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Theoretical Based Investigation on the effects of Cu/water nanofluid in flat-plate solar collector

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Abstract The performance of heat transfer applications may be considerably enhanced using the nanofluids as an alternative. Present works the performances of a (Cu) based flat plate solar collectors (FPSC) and water based were examined numerically. In this work we have determined the impact of nanofluids that is distributing of copper (Cu) nanoparticles in the water. A numerical model was also presented to present the influence of the nanofluid in the thermophysical properties of nanofluids which are density, Specific heat and thermal conductivity over the base fluid collector. The effect of adding nanofluids as compared to water based collector have been compared for the on Reynolds number, Fluid outlet temperature and Nusselt number. Results show that by adding (Cu) in base fluids, it shows the higher values of all the above stated parameters as compared to H_2O based FP collector.

Key Words: Nanofluid, Flat-plate solar collector, Density, Efficiency

1. INTRODUCTION

Nanofluids are a potential alternative to significantly improving the performance of heat transfer applications. In this work, a numerical analysis to examine the effect of dispersing copper (Cu), copper oxide (CuO), and aluminum (Al_2O_3) nanoparticles in pure water on the performance of a flat plate solar collector (FPSC) and a numerical model was proposed. The influence of the nanofluid type on the thermal efficiency was critically investigated and discussed. The effect of the mass flow rate on the performance was also analyzed and discussed. Based on correlations of the thermophysical properties of nanofluids, a sensitivity analysis was used to analyze the impact of the nanoparticles on the base fluid. The results indicate that the performance of the FPSC with Cu/water nanofluid was better than that of FPSCs using CuO/water or Al2O3/water nanofluids. When the mass flow rate of the nanofluids was 8.0 L/min, the efficiency of the FPSC was much greater than those at the flow rates of 5.0 L/min and 2.0 L/min. Mean enhancements in thermal efficiency of 4.44%, 4.27%, and 4.21% were observed when 2.0 L/min was applied using Cu/water, CuO/water, and Al2O3/water nanofluids, respectively. Improvements in thermal efficiency of 2.76%, 2.53%, and 2.47% occurred when 8.0 L/min was applied.

Nanofluid is a colloidal mixture of nano-sized particles in a host fluid to improve the heat transfer characteristics, suited for practical applications [1-7].

Basically, conversion and transportation of energy take place in atomic or molecular levels, but nanotechnology provides a significant role in energy utilization of thermal systems without having any environmental impact.

There are many research works that concentrate on nanofluids containing different nanoparticles with various volume concentration and size.

Originally various base fluids such as ethylene glycol, form amide, water etc., have been used in many heat transfer applications [7]. Thermal conductivity and convective heat transfer of base fluids (such as ethylene glycol, form amide, water etc) had been increased by mixing micro-sized particles with a base fluid. Erosion in pipelines, sedimentation and clogging leads to high pressure drop caused by these particles. The enhancement in thermal properties is attained by mixing nano-sized particles which dispersed uniformly in the base fluids. Kumar et al. [21] have worked on solar air heater of flat plate type.

Nanofluids is a colloidal suspension of nanoparticles of size 1 to 100nm (10-9m) in the base fluid (water, ethylene glycol, oil etc.). This is the term first coined by Choi in the year 1995 at the Argonne National Laboratory to develop a new form of nanotechnology based heat transfer fluids. Nanoparticles have larger relative surface area since particle size is very less, high mobility, better suspension stability, improved thermal conductivity and less particle momentum of the mixture than micro-sized particles. Due to these properties, nanofluids are being used as coolants, lubricants, hydraulic fluids and metal cutting fluids.

Depending on the application, nanofluids have been made of various materials such as metals, metal oxides, ceramics and carbon nanotubes (CNT) [7-8]. Carbon nanotubes provide more heat transfer when compared to other materials but the synthesis processing of carbon nanotubes is difficult and also unaffordable in cost. Metal and metal oxide nanoparticles can be synthesized easily even from naturally available green leaves.

The objective of present paper is to investigate the effect of Cu nanoparticle in flat collector and investigate the enhancement in the thermophysical properties over the H_2O based flat collector.

LIST OF ABBREVIATIONS/ SYMBOLS/ NOMENCLATURE

A_c	Collector Surface area	m^2
C_b	Bond conductance	W/m^2K
C_p	Specific heat capacity	J/kg K
D	Diameter of tube	m
Di	Inner diameter of tube	m
Do	Outer diameter of tube	m
Dp	Size of particle	m
F	Fin efficiency	–
F'	Collector efficiency factor	–
F_R	Heat removal factor	–
h	Heat transfer coefficient	W/m^2K
P	Pressure	Pa
P_m	Pumping power	W
Qu	Useful heat gain	W
T_{sun}	Sun temperature	K
T_g	Cover glass Temperature	K
T_{fo}	Outlet air temperature	K
T_s	(Tsun) Sky temperature	K
T_{fi}	(Ti) Air Inlet Temperature	K
T_a	Ambient temperature	K
T_{pm}	Mean plate temperature	K
hw	Wind heat transfer coefficient	W/m^2K
I	Intensity of solar radiation (Insolation)	W/m^2
Kp	Thermal conductivity of plate	W/m K
K_g	Thermal conductivity of glass cover	W/m K
K_i	Thermal conductivity of glass wool insulation	W/m K
L	Length of Collector	m
L_g	Thickness of glass cover	m
m	Mass flow rate of air	kg/s
Ng	Number of glass covers	-
ΔP	Pressure drop	N/m^2
U_b	Bottom loss coefficient	$W/m^2 K$
U_s	Side loss coefficient	$W/m^2 K$
U_t	Top loss coefficient	$W/m^2 K$
V	Average velocity of fluid in collector	m/s
V_w	Wind velocity	m/s
w	Width of solar air heater duct	m
W	Riser tube spacing	m
Wp	Pumping or Mechanical power	W
T_{fm}	Mean fluid temperature	K
U_L	Overall heat loss coefficient	$W/m^2 K$

DIMENSIONLESS PARAMETERS

f	Friction factor
F_R	Collector heat-removal factor
F'	Collector efficiency factor
F_o	Collector heat removal factor referred to outlet air temperature
Nu	Nusselt number
Pr	Prandtl number

Re	Reynolds number

GREEK SYMBOLS

μ	Absolute viscosity fluid	N s/m^2
ρ	density	kg/m^3
Ø	Volume fraction (%)	
σ	Stefan-Boltzman's constant	W/m^2 K^4
$(\tau\alpha)$	Effective transmittance-absorptance product	
α_c	Absorptivity of the glass cover	-
ε_p	Emissivity of absorber plate	-
ε_b	Emissivity of bottom plate	-
ε_g	Emissivity of glass cover	-
δ_i	Insulation thickness,	m
β	Tilt angle of collector surface	degree
ν	Kinematic viscosity of air	m^2/s
η_{th}	(η_E) Thermal efficiency	-
α_p	Absorptivity of absorber plate	-
τ	Transmissivity of glass cover	-

OTHERS

in	Inlet
out	Outlet
NP	Nanoparticles
NF	Nanofluid
BF	Basefluid
amb	Ambient
max	Maximum
min	Minimum
ave	Average
T	Temperature

2. RESEARCH METHODOLOGY

Many research works have been carried out using nanofluid as the heat transfer medium, an attempt is made to analyze the heat transfer characteristics of nanofluid under solar radiation by keeping the following objectives in mind.

To enhance the heat transfer characteristics of CuO nanofluids by varying the nanoparticle concentrations and mass flow rates. To understand the application of CuO nanofluids on density, Specific heat and thermal conductivity over the base fluid collector. The effect of adding nanofluids as compared to water based collector and it have been compared for the parameters; Reynolds number, Fluid outlet temperature and Nusselt number under various fluids flow rate and volume fraction (Ø).

3.MODELLING ANALYSIS

PROPERTIES OF NANOFLUIDS

3.1. The density of the nanofluid (ρ_{nf}), is evaluated based on the principle of the mixture rule as follows [19-23];

$$\rho_{nf} = \phi\rho_p + (1-\phi)\rho_{bf} \qquad 1$$

3.2. The specific heat of the nanofluids $(C_{P,nf})$ is predicted by using the thermal equilibrium model [19-23]

$$C_{P,nf} = \frac{\phi(\rho C)_p + (1-\phi)((\rho C)_{bf}}{\rho_{nf}} \quad 2$$

3.3. Thermal Conductivity

The thermal conductivity of nanofluids can be evaluated as the equation given by Maxwell which shows a good agreement with the experimental data's over the other proposed models [19-23]:

$$\frac{k_{nf}}{k_{bf}} = \frac{k_p + 2k_{bf} - 2\phi(k_{bf} - k_p)}{k_p + 2k_{bf} + \phi(k_{bf} - k_p)} \quad 3$$

The conductivity of the base fluid is evaluated at the average temperature from the following equation:

$$k_{bf} = [1.488445 + 4.12292(T_{avg} / 298.15) - 1.63866(T_{avg} / 298.15)] \times 0.6065 \quad 4$$

3.4. Dynamic Viscosity

Dynamic Viscosity of nanofluids can be calculated by the equation which is given by Brinkman's model [19-21]

$$\frac{\mu_{nf}}{\mu_{bf}} = \frac{1}{(1-\phi)^{2.5}} \quad 5$$

In Eq. (3.5) the viscosity of the base fluid, is given by the equation as

$$\mu_{bf} = 2.414E^{-5} \times 10^{247.8/(\mathrm{Tavg}-140)} \quad 6$$

3.5. EFFICIENCY OF THE SOLAR COLLECTOR

The energy efficiency of the solar collector is defined by [20]

$$\eta_{th} = \frac{Qu}{A_c I} \quad 7$$

3.6. In above Eq., Qu represents the useful heat gain from available solar energy

$$Qu = mCp(T_{out} - T_{in}) \quad 8$$

3.7. Useful heat gain (Qu) can also be calculated as

$$Qu = A_c F_R [I(\tau\alpha) - U_L(T_{fi} - T_a)] \quad 9\ (a)$$

$$Qu = A_c [I(\tau\alpha) - U_L(T_{pm} - T_a)] \quad 9\ (b)$$

3.8. The collector heat removal factor, F_R, which is calculated as

$$F_R = \frac{mCp(T_{out} - T_{in})}{A_c[S - U_L(T_{in} - T_a)]} \quad 10$$

The collector heat removal factor, F_R, which is also can be calculated as

$$F_R = \frac{mCp}{A_c U_L}\left[1 - \exp\left(-\frac{U_L F' A_c}{mCp}\right)\right] \quad 11$$

In above Eq., (F') is the collector efficiency factor which can be calculated as

$$F' = \frac{1/U_L}{W[1/[U_L(D + (W-D)F] + 1/\mathrm{C_b} + 1/\pi \mathrm{Dh_f}]} \quad 12$$

In above Eq., (W)= Tube spacing, (F)= Fin efficiency, (D) = Diameter of tube, (C_b)= Bond Conductance

The Fin efficiency (F) can be calculated as

$$F = \frac{\tanh[m(W-D)/2]}{[m(W-D)/2]} \quad 13$$

3.10. New mean temperature of the absorber plate is calculated as

$$T_{pm} = T_{in} + \frac{Qu}{A_c F_R U_L}(1 - F_R) \quad 14$$

3.11. The collector's heat transfer coefficient can be calculated as [27-28]

$$h_{fi} = \frac{Nu.k_{nf}}{Di} \quad 15$$

3.12. The Reynolds number can be calculated as

$$\mathrm{Re}_{nf} = \frac{\rho_{nf} V D_i}{\mu_{nf}} \quad (16)$$

3.13 Prandtl number can be calculated as

$$\mathrm{Pr}_{nf} = \frac{\mu_{nf} C_{p,nf}}{k_{nf}} \quad (17)$$

3.14. Average temperature of the air can be calculated as

$$T_{avg} = T_{fm} = \frac{T_{fo} + T_{fi}}{2} \quad (18)$$

3.15. PUMP WORK

Pump work is given by the equation [17,21].;

$$W_p = \dot{m}\Delta P / \rho \quad (19)$$

3.16. Pressure drop (ΔP) in the collector is evaluated by using the equation;

$$\Delta P = f \frac{\rho V^2}{2} \frac{L}{D} + \frac{\rho V^2}{2} \quad (20)$$

3.17. The friction factor for FP Collector having water and nanofluid as circulating fluid can be evaluated as equation [17,21].

$$f = \frac{64}{\mathrm{Re}} \quad (21)$$

The above equation is valid for laminar flow
The friction factor for FP Collector having water and nanofluid as circulating fluid for the turbulent flow [17,21].

$$f = \frac{0.079}{(\mathrm{Re})^{1/4}} \quad (22)$$

3.18. The Nusselt number (Nu) for FP Collector having nanoparticle, is evaluated by using the correlation [29].

$$Nu_{NP} = 0.023\,\mathrm{Re}^{0.8}\,\mathrm{Pr}^{0.4} \quad (23)$$

The above equation is valid for turbulent flow
The (Nu) for nanoparticle base Collector having laminar flow ($\mathrm{Re} \leq 2100$) is evaluated as

$$Nu_{NP} = 0.000972\,\mathrm{Re}^{1.17}\,\mathrm{Pr}^{1/3} \quad (24)$$

The (Nu) for water based FP Collector is evaluated by using is evaluated by using

$$Nu_{NP} = 0.021\,\mathrm{Re}^{0.8}\,\mathrm{Pr}^{1/2} \quad (25)$$

Kumar et al. [21] have worked on solar air heater of flat plate type.

3.1. INPUT DATA

The nanofluid water enters the collector through circular shape riser tube as shown in Fig. for the present analysis collector is have a single glass cover and proper insulation is provided in the bottom and on the sides.
The values of environmental conditions like; solar irradiance (I), wind velocity (Vw), and ambient temperature (Ta) and other details of the FP collector and assumptions are given in Table 1.

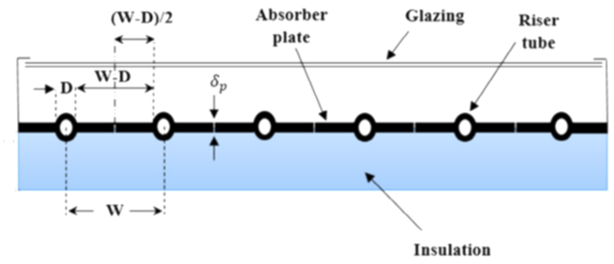


Fig.1. A schematic of structure and basic components of flat plate solar collector.

Table 1. Specifications and input data's of the collector for the present analysis

S. No	Parameter	Value
1	Collector dimension	Length=2.0 m width = 0.95 m H = 0.095 m
2	Absorption area (Ac)	1.90 m^2
3	Header pipe diameter (D_H)	22 mm, t = 0.9 mm
4	Distance between two parallel tubes (W)	0.145 m
5	Riser pipe diameter (Di)	10 mm, t = 0.9 mm
6	Collector tubes diameter	0.009 m
7	Working fluid	Al_2O_3–water nanofluid, Cu nanofluid and water
8	No. of Glazing (Ng)	1
9	Thermal emission of absorption sheet (εp)	0.07
10	Solar absorption of	0.95

	absorption sheet	
11	Glass cover emissivity, (εg)	0.88
12	Collector plate thickness (t)	0.005 m
13	Collector plate thermal conductivity (kp)	383 W/mK
14	Collector tilt, β	45°
15	Insulation thermal conductivity, (ki)	0.05 W/mK
16	Back insulation thickness (tb)	0.05 m
17	Solar radiation (I)	800 W/m^2
18	Sun temperature (Tsun)	4350 K
19	Wind velocity (Vw)	3.2 m/s
20	Ambient temperature (Ta)	300 K
21	Inlet temperature (Ti)	302 K

Table 2. Thermo-physical Properties of different nanomaterials and base (water) fluids

S.No	Nanoparticle Type	Formula	Density (ρ) (kg/m^3)	Specific Heat (Cp) (J/kg.K)	Thermal Conductivity (k) (W/m.K)	Ref. Number
1	Aluminium Oxide	(Al_2O_3)	3690	774	40	[19-23]
2	Copper oxide	(CuO)	6000	551	34	[19-23]
3	Water	(H2O)	997	4180	0.607	[19-23]
4	Copper	(Cu)	8978	388	381	[19-23]

4.RESULT AND DISCUSSION

For the calculations the flow in the FP solar collector is fully developed flow and Steady State operation have been assumed.

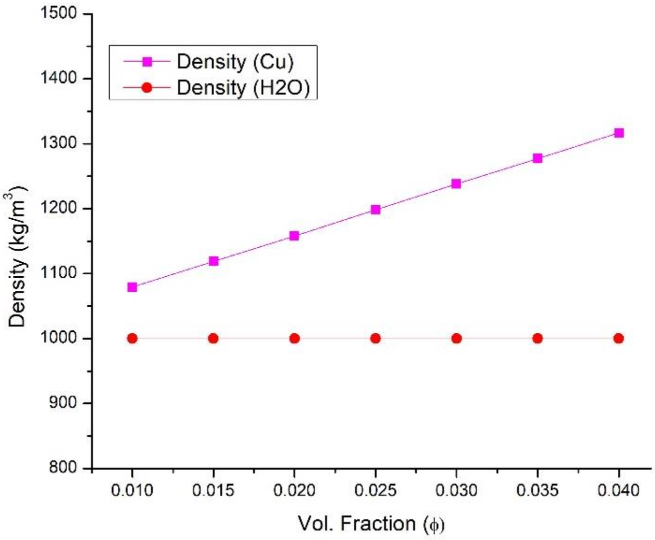


Fig. 2. Variation of Density for (Cu) nanofluids and (H2O) with different Volume fraction.

Figs. 2 to 4 shows the thermophysical properties that is the density, specific heat and thermal conductivity of (Cu) nanofluid and water base FP collector.

The volume fraction (Ø) ranges have been considered from 0.010 to 0.040 % which also have been considered for their analysis by the Alim et al. [13] and Said et al. [17].

The volume flow rate (m) = 0.0050 kg/s have been considered for these figures.

Fig. (2) has been prepared for the density of the nanomaterial (ρ_{NP}) base FP collector, density has been evaluated by the Eq. (3.1) and properties of nanomaterials have been taken from Table 3.2.

It can be seen from Fig. (2) that the density of nanofluid increases by increasing the volume fraction (Ø) of nanoparticles while the rate of change density of H2O with (Ø) is almost negligible.

The value of (ρ_{NP}) = 1079 kg/m^3 for the value of (Ø) = 0.01 % while for (Ø) = 0.040 % the value of reaches to (ρ_{NP}) = 1317 kg/m^3.

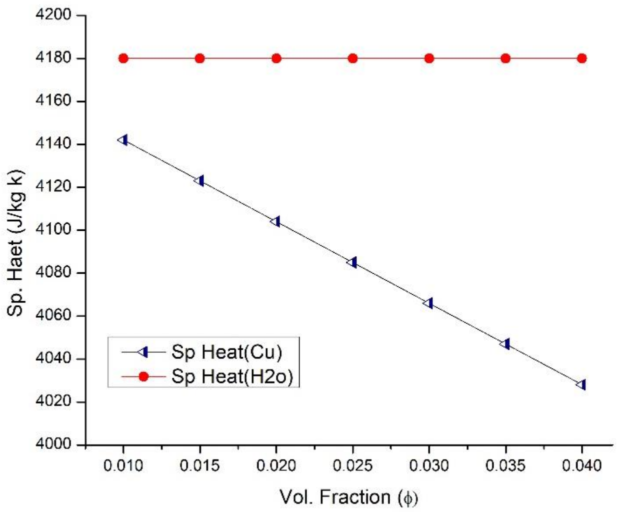


Fig. 2. Variation of Specific heat for (Cu) nanofluids and (H2O) with different Volume fraction.

Fig. (2) has been drawn for the Specific heat of the nanomaterial based $(C_{p,nf})$ FP collector, and comparison with the H2O as function with the volume fraction (Ø).

It can be seen from Fig. (2) that the $(C_{p,nf})$ of nanofluid decreases with higher rate with the increasing the values of (Ø) for the nanoparticles while the rate of change density of H2O with (Ø) is almost negligible.

The value of $(C_{p,nf})$ is 4142 J/ kg k when the value of (Ø) is 0.01 %, while for (Ø) = 0.040 % the value achieved to (ρ_{NP}) = 4028J/ kg k.

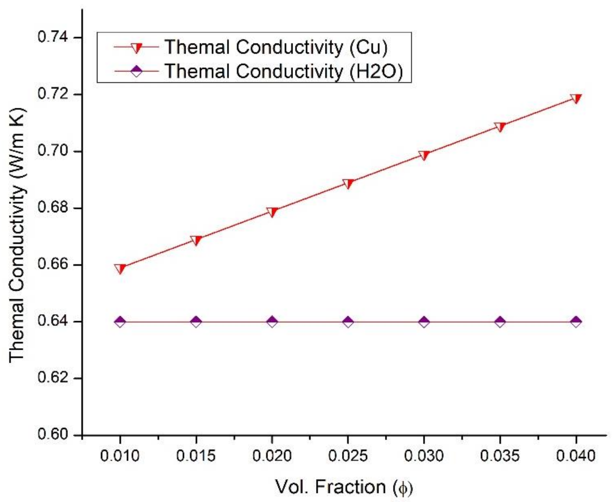


Fig.3. Variation of Thermal conductivity for (Cu) nanofluids and (H2O) with different Volume fraction.

Fig. (3) shows the variations of thermal conductivity the nanomaterial based (k_{nf}) FP collector, and comparison with the H2O as function with the volume fraction (Ø).

It can be suggests from the Fig. (3) that the (k_{nf}) of nanofluid increases with increasing the values of (Ø) for the nanoparticles while the values of (k_{bf}) of H2O with (Ø) is negligible with change in the values of (Ø).

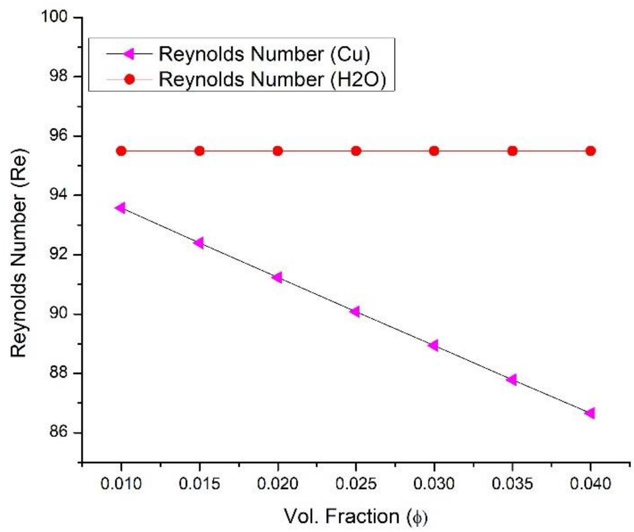


Fig. 4. Variation of Reynolds number for (Cu) nanofluids and (H2O) with different Volume fraction

The volume flow rate (m) = 0.0050 kg/s have been considered for these figures.

Fig. (4) has been resented the effect of the volume fraction (Ø) for the Reynolds number (Re) of the nanomaterial based and water based FP collectors. The volume flow rate (m) = 0.0050 kg/s have been considered for Fig.4.

(Re) has been evaluated by the Eq. (3.20) and properties of nanomaterials have been taken from Table 3.2, it can be seen that while calculation of (Re) the density and viscosity play the important role.

It can be seen from Fig. (4) that the (Re) of nanofluid decreased by increasing the volume fraction (Ø) for the nanoparticles while for the H2O with (Ø) it shows negligible changes.

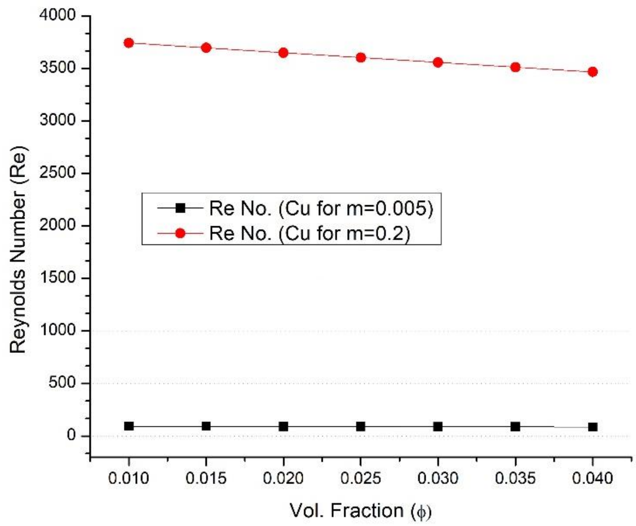


Fig. 5. Variation of Reynolds number for (Cu) and (H2O) for Laminar and Turbulent flow region with different Volume fraction.

Fig. (5) has been resented the effect of the volume fraction (Ø) on the Reynolds number (Re) for the nanomaterial on the laminar and also for the turbulent regions. The volume flow rate (m) = 0.0050 kg/s have (Re)= 95.9 while the (m) = 0.20 kg/s have (Re)= 3750.

By the Eq. (3.20) we can see that Reynolds number is the function of the velocity (V) of the fluid i.e (Re) shows the directly proportional ratio of the flow of the fluid in the collector.

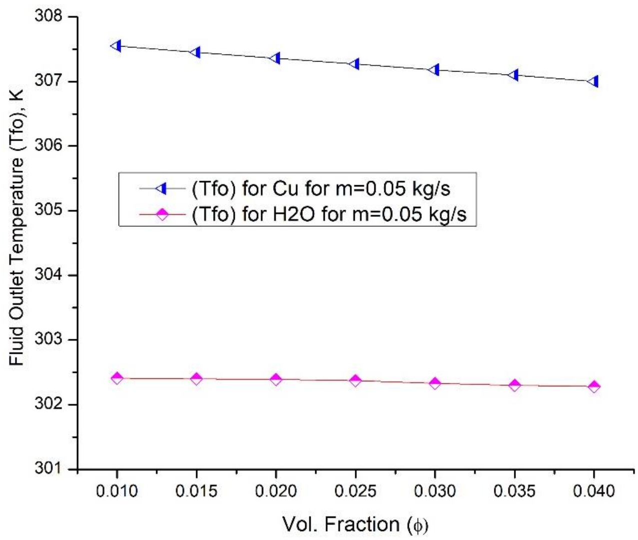
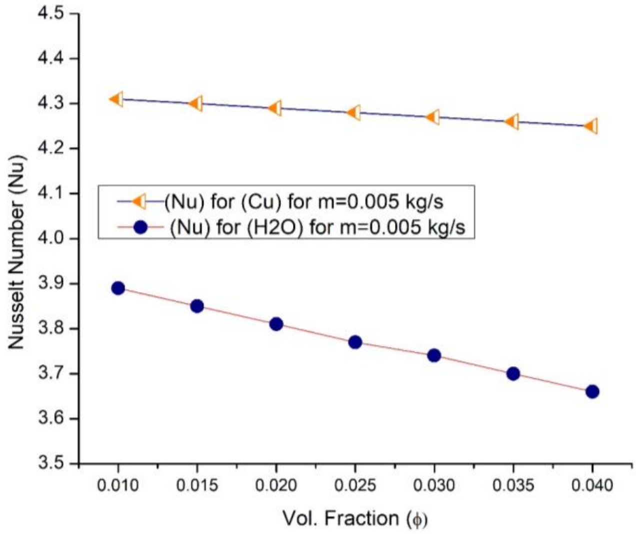


Fig. 6. Variation of Fluid outlet temperature for (Cu) for Laminar and Turbulent flow region with different Volume fraction.

Fig. 6. shows the fluid outlet temperature comparison of nanofluids and H2O for mass flowrate =0.05 kg/s.

It can be seen that for H2O there is no visible effect on the outlet temperature as function of (Ø) but it is found the outlet temperature decreases with steeper rate for higher value of (Ø) for the (Cu) based FP collector.



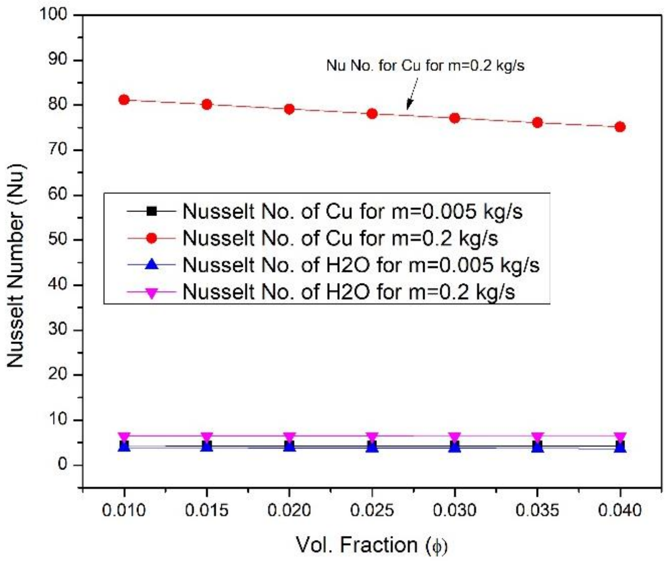


Fig. 7. Variation of Nusselt number for (Cu) and H2O for Laminar and Turbulent flow region with different Volume fraction.

Fig. 7. (a) shows the variations of the (Nu) with different volume fractions (Ø) for (Cu) based and water based FP collectors for mass flow rates of 0.005 and 0.2 kg/s.

It can be seen from both Figs that the Nusselt number decreases for both types of collectors with increases in the value of (Ø),

but the values of (Nu) for nanofluids based collector is higher as compared to the water based collector.
It occurred due to the fact that Reynolds numbers (Re) are different for the different working fluids. By increasing the (Ø), the viscosity of the nanofluids increases and due to this the (Re) decreases.
We can see for turbulent flow (Cu) based FP collector show significant enhancement in (Nu) because in turbulent flow, the (Nu) is directly proportional to (Re) and Prandtl numbers.

The value of (Nu) for Cu based collector is (Nu) = 4.31 for the value of (Ø) = 0.01 % and m=0.005 kg/s while for the same value of (Ø) and m=0.2 kg/s the value of reaches to (Nu) = 81.16 , which shows 18 times enhancement.

The value of H2O based collector is (Nu) = 3.89 for the value of (Ø) = 0.01 % and m=0.005 kg/s while for the same value of (Ø) and m=0.2 kg/s the value of reaches to (Nu) = 6.46 , which shows 0.67 times enhancement.

5. CONCLUSIONS

1.With increasing the (Cu) nanoparticles volume fraction (Ø), the density and Thermal conductivity of nanofluids based FP collector improves.

2.With increasing the (Cu) nanoparticles volume fraction (Ø), the Specific heat of nanofluids based FP collector decreases.

3.With increasing the (Cu) nanoparticles volume fraction (Ø), the Reynolds number of nanofluids based FP collector decreases.

4.With increasing the (Cu) nanoparticles volume fraction (Ø), the Fluid outlet temperature and Nusselt number of nanofluids based FP collector decreases but its values found higher as compared to water based FP collector for all value of volume fraction (Ø).

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