Experimental Investigation of Heat Transfer Characteristics of ZnO Nanofluid in Parabolic Trough Collector

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***Abstract*— Free and forced heat transfer studies have been carried out in a parabolic trough collector using ZnO/water nanofluid. Experiments have been carried out in a parabolic trough collector at various concentrations of ZnO nanoparticles in water (0.2 % and 0.4% vol.) and flow rates (2.2 lpm. and 0.66 lpm.). Enhancement in heat transfer due to the use of nanofluid has been reported in terms of temperature and heat transfer coefficient. Various convective dimensionless parameters such as Nusselt number, Prandtl number, Rayleigh number, Reynolds number and Grashof number are determined and empirical correlations between them is derived.**

***Index Terms*—Convection, Nanofluid, Solar, thermal conductivity, trough collector.**

I. INTRODUCTION

Our world is shrinking as we are becoming more connected but the demand of energy is increasing exponentially. More than 80% of world's population still depends on conventional fuels but the problems related to conventional energy sources are, they are non-renewable and polluting in nature. The burning of fossil fuels produces around 21.3 billion tons of carbon-dioxide per year but still around 1.2 billion (16% of world's population) do not have access to electricity and many more suffer from supply that is of poor quality. Therefore the dire need of the situation is energy, which is renewable, sustainable, reliable, non-polluting and readily available.

A solar collector is a device that transforms solar radiation from the Sun into heat, which is then transferred to working fluid. The use of solar collectors reduces energy costs over time as they do not use fossil fuels or electricity like that as in traditional water heating. As well as in domestic settings, a large number of these collectors can be combined in an array and used to generate electricity in solar thermal power plants.

There are a number of different types of solar collector designs that use the energy of the sun to heat working fluid. Each design whether a basic blackened flat panel collector or a more advanced evacuated tube collector all have their own advantages and disadvantages. Parabolic trough reflector provides a better alternative way in order to generate higher temperatures with better efficiency. The parabolic trough reflector is a solar energy collector designed to capture the sun's direct solar radiation over a large surface area and focus or "concentrate it" onto a small focal point area, increasing the solar energy received by more than a factor of two.

Connecting together parabolic troughs to form collector fields requires large areas of land for the installation. Also, parabolic troughs have a small absorber area and have efficiencies of around 12% with smaller angle of view.

The cost of power production through solar has reduced considerably but still the levelized cost of solar is four times that of supercritical coal. Increasing the efficiency of solar collectors can reduce the aggravation of this problem.

Heat transfer characteristics of solar collectors can be improved by increasing the thermal conductivity of the working fluid. Advancement in nanotechnology has shown that by suspending finer particles (Metals, Metal oxides, Nanotubes etc.) can significantly increase the thermal conductivity of the base fluid.

The term nanofluid was coined by Choi in 1995 at the annual winter meeting of the American Society of Mechanical Engineers where he presented the possibility of doubling the convection heat transfer coefficients using nano-fluids.

Convective heat transfer can be enhanced passively by enhancing thermal conductivity of the fluid. Modern nanotechnology provides new possibilities to enhance heat transfer performance compared to pure liquids.

Nanofluids are engineered colloidal suspension of Nano meter sized particles called Nano particles in a base fluid. Metals, oxides, carbides or carbon nanotubes are the general precursors for nanoparticles. Common base fluids include water, ethylene glycol and oil. Nanofluids exhibit enhanced thermal conductivity due to large area to volume ratio and high turbulence properties.

Due to its novel properties nanofluid find their applications in many fields of heat transfer, including microelectronics, fuel cells, pharmaceutical processes, and hybrid-powered engines, , in grinding, machining ,engine cooling/vehicle thermal management, domestic refrigerator, chiller, heat exchanger and in boiler flue gas temperature reduction. Knowledge of the rheological behaviour of Nanofluids is found to be very critical in deciding their suitability for convective heat transfer applications.

Heris et al observed an increase of about 40% in heat transfer by conducting experiments with the Al_2O_3 and CuO nanoparticles suspended in water under laminar flow.

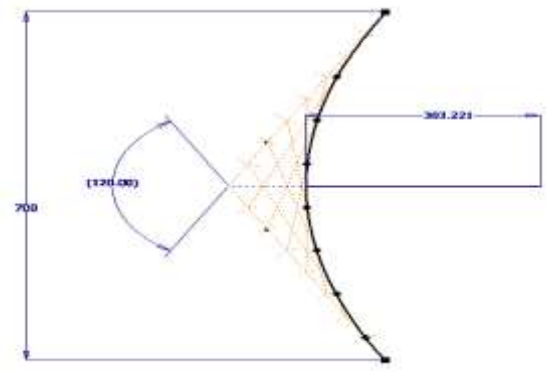
Tyagi et al studied theoretically found the effect of volume fraction on heat transfer using a mixture of water and aluminium by varying theconcentration from 0.1 % to 5% in andirect absorption solar collector. They found a significant increasein efficiencyfor low volume fractions of nanoparticles, and also for values higher than 2% the efficiency levels even out.

In 2010, Otanicar et al made a similar studyon the effect of different nanofluids such as carbon nanotubes, graphite and silver on the performances of a micro scale direct absorption solar collector. However they observed a remarkable increase in the efficiency up to 0.5%volume fraction. He also concluded that with decreasing size of nanoparticles there wasincreasein the efficiency.

II. DESIGN OF THE TROUGH COLLECTOR

The width and angle of view of parabola are selected according to construction convince and tangent method is used to find the focus and equation of parabola.

A. *Parabola Design*



Focus = 303.221 mm
Eqn. of parabola : $y^2 = 1.21284\ x$

B. *Final CAD model*



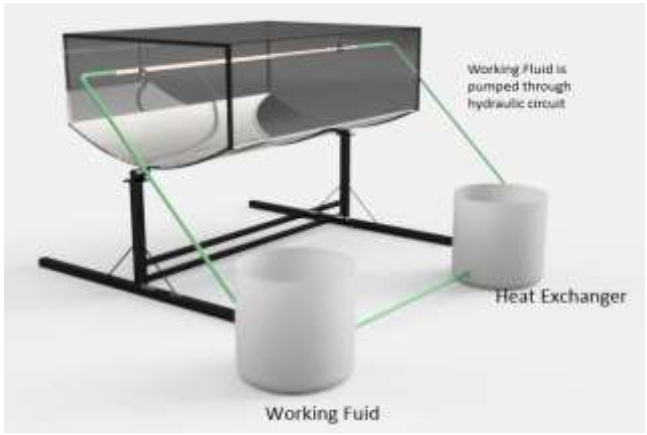
- Trough Length = 1m ,
- Absorber tube diameter = 1.25cm ,
- Parabola angle = 120deg ,
- Aperture width = 0.7m

III. EXPERIMENTATION

A. *Free Convection*



B. *Forced Convection*



IV. THEORY

The thermal characteristics of ZnO nanofluid is required in order to determine the convection equatdions.

4.1 Heat Flux

The heat flux of the nanofluid is determined by Fourier conduction equation

$$Q = \frac{m*Cp*(To-Ti)}{t} \qquad (1)$$

In the above equation, To is the outlet temperature of water Ti is the inlet temperature of water to the collector.

4.2 Heat transfer coefficient

From the heat flux determined the heat transfer coefficient is calculated

$$Q = h * A * (Tw - Tb) \qquad (2)$$

Where Tw is the Surface temperature of receiver pipe and T_b is given by

$$Tb = \frac{Ti+To}{2} \qquad (3)$$

4.3 Volume Fraction (φ_{ZnO})

The volume fraction of the nanofluid is critical in determining other nanofluid properties. It is determined by the formula

$$\varphi_{ZnO} = \frac{\frac{W_{ZnO}}{\rho_{ZnO}}}{\frac{W_{ZnO}}{\rho_{ZnO}}+\frac{W_{bf}}{\rho_{bf}}} \qquad [16] \qquad (4)$$

Where ρ_{ZnO} is density of ZnO particles which is 5610 kg/m^3 and ρ_{bf} is the density of water which is 992.2 kg/m^3.

4.4 Density of Nanofluid (ρ_{nano})

Density of nanofluid is found by the relation

$$\rho_{nano} = (1 - \varphi_{ZnO})\rho_{bf} + \varphi_{ZnO}\rho_{ZnO} \qquad [16] \quad (5)$$

4.5 Specific Heat ($C_{p_{eff}}$)

The specific heat of the nanofluid is calculated by the relation

$$C_{p_{eff}} = \frac{(1-\varphi_{ZnO})(\rho C_p)_{bf}+\varphi_{ZnO}(\rho C_p)_{ZnO}}{\rho_{nano}} \qquad [16] \quad (6)$$

Where specific heat of ZnO particles is 495.207667 J/kg-K and specific heat of water is 4187 J/kg-K

4.6 Thermal Conductivity (K_{eff})

The thermal conductivity of nanofluid is determined by Maxwell's Equation

$$K_{eff} = K_{bf} * \frac{K_{ZnO}+2K_{bf}+2\varphi(K_{ZnO}+K_{bf})}{K_{Zno}+2K_{bf}-(K_{ZnO}-K_{bf})\varphi} \qquad [16] \qquad (7)$$

Where

$K_{ZnO} = 50\ {}^{W}/_{mK}$

$K_{water} = 0.6305\ {}^{W}/_{mK}$

4.7 Dynamic Viscosity (μ)

The dynamic viscosity of the nanofluid is determined by Einstein's equation.

$$\mu = (1 + 2.5\varphi_{ZnO})\mu_{bf} \qquad [16] [17] \qquad (8)$$

Where μ_{bf} is dynamic viscosity of water which is 0.6531 * 10^{-3} Ns/m^2.

4.8 Reynolds Number:

Reynolds number gives the information, whether the flow is inertial or viscous force dominant. It tells us whether the flow is laminar or turbulent.

$$Re = \frac{\rho UL}{\mu} = \frac{UL}{V} \qquad (9)$$

4.9 Prandtl Number

Prandtl Number is determined in order to calculate Rayleigh number

$$Pr = \frac{v}{\alpha} = \frac{\mu c_p}{k} \qquad (10)$$

4.10 Nusselt Number

Nusselt number gives the comparison between the conduction and convection heat transfer rates.

$$Nu = \frac{hl}{k} \qquad (11)$$

4.11 Grashof Number

Grashof number is determined to plot a graph of Nusselt and Rayleigh number and the ΔT term in this number causes the variation.

$$Gr = \frac{g\rho^2\beta\Delta T L^3}{\mu^2} \qquad (12)$$

V. Results And Discussion

The experiments were carried out first with water and subsequently with ZnO nanofluid of different concentrations (0.2% and 0.4%)as the working fluid in the trough collector. There was significant rise in the temperatures and heat transfer coefficient reached due to the use of ZnO/water nanofluid. Heat flux and heat transfer coefficients were calculated from equations (1) and (2) and the nanofluid properties are calculated from equations (3) to (8). These values are used to determine the dimensionless numbers given from equations (9) to (12).

Fig 1. shows the variation of temperature at various intervals of the day for water and nanofluid. From the figure it can be seen that there is clearly improvement in the temperature reached by the use of nanofluid. Also it can be seen that 0.4% ZnO/water nanofluid is better than 0.2%.

Fig 2. shows the variation of heat transfer coefficient at various intervals of the day for water and nanofluid. From the figure it can be concluded that during the beginning of the day the value of heat transfer coefficient is more as the temperature of collector pipe and receiver pipe is almost same. It can also be seen that there is enhancement in heat transfer coefficient by the use of ZnO/water nanofluid.Also it can be seen that 0.4% ZnO/water nanofluid is better than 0.2%.

Fig 3. shows the variation of Nusselt number due to the change in Rayleigh number for 0.2% ZnO/water nanofluid

working in free convection. A power curve is fit into the points in order to determine the correlation between them.

Fig 4. shows the similar variation of Nusselt number and Rayleigh number for 0.4% ZnO/water nanofluid working in free convection and a power curve is fit into the points in order to determine the correlation between them.

In case of forced convection experiments are done at two different flow rates so that there are two sets of Reynold's and Nusselt number. As Prandtl number remains constant over the variation of flow rate the coefficients of the convection equation.

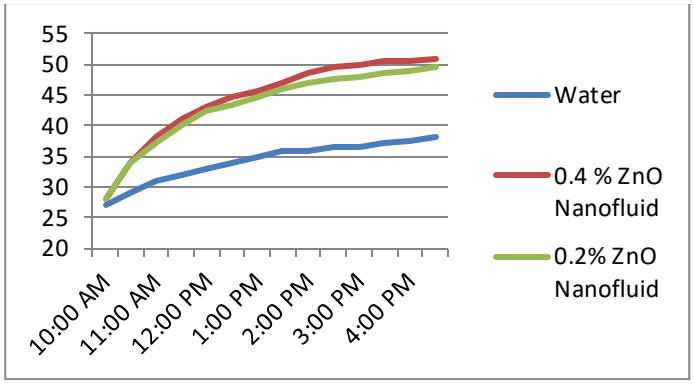


Fig.1 Graph of temperature vs. Time

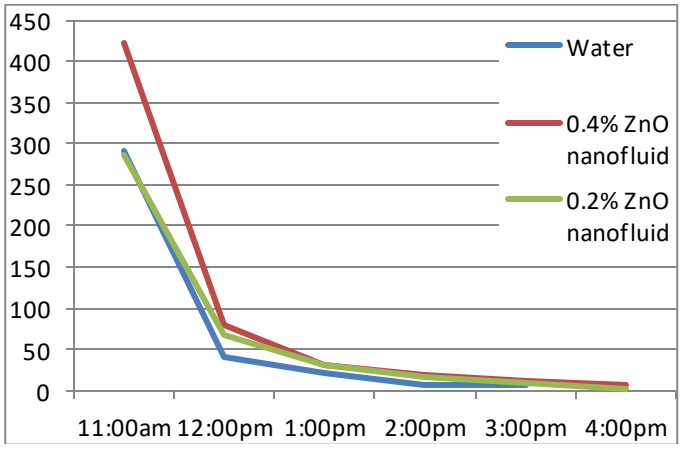
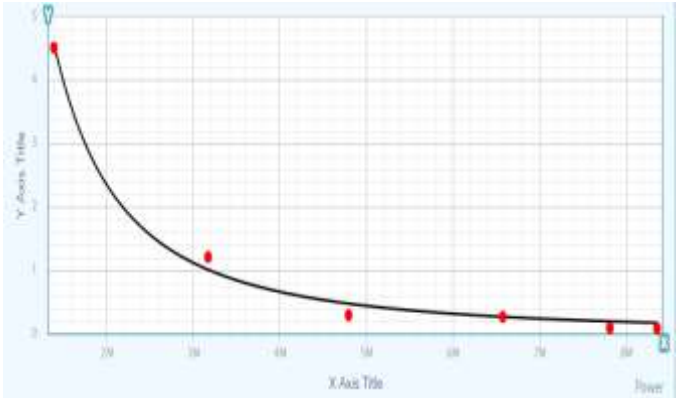
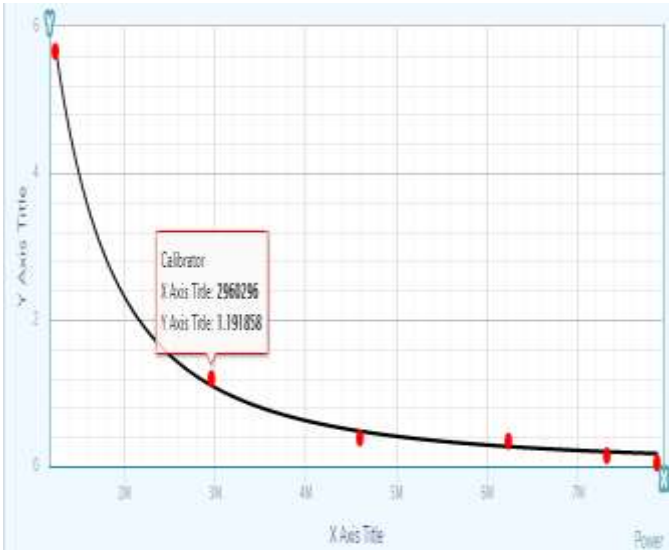


Fig.2 Variation of heat transfer coefficient vs. time



Goodness Measures What's this?	
R^2	0.9938
aR^2	0.9907
P	0.00003855
SE	0.153
F	320.1
Coefficients	
a	758018500000 ± 1431000000000
b	−1.826738 ± 0.1328
Equation	
y = 758018500000*x^−1.826738	

Fig.3 Nusselt number vs. Rayleigh number of 0.2% ZnO/ water nanofluid



Goodness Measures What's this?	
R^2	0.9982
aR^2	0.9974
P	0.000003068
SE	0.1019
F	1140
Coefficients	
a	2024671000000 ± 2275000000000
b	−1.895257 ± 0.07978
Equation	
y = 2024671000000*x^−1.895257	

Fig.4 Nusselt number vs. Rayleigh number of 0.4% ZnO/ water nanofluid

VI. Outcomes and Conclusion

The empirical correlations between dimensionless numbers of convection were found and are as in the table given below:

Fluid	Relation
0.4% ZnO Free Convection	$N_u = 2.024671 * 10^{12} (Gr.Pr)^{-1.895257}$

0.4% ZnO Forced Convection	$N_u = 1.17498769\,(R_e)^{0.019895}\,P_r^{1/3}$
0.2% ZnO Free Convection	$N_u = 7.580185 * 10^{11}\,(Gr.Pr)^{-1.826738}$
0.2% ZnO Forced Convection	$N_u = 1.0630356\,(R_e)^{0.0186647}\,P_r^{1/3}$

From the experimentation it was found that there was an increase of 34.6% in the final temperature reached by the reservoir. By water it was seen that the maximum temperature reached was 41.5^{o}C but by using nanofluid temperatures up to 52^{o}C was reached.

By the addition of nanoparticles to the base fluid the thermal conductivity value of the base fluid is increased as shown in the calculations where as the specific heat value decreases i.e. there is increase in heat conduction but at the same time the temperature rise and fall takes place at a faster rate.

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REFERENCES

[1]. Timilsina GR, Kurdgelashvili L, Narbel PA, A review of solar energy markets, economics and policies. Policy Research Working Paper; 2011.
[2]. Xiaowu W, Ben H. Exergy analysis of domestic-scale solar water heaters. Renew Sustain Energy Rev 2005;9(6):638–45.
[3]. Wang X, Wang R, Wu J. Experimental investigation of a new-style double-tube heat exchanger for heating crude oil using solar hot water. ApplThermEng 2005;25(11–12):1753–63.
[4]. Al-Madani H. The performance of a cylindrical solar water heater. Renew Energy 2006;31(11):1751–63.
[5]. Ho CD, Chen TC. The recycle effect on the collector efficiency improvement of double-pass sheet-and-tube solar water heaters with external recycle. Renew Energy 2006;31(7):953–70.
[6]. Eric DK. Engines of creation. 4th edition. London: Oxford Press; 1986.
[7]. Maxwell JC, A treatise on electricity and magnetism, vol. 1. UK: Oxford.
[8]. Terekhov VI, Kalinina SV, Lemanov VV. The mechanism of heat transfer in nanofluids: state of the art (review). Part 2.Convective heat transfer.ThermophysAeromech 2010;17(2):157–71.
[9]. S. Kakaç, A. Pramuanjaroenkij, Review of convective heat transfer enhancement with nano-fluids,Int. J. Heat Mass transfer, vol. 52, pp. 3187-3196,2009.
[10]. Das, U.S. Choi, Wenhua Yu, T. Pradeep, Nano-fluids science and technology,John Wiley & Sons.
[11]. S. Z. Heris, S. Gh. Etemad, M. N. Esfahany, Experimental investigation of oxide nano-fluids laminar flow convective heat transfer, IntCommun Heat Mass Transfer, vol. 33, pp. 529-535, 2006.
[12]. H. Tyagi,P. Phelan, R. Prasher, Predicted efficiency of a low temperature nano-fluid based direct absorption solar collector, J Sol. Energy. Eng, vol. 131, pp. 041004, 2009.
[13]. T. P. Otanicar, P. E. Phelan, R. S. Prasher, G. Rosengarten, R. A. Taylor, Nanofluid-based direct absorption solar collector, J Renew Sustain Energy, vol. 2, pp. 33102, 2010.
[14]. V. Khullar, H. Tyagi, P. E. Phelan, T. P. Otanicar, H. Singh, R. A. Taylor, Solar energy harvesting using nanofluids-based concentrating solar collector, J Nanotechnology Eng Med, vol. 3, pp. 031003, 2012
[15]. Manual making of a parabolic solar collector Gang Xiao
[16]. A review on nanofluids - Part 1: Theoretical and Numerical investigations Xiang-Qi Wang and Arun S. Mujumdar
[17]. Experimental investigations of the viscosity of nanofluids at low temperatures Bahadir Aladag, Halelfadl Salma, Nimeti Doner, Thierry Mare', Duret Steven,Patrice Estelle'
[18]. Preparation and Stability of Nanofluids-A Review Sayantan Mukherjee, Somjit Paria