

Comparison of Thermal Performance Evaluation of FPC-Based Solar Thermal Water Heater Using Composite Al_2O_3 & CuO -Water Nanofluids and Ni-Water Nanofluids: A Numerical Study in Ansys Fluent

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Abstract: The study compares the thermal performance of solar thermal water heaters based on Flat Plate Collectors (FPCs) using two different kinds of nanofluids: Ni-water nanofluids and composite Al_2O_3 & CuO -water nanofluids. The Finite Volume Method (FVM) was used in Ansys Fluent software to simulate the thermal efficiency and heat transmission characteristics. The study looks at how the kind, concentration, and operating circumstances of the nanofluid affect the system's overall performance. Although there were noticeable variations in performance depending on the fluid composition and nanoparticle concentration, simulation findings showed that both types of nanofluids significantly improved the heat transfer coefficient and thermal efficiency.

Keywords: Ansys Fluent, Al_2O_3 - CuO , Finite Volume Method, Flat Plate Collector, Nanofluids, Ni, Solar Thermal Water Heater, Thermal Performance.

I. INTRODUCTION

Significant interest in solar thermal systems for water heating applications has been sparked by the growing need for sustainable energy sources. Because of its ease of use and effectiveness, the Flat Plate Collector (FPC) is frequently used. Optimizing its thermal performance is still a major obstacle, though. Nanofluids provide a possible option because of their exceptional heat transfer capabilities.

In this work, composite Al_2O_3 & CuO -water nanofluids and Ni-water nanofluids are used to assess the thermal performance of an FPC-based solar thermal water heater.

A. Problem Statement

Although there is currently a lack of comparison research between metal-based and composite metal

oxide-based nanofluids, nanofluids have demonstrated a great promise for improving the efficiency of solar collectors. By comparing the thermal performance of various nanofluids under comparable operating circumstances, our study seeks to close the gap.

II. LITERATURE REVIEW

A. Nanofluids in Solar Thermal Water Heaters

Nanofluids have been shown in studies to improve heat transfer properties in solar thermal water heaters due to their increased thermal conductivity. Composite nanofluids, including Al_2O_3 and CuO , have better thermal performance than single-phase fluids. Ni-water nanofluids are well known for their heat transfer capabilities, especially in solar applications. However, there is still a need to compare these nanofluids in real-world solar thermal systems.

Choi et al. [12], Masuda et al. [13], and Lee et al. [16] have demonstrated that metals and non-metal's solid particles may be reduced to a size where they can more successfully float in liquids. As a result, the concept of nanoparticle suspension advanced. Nano fluids are employed in a variety of applications because of the nanoparticle dispersion in the base fluid they contain. Nanoparticles made from a variety of materials, including ceramics, metals (Al, Cu, Ti, Si, Mg, etc.), metallic oxides (Al_2O_3 , TiO_2 , and CuO), have been used to create nanofluid.

Lee et al. [42] provided a technique to compute the thermophysical characteristics of Al_2O_3 and CuO

particles combined with ethylene glycol. The conductivity of nanofluids was determined through experimental study, and it was shown that they had higher conductivities than base fluid, but their specific heat capacity (C_p) is decreasing.

Choi and Eastman et al. [18] found that at volume concentrations of 2.5% and particle sizes of 30 nm, Al_2O_3 and CuO-based NFs boosted conductive heat transfer by 22%.

Das and Vajjha et al. [36] reported finding thermal conductivities of Al_2O_3 and CuO-based materials. The basic fluid in nano fluid is a mixture of ethylene glycol and water. He employed nanofluids with a volumetric concentration of 3 to 6 percent and a temperature range of 300 K to 355 K, and he saw a 20 to 24% improvement in the conductivity of these nanofluids.

Otanicar et al. [37] reported in his research on utilizing nanofluids in direct absorption solar FPCs. With a nanoparticle concentration of 0.5 to 2%, the effective conductivity of the nanofluid increases by 20 to 25%. For the given solar radiation, flat plate collector efficiency is increased by up to 10%.

Ghoneim et al. [55] stated that the efficiency of solar flat plate collectors was observed to be impacted by forced and natural convective modes of heat transfer losses. Flat plate collector efficiency is decreased by the resistance to heat transmission provided by the air at the bottom and top of the collector. When the top & bottom heat transfer loss coefficients were calculated for natural & forced convection, it was discovered that an air layer of the ideal thickness of 3 mm offered the least amount of resistance to the passage of heat and that the loss coefficients were optimized.

Devendra Singh et al. [61] stated the Experimental performance of flat plate solar collector using Al_2O_3 -water nanofluid.

B. Simulation of Heat Transfer

Ansys Fluent is a popular tool for modelling the thermal and fluid dynamic properties of nanofluids in solar collectors. The Finite Volume Method (FVM) is very effective for solving the governing equations of heat transfer and fluid movement.

III. METHODOLOGY

A. Model Setup in Ansys Fluent

The simulations were carried out in Ansys Fluent, with a 3D model of an FPC-based solar thermal water heater. The model contained a copper absorber plate, a glass cover, insulation, and a working fluid that flowed through tubes. Two types of nanofluids were utilized:

1. Al_2O_3 and CuO-water nanofluids with different nanoparticle concentrations (0.1%, 0.2%, 0.5%, 1%, 1.25%, 1.5%, and 2%).
2. Ni-water nanofluids with similar concentration ranges.

B. Governing Equations

The governing equations for fluid flow and heat transfer were solved using the Finite Volume Method (FVM). The main equations considered were:

Continuity Equation:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot \rho v = 0$$

For Steady Flow

$$\frac{\partial \rho}{\partial t} = 0 ; \nabla \cdot \rho v = 0 ;$$

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = 0$$

Momentum Equation:

$$\int \rho \frac{Dv}{Dt} d = \Sigma F$$

X-momentum equation

$$\left(u \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y} + w \frac{\partial u}{\partial z} \right) \rho = - \frac{\partial p}{\partial x} + \mu \left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} + \frac{\partial^2 u}{\partial z^2} \right)$$

Energy Equation:

$$\rho c_p \left(u \frac{\partial T}{\partial x} + v \frac{\partial T}{\partial y} + w \frac{\partial T}{\partial z} \right) = \lambda \left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} \right)$$

C. Boundary Conditions

1. Inlet temperature: 300 K
2. Outlet boundary: Pressure outlet
3. Solar radiation: 800 W/m²
4. No-slip condition at the walls
5. Insulated boundaries for the sides and back of the collector.

D. Material Properties of Nanofluids

The thermal conductivity and specific heat of the nanofluids were obtained from literature and calculated using the Maxwell-Garnett and Hamilton-Crosser models for effective thermal conductivity.

The Maxwell et al. [1] Model stated that the

conductivities of nanofluids were originally calculated by. Although ignoring interactions between nanoparticles, he took into account the dispersion of tiny, spherical-shaped particles. The effective conductivity of nanofluids, including spherical particles with thermal conductivity K_{np} suspended in a base fluid with thermal conductivity K_b at NPC of ϕ %, is determined using Maxwell's equation as follows:

$$\frac{k_{nf}}{k_b} = \frac{k_p + 2k_b - 2\phi(k_b - k_p)}{k_p + 2k_b + \phi(k_b - k_p)}$$

Hamilton and Crosser et al. [5] gave a model to compute the nanofluid's thermal conductivity after Maxwell and Bruggemen had provided one to determine nanofluid's effective thermal conductivity. With the addition of the shape parameter, they updated the Maxwell equation. Also, they altered the model so that the effects of several characteristics, such the form of nanoparticles and the combination of discontinues and continuous phases, could be included in the equation. The findings of studies with low and highvolume concentrations of nanoparticles in nanofluid were better supported by this model. Using the following equation, the Crosser and Hamilton model calculates effective conductivity-

$$\frac{k_{nf}}{k_b} = \frac{k_p + (n-1)k_b - (n-1)\phi(k_b - k_p)}{k_p + (n-1)k_b + \phi(k_b - k_p)}$$

Where $n = \frac{3}{\epsilon}$

In which,

N = Nanoparticle's shape factor and ϵ = sphericity (ratio of the sphere's curved surface area for equal volume of nanoparticle to the particle). Sphericity for the cylindrical and spherical NPs is 0.5 and 1 respectively.

Yu and Choi et al. [26] determined the nanofluid's thermal conductivity, by taking into consideration the fact that base fluid molecules interacting with solid nanoparticles have a layer-type structure. While being relatively thin, this layer has an impact on heat conductivity.

$$\frac{k_{pe}}{k_p} = \frac{\gamma[2(1 - \gamma) + (1 + \beta)^3(1 + 2\gamma)]}{(\gamma - 1) + (1 + \beta)^3(1 + 2\gamma)}$$

Where $\gamma = \frac{\text{conductivity of layer}}{\text{conductivity of Nano particle}}$

$$\beta = \frac{\text{layer thickness}}{\text{radius of particle}}$$

Nanofluid's effective thermal conductivity is calculated by-

$$\frac{k_{nf}}{k_{bf}} = \frac{k_{pe} + 2k_{bf} + 2(k_{pe} - k_{bf})(1 + \beta)^3\phi}{k_{pe} + 2k_{bf} - (k_{pe} - k_{bf})(1 + \beta)^3\phi}$$

Pak and Cho et al. [40] provided an equation to determine the specific heat of nanofluid, which is

$$C_{pnf} = \phi C_{pnp} + (1 - \phi)C_{pbf}$$

In addition to providing an equation to calculate the heat capacity of a nanofluid, Xuan and Roetzel et al. [41] took into account the thermal equilibrium between two phases. So an equation to determine the heat capacity of a nanofluid is -

$$(\rho C_p)_{nf} = \phi(\rho C_p)_{np} + (1 - \phi)(\rho C_p)_{bf}$$

IV. COMPARATIVE DISCUSSION AND RESULTS

A. Raw Specifications of Solar Thermal Collector's Design Conditions

Table I: Raw Specifications of Solar Thermal Collector's Design Conditions for (Location: Banswara, Rajasthan)

Solar thermal water heater capacity	60-70 Litres/day
Minimum attaining temperature of heated water	60-80°C (expected)
Collector's Inclination based on location: Banswara, Rajasthan	23°-27° (According to UNDP and MNRE date handbook)
Absorber plate	
Absorber / Collector area	1 m ² (Experimental), 2-4 m ² (Domestic)
Collector's Shape	200cm X 50cm (Rectangular)
Covering	Low-iron tempered flat glas, 4-6 mm thick
Thickness	0.2-0.5 mm
Cover's Transmissivity	90-95 %
Absorptivity	91-96 %
Emissivity	0.06-0.15 (Etched copper)
Tubes	
Number	6, (6-12 depending on the collector size)
Outside Diameter	60-70 mm
Thickness	2-3 mm
Inside Diameter	45-54 mm
Tube Clearance	20 mm

Tube and Side walls Clearance	20 mm
Insulation	
Back Insulation Thickness	20-30 mm
Side Insulation Thickness	15-20 mm
Thermal conductivity	0.04-0.06 W/m-K (for glass-wool material)
Thermal conductivity	385-400W/m-K (Copper)
Depth of whole assembly	100 mm (excluding insulation)

B. Materials Characteristics and Method of Calculation

Table II: Thermo-physical Characteristics of Nanoparticle (Nickel) and Base fluid (water)

Phase /NPs	Thermal Conductivity (W/m-k)	Density (kg/m ³)	Specific heat (J/kg-K)	Viscosity (Pa-Sec.) at 25°C
Water at 25°C	0.607	997.2	4182	0.0008904
Nickel	90.7	8907	446	-

Table III: Thermo-physical Characteristics of Composite Al₂O₃ & CuO and Base fluid (water)

Phase /NPs	Thermal Conductivity (W/m-k)	Density (kg/m ³)	Specific heat (J/kg-K)	Viscosity (Pa-Sec.) at 25°C
Water at 25°C	0.607	997.2	4182	0.0008904
Al ₂ O ₃	35	3970	765	-
CuO	20	6310	540	-
Al ₂ O ₃ (80%) & CuO (20%) (Hybrid, Weighted Avg.)	32	4446	720	-

Table IV: Determined Thermo-physical Characteristics of Nanofluid (Nickle - Water) for varied volume fraction of NPs

NFs (NPC volume %)	Thermal Conductivity (W/m-k)	Density (kg/m ³)	Specific heat (J/kg-K)
0.1	0.609	1005.11	4178.26
0.2	0.611	1013.02	4174.53
0.5	0.616	1036.75	4163.32
1.0	0.625	1076.30	4144.64
1.25	0.630	1096.07	4135.30
1.5	0.634	1115.85	4125.96
2.0	0.643	1155.40	4107.28

Table V: Determined Thermo-physical Characteristics of composite Al₂O₃ & CuO-Water Nanofluid for varied volume fraction of NPs

NFs (NPC volume %)	Thermal Conductivity (W/m-k)	Density (kg/m ³)	Specific heat (J/kg-K)
0.1	0.609	1000.65	4178.54
0.2	0.610	1004.10	4175.08
0.5	0.616	1014.44	4164.69
1.0	0.624	1031.69	4147.38
1.25	0.629	1040.31	4138.73
1.5	0.633	1048.93	4130.07
2.0	0.642	1066.18	4112.76

Calculation Method

Assumptions:

- Volume fraction of Al₂O₃ ($\phi_{Al_2O_3}$) = $\phi_{total}/2$
 - Volume fraction of CuO (ϕ_{CuO}) = $\phi_{total}/2$
- Where, ϕ_{total} represents the total nanoparticle concentration volume percentage.

Properties:

- Water Density (ρ_{water}): 997.2 kg/m³
- Al₂O₃ Density ($\rho_{Al_2O_3}$): 3970 kg/m³
- Density of CuO (ρ_{CuO}): 6310 kg/m³
- Specific heat capacity of water ($c_{p, water}$): 4182 J/kgK
- Specific heat capacity of Al₂O₃ (c_{p, Al_2O_3}): 765 J/kgK
- Specific heat capacity of CuO ($c_{p, CuO}$): 540 J/kgK

7. Thermal conductivity of water (k_{water}): 0.607 W/mK
8. Thermal conductivity of Al_2O_3 ($k_{\text{Al}_2\text{O}_3}$): 35 W/mK
9. Thermal conductivity of CuO (k_{CuO}): 20 W/mK
10. Viscosity of water (μ_{water}): 8.9×10^{-4} Pa-s

For Al_2O_3 & CuO -Water Nanofluid

Density (ρ_{nf}):

$$\rho_{nf} = \varphi_{\text{Al}_2\text{O}_3} \cdot \rho_{\text{Al}_2\text{O}_3} + \varphi_{\text{CuO}} \cdot \rho_{\text{CuO}} + (1 - \varphi_{\text{total}}) \cdot \rho_{\text{water}}$$

Where $\varphi_{\text{total}} = \varphi_{\text{Al}_2\text{O}_3} + \varphi_{\text{CuO}}$

Specific Heat ($C_{p,nf}$)

$$C_{p,nf} = \frac{\varphi_{\text{Al}_2\text{O}_3} \cdot \rho_{\text{Al}_2\text{O}_3} \cdot C_{p,\text{Al}_2\text{O}_3} + \varphi_{\text{CuO}} \cdot \rho_{\text{CuO}} \cdot C_{p,\text{CuO}} + (1 - \varphi_{\text{total}}) \cdot \rho_{\text{water}} \cdot C_{p,\text{water}}}{\rho_{nf}}$$

Thermal Conductivity (k_{nf}): Using Maxwell model for a two-component nanoparticle mixture:

$$k_{nf} = k_{\text{water}} \cdot \left(\frac{k_{\text{eff}} + 2k_{\text{water}} - 2\varphi_{\text{total}}(k_{\text{water}} - k_{\text{eff}})}{k_{\text{eff}} + 2k_{\text{water}} + \varphi_{\text{total}}(k_{\text{water}} - k_{\text{eff}})} \right)$$

$$\text{Where } k_{\text{eff}} = \frac{\varphi_{\text{Al}_2\text{O}_3} \cdot k_{\text{Al}_2\text{O}_3} + \varphi_{\text{CuO}} \cdot k_{\text{CuO}}}{\varphi_{\text{Al}_2\text{O}_3} + \varphi_{\text{CuO}}}$$

or

$$k_{nf} = (1 - \varphi_{\text{total}})k_{\text{water}} + \varphi_{\text{Al}_2\text{O}_3} k_{\text{Al}_2\text{O}_3} + \varphi_{\text{CuO}} k_{\text{CuO}}$$

Viscosity (μ_{nf}): Using the Einstein model for viscosity of nanofluids:

$$\mu_{nf} = \mu_{\text{water}} (1 + 2.5\varphi_{\text{total}})$$

These calculations assume a simple mixture model and linear approximations. More complex models may be required for precise applications, particularly at higher concentrations.

V. MESHING AND GEOMETRY

First, using Ansys tool and design modular geometry, a 3-Dimensional model of a solar thermal flat plate collector was created in Ansys Fluent Workbench software (version 19.2).

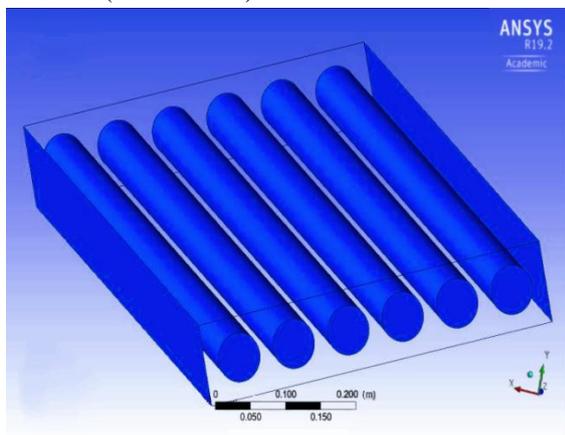


Fig. I. Geometry of FPC

A. Meshing

Using the Ansys Fluent Meshing tool, an unstructured quadrilateral or triangle mesh is handled. Discovering the flow behaviour of nanoparticles close to the tube wall is one of the simulation's primary goals.

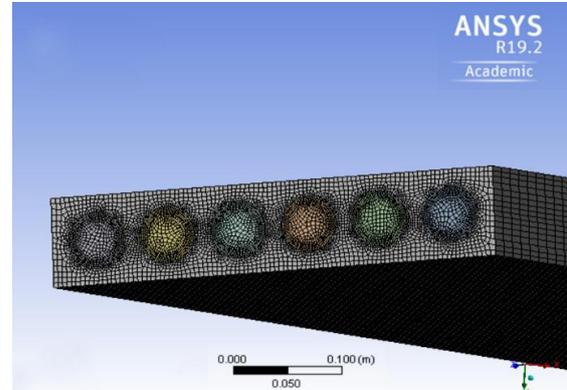


Fig. II. Meshing's Geometry

As a result, coarse meshing is done close to the center line area, while fine meshing is done close to the wall. However, it was kept in mind throughout the calculation that it's not very fine meshing, so that the least amount of computational work will be needed.

B. Comparison of Density with nanoparticle concentration between composite Al_2O_3 & CuO -Water Nanofluid and Ni-Water Nanofluid

In the below Fig.III the blue line with circles represents the Density of Ni-water, which increases as the nanoparticle concentration increases and the red line with circles represents the Density of composite Al_2O_3 & CuO -Water Nanofluid.

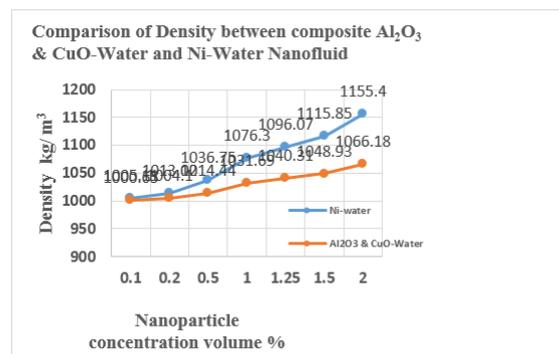


Fig. III. Calculated Density variation between composite Al_2O_3 & CuO -Water Nanofluid and Ni-Water nanofluid with NPC

The Density of composite Al_2O_3 & CuO -Water Nanofluid, which also increases as the nanoparticle concentration increases. We can clearly see that Density of Ni-water nanofluid is more than the

Density of composite Al₂O₃ & CuO-Water Nanofluid for the same NPCs.

C. Comparison of Specific heat with nanoparticle concentration between composite Al₂O₃ & CuO-Water Nanofluid and Ni-Water Nanofluid

In the below Fig.IV the blue line with circles represents the Specific Heat of Ni-water and the red line with circles represents the Specific Heat of composite Al₂O₃ & CuO-Water Nanofluid.

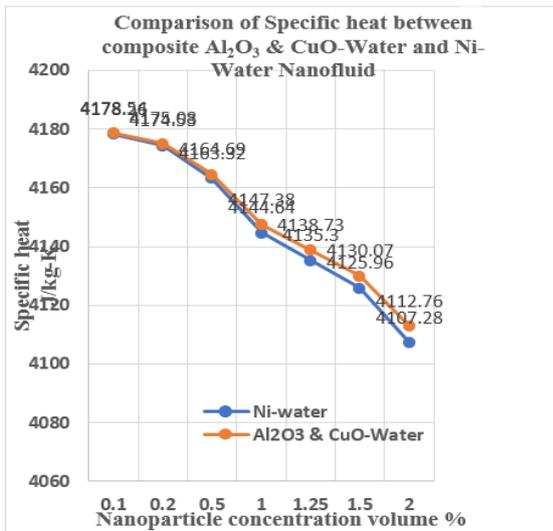


Fig. IV. Calculated Specific heat variation between composite Al₂O₃ & CuO-Water Nanofluid and Ni-Water nanofluid with NPC

In above Fig.IV we can see that the Specific Heat in both the cases of Ni-water nanofluid and composite Al₂O₃ & CuO-Water Nanofluid, which decreases first gradually and again decreases for some values and again decreases as the nanoparticle concentration increases. We can clearly see that variation of Specific Heat between Ni-water nanofluid and composite Al₂O₃ & CuO-Water Nanofluid for the same NPCs.

D. Enhancement of Thermal Conductivity with Nanoparticle Concentration

Thermal conductivity of a nanofluid is a crucial factor that impacts the pace at which heat is transferred from a nanofluid. Because NPs have a high conductivity, their addition to a fluid causes the effective conductivity of the nanofluid to increase.

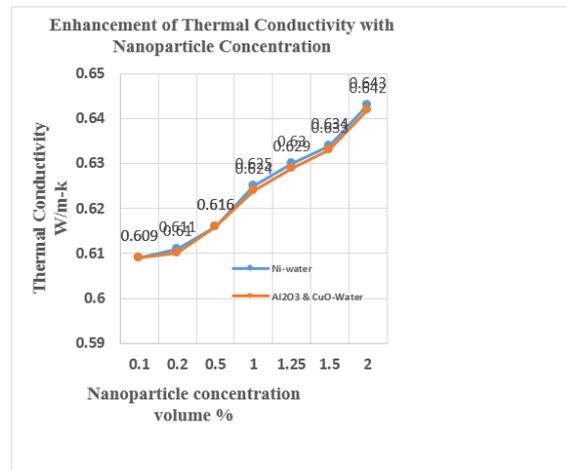


Fig. V. Enhancement of Calculated Thermal Conductivity with Nanoparticle Concentration

The above Fig. V. compares the enhancement of calculated thermal conductivity between composite Al₂O₃ & CuO-Water Nanofluid and Ni-Water nanofluid, where we can clearly see that at 0.1% and 0.5% (NPC) Thermal Conductivity of both composite Al₂O₃ & CuO-Water Nanofluid and Ni-Water nanofluid is same, at 0.2%, 1%, 1.25%, 1.5% and 2.0% (NPC) Thermal Conductivity of composite Al₂O₃ & CuO-Water Nanofluid will be more than the Ni-Water nanofluid and at (NPC) Thermal Conductivity of Ni-Water nanofluid will be approximately similar to the composite Al₂O₃ & CuO-Water Nanofluid.

Thermal Performance Comparison

Simulations were performed for both composite Al₂O₃ & CuO-water nanofluids and Ni-water nanofluids at varying concentrations. The thermal efficiency, heat transfer coefficient, and temperature rise of the working fluid were evaluated.

E. Effect of Nanoparticle Concentration on Thermal Efficiency

As nanoparticle concentration increased, the thermal efficiency improved for both nanofluids, with the composite nanofluid demonstrating a slightly higher rate of improvement.

VI. CONCLUSION

This work compares the thermal performance of FPC-based solar thermal water heaters employing composite Al₂O₃, CuO-water nanofluids, and Ni-water nanofluids. At certain nanoparticle concentrations, the composite nanofluid seems to operate nearly identically to the Ni-water nanofluid.

Composite metal oxide-based nanofluids, like metal-based nanofluids, have improved heat transfer capabilities, making them a superior candidate for boosting the efficiency of solar thermal water heaters. According to the Ansys software FVM simulation analysis, both forms of nanofluids increase in outlet temperature as nanoparticle concentration (NPC) increases. The composite (Al₂O₃ & CuO)-water nanofluid has a little higher outlet temperature 346.15 K (73° celsius) than the Ni-water nanofluid 343.15 K (70° celsius) at the same 2% nanoparticle concentrations (NPC). Using simply water without NPs resulted in a temperature increase of 311.8 K (38.65° Celsius). Further experimental validation is recommended to corroborate the numerical findings.

APPENDIX

A.1 Sample Calculation for Thermophysical Properties

For Ni-Water based Nanofluid

A.1.1 By Hamilton and crosser Model Thermal Conductivity of nanofluid is given by

$$\frac{k_{nf}}{k_b} = \frac{k_p + (n-1)k_b - (n-1)\phi(k_b - k_p)}{k_p + (n-1)k_b + \phi(k_b - k_p)} \dots\dots(1)$$

Where $n = \frac{3}{\epsilon}$

n = Nanoparticle’s shape factor for spherical particles
n = 3 and

€ = sphericity for the sphere (€ = 1)

Nanofluid (Nanoparticle concentration volume %)-
Ø = 0.2 % 0.002

k_b= Thermal Conductivity of base fluid = 0.608 W/m-k

k_p= Thermal Conductivity of Ni-nanoparticle = 90.7 W/m-k

According to formula (1)

$$k_{nf} = 0.611 \text{ W/m-k}$$

A.1.2 Pak and Cho gave equation to calculate specific heat of nanofluid

$$C_{pnf} = \phi C_{pnp} + (1 - \phi)C_{pbf} \dots\dots(2)$$

$$C_{pnf} = 0.002 \times 446 + (1 - 0.002) \times 4182$$

$$C_{pnf} = 4174.53 \text{ J/kg-K}$$

A.1.3 Nanofluid density by mixture theory is given by

$$\rho_{nf} = \phi \rho_{np} + (1 - \phi)\rho_{bf} \dots\dots(3)$$

$$\rho_{nf} = 0.002 \times 8907 + (1 - 0.002)997.2$$

$$\rho_{nf} = 1013.02 \text{ Kg/m}^3$$

For Al₂O₃ & CuO -Water based Nanofluid

A.1.4 By Hamilton and crosser Model Thermal Conductivity of nanofluid is given by

$$\frac{k_{nf}}{k_b} = \frac{k_p + (n-1)k_b - (n-1)\phi(k_b - k_p)}{k_p + (n-1)k_b + \phi(k_b - k_p)} \dots\dots(4)$$

Where $n = \frac{3}{\epsilon}$

n = Nanoparticle’s shape factor for spherical particles
n = 3 and

€ = sphericity for the sphere (€ = 1)

Nanofluid (Nanoparticle concentration volume %)-
Ø = 0.2 % = 0.002

k_b= Thermal Conductivity of base fluid = 0.608 W/m-k

k_p= Thermal Conductivity of Ni-nanoparticle = 32 W/m-k

According to formula (1)

$$k_{nf} = 0.610 \text{ W/m-k}$$

A.1.5 Pak and Cho gave equation to calculate specific heat of

$$C_{pnf} = \phi C_{pnp} + (1 - \phi)C_{pbf} \dots\dots(5)$$

$$C_{pnf} = 0.002 \times 446 + (1 - 0.002) \times 4182$$

$$C_{pnf} = 4175.08 \text{ J/kg-K}$$

A.1.6 Nanofluid density by mixture theory is given by

$$\rho_{nf} = \phi \rho_{np} + (1 - \phi)\rho_{bf} \dots\dots(6)$$

$$\rho_{nf} = 0.2 \times 4446 + (1 - 0.2)997.2$$

$$\rho_{nf} = 1004.10 \text{ Kg/m}^3$$

A.2 Thermal conductivities for the individual nanoparticles and their mixture:

A.2.1 Thermal Conductivity of Mixture

[Al₂O₃ (80%) & CuO (20%)]:

Thermal Conductivity of Mixture (Al₂O₃ & CuO):
Applying the effective medium theory (EMT) or the Maxwell-Garnett model.

The thermal conductivity of mixture k_{mixture} will be-

$$k_{mixture} = \phi_{Al_2O_3} \cdot k_{Al_2O_3} + \phi_{CuO} \cdot k_{CuO}$$

Where, $\phi_{Al_2O_3} = 80\% = 0.80$, $\phi_{CuO} = 20\% = 0.20$,

$$k_{mixture} = \phi_{Al_2O_3} \cdot k_{Al_2O_3} + \phi_{CuO} \cdot k_{CuO}$$

$$k_{Al_2O_3} = 35 \text{ W/m-K}, k_{CuO} = 20 \text{ W/m-K}$$

$$k_{mixture} = 0.80 \times 35 + 0.20 \times 20$$

$$k_{mixture} = 32 \text{ W/m.K}$$

A.2.2 Density of Mixture

[Al₂O₃ (80%) & CuO (20%)]:

$$\rho_{mixture} = \phi_{Al_2O_3} \cdot \rho_{Al_2O_3} + \phi_{CuO} \cdot \rho_{CuO}$$

$$\rho_{mixture} = 0.80 \times 3970 + 0.20 \times 6310$$

$$\rho_{mixture} = 4446 \text{ Kg/m}^3$$

A.2.3 Specific Heat of Mixture

[Al₂O₃ (80%) & CuO (20%)]:

$$c_{mixture} = \phi_{Al_2O_3} \cdot c_{Al_2O_3} + \phi_{CuO} \cdot c_{CuO}$$

$$c_{mixture} = 0.80 \times 765 + 0.20 \times 540$$

$$c_{mixture} = 720 \text{ J/Kg.K}$$

A.3 Ansys Software based Thermal Analysis

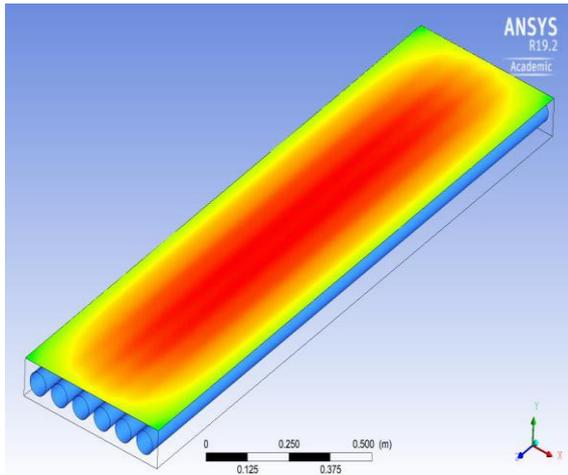


Fig. VI. Temperature contour of Absorber plate of FPC

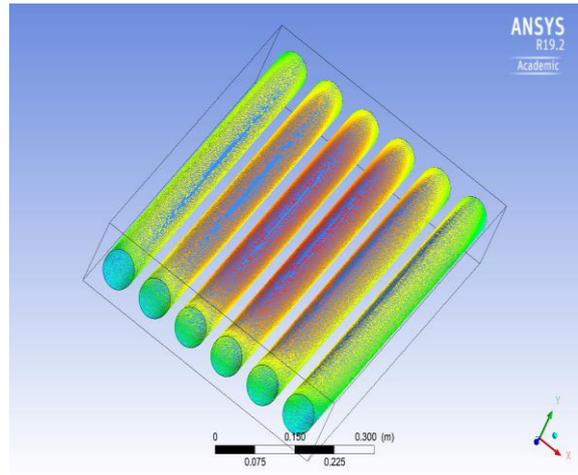


Fig. VIII. Temperature contour of inside wall of Tubes along the flow inside FPC

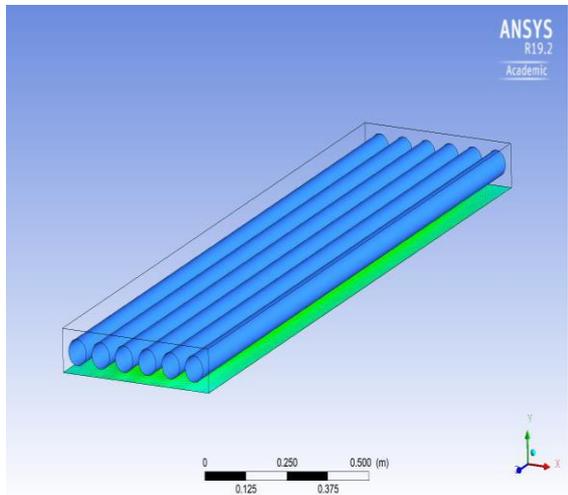


Fig. VII. Temperature contour of inside wall of bottom insulation of FPC

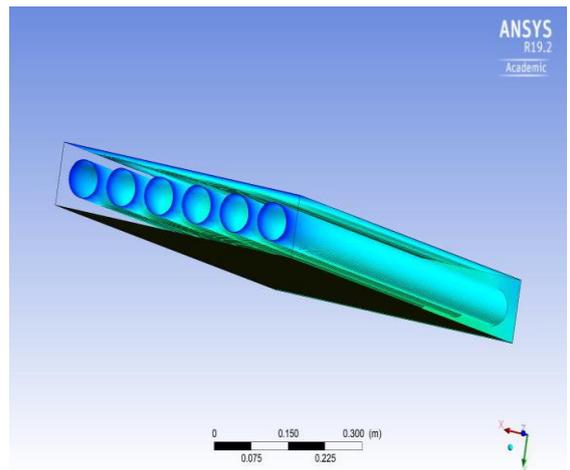
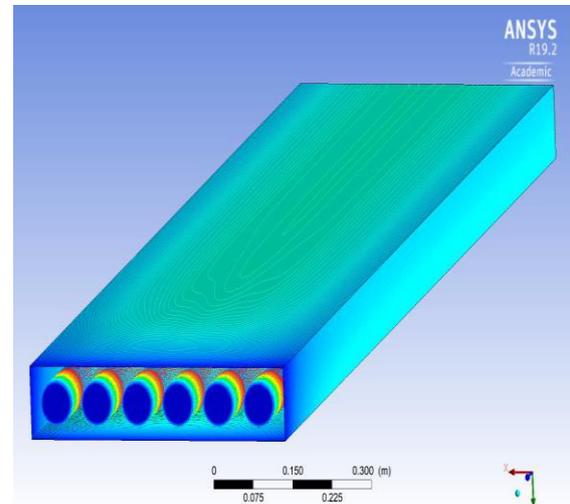


Fig. IX. Temperature contour at outlet of collector tubes

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REFERENCES

- [1] Maxwell, J.C. (1881). *Treatise on electricity and magnetism* (2nd ed.). Oxford, UK: Clarendon Press.
- [2] Bruggeman, D. A. G. (1935). "Conductivity of Nano fluids considering wide concentration range for homogenous mixture of nanoparticles" *Annalen der Physik*, 24, 636–679.
- [3] Brinkman, H. C. (1952). "The viscosity of concentrated suspensions and solutions." *Journal of Chemical Physics*, 20(4), 571–581.
- [4] Einstein A (1956) "Investigation on the Theory of the Brownian Movement." Courier Dover Publications. USA.
- [5] Hamilton, R. L., & Crosser, O. K. (1962). "Thermal conductivity of heterogeneous two-component systems." *Industrial and Engineering Chemistry Fundamentals*, 1(3), 182–191.
- [6] Liu BYH, Jordan RC (1963) "the long-term average performance of flat-plate solar energy collectors" With design data for the U.S., its outlying possessions and Canada. *Solar Energy* 7:53-74
- [7] Batchelor, G. K. (1977). "Effect of Brownian-motion on bulk stress in a suspension of spherical-particles." *Journal of Fluid Mechanics*, 83(1), 97–117.
- [8] Siebers DL, Viskanta R (1977) "Comparison of predicted performance of constant outlet temperature and constant mass flow rate collectors". *Solar Energy* 19:411-413
- [9] Cooper PI (1981) "the effect of inclination on the heat loss from flat-plate solar collectors" *Solar Energy* 27:413-420
- [10] Chiou JP (1982) "the effect of nonuniform fluid flow distribution on the thermal performance of solar collector" *Solar Energy* 29:487-502
- [11] Hollands KGT, Lightstone MF (1989) "A review of low-flow, stratified-tank solar thermal water heating systems" *Solar Energy* 43:97-105
- [12] Choi, U. S., Cho, Y. I., and Kas, (1992) "Degradation Effects of Dilute Polymer Solutions on Turbulent Friction and Heat Transfer Behaviour" *J Non-Newtonian Fluid Mechanics*, Vol. 41, pp. 289-307.
- [13] Masuda (1993) "New temperature dependent thermal conductivity data for water-based nanofluids." *International Journal of Thermal Sciences* 48:363-371
- [14] Masuda, H., Ebata, A., Teramae, K., & Hishinuma, N. (1993). "Alteration of thermal conductivity and viscosity of liquid by dispersing ultra-fine particles." *Netsu Bussei*, 7(4), 227–233.
- [15] Pak, B. C., & Cho, Y. I. (1998). "Hydrodynamic and heat transfer study of dispersed fluids with submicron metallic oxide particles." *Experimental Heat Transfer an International Journal*, 11 (2), 151–170.
- [16] Lee S, Choi SU-S, Li S, Eastman JA (1999) "Measuring Thermal Conductivity of Fluids Containing Oxide Nanoparticles." *J Heat Transfer* 121:280-289
- [17] Xuan Y, Roetzel W (2000) "Conceptions for heat transfer correlation of nanofluids. *International Journal of Heat and Mass Transfer* 43:3701-3707
- [18] Eastman JA, Choi SUS, Li S, Yu W, Thompson LJ (2001) "Anomalously increased effective thermal conductivities of ethylene glycol-based nanofluids containing copper nanoparticles". *Applied Physics Letters* 78:718
- [19] Xie, H., Wang, J., Xi, T., & Liu, Y. (2001). "Study on the thermal conductivity of SiC nanofluids". *Journal-Chinese Ceramic Society*, 29(4), 361–364.
- [20] *Introduction to Heat Transfer*, Wiley, New York, 2002; Y.S.Touloukian and C.Y.Ho, *Thermophysical Properties of Matter*, Vols.1–9, Plenum Press, New York, 1972; American Society for Metals, *Metals Handbook*, Vol.1, ASM, Metals Park, OH, 1961.
- [21] Xie HQ, Wang JC, Xi TG, Liu Y, Ai F, Wu QR (2002) "Thermal conductivity enhancement of suspensions containing nanosized alumina particles." *Journal Applied Physics* 91:4568-4572.
- [22] Xuan Y, Li Q (2003) "Investigation on convective heat transfer and flow features of nanofluids." *Journal of Heat Transfer* 125:151
- [23] Das, S. K., Putra, N., Thiesen, P., & Roetzel, W.

- (2003). "Temperature dependence of thermal conductivity enhancement for nanofluids." *Journal of Heat Transfer*, 125(4), 567–574.
- [24] Enibe (2003) "Life cycle assessment of a solar thermal collector glazed plate collector using phase change material (PCM)." *renewable Energy* 30:1031-1054
- [25] Yu, W. & Choi, S. U. S. (2003). "The role of interfacial layers in the enhanced thermal conductivity of nanofluids: a renovated Maxwell model." *Journal of Nanoparticle Research*, 5, 167-171.
- [26] Yu, W. & Choi, S. U. S. (2004). "The role of interfacial layers in the enhanced thermal conductivity of nanofluids: a renovated Hamilton–Crosser model." *Journal of Nanoparticle Research*, 6, 355-361.
- [27] Wen D, Ding Y (2004) "Experimental investigation into convective heat transfer of nanofluids at the entrance region under laminar flow conditions." *International Journal of Heat and Mass Transfer* 47:5181-5188
- [28] Murshed SMS, Leong KC, Yang C (2005) "Enhanced thermal conductivity of TiO₂ - water based Nanofluids." *International Journal of Thermal Sciences* 44:367-373
- [29] Wang, B.-X., Zhou, L.-P., & Peng, X.-F. (2006). "Surface and size effects on the specific heat capacity of nanoparticles." *International Journal of Thermophysics*, 27(1), 139–151.
- [30] Kim, S. H., Choi, S. R., & Kim, D. (2007). "Thermal conductivity of metal-oxide nanofluids: Particle size dependence and effect of laser irradiation." *Journal of Heat Transfer*, 129(3), 298–307.
- [31] Zhou SQ, Ni R (2008) "Measurement of the specific heat capacity of water-based Al₂O₃ nanofluid." *Appl Phys Lett* 92:1-3 L. Gao, X. Zhou, "Differential effective medium theory for thermal conductivity in nanofluids", *Phys. Lett., A* 348 (2006) 355–360.
- [32] Wang H (2009) "Dispersing carbon nanotubes using surfactants" *Current Opinion in Colloid & Interface Science* 14:364-371
- [33] Anoop, K. B., Sundararajan, T. & Das, S. K. (2009). "Effect of particle size on the convective heat transfer in nanofluid in the developing region" *International Journal of Heat and Mass Transfer*, 52, 2189-2195.
- [34] Buongiorno, J., Venerus, D. C., Prabhat, N., McKrell, T., Townsend, J., Christianson, R., Tolmachev, Y. V., Keblinski, P., Hu, L.-w. & Alvarado, J. L. (2009). "A benchmark study on the thermal conductivity of nanofluids." *Journal of Applied Physics*, 106, 094312.
- [35] Zhao Jia-Fe, Luo Zhong-Yang, Ni Ming-Jiang, Cen Ke-Fa (2009) "Dependence of nanofluid viscosity on particle size and pH value." *Chinese Physics Letters*; 26(6): 256-307.
- [36] R.S. Vajjha, D.K. Das (2009) "Experimental determination of thermal conductivity of three nanofluids and development of new correlations." *International Journal of Heat and Mass Transfer*, 52 (2009), pp. 4675-4682
- [37] Otanicar TP (2009) "Direct absorption solar thermal collectors utilizing liquid nanoparticle suspensions." Arizona State University. USA. *Journal of renewable and sustainable energy*, 2, 033102.
- [38] Tyagi H, Phelen P, R. Prasher (2009) Predicted efficiency of a low-temperature nanofluid based direct absorption solar collector. *Journal of Solar Energy Engineering* 131:41004-41010
- [39] R.S. Vajjha, D.K. Das, P.K. Namburu (2010) "Numerical study of fluid dynamic and heat transfer performance of Al₂O₃ and CuO nanofluids in the flat tubes of a radiator" *International Journal of Heat and Fluid Flow* 31 613–621.
- [40] Cengel YA, Boles MA (2010) *Thermodynamics: An Engineering Approach*. 7th edn. McGrawHill. USA.
- [41] Teng, T.-P., Hung, Y.-H., Teng, T.-C., Mo, H.-E., & Hsu, H.-G. (2010). "The effect of alumina/water nanofluid particle size on thermal conductivity." *Applied Thermal Engineering*, 30(14), 2213–2218.
- [42] Lee SW, Park SD, Kang S, Bang IC, Kim JH (2011) "Investigation of viscosity and thermal conductivity of SiC nanofluids for heat transfer applications." *International Journal of Heat and Mass Transfer* 54:433-438
- [43] Goudarzi Saidur R, Metselaar HSC (2011) "A review of nanofluid stability properties and characterization in stationary conditions." *International Journal of Heat and Mass Transfer* 54:4051-4068
- [44] Yousefi T, Veysi F, Shojaeizadeh E, Zinadini S (2012) "An experimental investigation on the effect of Al₂O₃-H₂O nanofluid on the efficiency of flat-plate solar collectors." *Renewable Energy* 39:293-298
- [45] Reddy, Rao, Kaushik SC, Tyagi SK (2012) Exergetic analysis and performance evaluation

- of parabolic trough concentrating solar thermal power plant (PTCSTPP). *Energy* 39:258–273
- [46] Said, Z., Saidur, R., & Rahim, N.A. (2012). Energy and exergy analysis of a flat plate solar collector using different sizes of aluminum oxide-based nanofluid. *Journal of Cleaner Production*, 44, 24-29. DOI: 10.1016/j.jclepro.2012.12.041.
- [47] Mahian, O., Kianifar, A., Kalogirou, S.A., Pop, I., & Wongwises, S. (2013). A review of the applications of nanofluids in solar energy. *International Journal of Heat and Mass Transfer*, 57(2), 582-594. DOI: 10.1016/j.ijheatmasstransfer.2012.10.037.
- [48] Sundar, L. S., Singh, M. K., & Sousa, A. C. (2013). “Thermal conductivity of ethylene glycol and water mixture based Fe₃O₄ nanofluid.” *International Communications in Heat and Mass Transfer*, 49, 17-24
- [49] Suganthi, K.S., M. Parthasarathy and K.S. Rajan, (2013). “Liquid-layering induced, temperature-dependent thermal conductivity enhancement in ZnO-propylene glycol nanofluids”. *New observations and discussion. J. Nanopart. Res.* 10.1007/s11051-013-1774-3
- [50] Teng, T.-P., & Hung, Y.-H. (2014). “Estimation and experimental study of the density and specific heat for alumina nanofluid.” *Journal of Experimental Nanoscience*, 9(7), 707–718.
- [51] Nagarajan, P.K., Subramani, J., Suyambazhahan, S., & Saidur, R. (2014). Nanofluids for solar collector applications: A review. *Energy Conversion and Management*, 123, 126-144. DOI: 10.1016/j.enconman.2016.05.053.
- [52] S. Senthilraja, k. Vijayakumar, r. Gangadevi (2015). A comparative study on thermal conductivity of Al₂O₃/water, CuO/water and Al₂O₃ – CuO /water nanofluids.
- [53] Fares, M. (2016). Performance evaluation of a flat-plate solar collector using various nanofluids. *Energy Conversion and Management*, 100, 324-333. DOI: 10.1016/j.enconman.2015.11.056.
- [54] Nang Khin Chaw Sint, I.A. Choudhury, H.H. Masjuki, H. Aoyama (2017) “Theoretical analysis to determine the efficiency of a CuO-water nanofluid based-flat plate solar collector for domestic solar thermal water heating system in Myanmar” *Solar Energy* 155 (2017) 608–619 0038-092X/(2017) Elsevier Ltd.
- [55] Mahmoud M. Hessie, Nehmdoh A. Sabiha, Sherif S. M. Ghoneim, and Ahmad A. Alahmadi (2017) *International Journal of Applied Engineering Research* ISSN 0973-4562 Volume 12, Number 24 pp. 15668-15673
- [56] Gupta, M., Singh, V., Kumar, R. and Said, Z. (2017), “A review on thermophysical properties of nanofluids and heat transfer applications”, *Renewable and Sustainable Energy Reviews*, Vol. 74, pp. 638-670
- [57] Popa, C. V., Nguyen, C. T., & Gherasim, I. (2017). New specific heat data for Al₂O₃ and CuO nanoparticles in suspension in water and Ethylene Glycol. *International Journal of Thermal Sciences*, 111, 108–115.
- [58] Sundar, L. S., Singh, M. K., Punnaiah, V., & Sousa, A. C. M. (2018). Experimental investigation of Al₂O₃/water nanofluids on the effectiveness of solar flat-plate collectors with and without twisted tape inserts.
- [59] Agbulut, Ü., Karagöz, M., Sarıdemir, S. and Öztürk, A. (2020), “Impact of various metal-oxide based nanoparticles and biodiesel blends on the combustion, performance, emission, vibration and noise characteristics of a CI engine”, *Fuel*, Vol. 270, p. 117521.
- [60] Gürbüz, E.Y., Variyenli, H.İ., Sözen, A., Khanlari, A., & Ökten, M. (2021). Experimental and numerical analysis on using CuO-Al₂O₃/water hybrid nanofluid in a U-type tubular heat exchanger. *International Journal of Numerical Methods for Heat & Fluid Flow*, 31(1), 519-540. DOI: 10.1108/HFF-04-2020-0195.
- [61] Devendra Singh, Ajay Kumar Sharma, Ritvik Dobriyal, Vipul Paliwal; (2023) Experimental performance of flat plate solar collector using Al₂O₃-water nanofluid. 2521 <https://doi.org/10.1063/5.0115724>