it gives mechanical strength to the parabolic structure. Then, glass mirror strips are sticked on the parabolic sheet with the help of double tape and fevetite raped. Total 26 glass mirror strips are used. The system has been designed and developed in the lab itself. A copper tube is employed as receiver tube. Its outside surface is painted black to absorb maximum solar radiation and is covered with glass tube to reduce the losses which are due to conduction, convection and radiation mechanism. Storage tank is made up of plastic having capability of 10 litre. Glass wool insulation is used on the storage tank to protect it from heat loss. The pump is placed inside the storage tank to circulate the working fluid. The support structure is made up of cast iron for parabolic solar collector system. It is constructed in such a manner that it holds easily stress loads, wind loads etc. Firstly, pipes are insulated with the help of aluminium foils and are further insulated with the help of Superlon insulation. This is done to reduce the heat losses as much as possible during the flow of liquid in the piping system. Manual tracking mechanism is used to track the sun position during the day. Ball valve is used to vary the volume flow rate of working fluid.

Figure 3 Experimental set up

Table 1 - Different parameters and their values for the fabricated PTSC

Collector length	1.2 m
Collector breadth	0.915 m
End plate thickness	2 mm
Aperture area	1.0188 m^2
Rim angle	90^0
Focal length	0.3 m
Receiver inside diameter	0.027 m
Receiver outside diameter	0.028 m
Glass envelope inside diameter	0.064 m
Glass envelope outside diameter	0.066 m
Insulation on pipes	Aluminium foil, Superlon
Concentration ratio	9.66
Tank insulation material	Glass wool
Circulating pump	18 W
Volume flow rate	20 l/h, 40 l/h, 60 l/h

VI. RESULTS AND DISCUSSIONS

(1) Variation in solar intensity and temperature with time (a) For SiO_2-water based nanofluid (0.01% and 0.05% conc.) at volume flow rate of 20 l/h

For both the concentrations the solar intensity continuously increases upto 1:00 pm as shown in Fig.4. After 1:00 pm, solar intensity decreases continuously. Also, nanofluid temperature at inlet and outlet of the receiver increases continuously upto 3:00 pm in both.

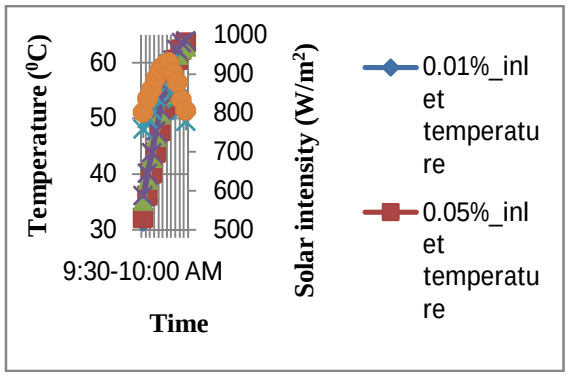

Fig.4 Variation in solar intensity and temperature with time for SiO_2-water based nanofluid (0.01% and 0.05% conc.) at volume flow rate of 20 l/h

(b) For SiO_2-water based nanofluid (0.01% and 0.05% conc.) at volume flow rate of 40 l/h

At 0.01% conc., the solar intensity continuously increases upto 1:00 pm as shown in Fig.5. After 1:00 pm, solar intensity decreases continuously. At 0.05% conc., the solar intensity continuously increases upto

12:30 pm. Also, nanofluid temperature at inlet and outlet of the receiver increases continuously upto 3:00 pm in both.

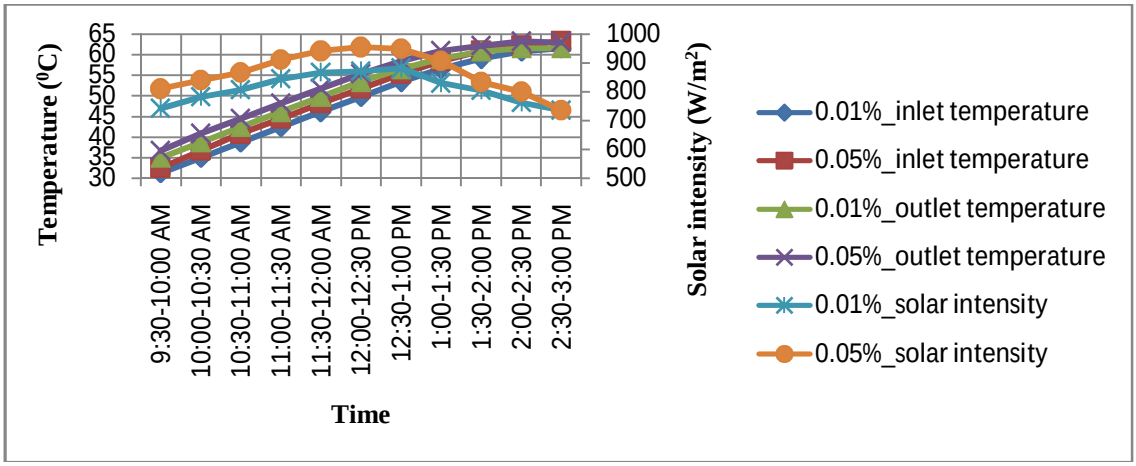

Fig.5 Variation in solar intensity and temperature with time for SiO_2-water based nanofluid (0.01% and 0.05% conc.) at volume flow rate of 40 l/h

(c) For SiO_2-water based nanofluid (0.01% and 0.05% conc.) at volume flow rate of 60 l/h

At both conc., the solar intensity continuously increases upto 1:00 pm as shown in Fig.6. After 1:00 pm, solar intensity decreases continuously except 2:30 pm at 0.01% conc. Also, nanofluid temperature at inlet and outlet of the receiver increases continuously upto 3:00 pm in both.

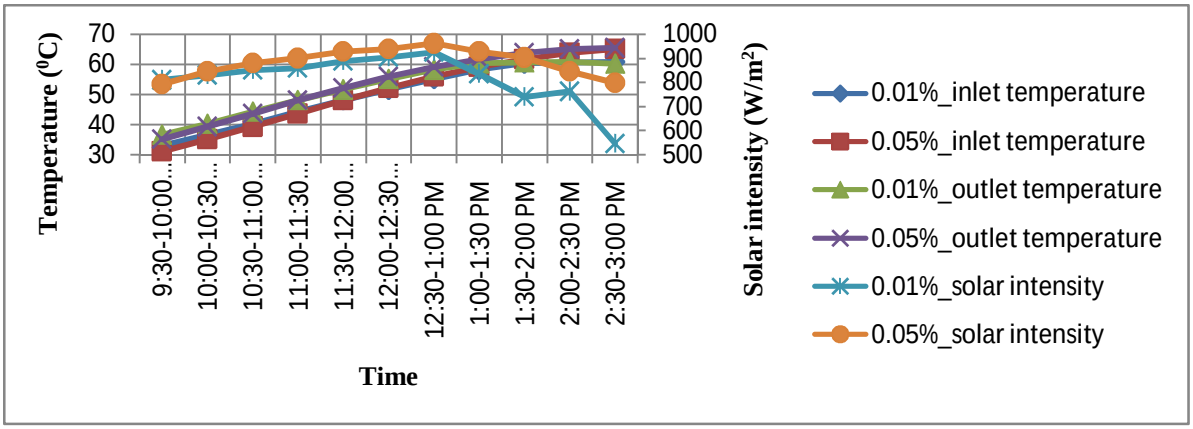

Fig.6 Variation in solar intensity and temperature with time for SiO_2-water based nanofluid (0.01% and 0.05% conc.) at volume flow rate of 60 l/h

(2) Variation in useful heat gain with time

For SiO_2-water based nanofluid (0.01% and 0.05% conc.) at different volume flow rates

Fig.7 shows variation in useful heat gain with time for SiO_2-water based nanofluid (0.01% and 0.05% conc.) at different volume flow rates (20 l/h, 40 l/h and 60 l/h). As the volume flow rate increases, useful heat gain also increases. The variation in useful heat gain depends upon the temperature difference. After 1:30 pm, useful heat gain decreases due to decrease in solar intensity and as a result of this, temperature difference also decreases.

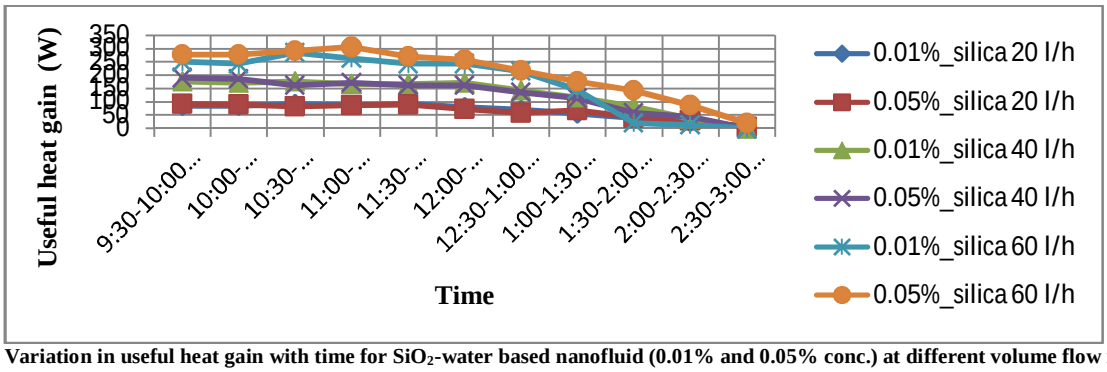

Fig.7 Variation in useful heat gain with time for SiO_2-water based nanofluid (0.01% and 0.05% conc.) at different volume flow rates

(3) Variation in instantaneous efficiency with time
For SiO_2-water based nanofluid (0.01% and 0.05% conc.) at different volume flow rates

The instantaneous efficiency is maximum at volume flow rate of 60 l/h for SiO_2-water based nanofluid (0.01% conc.) except at 1:30-3:00 pm as shown in Fig.8. The instantaneous efficiency is more at volume flow rate of 60 l/h for SiO_2-water based nanofluid (0.05% conc.) as compared to volume flow rate of 20 l/h and 40 l/h. The reasons for this are high volume flow rate, high useful heat gain.

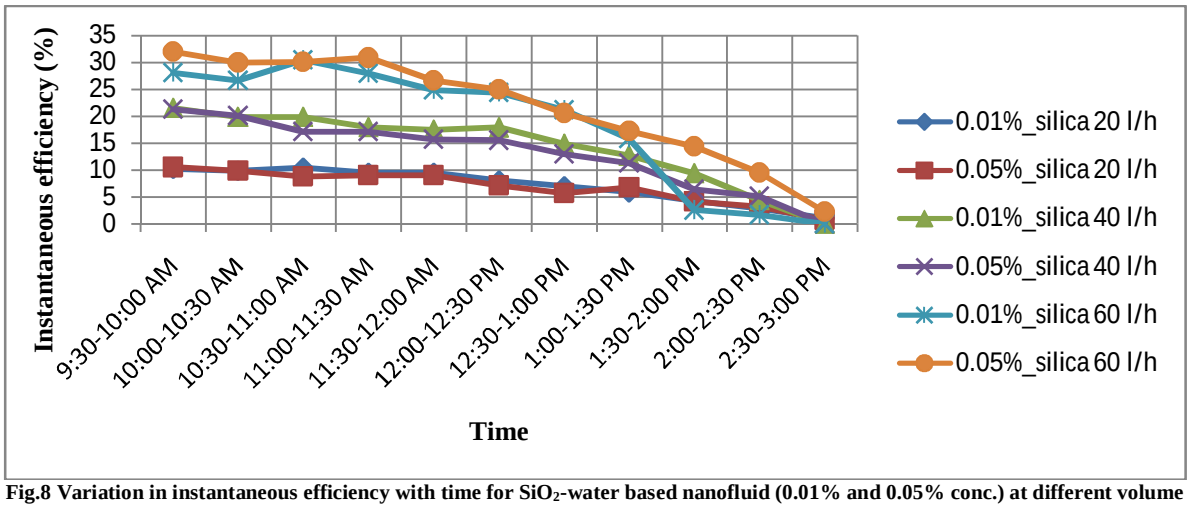

Fig.8 Variation in instantaneous efficiency with time for SiO_2-water based nanofluid (0.01% and 0.05% conc.) at different volume flow rates

(4) Variation in thermal efficiency with time
For SiO_2-water based nanofluid (0.01% and 0.05% conc.) at different volume flow rates
Fig.9 shows the variation in thermal efficiency with time for SiO_2-water based nanofluid (0.01% and 0.05% conc.) at different volume flow rates (20 l/h, 40 l/h and 60 l/h). The thermal efficiency of SiO_2-water based nanofluid (0.01% and 0.05% conc.) at volume flow rate of 40 l/h is more as compared to 20 l/h and 60 l/h. The reason for this is high solar intensity, due to which temperature difference increases.

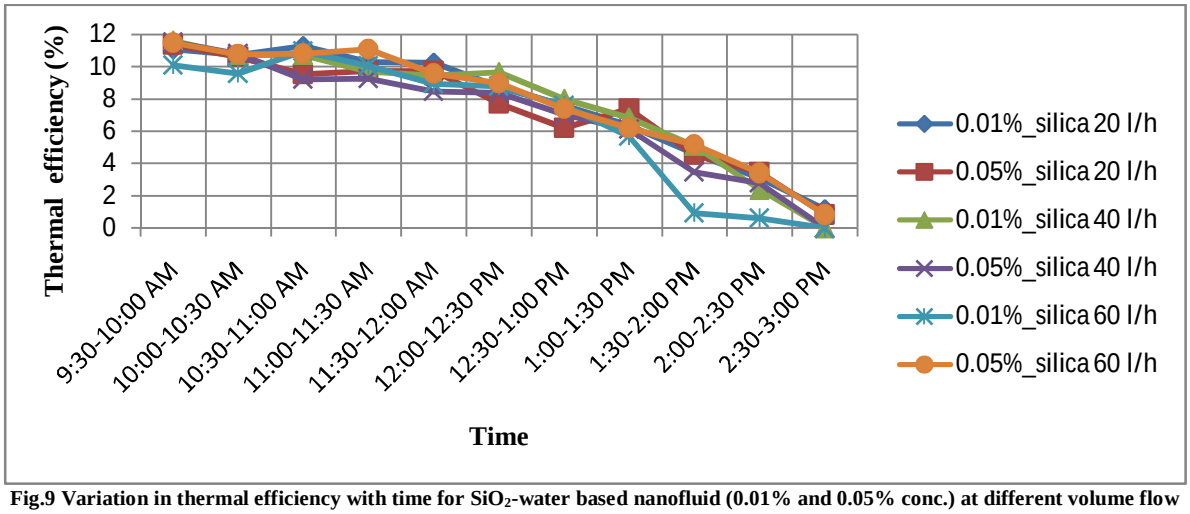

Fig.9 Variation in thermal efficiency with time for SiO_2-water based nanofluid (0.01% and 0.05% conc.) at different volume flow rates

CONCLUSIONS

The present work examines experimentally the performance of a parabolic solar collector using SiO_2-H_2O based nanofluid. The different volume flow rates taken are 20 l/h, 40 l/h and 60 l/h. The volumetric concentration of nanoparticles taken is 0.01% and 0.05%. For this, instantaneous efficiency, thermal efficiency and overall system efficiency is calculated. Manual tracking system is used to absorb maximum solar radiation. Convective heat transfer coefficient and collector heat removal factor is also calculated. From the results, the following points are concluded as given below:

- The maximum temperature obtained from SiO_2-water based nanofluid (0.01% vol. conc.) for volume flow rate of 20 l/h, 40 l/h and 60 l/h is 62.9 ^{0}C, 61.6 ^{0}C and 60.8 ^{0}C respectively. Whereas, at (0.05% vol. conc.) for volume flow

rate of 20 l/h, 40 l/h and 60 l/h the maximum temperature rise is 63.9 ^{0}C, 63.2 ^{0}C and 65.4 ^{0}C respectively.

- Instantaneous efficiency increases with increase in volume flow rate. The maximum instantaneous efficiency obtained from SiO_2-water based nanofluid (0.01% vol. conc.) for volume flow rate of 20 l/h, 40 l/h and 60 l/h is 10.45%, 21.55% and 30.48% respectively. Whereas, at (0.05% vol. conc.) for volume flow rate of 20 l/h, 40 l/h and 60 l/h this value is 10.54%, 21.34% and 31.96% respectively.
- The maximum thermal efficiency obtained from SiO_2-water based nanofluid (0.01% vol. conc.) at volume flow rate of 20 l/h, 40 l/h and 60 l/h is 11.27%, 11.61% and 10.95% respectively. Whereas, at (0.05% vol. conc.) for volume flow rate of 20 l/h, 40 l/h and 60 l/h this value is 11.36%, 11.5% and 11.48% respectively.
- The maximum overall thermal efficiency obtained from SiO_2-water based nanofluids (0.01% vol. conc.) at volume flow rate of 20 l/h, 40 l/h and 60 l/h is 7.76%, 7.73% and 7.48% respectively. Whereas, at (0.05% vol. conc.) for volume flow rate of 20 l/h, 40 l/h and 60 l/h it is 7.4%, 7.73% and 7.83% respectively.
- At (0.01% vol. conc.), the maximum convective heat transfer coefficient and heat removal factor is 351.26 W/m^{2}K and 0.953 respectively. Whereas, at (0.05% vol. conc.), the maximum convective heat transfer coefficient and heat removal factor is 347.67 W/m^{2}K and 0.9524 respectively.

Nomenclature

c_{nf} = Specific heat of nanofluid, J kg^{-1} K^{-1}
c_f = Specific heat of base fluid, J kg^{-1} K^{-1}
c_{np} = Specific heat of nanoparticles, J kg^{-1} K^{-1}
k = Thermal conductivity, W m^{-1} K^{-1}
q_u = Useful heat gain, W
□ = Mass flow rate of working fluid, kg s^{-1}
T = Temperature of working fluid, K
A = Area, m^2
G_T = Incident solar flux, W m^{-2}
m = Mass of working fluid in storage tank, kg
W = Width of the reflector, m
D = Diameter of receiver tube, m
L = length of receiver tube, m
h_f = Convective heat transfer coefficient, W m^{-2} K^{-1}
N_u = Nusselt number
F_R = Collector heat removal factor
F' = Collector efficiency factor
U_l = Overall heat transfer coefficient, W m^{-2} K^{-1}
l/h = Litre per hour
vol. = Volumetric
conc. = Concentration

Greek Symbols

ρ = Density, kg m^{-3}
φ_p = Volumetric concentration of nanoparticles
μ = Dynamic viscosity, kg m^{-1} s^{-1}
η = Efficiency

Subscripts

nf = Nanofluid
np = Nanoparticle
f = Base fluid
ot = Overall thermal
i = Instantaneous
th = Thermal
o = Outer
out = Outlet
in = Inlet
max = Maximum
min = Minimum
aper = Aperture

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