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Research Article

Heat transfer intensification of ethylene glycol dispersed with nano alumina in a spiral tube heat exchanger for application in solar thermal systems

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ABSTRACT

The study investigates the heat transfer properties of ethylene glycol-alumina nanofluids in a double-tube spiral coil heat exchanger operating under laminar flow conditions. The present study is related to solar thermal systems and discusses the effects of surface modification of nanomaterials before dispersion in ethylene glycol. Further, the study compares the experimental values with a computational fluid dynamics model. The fluid used consists of ethylene glycol with dispersed nano-alumina (Al_2O_3) with a diameter of 50 nm in concentrations of 1%, 0.5%, 0.25% and 0.125%. The aluminum oxide nanoparticles were surface modified with the surfactant hexadecyl cetyl trimethyl ammonium bromide to improve the dispersion stability. To determine the thermal conductivity and dynamic viscosity at different concentrations, C-Therm thermal analyzer and a Brookfield viscometer were employed. The heat transfer intensification studies were conducted in a double-tube spiral heat exchanger. The dispersion of nanoparticles leads to an increase in thermal conductivity of up to 20 %. The results show that adding alumina nanoparticles to ethylene glycol resulted in an increase in the heat transfer coefficient by up to 32% compared to base ethylene glycol. The heat transfer coefficients of the test fluids increased by 22%, 27%, 30% and 32% when nanofluids with alumina concentrations of 0.125%, 0.25%, 0.5% and 1%, respectively, were used. The validity of the results was confirmed by comparing the experimental data with computational fluid dynamics models. The validation of the mesh confirmed the accuracy of the numerical flow model. The deviation between the experimental data and the values predicted by the flow model is negligible.

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INTRODUCTION

Coil or spiral tube heat exchangers are used in various industries due to their small size and remarkable heat transfer properties. The hydrodynamic and convective heat transfer in a spiral tube is more complex compared to a straight tube because the behavior of the secondary flow due to centrifugal forces has a great influence on it. The occurrence of secondary flow caused by the curvature effect and the subsequent centrifugal force leads to a higher heat transfer coefficient compared to a straight tube. In addition, the temperature and velocity distributions are further complicated by the torsion of spirally wound pipes.

The flow and heat transfer properties of single-tube and double-tube spiral heat exchangers have been investigated in numerous experiments. The investigations were carried out using experimental approaches and numerical simulations [1–29]. Belhadj et al. [1, 2] conducted a numerical investigation of laminar forced convection of nanofluid-based water/ (Al_2O_3) in a two-dimensional horizontal microchannel heat sink. The finite volume method with a simple algorithm solves the governing equations. The test results were compared with experimental data to investigate the heat transfer effect of solid nanoparticles. The initial results showed that the nanofluid improved the heat transfer compared to the pure liquid and the (Al_2O_3) concentration improved the thermal and dynamic properties. They found that the Nusselt number and the friction coefficient increase with the Reynolds number.

Ardekani et al. [5] investigated the convective heat transfer and friction coefficient in a spiral tube heat exchanger using Ag-water and SiO2-water nanofluids. The results indicate that nanoparticles in coiled tubes improve heat transfer more than in straight tubes. The performance evaluation criterion or thermal performance factor shows that the Ag nanofluid has the highest value of 3.57 at a Reynolds number of 1336. Empirical correlations from experimental data predict the Nusselt number and friction factors.

Palanisamy and Kumar [12] numerically investigated the flow and heat transfer parameters of a tube-in-tube heat exchanger (TTHC) with different flow velocities in the inner and outer tubes. The hydrodynamics and heat transfer in the outer tube of a tube-in-tube coil heat exchanger (TTHC) were predicted using a novel empirical correlation. At a constant wall temperature, the heat transfer coefficient increases with the flow rate of the inner spiral tube. The heat transfer coefficient was estimated for different annulus flow rates while the flow rate in the inner tube was kept constant. Increasing the operating pressure in the inner tube improved the heat transfer coefficient. The inner and outer tubes of the double tube coil heat exchanger transferred more heat.

Naphon [16] carried out a comparative analysis of the thermal efficiency and pressure difference between spiral tube heat exchangers with and without corrugated fins. The results show that an increase in the mass flow of hot water leads to a reduction in the friction factor.

Heris et al [19, 29] investigated the convective heat transfer coefficient of water-based nanofluids with (Al_2O_3) and CuO nanoparticles in a spiral ring tube with constant wall temperature. The heat transfer coefficient increases with the Peclet number and the volume fraction. Compared to the CuO-water nanofluid, the (Al_2O_3)-water nanofluid performs better.

According to recent studies, nanoparticles in fluids improve heat transfer and thermal conductivity. Nanofluids are used in heat exchangers, engineering, car cooling and other applications due to their unique properties. Rennie and Raghavan [20, 21] conducted studies on heat transfer in a heat exchanger consisting of a coil-in-coil configuration with one circuit. This configuration leads to the development of secondary flows in both the inner tube and the annulus. Increasing the Dean numbers in the tubes or in the annulus resulted in an improved heat transfer coefficient.

Kumar et al [22, 23] investigated the heat transfer and hydrodynamics of spiral wound tube-in-tube designs. The authors conducted a study specifically on turbulent flow and predicted an empirical correlation to accurately predict the hydrodynamic and heat transfer phenomena in the outer tube of the spiral tube-in-tube configuration. Vadapalli et al [24] investigated the heat transfer capabilities of MWCNTs dispersed in mono-ethylene glycol-water solutions. Their study of a spiral heat exchanger [24] shows that the addition of multi-walled carbon nanotubes (MWCNTs) to ethylene glycol-water mixtures leads to remarkable performance improvements under spiral flow conditions, with a maximum heat transfer coefficient increase of 25 % being achieved at a weight fraction of 0.5 %.

Coiled heat exchangers with ethylene glycol are used in solar thermal systems to efficiently transfer heat from the solar collector to a storage tank. Several experts have claimed that the use of spiral coils leads to an improvement in heat transfer. Although several studies have been conducted on the effects of nanoparticle size and concentration on convective heat transfer in spiral coils, the present study aims to fill some critical gaps in these studies.

Spiral tube heat exchangers using ethylene glycol are used in solar thermal systems to efficiently transfer heat from the solar collector to a storage tank. Several experts have claimed that the use of spiral tubes leads to an improvement in heat transfer. Although several studies have been conducted on the effects of nanoparticle size and concentration on convective heat transfer in spiral tubes, there are some critical gaps in the studies that the present study aims to address.

The current study is characterized by several elements of uniqueness. The most important research gap compared to the state of the art is the stabilization of nanomaterials in a liquid medium. Therefore, the production of nanofluids with surface-modified (Al_2O_3) nanoparticles by non-covalent functionalization is discussed in the study. In addition, the current work investigates the dynamic viscosity, thermal conductivity and heat transfer enhancement of nanofluids in the temperature range of 30 to 180°C. In this study, the properties of ethylene glycol were evaluated in combination with (Al_2O_3) at concentrations ranging from 0.125% to 1% w/w, while most studies were conducted at lower mass fraction ranges. The dynamic viscosity and thermal conductivity determined in this study were used to calculate the heat transfer coefficients in a test configuration with a spiral heat exchanger. To evaluate the correctness of the experiments, the experimental heat transfer data were analyzed and simulated with CFD.

METHODS AND EXPERIMENTATION

Preparation of Nanofluids

Ethylene glycol was chosen as the base liquid due to its wide temperature range. The (Al_2O_3) nanoparticles are surface-modified using non-covalent functionalization and dispersed in the base fluid at concentrations of 1, 0.5, 0.25, and 0.125 %Wt by using an ultrasonicator to achieve a homogeneous dispersion of the nanomaterials. The details of test liquids are shown in Table 1.

Table 1. Base fluids description

S. No	Configuration
1	Ethylene glycol
2	Ethylene glycol - 1 % (Al_2O_3) nanoparticles
3	Ethylene glycol - 0.5 % (Al_2O_3) nanoparticles
4	Ethylene glycol - 0.25 % (Al_2O_3) nanoparticles
5	Ethylene glycol - 0.125 % (Al_2O_3) nanoparticles

Non-covalent functionalization or dispersants/surfactants are the most frequent ways to stabilize nanofluids and avoid nanoparticle clumping. Reduce base fluid surface tension. Dispersant overuse can impair nanofluid thermal conductivity and chemical stability. Thus, dispersant loading must be optimized. A hydrophilic polar head group and a hydrophobic tail of long-chain hydrocarbons make up surfactants. Hexadecyl cetyl trimethyl ammonium bromide, also called CTAB, a nonionic surfactant was used to prepare stable nanofluid suspensions in this work.

Characterizations of Nanoparticles

The Al_2O_3 nanoparticle structure to determine its size range was examined with a transmission electron microscope. A transmission electron microscope can give high-clarity images of nanoparticles. As can be seen in Figure 1, the particles are clearly visible and seem to be circular with an average diameter of nearly 50 nm.

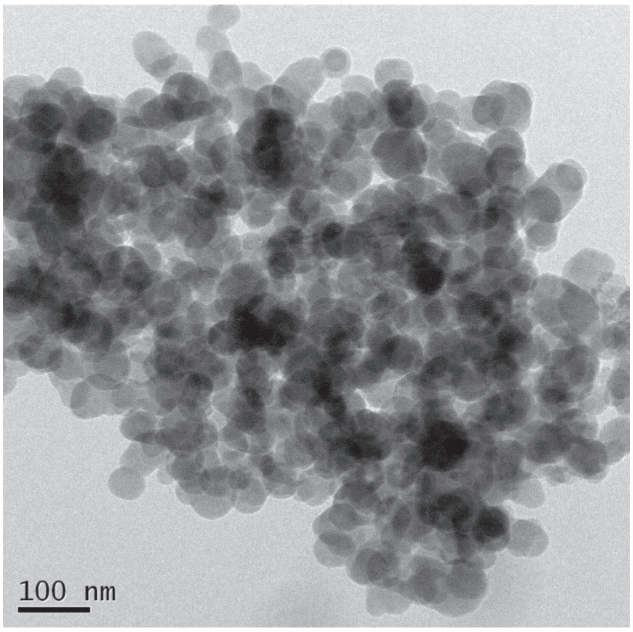

Figure 1. HRTEM pictograph of Al_2O_3 nanoparticles.

Method for the Estimation Thermal Conductivity and Dynamic Viscosity

The presence of convection in liquids makes it more difficult to measure thermal conductivity compared to solids. The C-Therm trident MTPS sensor, which complies with ASTM standard D7984, uses MTPS (Modified Transient Plane Source) technology to accurately determine thermal conductivity and effusivity. The presence of a protective ring surrounding the sensor coil facilitates the one-way transfer of heat into the sample. The change in sensor voltage determines the thermal properties of the sample. The thermal conductivity at the interface between the sensor and the sample decreases with increasing temperature. As a rule, the duration of the measuring pulse is 10–20 seconds. The MTPS sensor was used because of its short measurement duration, which minimizes convection errors.

The Cone & Plate Viscometer was used to measure the absolute viscosities of the base and the nanofluid. The Cone and Plate Viscometer quantifies the torque at certain rotational speeds. This device measures the torque required to rotate the fluid sample between a cone and a stationary flat plate. The torque is directly proportional to the shear stress of the liquid as it acts against the rotation of the cone.

Investigations on Heat Transfer Test Rig

In this paper, a heat exchanger test setup is constructed to simulate the thermal properties and conditions of a solar thermal system using a two-fluid, double-tube spiral heat exchanger. It is a heat exchanger with concentric tubes and reverse flow, where the inner tube contains the hot fluid and the annulus contains water as reference fluid. The hot fluid consists of ethylene glycol. The heat transfer coefficient on the cold side can be quickly evaluated by using water as the reference fluid with a standard flow rate of 4 LPM, as all the properties of water are well known. The visual representation of the experimental setup can be found in Figure 2.

Components of heat transfer test rig

1. Reverse loop heat exchange unit
2. Flowmeter
3. Hot and cold Pumps
4. Heater
5. RTD Sensors
6. Hot and cold fluid tanks

The experimental setup shown in Figures 2 and 3 comprises two tanks: one designated for the storage of cold fluid, namely water, and another designated for the storage

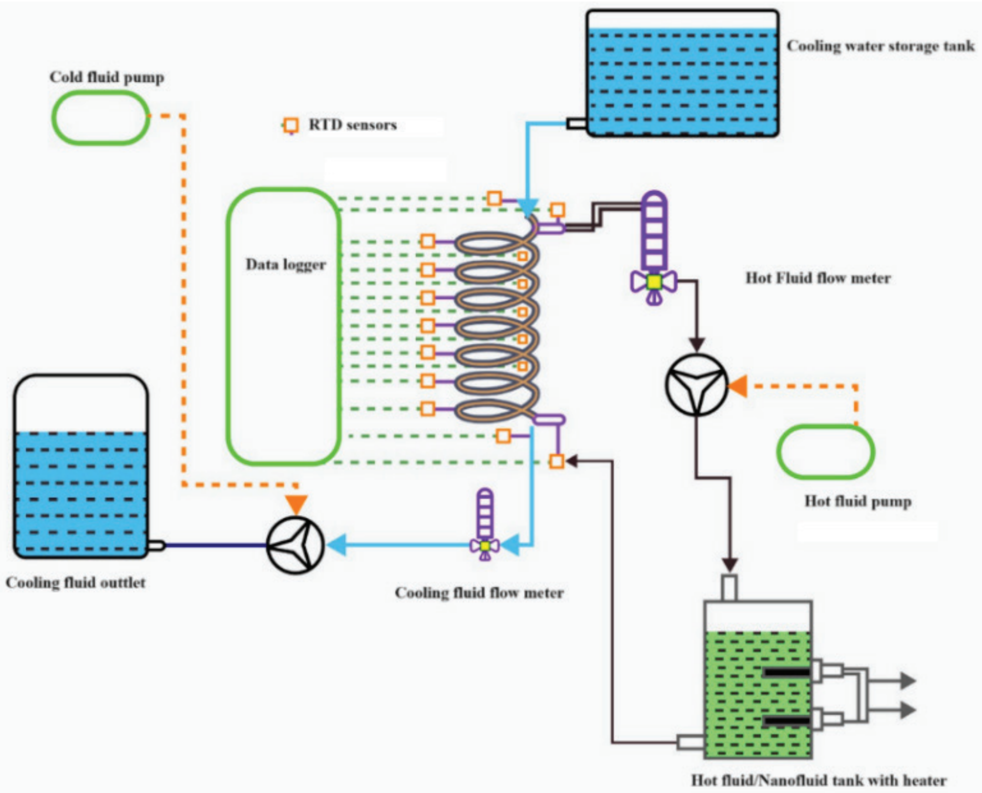

Figure 2. Schematic description of the heat transfer test apparatus.

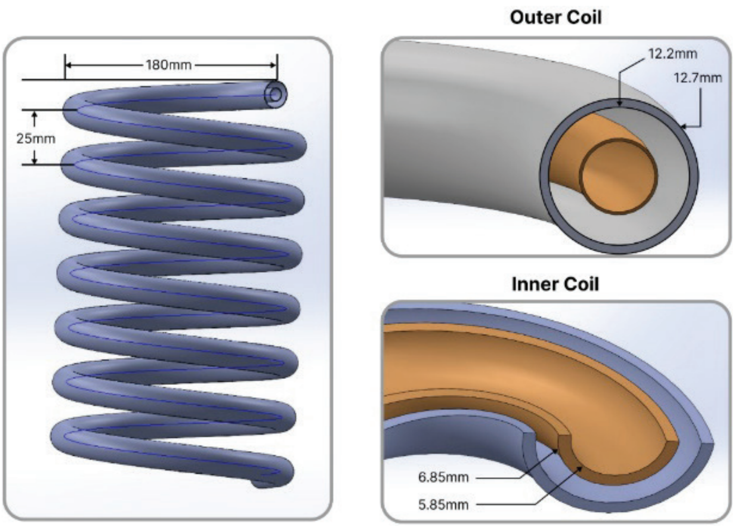

Figure 3. 3D view of the spherical coil heat exchanger.

of the experimental liquid, which is ethylene glycol. An 8-kW heater is inserted in the nanofluid/base fluid storage container to effect the temperature rise of the liquid. The spiral tube heat exchanger consists of an inner tube, which acts as a pathway for the movement of a hot fluid (ethylene glycol), and an outer tube, which acts as a channel for the movement of a cool fluid (water).

The nanofluid inlet is connected to one side of the heat exchanger, while the water inlet is linked to the other side, creating a reverse-flow configuration between the two fluids. The liquid is transported through the flowmeter, where the flow rate is measured. The outflowing water is channelled into a specially designed storage tank using the aid of a pump, while the outflowing nanofluid is fed back into the storage tank through a delivery line. This process is repeated for every conceivable configuration of the device. The temperatures of the nanofluid and water at the site of entry and exit are measured using Resistance Temperature Detector (RTD) sensors. A total of 12 RTD sensors were securely placed along the length of the coil to accurately monitor the temperature distribution on the airside of the heat exchanger. The flow rate of the ethylene glycol water solution is adjusted between 1-5 liters per minute (LPM) in steps of 1 LPM.

The fluid samples listed in Table 1 were synthesized and tested to evaluate thermal conductivity and dynamic viscosity at various temperatures. Experiments are used to examine all potential configuration changes by varying two variables: the weight percentage of Al_2O_3 and the flow rate of the nanofluid. The heat transfer coefficient is derived from the obtained data, and the improvement of the HTC in comparison to the base fluid is used to evaluate the effectiveness of the nanofluid.

Design specifications of a tube in the spiral tube heat exchanger

Total no. of tubes = 2 (copper)
Total length of the coil = 350 mm
The diameter of the entire coil, D = 165 mm
Outer coil dimensions
    Outer diameter, = 12.7mm
    Inner diameter = 12.4 mm
Curvature ratio of outer tube (d/D) = 0.075
Inner coil dimensions
    Outer diameter = 6.85 mm
    Inner diameter =5.85 mm
Curvature ratio of inner tube (d/D) = 0.035

Determination of flow and heat transfer parameters

The thermal parameters for both the water and nanofluid sides are as follows:

Nu = hD/K; Re = ρVD/μ; Pr = μc_p/K Where Re = Reynolds number; Pr = Prandtl number; Nu = Nusselt number, V = velocity; μ = viscosity; C_p = specific heat of water; ρ = density; h= heat transfer coefficient D = diameter of pipe; K= thermal conductivity

Heat transfer on the cold side of heat exchanger

To evaluate the heat transfer of the nanofluid pumped in the inner tube, water flowing through the outer tube is used as a reference fluid. The constant water flow rate for all test conditions is 5 LPM. On the water side, the heat transfer coefficient is calculated using the equation of Xin et al. [27].

For Laminar flow, Xin et al. equation [27] is given by

$$Nu_{av} = (2.153 + 0.318\, De^{0.643})Pr^{0.177}$$
$$20 < De < 2000,\ \ 0.7 < Pr < 175 \qquad (1)$$
$$0.0267 < \frac{d}{D} < 0.0884$$

Where Dean number $\mathrm{De} = Re\left(\frac{d}{D}\right)^{1/2}$ which takes account of the impact of the curving of the spiral coil. The water-side heat is estimated by the equation

$$q_{waterside} = m_w C_{pw} \Delta T_{water} \qquad (2)$$

Airside heat transfer of the test setup

The heat lost to air is calculated using the equation

$$q_{airside} = h_{air} A_{air\Delta T_{air}} \qquad (3)$$

The air-side heat transfer coefficient (h_{air}) is determined using the conventional Nusselt number equation for free convection, which are expressed as follows: Xin and Ebadian's equation [27] for the coiled tube

$$Nu_{av} = 0.3((Gr.Pr)^{0.3}) \qquad (4)$$

Nanofluid side heat transfer coefficient

From the equation (7) the heat transfer coefficient of the nanofluid has arrived using the following energy balance

$$q_{nf} = \frac{\Delta T}{R} = q_{\,water} + q_{air} \qquad (5)$$

$$\Delta T_{overall} = T_b - T_{air} \qquad (6)$$

$$\frac{1}{R} = \frac{1}{h_w A_w} + \frac{1}{h_{air} A_{air}} + \frac{1}{h_{nf}\, A_{nf}} \qquad (7)$$

RESULTS AND DISCUSSION

Thermophysical Properties

The dispersion of particles in liquids improves thermal conductivity and heat transfer. The fraction of aluminum oxide nanoparticles surface-modified with CTAB has a direct effect on the thermal conductivity of the nanofluid (Fig. 4a). In all liquids tested, the nanofluids had a significantly higher thermal conductivity than the base fluids. However, the thermal conductivity of pure ethylene glycol

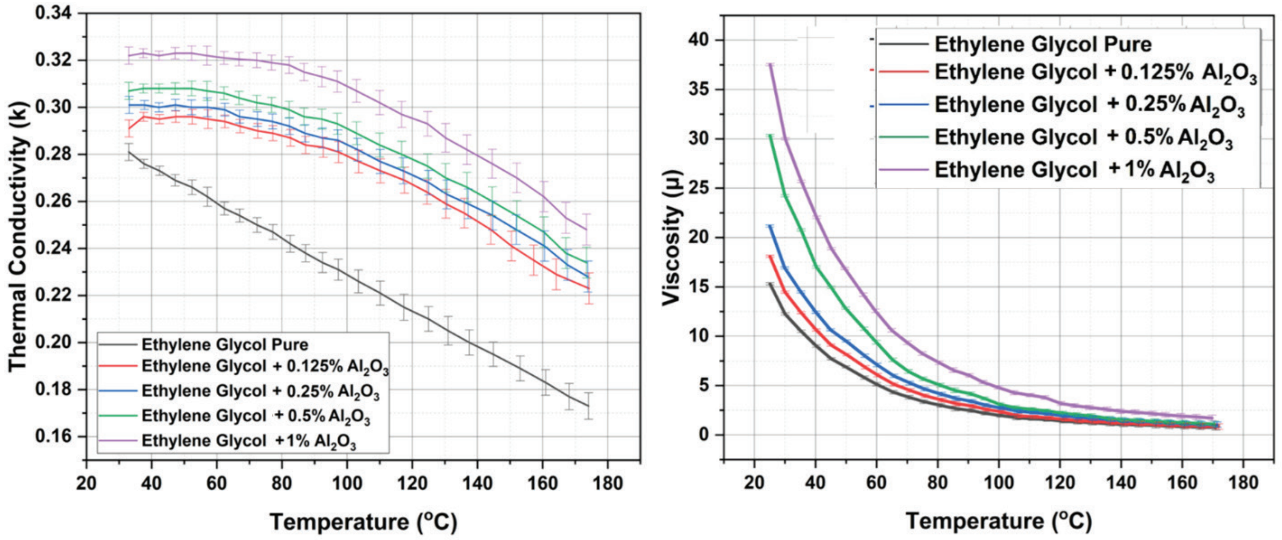

Figure 4. Variation of a) thermal conductivity and b) dynamic viscosity of ethylene-glycol with different weight % of Al_2O_3 nanoparticles surface modified with CTAB.

increased slightly. The temperature also improves the thermal conductivity. The thermal conductivity increases significantly at higher temperatures. The use of 0.125, 0.25, 0.5 and 1% aluminum oxide nanoparticles increased the performance by 11%, 14%, 18% and 22% respectively.

Various diagrams of the temperatureand dynamic viscosity of the nanofluid show an increase in the Al_2O_3 weight fractions (Fig. 4b). The dispersion of Al_2O_3 increases the dynamic viscosity in nanofluids. This increase can only be observed at lower temperatures. The dynamic viscosity of nanofluids increases only insignificantly at high temperatures compared to base fluids. Other studies have shown that nanofluids with interspersed Al_2O_3 have negligible effects on viscosity at high temperatures. The specific heat of ethylene glycol–water samples containing Al_2O_3 nanoparticles was measured with a C-Therm three-prong probe. The values can be found in Table 2.

Due to such low concentrations, nanofluids have less specific heat variation compared to their base fluids. As Al_2O_3 weight fraction increases, values decline slightly.

Table 2. Specific heat values for ethylene-glycol water mixtures with varied concentrations of Al_2O_3 at room temperature

S. No	Test fluid	Specific heat, Cp, kJ/kg K
1	Ethylene glycol	2.71
2	Ethylene glycol+ 0.125% Al_2O_3	2.7
3	Ethylene glycol+ 0.25% Al_2O_3	2.68
4	Ethylene glycol+ 0.5% Al_2O_3	2.66
5	Ethylene glycol+ 1 % Al_2O_3	2.64

Correlations for Thermophysical Properties

In the past, researchers have described the increase in thermal conductivity through the addition of nanoparticles. However, the experimental results differ greatly. Therefore, a mathematical model is required to accurately determine the thermal conductivity and dynamic viscosity of test fluids. Comparing the theoretical and experimental results of a predictive model helps to evaluate its predictive power. This is important when the model predicts new or undiscovered data. To evaluate the properties, regression models are created by examining the experimental data on thermal conductivity and dynamic viscosity independently of each other. The statistical program Minitab is used to create a non-linear mathematical model. The dynamic viscosity and thermal conductivity are considered. The dependent variables in this study are temperature and Al_2O_3 concentration.

$$k_{nf} = 1.8(1+\varphi)^{0.33}\,(1+\frac{T}{T_{max}})^{0.88}(k_b)^{1.6} \tag{8}$$

$$\mu_{nf} = 12.5(1+\varphi)^{1.23}\left(1+\frac{T}{T_{max}}\right)^{-4.3}(\mu_b)^{0.26} \tag{9}$$

The figure helps evaluate the theoretical model's congruence with experimental data. Figure 5 shows that Equations 1 and 2 were verified. Ethylene glycol nanofluids' dynamic viscosity and thermal conductivity are predicted by the equations at certain temperatures and Al_2O_3 weight percentages. Furthermore, both equations deviate by up to ±3% from experimental data.

Heat Transfer Analysis

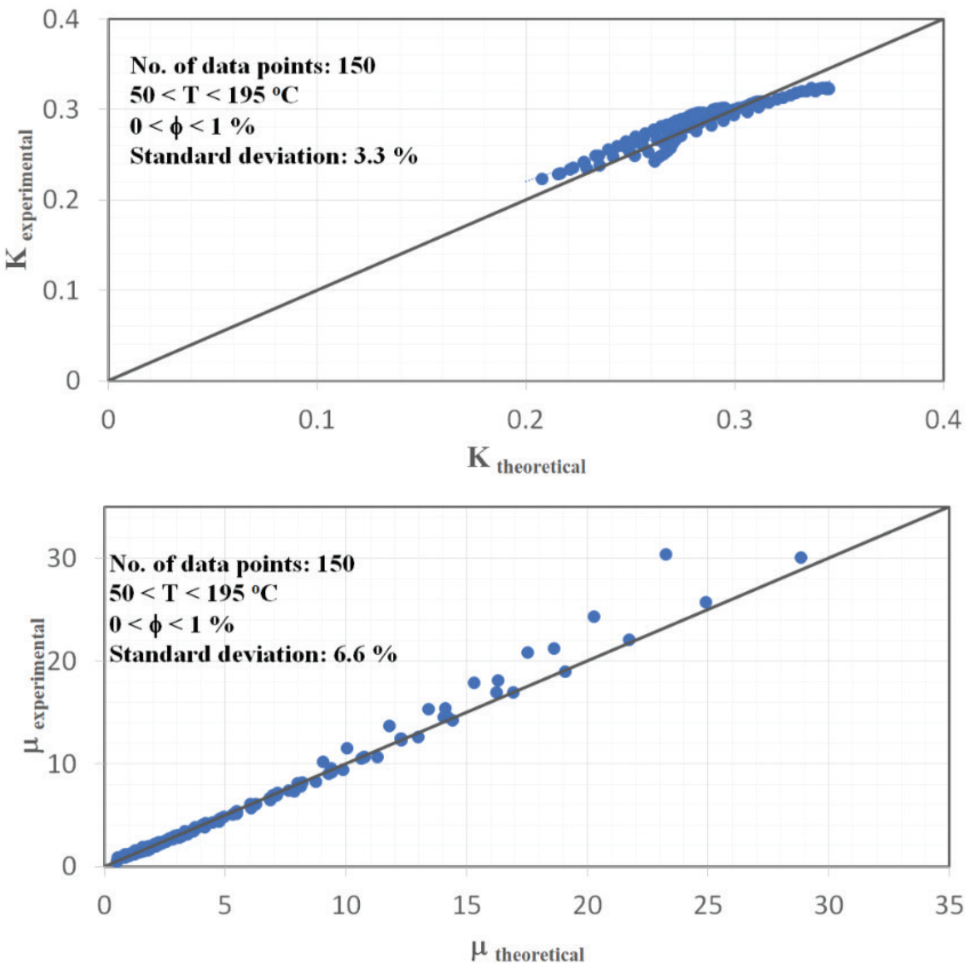

Figure 5. Confirmation of validity of a) Equation 8 for thermal conductivity and b) Equation 9 for dynamic viscosity.

Validation of test results

To test the reliability and precision of the experiments, the heat transfer of ethylene glycol is measured before measuring the heat transfer of nanofluids. The results are compared with the equation of Xin et al [27]. Figure 6 shows the experimental data with the ethylene glycol equation of Xin et al [27]. Figure 6 shows that the experimental data agrees with the equation of Xin et al. [27] for all Reynolds values, indicating the correctness of the experimental data.

Heat transfer with nanofluids under laminar conditions

In the experiment, ethylene glycol is dispersed with concentrations of 0.25%, 0.5% and 1% Al_2O_3. The diagrams show the relationship between the heat transfer coefficient (hi) of the nanofluid and the Reynolds number (Re) for all fluids tested. All investigations were carried out under laminar flow conditions, which generally prevail in spiral tube heat exchangers. Figure 7 shows the relationship between the heat transfer coefficient (HTC) and the Reynolds number in a coiled heat exchanger. This relationship is observed for the original fluids and the corresponding nanofluids when the heat exchanger operates under laminar flow conditions.

The results show that the nanofluid has the potential to significantly improve the heat transfer effectiveness of nanofluids by increasing their heat transfer coefficients. There is a clear correlation between the Reynolds number and the increase in the heat transfer coefficient (HTC). The increase in the Reynolds number has led to a more significant improvement. It was also found that the proportion of Al_2O_3 also influences the HTC. Nanofluids with higher concentration have a higher heat transfer coefficient (HTC).

Figure 7 shows that using ethylene glycol as a base fluid leads to a remarkable improvement in heat transfer coefficients for nanofluids with a concentration of 0.25%, 0.5 % and 1% Al_2O_3, with increases of up to 26%, 28% and 30%, respectively. The combined effects of Brownian motion and increased thermal conductivity resulted in improved transfer under laminar flow conditions. Brownian motion is the random and non-uniform movement of nanoparticles suspended in a fluid. This motion is caused by the collisions between the nanoparticles and the molecules of the liquid. The stochastic motion of nanoparticles promotes the

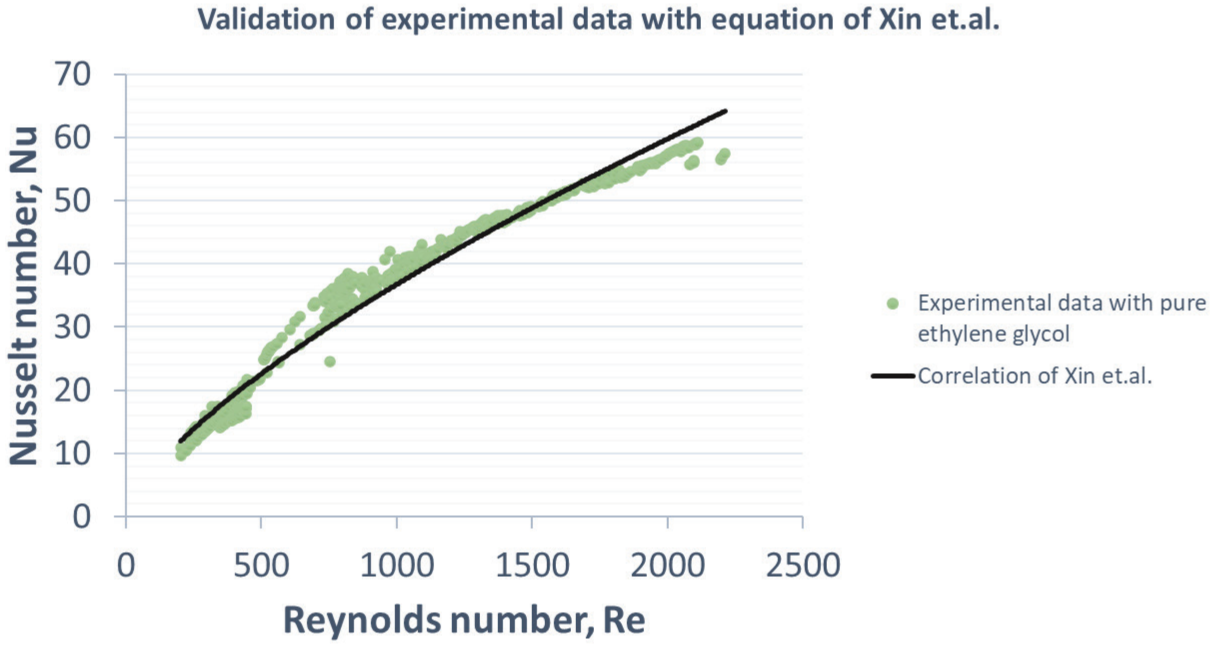

Figure 6. Validation of experimental data with correlation of Xin et al. [28].

dispersion of energy throughout the fluid. This augmented energy transfer contributes to a general rise in thermal conductivity.

The results of the study suggest that the improvement in heat transfer in nanofluids is not solely due to the increase in thermal conductivity. Additional factors such as the long-term stability of nanofluids and the occurrence of small-scale fluid movement caused by the interaction between particles and the liquid also have an influence. The incorporation of surface-modified Al_2O_3 into the fluids resulted in a very stable nanofluid that significantly increased the heat transfer coefficient (HTC).

Influence of inlet temperature on the efficiency of nanofuid

The effectiveness of a nanofluid is often associated with its ability to increase thermal conductivity and thus increase the efficiency of heat transfer in various applications. Efficiency can be measured by comparing the heat transfer properties of the nanofluid with those of the base

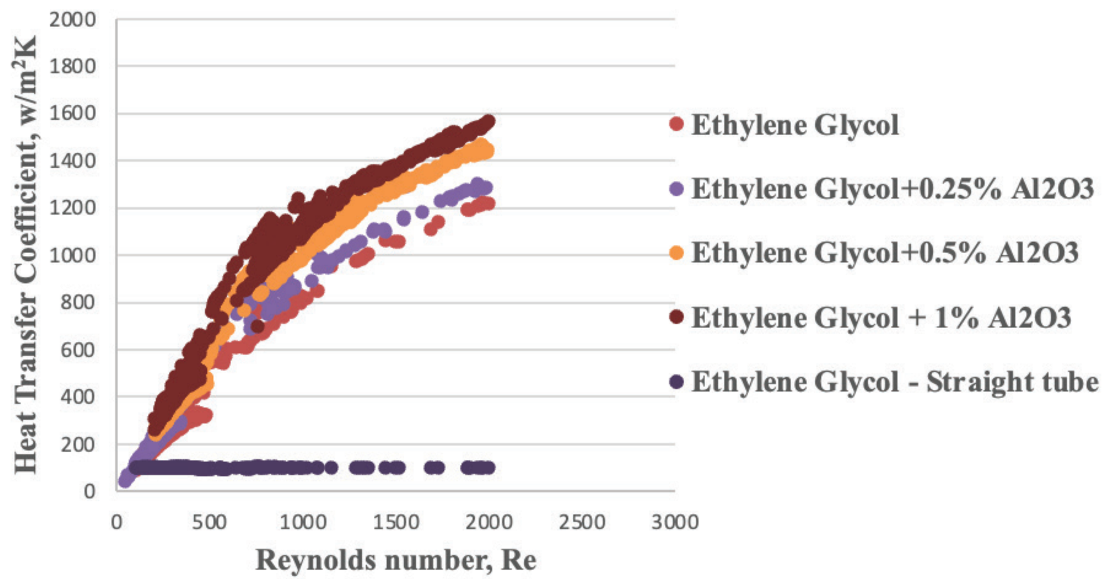

Figure 7. The graph between Reynolds number and heat transfer coefficient for laminar flow for ethylene glycol based fluids.

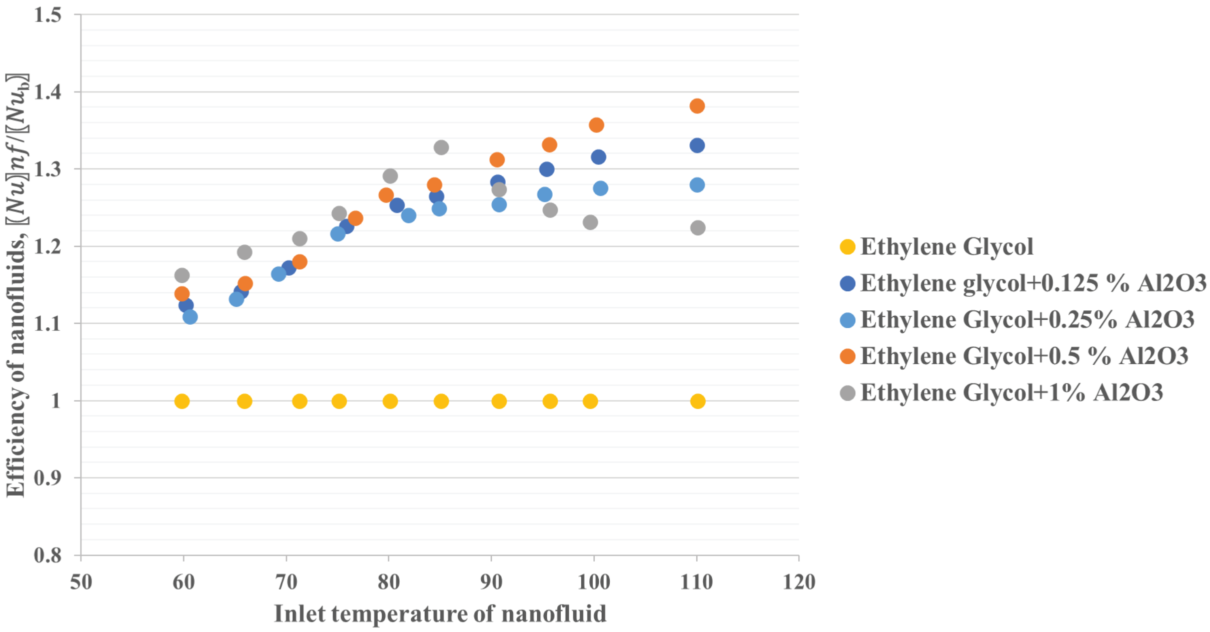

Figure 8. Influence of inlet temperature on the efficiency of nanofluids.

fluid. Improving thermal conductivity is the most important property typically used for this purpose. However, the flow properties are not taken into account. Hence, an efficiency term in terms of the ratio of Nusselt numbers of nanofluid and base fluid has been proposed as the $\frac{Nu_{nf}}{Nu_b}$.

Figure 8 illustrates the correlation between the efficiency of the nanofluid and the temperature of the hot liquid at the inlet. It is obvious that higher temperatures lead to improved efficiency of nanofluids at all concentrations. The efficiency of nanofluids can be influenced by temperature in many ways. Nanofluids have thermal properties, such as thermal conductivity and viscosity, which vary with temperature. The thermal conductivity of nanofluids generally increases with increasing temperature, with higher temperatures leading to a greater improvement in thermal conductivity. The viscosity of nanofluids can be influenced by temperature.

As a rule, an increase in temperature leads to a decrease in the viscosity of the base fluid. The presence of nanoparticles can affect the viscosity behavior, which varies with temperature. The heat transfer efficiency is closely related to the heat transfer coefficient and the viscosity of the fluid. At lower mass fractions, as the viscosity is lower, there is a progressive increase in efficiency. At higher mass fractions (1%), the viscosity effects dominate the heat transfer coefficient, and at higher temperatures the viscosity effects are dominant compared to the heat transfer. Therefore, the heat transfer efficiency decreases.

Furthermore, the collective behavior can be altered by factors such as the clustering of nanoparticles or alterations in the characteristics of the underlying fluid. The stability of nanoparticles in the nanofluid can be affected by temperature. Higher temperatures can cause greater Brownian motion of the nanoparticles, resulting in enhanced thermal conductivity and, thus, improved efficiency. Furthermore, the clustering of nanoparticles due to elevated temperatures diminishes the effectiveness of the nanofluids and perhaps compromises their long-term durability. Nevertheless, the accurate alteration of the surface guaranteed the conservation of the characteristics, hence enhancing efficacy at elevated temperatures.

The impact of the inlet temperature of the nanofluid heat transfer coefficient

The influence of the inlet temperature of the nanofluid on the improvement of heat transfer with Al_2O_3 was also investigated. As shown in Figure 9, a diagram was drawn with an average of HTC on the hot fluid side. As the temperature increases, the viscosity of the fluid decreases and thus the Reynolds number increases. In addition, the temperature difference is greater with the same flow rate and increasing inlet temperature of the liquid, so that the heat transfer is also greater. The diagrams also show the influence of the inlet temperature of the liquid on the heat transfer coefficient for the base liquid and the base liquid with the dispersion of Al_2O_3, and the respective performances are evaluated in laminar flow.

An increase in the inlet temperature of the nanofluid is characterized by an increase in the Reynolds number, which leads to an improvement in heat transfer with the dispersion of Al_2O_3. The improvement with the dispersion of Al_2O_3 is also exceptionally well adapted to the base fluid.

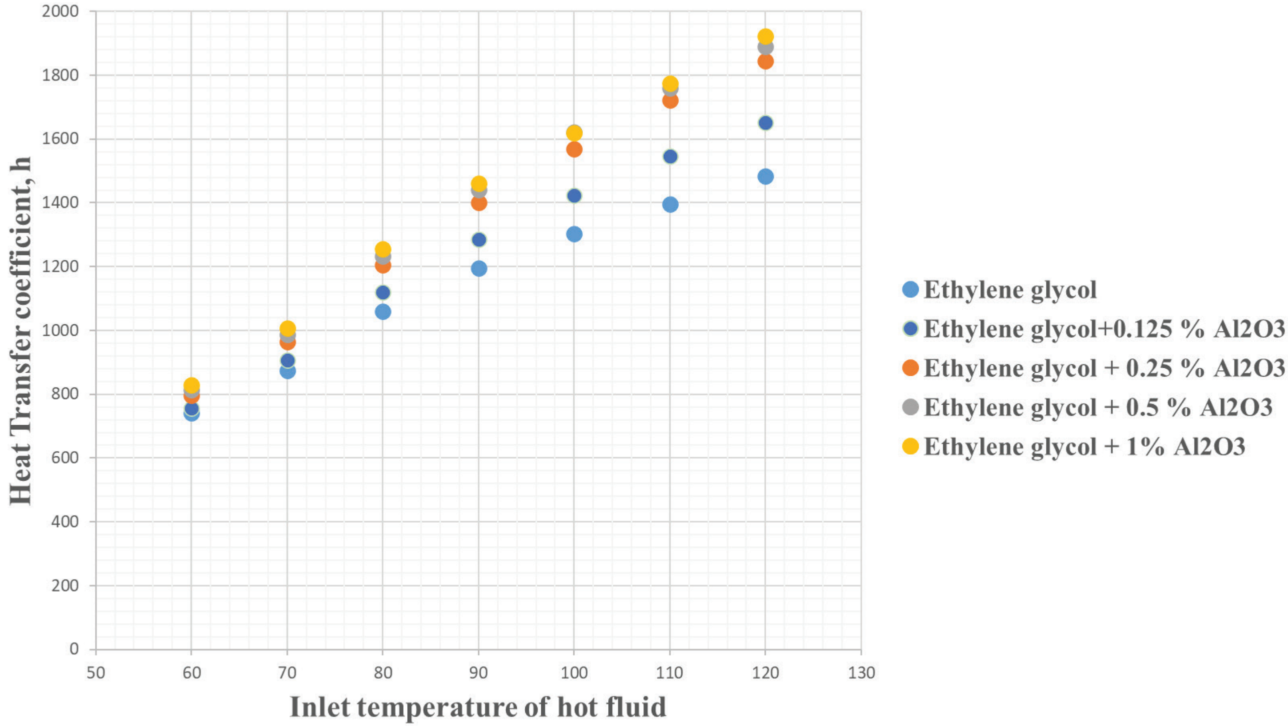

Figure 9. The plot of hot fluid inlet temperature vs heat transfer coefficient**.**

Table 3. Percentage change in the heat transfer coefficient with inlet temperature

base fluid		Base fluid+0.125 % Al_2O_3			Base fluid+0.25 % Al_2O_3			Base fluid+0.5 % Al_2O_3			Base fluid+1 % Al_2O_3		
T	h	T	h	% change	T	h	% change	T	h	% change	T	h	% change
60	740	60	756	2.1	60	796	7.4	60	813	9.8	60	830	12.0
70	874	70	908	3.9	70	966	10.6	70	988	13.1	70	1007	15.2
80	1060	80	1121	5.7	80	1205	13.6	80	1234	16.4	80	1257	18.5
90	1196	90	1286	7.6	90	1401	17.1	90	1442	20.6	90	1462	22.2
100	1304	100	1424	9.2	100	1568	20.3	100	1623	24.5	100	1619	24.2
110	1396	110	1547	10.8	110	1723	23.4	110	1759	26.0	110	1774	27.0
120	1483	120	1652	11.4	120	1846	24.5	120	1890	27.4	120	1922	29.6

CFD Analysis of Heat Transfer with Nanofluids

CFD (Computational Fluid Dynamics) analyses enable the verification of experimental results. CFD can validate the accuracy of the numerical model in predicting observed phenomena by reproducing the same conditions as in the experiment. This helps to verify the reliability of both experimental and computational approaches. Below is a flowchart illustrating the sequential processes involved in performing a CFD analysis

Numerical setup

An analysis was carried out to investigate the heat transfer characteristics of spiral tubes during the test, using nanofluids and base fluids in a numerical simulation. The ANSYS-FLUENT program is used to discretize and simulate the governing equations using the finite volume method. It is recommended to use a steady-state pressure-based solution for the settings. The heat transfer analysis of the investigated system was performed using the homogeneous single-phase model and the SIMPLE method. The obtained results were discretized using the second order upwind method. The energy and momentum calculations were performed using a second-order upwind discretization method. In addition, the second-order discretization method was used for the pressure.

Mesh generation is a crucial component of numerical simulations that provide very precise results. Mesh independence studies use inflation rates and edge sizes to iteratively change the mesh. The method is iterated until the discrepancy between two successive refinements is less than 1%. A tetrahedral mesh was used for the surface, while a hexahedral mesh was used for the body (Fig. 10).

The numerical simulations were performed in laminar flow, considering a wide range of Reynolds numbers for ethylene glycol-based nanofluids at concentrations of 0.25, 0.5 and 1%.

The details of the mesh and boundary conditions are given in Tables 4 and 5:

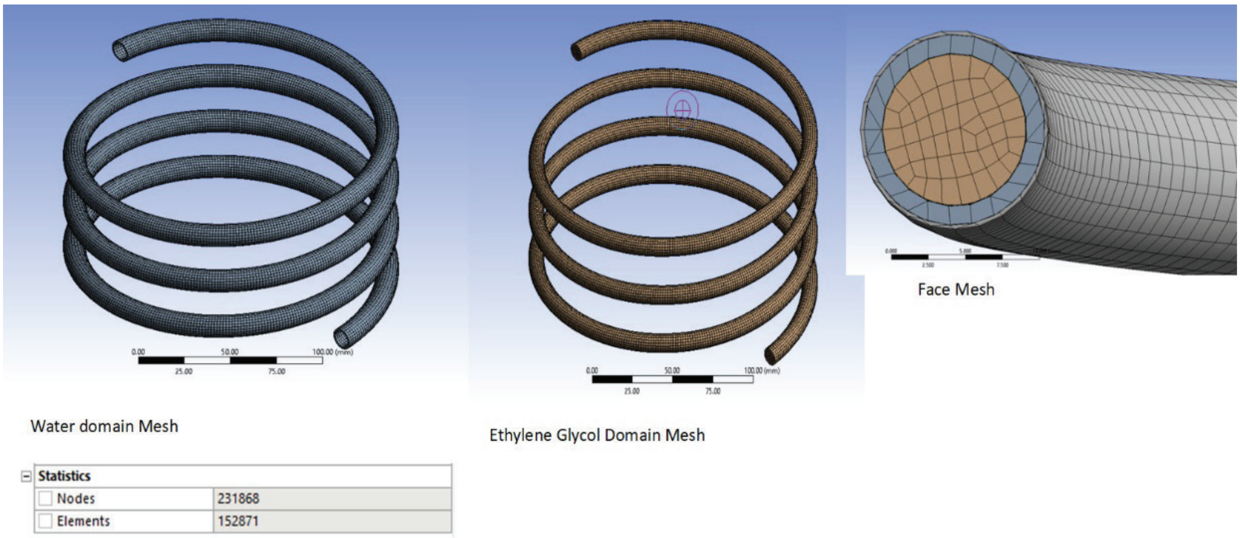

Figure 10. Mesh generation.

Table 4. The details of the mesh

Name	Type	Minimum Orthogonal Quality	Maximum Aspect Ratio
Hot fluid	Mixed Cell	0.561	8.67
Cold fluid	Mixed Cell	0.589	5.07
Inner pipe	Hex Cell	0.540	34.45
Outer pipe	Mixed Cell	0.350	16.67

Table 5. Boundary conditions

Region	Boundary	Type	Value	Units
Cold fluid	Cold fluid inner pipe interface	Interface		
	Cold inlet	Velocity inlet	0.906	m/s
		Temperature	28.5	°C
	Cold outlet	Pressure outlet	0	Pa
		Temperature	52.4	°C
Hot fluid	Inner fluid outer pipe interface	Interface		
	Hot fluid inner pipe interface	Interface		
	Hot inlet	Velocity inlet	0.469	m/s
		Temperature	75.9	°C
	Hot outlet	Pressure outlet	0	Pa
		Temperature	63.1	°C
Outer Pipe	Outer wall outer pipe	Wall, Temperature	Ambient	°C
	Side wall pipe outer pipe	Wall, Temperature	Ambient	°C

Assumptions in the analysis

Several assumptions were used in this study to simplify the simulation.

- The fluid used in this study is ethylene glycol, which is assumed to behave like a Newtonian fluid. The parameters were determined using correlations established in earlier chapters.
- Under stable conditions, the fluid flow was determined to be laminar in the range of Reynolds numbers from 100 to 1200.
- The system wall did not take into account the condition that no slip occurs.
- With the exception of the gravitational force, all other body forces and viscous dissipation were neglected.

Governing equations in the CFD model are taken as

1. Continuity Equation

$$\rho + \nabla.(\rho v) = 0$$

2. Navier stokes Equation

$$\rho\left(\frac{dv}{dt} + v.\nabla v\right) = -\nabla p + \mu \nabla v$$

3. Energy Equation

$$\rho\, Cp(T + v\,\nabla T) = \nabla.(k\nabla T)$$

Results of CFD Simulation

The primary focus of this study involves simulating the heat transfer of nanofluids and comparing the numerical findings with the experimental data.

Prediction of temperature variation between the inlet and outlet of the heated section

Figure 11 shows the different temperature distributions of the water-based Al_2O_3 nanofluid within the inner liquid at different Reynolds numbers. These data are presented to evaluate the results of the simulation. It can be deduced that higher concentrations of nanoparticles lead to a slight decrease in temperature in the heated region. The decrease in wall temperature is due to an increase in the heat transfer coefficient. The concentration of nanoparticles in the base fluid has a major influence on the heat transfer efficiency of the nanofluid.

As the mass fraction increases, so does the temperature difference between the inflow and outflow. As a result, heat absorption increases, which indicates a higher heat transfer coefficient. Higher concentrations of nanoparticles lead to a slight drop in temperature in the heated zone. The decrease in the temperature difference results from an increase in the heat transfer coefficient. The concentration of nanoparticles in the base fluid has a major influence on the heat transfer efficiency of the nanofluid. Increasing the volume concentration significantly improves the heat transfer efficiency, but also causes a greater pressure drop, which should be kept to a minimum. The graph in Figure 12 shows the relationship between the Nusselt number and the Reynolds number. The agreement between the experimental results and computational fluid dynamics (CFD) is strong evidence of the role of nanoparticle dispersion in improving heat transfer. The CFD simulations show that the heat transfer coefficient increases with increasing Reynolds number and nanoparticle volume concentration.

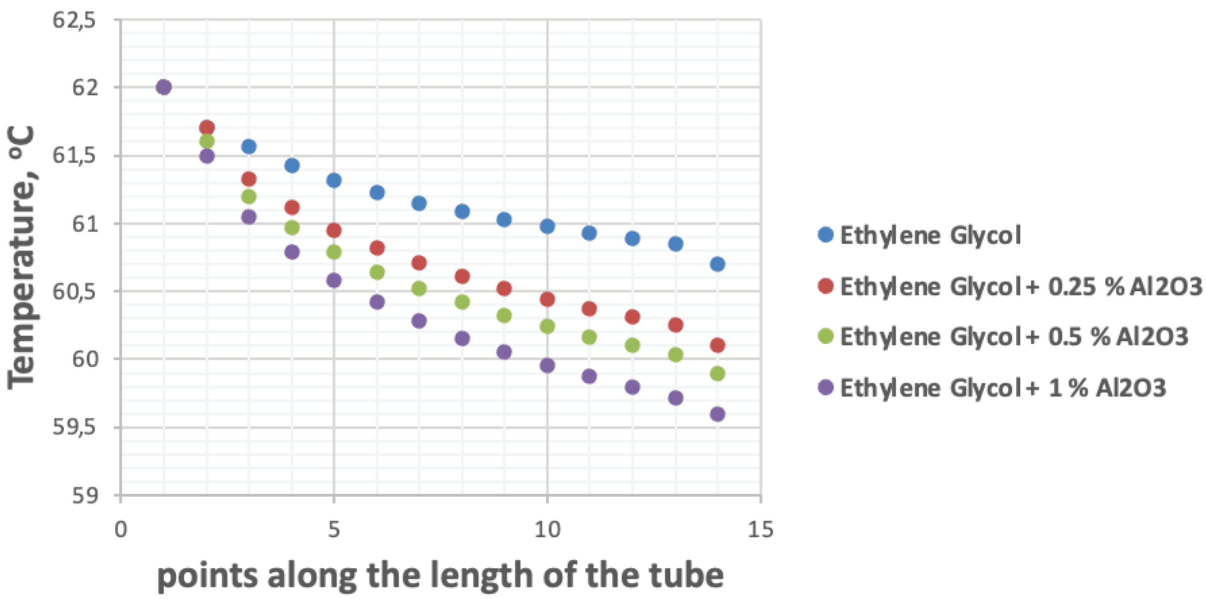

Figure 11. Plot showing the variation of temperature differential across the spiral coil.

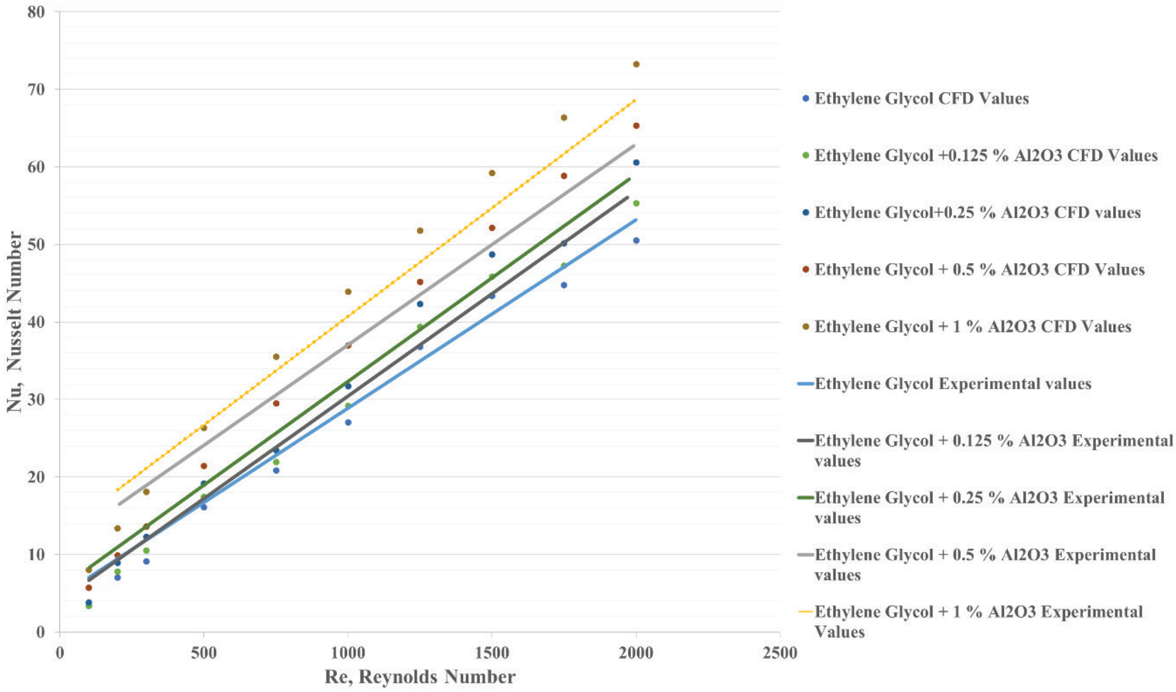

Figure 12. Comparison of results of experimentation and CFD analysis.

Mesh validation studies

In order to achieve numerical accuracy and reliability, mesh validation tests are required for calculation simulations. These tests usually check whether the simulation mesh or grid is fine enough and well structured to capture the essential physical aspects of the problem. Convergence studies have been performed by running the simulation with increasingly finer grids to determine whether the solution achieves a stable result. The mesh is sufficiently refined if the results remain consistent even when using more detailed meshes. Table 6 shows that grid independence was achieved with grid refinement and the error stabilized at a mesh size of 0.5 mm. This indicates that additional refinement of the mesh does not result in significant changes to the solution. It also shows that the mesh-related numerical errors are reduced to a minimum.

Table 6. Mesh validation of the CFD model

Cell size, mm	Mesh Nodes	htc hot	E%
0.5	636140	1039.2	1.88
1	481050	875.72	1.92
2	215140	831.75	5.15
3	210005	806.81	6.21
4	190111	805.9	8.33

CONCLUSION

The conclusions made from the results are as follows.

1. A novel investigation on the enhancement of heat transfer due to surface modification of nanomaterials prior to dispersion in ethylene glycol for use in spiral tube heat exchangers was presented in detail.
2. The dispersion of Al_2O_3 nanoparticles carried out in 0.25 %, 0.5 %, and 1% in monoethylene glycol for solar thermal applications could substantially improve the heat transfer properties.
3. The reliability and accuracy of the experiments were checked using the standard equation for ethylene glycol proposed by Xin et al [27] and found to be in good agreement.
4. Although the heat transfer coefficient generally increases with an increase in the Reynolds number, the results show that the increase in the heat transfer coefficient appears to be more pronounced at higher Reynolds numbers.
5. A correlation between the increase in the liquid inlet temperature and the corresponding increase in the heat transfer coefficient is evident from the studies.
6. The heat transfer coefficients of the test fluids increase by 22%, 27%, 30%, and 32%, respectively, for nanofluids with Al_2O_3 concentrations of 0.125%, 0.25%, 0.5%, and 1%.
7. CFD analysis of the experimental data validated the correctness of experimentation. It is found that the

experimental outcomes have matched well with the results obtained from CFD analysis.

NOMENCLATURE

C_p	Specific heat of the fluids (kJ/kg K)
D	Coil diameter, m
d	Coil tube diameter, m
h	Heat transfer coefficient ($W/m^2/K$)
k	Thermal conductivity (W/m/ K).
m	Mass flow rate of water (kg/s).
Q	Rate of heat transfer (W).
T	Temperature (°C).
V	Velocity (m/s)
$\frac{d}{D}$	Curvature ratio
Gr	Grashoff number $\left[\frac{\rho^2 g\beta\Delta T d^3}{\mu^2}\right]$
Re_{cr}	Critical Reynolds number
Re	Reynolds number $\left[\frac{\rho V d}{\mu}\right]$
Nu	Nusselt number $\left[\frac{hd}{k}\right]$
Pr	Prandtl number $\left[\frac{\mu c_p}{k}\right]$
De	Dean Number $\left[Re\left(\frac{d}{D}\right)^{1/2}\right]$

Greek symbols

α	Volume percentage of ethylene glycol in water
f	The weight fraction of nanoparticles
μ	Dynamic viscosity (cP).
n	kinematic viscosity (m^2/s)
ρ	Density of the fluid (kg/m^3)

Subscripts

Air	Airside
w	Water/wall
nf	Nanofluids
max	Maximum
1	Inlet
2	Outlet

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AUTHORSHIP CONTRIBUTIONS

Authors equally contributed to this work.

DATA AVAILABILITY STATEMENT

The authors confirm that the data that supports the findings of this study are available within the article. Raw data that support the finding of this study are available from the corresponding author, upon reasonable request.

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CONFLICT OF INTEREST

The author declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

ETHICS

There are no ethical issues with the publication of this manuscript.

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