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Enhancement of Convective Flow and Heat Transfer using Nanofluids: A Critical Review

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ABSTRACT

Nanofluids are an innovative class of materials that have been recently developed due to their superior ability to improve thermal performance in industrial applications. It is prepared by dispersing metal particles and metal oxides in the base liquid to ensure proper distribution. Thermal conductivity is a key criterion in developing thermal energy transmission fluids. A literature reviesw was conducted to study the types of nanoparticles used at different concentrations and to review the stability evaluation of nanofluids. Researchers have also suggested adding surfactants such as Colace (docusate sodium), trisodium citrate dihydrate (TSC), and sodium lauryl sulfonate (SLS) to increase stability. The effect of physical and thermal properties was analyzed and the impact of different particle shapes was investigated, where spherical and cylindrical shapes were used because they provide a better heat transfer rate than other shapes. The results show that there is a positive correlation between the concentration of solid nanoparticles, thermal conductivity, and Nusselt number.

1. Introduction

The rate of heat transfer is determined by the temperature difference between two objects or two locations. Various types of fluids can be employed as heat carriers in heat transfer applications. Common examples are water, oil, and air. Each fluid possesses unique properties that make it more or less suitable for specific heat transfer tasks. In general, fluids with higher heat capacity and thermal conductivity are better suited as heat carriers [1].

Heat exchangers facilitate the transfer of heat between hot and cold fluids that flow in the same or opposite directions. Tube heat exchangers are the most prevalent type of heat exchangers. Double-tube heat exchangers come in two types, parallel flow and counter flow. When processing products with particles, these heat exchangers provide a big benefit without running the danger of clogging. [2]. They are frequently used for a variety of tasks including pasteurization, sterilization, warming, preheating, digester operations, and effluent heating in the chemical, food, oil, and gas sectors [3].

When it comes to their mechanical, optical, magnetic, electrical, and thermal transmission properties, nanofluids are superior to ordinary fluids. Consequently, nanofluids hold considerable potential for mass transport, biomechanics, mechanics, and energy applications. [4]. Utilizing the superior thermal and physical characteristics of nanofluids, heat exchanger performance in heat transfer can be raised [5].

By suspending nanoparticles in a base fluid, such as water, ethylene glycol, or oil, nanofluids are produced. A variety of materials, including copper, silver, titanium dioxide, and zinc oxide, can be used to create nanoparticles. Compared to a regular liquid, the Nanofluid's random movement of nanoparticles increases the fluid's turbulence intensity and decreases its thermal resistance [6].

Considerable efforts have been made to improve heat transfer through geometrical modification. In 1864, Scottish physicist James Clerk Maxwell proposed dispersing solids in fluids more than 120 years ago. His theoretical work on the subject laid the groundwork for future research in fluid dynamics [7]. Maxwell showed that creating a stable, homogeneous mixture was possible by dispersing solids in fluids. This discovery has since been used in various applications, from manufacturing to medicine.

The heat exchanger is crucial to many systems, including power plants, refrigeration units, and air conditioners, plants of the chemical processing, automobiles, and appliances of everyday household like boilers and heaters of the water [8]. The main objectives in thermal systems are to improve the efficiency of the heat transfer and reduce the size of the heat exchanger. This can be achieved by optimizing the performance of the heat exchanger [9]. These systems typically involve both conduction and convection mechanisms, requiring analysis of multiple parameters related to heat transfer in solids and fluids.

The thermal conductivity is high in metals which can be attributed to the vibrational motion of their atoms. Where in metals, a large quantity of free electrons was existed, therefore heat conduction originally give raise to electronic conduction, and the free electrons enable to move freely everywhere the solid and consequently transfer the thermal energy with high rate in comparison to insulators.

In metals, atoms are held together by electromagnetic forces, and when these forces are disrupted, the atoms start to vibrate. This vibration creates a lattice of atoms that can conduct heat. The same forces do not hold together the atoms in a fluid, so they cannot conduct heat as well. The high thermal conductivity of metals is due to the ability of their atoms to vibrate.

Nanofluid researchers are investigating ways to increase the thermal conductivity magnitudes of fluids with low thermal conductivity. One technique is to enhance the fluid's thermal conductivity by adding metal granules in the nanosize [4]. Liquids' physical and thermodynamic properties can be changed to increase their thermal conductivity. Comparing conventional liquids to non-metallic solids like alumina and copper oxide, the former often exhibits lesser heat conductivity. Other metallic solids, like copper and aluminum, are also being studied to improve the characteristics of fluids. [10]. After being distributed throughout the base fluid, nanoparticles' high thermal conductivity raises the fluid's overall thermal conductivity. Studies on heat transfer utilizing different nanofluid samples have shown that the performance of nanofluids in heat transfer applications is much better than that of base fluids. An appealing solution for improving fluid-based systems' thermal performance is the use of nanofluids. [11].

The numerous characteristics of copper oxide nanoparticles render them highly flexible for a wide range of applications. These uses include those of superconductors, batteries, magnetic storage devices, solar energy components, and catalysts. [12]. A prominent benefit of CuO nanofluids is their higher heat transfer efficiency, which can be attributed to increased convection brought about by the nanoparticles' Brownian motion inside the fluid. Because of the fluid turbulence produced by this Brownian motion, convection is improved, which improves heat transmission [13].

Copper oxide nanoparticles are superior than traditional materials in a number of ways. Nevertheless, using them comes with certain difficulties. One significant barrier that causes the surface energy to drop is the tendency of these particles to coalesce over time. Copper oxide nanoparticles remain a potential option for a range of industrial applications in spite of this disadvantage. This is mostly because of their exceptional capacity to speed up hydrocracking reactions, which is very beneficial in many industrial processes [14].

When analyzing the physical characteristics of liquids, two main methods are used: numerical and experimental methods. The abovementioned techniques are used to investigate several attributes, such as density, thermal conductivity, and specific heat capacity. These physical properties are of significant interest and importance in several scientific and engineering disciplines. Additionally, they are employed to analyze operational parameters, including flow rate and heat transfer [15].

Heat exchangers, traditionally used with low thermal conductivity fluids, have limited efficiency due to their size and limited efficiency. Nanofluids, a novel heat transfer medium, have been discovered to enhance thermal characteristics by suspending Nanoparticles within traditional fluids. These nanofluids have increased thermal conductivity, this leads to an increased rate of heat transmission and enhanced stability. The study conducted by Duangthongsuk and Wongwises [16,17].

1. Thermophysical properties of Nanofluids

Scientific experiments and practical applications have proven that nanoparticles possess very high physical properties, especially with regard to heat transmission rate, when compared to millimeter or micrometer size particles materials. Thus, nanofluids have gotten much attention from academics because they are much better at conducting heat [11].

2.1 Thermal conductivity

The thermal conductivity of a material is a measure of its ability to conduct heat. Thermal conductivity is a material property that is heavily reliant on the type of atoms present within the material and how those atoms are arranged. Good thermal conductors can quickly move heat through a material. Nanofluids are a very promising area of research when it comes to enhancing thermal conductivity.

Researchers have achieved much better thermal characteristics by adding nanoparticles to base fluids. This is because nanoparticles have a very large surface area-to-volume ratio, so they can transfer heat much more effectively. In addition, nanoparticles are also very good at dissipating heat.

The current system has some large solid particles that affect heat transfer. A solution to this model has been obtained by analyzing the equation describing the temperature transfer rate in a liquid medium containing solid particles in a steady and random suspension. The determination of the same formula that was employed in earlier studies may be utilized to determine total or effective thermal conductivity. The thermal conductivity of a nanofluid can be calculated using the following equation [4] :

$$k_{nf} \frac{k_p + 2k_{bf} + 2(k_p - k_{bf})\varphi}{k_p + 2k_{bf} - 2(k_p - k_{bf})\varphi} k_{bf} \quad (1)$$

2.2 Dynamic Viscosity

Cohesion is the attractive force between molecules of the same substance. The greater the cohesion force, the greater the viscosity of the liquid. This is because cohesion brings the liquid together and prevents it from flowing freely. The strength of its cohesion determines the viscosity of a fluid. The equation below is used to calculate the dynamic viscosity of Nanofluid [16]:

$$\mu_{nf} = (1 + 2.5 * \varphi) * \mu_{bf} \quad (2)$$

2.3 Density

The fluid density being used is a critical characteristic in systems since it directly affects the pressure drop and pumping energy. Although there is a limited amount of study available on this particular topic at the moment, it is regarded with the same importance as both heat conductivity and viscosity by many in the industry. The density of nanofluids can be determined by the following equation [18]:

$$\rho_{nf} = (1 - \varphi)\rho_{nf} * \varphi_{\rho f} \quad (3)$$

2.4 Specific Heat

Nanofluids have a higher specific heat capacity than conventional fluids, meaning they can absorb and store more heat. This increased heat capacity results in a higher heat transfer rate, making nanofluids an ideal choice for applications where heat needs to be quickly and efficiently transferred. Several factors affect the ($\boldsymbol{c_p}$) of nanoparticles. These include the type and concentration of nanoparticles,

Their size and shape, and the properties of base fluids. One notable effect of incorporating nanoparticles into base fluid is the increased thermal conductivity of nanofluids. This can lead to higher ($\boldsymbol{c_p}$) values.The following equation is used to find the specific heat of nanofluids [19]:

$$C_{Pnf} = \frac{(1 - \varphi)C_{pbf} \times \rho_{bf} + \varphi \times \rho_p \times C_{p_p}}{\rho_{nf}} \quad (4)$$

2. Types of Nanofluids:

A nanofluid is a fluid that is made up of tiny particles. Nanoparticles are made of a single element. They are so small that they can only be seen with a microscope. Nanofluids have many applications, such as in medicine and engineering. (Cu, Fe, and Ag), simple constituent oxides (CuO, Al2O3, and TiO2), alloys (Cu-Zn, Fe-Ni, and Ag-Cu), multielement oxides (CuZnFe4O4, NiFe2O4, and ZnFe2O4), metal carbides (SiC, B4C, and ZrC), metal nitrides (SiN, TiN, and AlN), and carbon-based materials (graphite, carbon nanotubes, and diamond).

These particles are present in various fluids like water, ethanol, engine coolant, and oil. The specific substances in which these particles are suspended depend on their composition and intended use. For instance, certain particles are made to endure high temperatures, while others are designed to degrade and soak up pollutants. These characteristics and applications of the particles have been studied and documented in references [20,22].

3. Techniques for Preparation Nanofluids

Nanofluids need to be stable and long-lasting if their properties are to be fully optimized. The primary reason why nanoparticles distributed in a base fluid tend to lose their stability over time is because the nanoparticles start to accumulate within the base fluid. The propensity of nanoparticles to aggregate is commonly attributed to the diminishment of their stability due to gravitational forces and Van der Waals forces, which degrade the Nanofluid's properties. Therefore, creating a nanofluid with excellent nanoparticle stability is a major challenge [23, 24]. The methods for preparing nanofluids may be split up into two groups based on the following section:

4.1 Single-step method

This method effectively bypasses multiple processes, including nanoparticle dehydration, preservation, conveyance, and scattering. The Physical Vapour Deposition (PVD) process is employed to generate a stable nanofluid, wherein the basic fluid undergoes direct evaporation and subsequent condensation of nanoparticles. This process produces nanoparticles distinguished by their high purity level and consistent size distribution. Hence, the aggregation of nanoparticles is reduced. One of the main constraints associated with the one-step methodology is the existence of residual reactants within the nanofluids. Furthermore, this technique is distinguished by a significant expenditure, see Figure 1 [25].

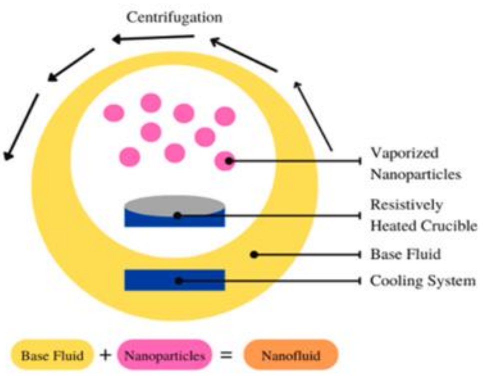

Fig. 1. Single-Step Method [25]

4.2 Two-step method

The utilization of this technology represents the most economically efficient method for the extensive production of Nanofluid on a significant scale. The two-step procedure encompasses the procurement of nanoparticles by diverse methodologies. Subsequently, the nanoparticles are dispersed throughout a base liquid to generate the desired Nanofluid. Its cost-effectiveness and large-scale nature characterize the production method. One of the primary limitations associated with the two-step technique is the phenomenon of nanoparticle aggregation. Surfactant is utilized because of its capacity to mitigate instability. The following procedure outlines the commercial approach for the preparation of nanofluids. The approach of preparing Nanofluid for research is widely favsoured by most researchers [26], Surfactants are applied and combined with nanoparticles such as sodium dodecyl sulfate (SDS), Colace (docusate sodium), trisodium citrate dihydrate (TSC), and sodium lauryl sulfonate (SLS)[16].see Figure.2 [27].

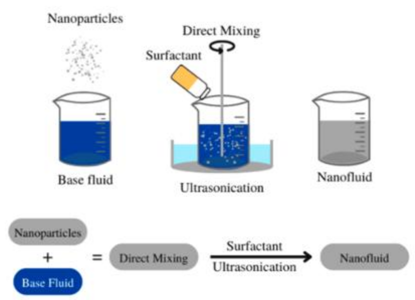

Fig. 2. Two-Step method [27]

Researchers commonly utilize a wide range of concentrations of both base fluids and nanoparticles in their experiments. This is illustrated in Figure 3 and 4, respectively.

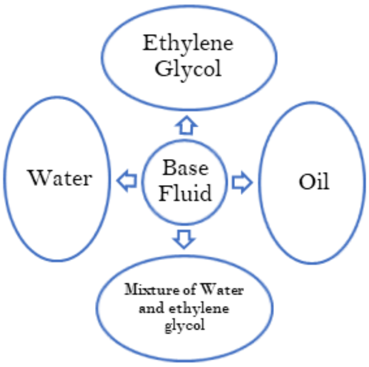

Fig. 3. Base fluids that are frequently utilized Presented by Sajid and Ali. [28]

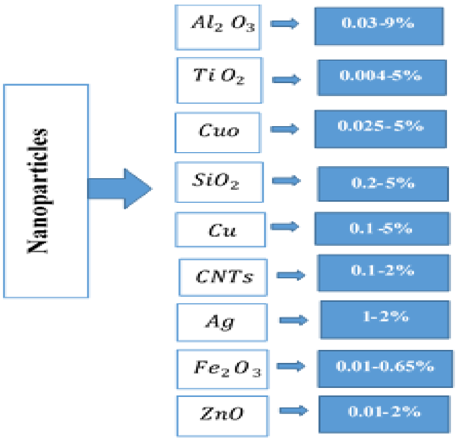

Fig. 4. The concentration ranges of nanoparticles utilized in the papers under consideration are presented by Sajid and Ali. [29]

4. The Recent Studies Related to nanomaterials

In [30] did an experimental study on the frictional heat transfer and heat transmission in heat exchangers with parallel tubes. They employed Al_2O_3 nanoparticles distributed in a diameter 50 nm in size ethylene glycol (EG) with 0.1%, 0.3%, 0.5%, 0.7% of volume concentrations and 1%. The study reveals a direct relationship between friction factor and weight concentration and a positive correlation between factor of friction and Reynolds number Re and volume concentration. Small alumina particles in ethyl EG improve heat transmission in twin pipe heat exchangers by 20%, enhancing thermophysical properties and reducing friction compared to pure EG.

Also in [22] did an experimental investigation to evaluate the effectiveness of PHE with a raw surface, using carbon dioxide/nafluoride/water as active liquids .The results indicated a direct relationship between the proportional dimensions of the nanoparticles and the surface roughness with respect to the rate of heat transfer in the tin amplitude exchange, also known as PHE. A significant increase in pressure reduction characterizes this correlation, therefore, when evaluating the effect of surface irregularities on the heat exchange width in the plates compared to the effect of nanoparticle size, the previous component appears as the dominant determinant. In addition,coefficient of heat transfer shows an incremental improvement of 2%, 3.7%, and 5.4% for different nanoparticle sizes at 1.2V, 1.9V, and 2.6V, respectively, under a smooth transition state. In contrast, it is well recognized that when the maximum surface clothing reaches 3.657 mcg, the corresponding values show a significant increase of 9.4%, 11.8%, and 13.7%. The gained experimental results have yielded a new experimental relationship to estimate the number of Nusslets based on the liquid medium. The correlation shows a maximum discrepancy of 2.87%.

In [20] The investigation showed that the examined characteristics of SiO_2/water nanofluids for a copper pipe that is exposed to convective heat transfer a raging current. The findings over a wide concentration range reveal that the heat transfer coefficients dramatically improve. 0.001% and 0.007%, with potential factors including particle migration, turbulent motion, fluid fluctuations, and increased Nano fluid thermal conductivity. The greatest boost recorded was 8-9%, with a volumetric concentration of SiO_2 nanoparticles at 0.001%. In contrast, when SiO_2 nanoparticles were present at a volumetric concentration of 0.007%, a notable increase of 27%. The coefficient for heat transmission via convection changed.

Followed by [21] conducted a research on improving heat conduction efficiency through synthesizing nanomaterials and their subsequent evaluation in an experimental coil heat exchangers . The findings demonstrated a significant rise in the proportion of nano-soil to water., hence illustrating the prospective utility of nanoparticles. The most significant rise in the Nusselt number occurred at Nanofluid resulting in enhancements of 15%, 18%, and 22%, respectively. In a similar vein, it was observed that coil B exhibited a maximum increase in the Nusselt number by 14%, 17%, and 20% at Ferrofluid (Ø) of 0.02%, 0.05%, and 0.1%, correspondingly.

Also, it is important to acknowledge that the Nanofluid and Ferrofluid under investigation exhibited volume concentrations of 0.01% and 0.05%. Likewise, the results of the research demonstrate a significant increase in the quantity of water relative to water, a substantial flow rate of nanomaterials mass, and a notable rate of heat transfer. The observed increases in each concentration are 10%, 20%, and 30%. The specification encompasses a large variation in geometric and operational characteristics.

Later in [30] conducted a comparative analysis of heat transport agents under low-pressure and low-temperature conditions inside circular tubes measuring 4.4 mm and 5 mm in diameter. Based on the empirical findings, it can be inferred that altering the concentration of Al_2O_2 and Al_2O_3 in water across five distinct levels does not substantially influence on the Reynolds number. The thermal performance of nanofluids exhibit a reduced temperature transfer factor compared to pure water. However, there has been a minor enhancement in flow.

In the same year [19] did a study in main goal to preliminary examine TiO_2 nanoparticles, combining heat and pressure capabilities to emphasize their self abilities. This analysis was performed within a multiport microchannel, which possesses a hydraulic diameter of 1.22 mm. The outcomes showed that the incorporation nanoparticles of 1% in nanofluid not only yields a mean enhancement of 4.2% in thermal conductivity but also induces a substantial elevation of 14.9% in viscosity. Correlations can be employed to determine density and thermal conductivity precisely in addition to viscosity. Also, it is observed that there is a noticeable improve in heat transfer efficiency and an increase in friction factor. As well,, it is noteworthy that the thermal performance surpasses one within the specified range of Reynolds numbers, namely ranging from 1500 to 2200, where at a Re of 1800, the value is at its highest of 1.57.

As well, in [31] accomplished an experimental investigations that encompassed formulating and analyzing aqueous solutions containing scattered titanium dioxide nanoparticles in a Coiled Flow Inverter (CFI). The primary objective was to investigate the impact of nanofluids on heat transfer in case of forced convective thermal loop. Coefficients of heat transfer due to convection have been measured through the conduction of tests at different Reynolds numbers (Re) values ranging between 1400 and 9500, with volume concentrations of TiO_2 nanoparticles of 0.2% and 1.5%, respectively. A substantial increases of Nusselt numbers (Nu) from 41 to 52% in the coefficient of heat transmission during convection have been experienced when a nanofluid with a volume percentage of 1.0% was introduced, as compared to the pure base fluid, specifically water. The Nu showed up a modest increase of 4 to 8% when utilizing TiO_2/water nanofluid with a volume concentration of 1.5 % in comparison to pure water. Two innovative correlations have been proposed for prediction Nu in CFI circular finned tube when values of Re ranging from 1400 to 9500.

Also, [32] experimentally examineded the effects of slope angle(θ) on the performance of a rocket and tube-warming exchanger employing a shell and helically coiled tube heat exchanger (SHCT-HE) with pure water-based nanofluids, Al_2O_3 /water, and SiO_2/water with different volume concentrations passed through a coiled tube. The values of Reynolds number Re was adjusted from 6000-15000. The outcomes showed a notably increase in Nusselt number of the coil and effectiveness by 35.7% and 35.5%, compared to pure water, respectively. A multiple regression analysis reveals that increasing the inclination angle and elevating the object into a vertical position reduces the Potential Energy Consumption. As well as, In order to determine the Nusselt number of the coil (Nuc) for pure water and Al2O3/water, empirical correlations have been presented, and SiO_2/water nanofluids as a function of Re and angle of inclination.

In [33] conducted an experimental study to assess three different nanofluids within a helical coil apparatus and flow rates varied between 1 and 3 L/s The intake temperatures were set at 30 °C and 60 °C. The inclusion of TiO_2, ZnO and Ag nanoparticles led to improvements in the coefficient of thermal conductivity, with increase of 32%, 21%, and 16%. These improvements were accompanied by rises in the Nu of 27.31%, 16.03%, and 10.38%.

[34] in the same year, used a thermal exchange system including a dual-channel heat exchanger, whereby The utilized cooling fluid was nanofluid composed of multi-wall carbon nanotubes dispersed in water. The experimental findings demonstrated a significant enhancement in heat transfer efficiency when contrasted with pure water application. Furthermore, a correlation has been proposed between the concentration rate of heat transfer and the concentration of multi-wall carbon nanotubes in the Nanofluid. The empirical findings indicate that using Nanofluid, which comprises a water-based solution with a volume content of 0.6 percent of multi-walled carbon nanotubes (MWCNTs), yielded the maximum achievable temperature transmission efficiency via friction, reaching 35 percent. The experimental parameters consisted of a flow rate of 140 L/min and a Dean number of 1400. Based on the available data, it was found that the friction properties of multi-walled carbon nanotubes (MWCNT) were 40% greater than the corresponding qualities of water throughout the specified range of the brigadier-general number, which spans from 1400 to 2400.

As well in [35] conducted experiments and computational study entails evaluating the results of the relationship between total heat transfer coefficient and pressure drop on a counter-flow helical tube's operational efficiency heat exchanger that uses a hybrid nanofluid made of water, nickel, and copper. The technique used for the regulation of nanoparticle sedimentation in the underlying fluid consists of a sequential process that combines ultrasonication and magnetic stirring. The main objective of this study is to investigate methods for raising nanomaterials' heat transport efficiency, with a lesser focus on maintaining their stability. Experiments are conducted to investigate the results of concentration and coil-turn fluctuations in laminar flow circumstances, which are the subject of this investigation. The findings indicate that the Cu-Ni/H_2O solution with a concentration of 0.04% vol and 12 turns is particularly advantageous for food processing purposes, primarily due to its ability to consistently maintain a stable temperature.

Followed by [36] numerically studied the impact of introducing aluminium oxide nanoparticles to the water in heat exchanger with two pipes that are outfitted using six gear disc turbulators . To conduct the experiment, the nanoparticles are injected with concentrations of 1%, 4%, and 6% into a tube carrying a heated fluid. The values of Reynolds number Re ranging between 3000-13000. H_2O is a chilly liquid that is shown to flow having a Re of 500 through the shell. In order to increase the local Nusselt number Nu and the heat transfer rate, it is advisable to increase them by around 70%. Furthermore, the incorporation of nanoparticles within the heat exchanger, along with the integration

of turbulators, results in an augmentation of mean values for the transfer efficiency and Nusselt number.

In [37] carried out an experimental investigation to determine how CuO/water nanofluid with a 0.004% volume percentage, might improve internal temperature exchange in a system that has two pipes running at different temperatures. The study reveals a positive correlation between the rate of heat transmitted and volumetric expression of nanoparticle concentration within a base fluid. The enhancement of using nanofluids for heat transmission is dependent on the properties of nanoparticles, including type, size, shape, and concentration.

Also, in [38] performed an experimental and numerical study to investigate the influence of utilizing of Fe_3O_4 nanoparticles dispersed in filtered water with 20 % Ethylene glycol (EG) as a base fluid on the thermal efficiency of the helically coiled tube heat exchanger (HCHE) .They examined the influence of multiple parameters such as nanoparticles volume concentration, temperature on the coil`s inlet, shell and coil flow velocity, and coil`s diameteron on the heat exchanger heat tranmission. The findings illustrated that with rising the rate of the flow on the coil`s side, the Nusselt number and coefficient of heat transmission become greater. Where the heat transmission coefficient of the nanofluid of Fe3O4/filtered water-EG rises up to 60 % when the volume concentration of nanoparticles is 0.1. As well when the temperature at the coil`s inlet rises from 40-60 , the total Nu rises up to 22 %. In addition, as the flow rate of the nanofluid rises, the coefficient of heat transmission becomes greater.

Later [39] accomplished a numerical study in aim to evaluate the performance of the heat exchanger consisting of a tube and a shell with a helical coil by integrating two passive techniques; utilizing nanofluid and coiled tubes. The evaluation was performed utilizing nanofluids comprising water and multi-walled carbon nanotubes (MWCNT) with volume concentration of 0.1%, 0.3%, and 0.5% and coil`s Reynolds numbers Re ranging from $9\times10^3$-$15\times10^3$. The outcomess showed that the Nu rises when coil`s Re and volume concentration of the nanofluid rise. That is, at volume concentration of 0.5% and coil`s Re of 15×10^3, the Nu and pressure drop become greater up to 31.5% and 47.35%, respectively.

Followed by [40]. in same year, studied the rate of heat transmission, temperature distributions and properties of a Fe_3O_4/water nanofluid flowing in a plate heat exchanger equipped with Y-shaped fractal baffles employing CFD methodology . The pressure drop and convective heat transfer coefficient

Demonstrated a substantial enhancement of 5.85 and 2.36 times, correspondingly, contrasted with the conventional fluid. They put into action numerical simulation means through which to evaluate the performance of Fe_3O_4/water nanofluid. The Nanofluids were characterized by a uniform approximately 30 nm in nanoparticle size, a different The range of nanoparticle volume concentration between 0.2% and 1%, whereas the range of Re between 400 and 1400.

Also, in [41] conducted a numerical investigation utilizing a Al_2O_3/water nanofluid. The nanofluid flows through cylindrical conduit when the intake heat flow and temperature are both constant. They employed ANSYS FLUENT software to analyze Re from 680-2030, revealing a significant improvement in heat transfer efficiency when the twisted tape is combined with nanofluid. The experimental findings demonstrated a slight enhancement from 10-24% in the heat transfer rate.

As well in [42] examined the impacts of adding TiO_2/water nanofluid to a spindle-shaped turbulator in a double-pipe heat exchanger. The investigation's primary emphasis was on the rate of heat transfer and pressure decrease within a state of fluid motion characterized by irregular and chaotic behavior. The results of the experiment suggest that the incorporation of 0.01% nanoparticles volume concentration results in increase of heat transfer coefficient rises by 11.45% in comparison to the base fluid, at Re of 4000 and by 11.91% at a Re of 7000.

Also, in [43] conducted an investigation includes an extensive examination of the characteristics pertaining to heat transport and pressure decrease of Al_2O_3 and SiO_2 nanofluid flow of base oil in a helical tube under continuous heat fluxes. This investigation incorporates both numerical simulations and experimental analyses. The SN-300 base oil was used as the operational medium to create the nanofluid of 0.05%, 0.1%, 0.3%, and 0.5% mass concentrations. The results of the investigation showed that using nanofluid in place of base fluid resulted in the production of a heat transfer coefficient and pressure drop. Regarding SiO_2 and Al_2O_3 nanofluids, the maximum rate of heat transfer is shown at mass concentrations of 0.5%, leading to an increase of 41.4% and 27.3% in comparison to the base oil, respectively. When utilizing a helical tube as opposed to a straight one, the heat transfer efficiency was shown to increase by 19.5%. Moreover, a 6% and 16.5% increase in heat transmission was obtained with a decrease in pitch circle diameter and helical pitch, respectively.

As well in [44] created and built a specialized lab experiment configuration for a horizontal spiral-coil ground heat exchanger (HSGHE). This research sought to determine

The impacts of different CuO/water nanofluid volume concentrations on the energy-efficient solar-driven gas heat exchanger (HSGHE) in a high-temperature system. The results of the experiment show that the CuO/water nanofluid exhibits particular characteristics when it is present at a volumetric concentration of 1%. Significantly, the heat exchange rate of the high-temperature solar-driven gas heat exchanger (HSGHE) has improved by 9.4%. The use of clean water and other substances are contrasted. As the volume percentage of CuO/water nanofluid grew, the high-temperature solar heat generation system's (HSGHE) heat transfer rate increased as well. The measured value showed a significant rise of 9.4% when the volume concentration reached 1% while the fluid was moving at a speed of 0.8 m/s.

Followed by [45] in the same year, accomplished an experimental and computational investigation to examine the effects of the coil inclination on improving heat transmission properties. Al_2O_3/DW nanofluid with a volumetric content of 0.1% was selected. Nanoparticles were enhanced by comparing the heat transfer rate and friction factor with pure water. The rise in coil temperature resulted in a corresponding improvement in heat transmission efficiency. Three experiments were performed on coil with pitches of 20, 35, and 50 mm. Furthermore, a correlation exists between Re and Pr numbers. The nanofluid flow inside the coils establishes the relationship between the coil curvature ratio and Nu.

5. Summary of the Review

The field of nanofluids contains a vast amount of data regarding the alteration of thermophysical properties in traditional fluids through the incorporation of different nanoparticles. These nanofluids give engineers the chance to design small, effective thermal systems and have a great deal of potential for enhancing heat transfer.

This article provides a thorough overview of numerous research that looked into the effects of employing nanoparticles and how they affected the thermophysical properties seen in various conventional fluids, accounting for the variables that varied depending on the type of base fluid.

Many researchers' studies show that the temperature, density of the base fluids, and the kind and size of the nanoparticles all affect how thermally conductible nanofluids are.

Thermal conductivity can be significantly increased by adding solid particles, even at very low concentrations, to a base fluid. Thermal conductivity behavior depends on the Brownian motion and nanoparticle clustering.

When the temperature of the fluids rises and the size of the nanoparticles decreases, it is seen that the thermal conductivity of the fluids increases.. However, Studies on the enhancement of heat conductivity are not in agreement. It has been shown that when the volume concentration of nanoparticles in a fluid increases, the thermal conductivity of the fluid falls because of the instability caused by the agglomeration of nanoparticles. [46]

A model has been proposed by Jiang et al., which takes into account the nano-shell genereted by molecules of the fluid about the nanoparticles to determine the effective thermal conductivity [47]. The model shows that the ratio of the thermal conductivities of the particle and liquid, as well as their respective volume fractions, all affect the thermal conductivity. It also depends on the size and thickness of the interfacial nano-shell surrounding the nanoparticles.

Followed by [49] shown that at a low temperature of 10 °C, ZnO–EG nanofluids display the largest augmentation of the thermal conductivity, despite the general trend of increasing thermal conductivity with temperature observed by various research groups [48]. Interestingly, there was a decrease in thermal conductivity between 10 and 30 °C because of the liquid molecules' organized arrangement's higher thickness. This phenomenon highlights the significant impact of molecular organization on thermal conductivity, even at lower temperatures However, When the temperature rises to between 30 and 60 °C, Brownian motion offsets

the effect of liquid layering on molecular movement, producing a temperature-independent thermal conductivity.

The summary of these suggested papers is listed in Table 1.

6. Conclusion

Based on previous literature, it was found that an increase in the heat transfer coefficient was commonly found while employing nanofluids. It was observed that adding solid nanoparticles to conventional fluids, including water, oil, and ethylene glycol, led to increased thermal improvement by enhancing the thermal conductivity of the nanofluids. It was observed that adding solid nanoparticles to conventional fluids, including water, oil, and ethylene glycol, led to increased thermal improvement by enhancing the thermal conductivity of the nanofluids. It can also be said that the viscosity of the solution has a linear correlation with the concentration of particles and with the concentration of nanoparticles. It is necessary to highlight future challenges including studying the causes of agglomeration and sedimentation of nanoparticles.

List of Acronyms

MWCNT	Multi Walled Carbon Nanotubes
CuO	Copper Oxide
SiO_2	Silicon dioxide
TiO_2	Titanium dioxide
CNT	Carbon nanotube
Al_2O_3	Aluminium oxide
Fe_2O_3	ferric oxide
Ag	Silver
Cu	Copper

Nomenclature

$\emptyset$	Volume fraction of nanoparticles
bf	Bace fluid
nf	Nanofluid
p	particle
q	heat transfer
μ	Dynamic viscosity, Pa.s
ε	Heat exchanger efficiency
i	Inlet
o	Outlet
act	Actual
max	Maximum
D_H	hydraulic diameter
$\emptyset$	volume concentrations
Nu	Nusselt Number
Pr	Prandtl Number
Re	Reynolds Number
NTU	Number of transfer units
T(K)	Temperature, K
L	m
A	m^2
$\dot{m}$	mass Flow rate, kg. s^{-1}
h	Heat transfer coefficient, $W.m^{-2}.k^{-1}$
K	Thermal conductivity $W.m^{-1}.k^{-1}$

References

[1] W. Yu and H. Xie, 'A review on nanofluids: Preparation, stability mechanisms, and applications', J. Nanomater., vol. 2012, 2012, doi: 10.1155/2012/435873.

[2] M. Hashemian, S. Jafarmadar, J. Nasiri, and H. Sadighi Dizaji, 'Enhancement of heat transfer rate with structural modification of double pipe heat exchanger by changing cylindrical form of tubes into conical form', Appl. Therm. Eng., vol. 118, pp. 408–417, 2017, doi: 10.1016/j.applthermaleng.2017.02.095.

[3] M. F. Fakoya and S. N. Shah, 'Emergence of nanotechnology in the oil and gas industry: Emphasis on the application of silica nanoparticles', Petroleum, vol. 3, no. 4, pp. 391–405, 2017, doi: 10.1016/j.petlm.2017.03.001.

[4] S. U. S. Choi, 'Enhancing thermal conductivity of fluids with nanoparticles', Am. Soc. Mech. Eng. Fluids Eng. Div. FED, vol. 231, pp. 99–105, 1995.

[5] P. Kumar and R. M. Sarviya, 'Recent developments in preparation of nanofluid for heat transfer enhancement in heat exchangers: A review', Mater. Today Proc., vol. 44, pp. 2356–2361, 2021, doi: 10.1016/j.matpr.2020.12.434.

[6] M. M. Elias et al., 'Effect of nanoparticle shape on the heat transfer and thermodynamic performance of a shell and tube heat exchanger', Int. Commun. Heat Mass Transf., vol. 44, pp. 93–99, 2013,doi:10.1016/j.icheatmasstransfer.2013.03.014

[7] M. L. Levin and M. A. Miller, 'Maxwell's "Treatise on Electricity and Magnetism"', Uspekhi Fiz. Nauk, vol. 135, no. 11, p. 425, 1981, doi: 10.3367/ufnr.0135.198111d.0425.

[8] B. Çuhadaroğlu and M. S. Hacisalihoğlu, 'An experimental study on the performance of water-based CuO nanofluids in a plate heat exchanger', Int. Commun. Heat Mass Transf., vol. 137, 2022,doi:10.1016/j.icheatmasstransfer.202 2.10625.

[9] Dusan P. Sekulic, Ramesh K. Shah, "Fundamentals of Heat Exchanger Design", ISBN 978-1119883265

[10] N. Nikkam, Engineering Nanofluids for Heat Transfer Applications. 2014.

[11] S. Kalsi, S. Kumar, A. Kumar, T. Alam, and D. Dobrotă, 'Thermophysical properties of nanofluids and their potential applications in heat transfer enhancement: A review', Arab. J. Chem., vol. 16, no. 11, 2023, doi: 10.1016/j.arabjc.2023.105272.

[12] S. R. Chaurasia and R. M. Sarviya, 'Thermo-hydraulic Analysis of Helical Screw Twist Tape with Cuo/Water Nanofluid', SSRN Electron. J., 2019, doi: 10.2139/ssrn.3466220.

[13] S. R. Chaurasia and R. M. Sarviya, 'Thermal performance analysis of CuO nanofluid flow in a pipe with helical screw twist tape', Mater. Today Proc., vol. 18, pp. 3546–3555, 2019, doi: 10.1016/j.matpr.2019.07.285.

[14] S. R. Chaurasia and R. M. Sarviya, 'Thermal performance analysis of CuO/water nanofluid flow in a pipe with single and double strip helical screw tape', Appl. Therm. Eng., vol. 166, no. May 2019, p. 114631, 2020, doi: 10.1016/j.applthermaleng.2019.114631.

[15] P. K. Namburu, D. K. Das, K. M. Tanguturi, and R. S. Vajjha, 'Numerical study of turbulent flow and heat transfer characteristics of nanofluids

considering variable properties', Int. J. Therm. Sci., vol. 48, no. 2, pp. 290–302, 2009, doi: 10.1016/j.ijthermalsci.2008.01.001.

[16] Duangthongsuk W, Wongwises S. Effect of thermophysical properties models on the prediction of the convective heat transfer coefficient for low concentration nanofluid. International Communications in Heat and Mass Transfer 2008;35:1320.

[17] Duangthongsuk W, Wongwises S. An experimental study on the heat transfer performance and pressure drop of TiO2/water nanofluids flowing under a turbulent flow regime. International Journal of Heat and Mass Transfer, 54; 334–44.

[18] A. Vărdaru, G. Huminic, A. Huminic, C. Fleacă, F. Dumitrache, and I. Morjan, 'Aqueous hybrid nanofluids containing silver-reduced graphene oxide for improving thermo-physical properties', Diam. Relat. Mater., vol. 132, no. September 2022, 2023, doi: 10.1016/j.diamond.2023.109688.

[19] D. Zhong, H. Zhong, and T. Wen, 'Investigation on the thermal properties, heat transfer and flow performance of a highly self-dispersion TiO2 nanofluid in a multiport mini channel', Int. Commun. Heat Mass Transf., vol. 117, 2020, doi: 10.1016/j.icheatmasstransfer.2020.10478.

[20] Hafiz Muhammad Ali, 'In tube convection heat transfer enhancement: SiO2 aqua based nanofluids', Journal of Molecular Liquids, vol. 308, 2020, 113031. doi: 10.1016/j.molliq.2020.113031.

[21] A. H. Mola, A. H. Askar, and G. K. Salman, 'Experimental Enhancement of Helical Coil Tube Heat Exchanger Using CuFe2O4/Water Nanofluids', J. Mech. Eng. Res. Dev., vol. 43, no. 6, pp. 94–105, 2020.

[22] M. Attalla and H. M. Maghrabie, 'An experimental study on heat transfer and fluid flow of rough plate heat exchanger using Al2O3/water nanofluid', Exp. Heat Transf., vol. 33, no. 3, pp. 261–281, 2020, doi: 10.1080/08916152.2019.1625469.

[23] A. F. Chen, M. Akmal Adzmi, A. Adam, M. F. Othman, M. K. Kamaruzzaman, and A. G. Mrwan, 'Combustion characteristics, engine performances and emissions of a diesel engine using nanoparticle-diesel fuel blends with aluminium oxide, carbon nanotubes and silicon oxide', Energy Convers. Manag., vol. 171, pp. 461–477, 2018, doi: 10.1016/j.enconman.2018.06.004.

[24] R. T. Wang and J. C. Wang, 'Intelligent dimensional and thermal performance analysis of Al2O3 nanofluid', Energy Convers. Manag., vol. 138, pp. 686–697, 2017, doi: 10.1016/j.enconman.2017.02.010.

[25] H. T. Zhu, Y. S. Lin, and Y. S. Yin, 'A novel one-step chemical method for preparation of copper nanofluids', J. Colloid Interface Sci., vol. 277, no. 1, pp. 100–103, 2004, doi: 10.1016/j.jcis.2004.04.026.

[26] D. Zhu, X. Li, N. Wang, X. Wang, J. Gao, and H. Li, 'Dispersion behavior and thermal conductivity characteristics of Al2O3/H2O nanofluids', Curr. Appl. Phys., vol. 9, no. 1, pp. 131–139, 2009, doi: 10.1016/j.cap.2007.12.008.

[27] M. L. G. Ho, C. S. Oon, L. Tan, Y. Wang, and Y. M. Hung, 'Results in Engineering A review on nanofluids coupled with extended surfaces for heat transfer enhancement', vol. 17, no. September 2022, 2023, doi: 10.1016/j.rineng.2023.100957.

[28] M. U. Sajid and H. M. Ali, 'Recent advances in application of nanofluids in heat transfer devices: A critical review', Renew. Sustain. Energy Rev., vol. 103, no. December 2018, pp. 556–592, 2019, doi: 10.1016/j.rser.2018.12.057.

[29] F. A. Ali, A. M. Alsaffawi, and K. H. Mohammed, 'The impact of alumina nanoparticles suspended in ethylene glycol on the performance efficiency of a double pipe heat exchanger', Front. Heat Mass Transf., vol. 15, no. 1, 2020, doi: 10.5098/hmt.15.21.

[30] A. Briclot, J. F. Henry, C. Popa, C. T. Nguyen, and S. Fohanno, 'Experimental investigation of the heat and fluid flow of an Al2O3/water nanofluid in the laminar-turbulent transition region', Int. J. Therm. Sci., vol. 158, no. September 2019, p. 106546, 2020, doi: 10.1016/j.ijthermalsci.2020.106546.

[31] Barbara Arevalo-Torres, Jose L. Lopez-Salinas and Alejandro J. García-Cuéllar, 'Experimental study of forced convective heat transfer in a coiled flow inverter using TiO2-water nanofluids', Appl. Sci., vol. 10, no. 15, 2020, doi: 10.3390/APP10155225.

[32] Hussein M. Maghrabie, M. Attalla and Abrar A. A. Mohsen, 'Performance assessment of a shell and helically coiled tube heat exchanger with variable orientations utilizing different nanofluids', Appl. Therm. Eng., vol. 182, no. March 2020, p. 116013, 2021, doi: 10.1016/j.applthermaleng.2020.116013.

[33] Osama Hozien, Wael M. El-Maghlany, Medhat M. Sorour and Yasser S. Mohamed, 'Experimental study on thermophysical properties of TiO2, ZnO and Ag water base nanofluids', J. Mol. Liq., vol. 334, pg. 116-128, 2021, doi: 10.1016/j.molliq.2021.116128.

[34] P. C. Mukesh Kumar and M. Chandrasekar, 'Heat transfer and friction factor analysis of MWCNT nanofluids in double helically coiled tube heat exchanger', J. Therm. Anal. Calorim., vol. 144, no. 1, pg. 219-231, 2021, doi: 10.1007/s10973-020-09444-x.

[35] D. Sarath Chandra, OmprakashHebbal, K.Vijayakumar Reddy, 'Experimental analysis of heat transfer coefficient in counter flow shell and helical coil tube heat exchanger with hybrid nanofluids to enhance heat transfer rate using in food processing industries', Turkish Journal of Computer and Mathematics Education, Vol.12(2), 2021, pg. 2868-2875 2021.

[36] Iman Bashtani, Javad Abolfazli Esfahani and Kyung Chun Kim, 'Effects of water-aluminum oxide nanofluid on double pipe heat exchanger with gear disc turbulators: A numerical investigation', J. Taiwan Inst. Chem. Eng., vol. 124, pp. 63–74, 2021, doi: 10.1016/j.jtice.2021.05.001.

[37] R. Kavitha, Yousef Methkal Abd Algani, Kaustubh Kulkarni, and MK. Gupta, 'Heat transfer enhancement in a double pipe heat exchanger with copper oxide nanofluid: An experimental study', Mater. Today Proc., vol. 56, pp. 3446–3449, 2022, doi: 10.1016/j.matpr.2021.11.096.

[38] Afshin Ghaderi, Farzad Veysi, Saman Aminian, Zahra Andami and Mohammad Najafi, 'Experimental and Numerical Study of Thermal Efficiency of Helically Coiled Tube Heat Exchanger Using Ethylene Glycol-Distilled Water Based Fe3O4 Nanofluid', Int. J. Thermophys., vol. 43, no.

8, pp. 1–28, 2022, doi: 10.1007/s10765-022-03041-w.

[39] M. Basit Shafiq, Usman Allauddin, Mumtaz A. Qaisrani, Tauseef-ur- Rehman, Naveed Ahmed, M. Usman Mushtaq and Hafiz Muhammad Ali, 'Thermal performance enhancement of shell and helical coil heat exchanger using MWCNTs/water nanofluid', Journal of Thermal Analysis and Calorimetry, Volume 147, pages 12111–12126, (2022). doi: 10.1007/s10973-022-11405-5.

[40] Sirine Chtourou, Hassene Djemel, Mohamed Kaffel and Mounir Baccar, 'Numerical Analysis of Fe3O4 Nanofluids Flow in Plate Heat Exchangers Fitted with Fractal Y-Shaped Obstacles', International Journal of Fluid Mechanics Research, vol. 49(6), pp. 19-34, 2022, doi:10.1615/InterJFluidMechRes.2022043608.

[41] Santinath Bairagi, Ranendra Roy and Bijan Kumar Mandal, 'Heat Transfer Enhancement in Laminar Pipe Flow Using Al2O3–Water Nanofluid and Twisted Tape Inserts', J. Therm. Sci. Eng. Appl., vol. 15, no. 8, pp. 1–12, 2023, doi: 10.1115/1.4062433.

[42] Mohsen Izadi, Hashim M. Alshehri, Fazel Hosseinzadeh, Mozafar Shokri Rad and Mohamed Bechir Ben Hamida, 'Numerical study on forced convection heat transfer of TiO2/water nanofluid flow inside a double-pipe heat exchanger with spindle-shaped turbulators', Engineering Analysis with Boundary Elements, vol. 150, pp. 612–623, 2023, doi: 10.1016/j.enganabound.2023.02.046.

[43] SeyedMahmood Kia, Shoaib Khanmohammadi and Ali Jahangiri,' Experimental and numerical investigation on heat transfer and pressure drop of SiO2 and Al2O3 oil-based nanofluid characteristics through the different helical tubes under constant heat fluxes', International Journal of Thermal Sciences, Volume 185, March 2023, 108082.doi.org/10.1016/j.ijthermalsci.2022.108082

[44] Qinggong Liu, Yao Tao, Long Shi, Tingzheng Zhou, Yi Huang, Yuanling Peng, Yong Wang and Jiyuan Tu, 'Experimental investigation on the use of CuO/water nanofluid in horizontal spiral-coil ground heat exchanger', Int. J. Refrig., vol. 149, May 2023, pp. 204–223, 2023, doi: 10.1016/j.ijrefrig.2022.12.011.

[45] Mustafa Sabah Abdullah and Adnan M. Hussein, 'Impact of coil pitch on heat transfer enhancement of a turbulent flow of α-Al2O3/DW nanofluid through helical coils', Therm. Sci., pp. 131–131, 2023, doi: 10.2298/tsci230227131a.

[46] Sahooli M, Sabbaghi S. 'Investigation of thermal properties of CuO nanoparticles on the ethylene glycol–water mixture'. Mater Lett 2013;93:254–7

[47] Jiang H, Li H, Xu Q, Shi L. ,'Effective thermal conductivity of nanofluids considering interfacial nano-shells', Mater Chem Phys 2014;148(1):195–200.

[48] Suganthi KS, Radhakrishnan AK, Anusha N, Rajan KS., 'Influence of Nanoparticle Concentration on Thermo-Physical Properties of CuO-Propylene Glycol Nanofluids', J Nanosci Nanotechnol 2014;14(6):4602–7.

[49] Suganthi KS, Parthasarathy M, Rajan KS., 'Liquid-layering induced, temperature dependent thermal conductivity enhancement in ZnO – propylene glycol nanofluids', Chem Phys Lett 2013;561:1204.

Table 1. A summary of the literature on heat transfer enhancement

No.	Author (year, journal)	Title	Nanomaterial	Type of study	Volume concentration	Flow regime	Results
1	Ali et al., 2020 [27] Frontiers in Heat and Mass Transfer	The Impact of Alumina Nanoparticles Suspended In Ethylene Glycol on The Performance Efficiency of a Double Pipe Heat Exchanger	Al_2O_3/EG	Experimental	0.1%, 0.3%, 0.5%, 0.7%, 1%	Turbulent	The experiments demonstrated that ethylene glycol thermophysical properties can be improved by up to 20% when dispersed alumina is used in nanofluids, resulting in increased heat transfer and friction factor
2	Muhammad, 2020 [28] Journal of Molecular Liquids	In tube convection heat transfer enhancement: SiO_2 aqua-based nanofluids	SiO_2/water	Experimental	0.001%, 0.003%, 0.007%	Turbulent	The results showed that the best efficiency of 27% in the heat transfer coefficient by convection was achieved when using a volumetric concentration of 0.007% when using nanoparticles. (SiO2)
3	Mola et al., 2020 [29] Journal of Mechanical Engineering Research and Developments	Experimental Enhancement of Helical Coil Tube Heat Exchanger Using $CuFe_2O_4$/Water Nanofluids	$CuFe_2O_4$/Water	Experimental	0.02%, 0.05%, 0.1 %	Turbulent	The results showed that the heat transfer rate was improved, as was the mass flow rate of the nano instead of water. The best efficiency between 10% - 30% was achieved when using different volumetric concentrations ranging from (0.02-0.1)% .
4	Attalla & Maghrabie, 2020 [30] Experimental Heat Transfer	An experimental study on heat transfer and fluid flow of rough plate heat exchanger using Al_2O_3/water nanofluid	Al_2O_3/Water	Experimental	1.2 %, 1.9 %, 2.6 %	Laminar flow	The results of the empirical study showed that maximum improvement was achieved HTEF ranging from 2% to 5.4%. In addition to the noticeable improvement in the performance of PHE on rough surfaces compared to smooth surfaces,. Furthermore, the heat transfer rate has been enhanced in conjunction with the volumetric part of the nanoparticles, accompanied by pressure drop PEF. with a maximum deviation of 2.87%

No.	Author (year, journal)	Title	Nanomaterial	Type of study	Volume concentration	Flow regime	Results
5	Briclot et al., 2020 [31] International Journal of Thermal Sciences	Experimental investigation of the heat and fluid flow of an Al_2O_3-water nanofluid in the laminar-turbulent transition region	Al_2O_3/Water	Experimental	5w%	Laminar-turbulent	The results showed that increasing the concentration leads to an increase in pressure drop strongly, regardless of the flow, and the noticeable improvement in the heat transfer coefficient by convection, and the effect of pressure drop in a round pipe with an outer diameter of 5 mm and an inner diameter of 4.4 mm.
6	Zhong et al., 2020 [32] International Communications in Heat and Mass Transfer	Investigation on the thermal properties, heat transfer and flow performance of a highly self-dispersion TiO_2 nanofluid in a multiport mini channel	TiO_2	Experimental	0.5% , 1%	Laminar-turbulent	obtained results revealed improving performance in the heat transfer rate by conduction by 4.2%, in addition to a noticeable improvement and increase in viscosity by 14.9% and friction factors with a volumetric concentration of the nanofluid by 1%.
7	Arevalo-Torres et al., 2020 [33] Applied Sciences (Switzerland)	Experimental Study of Forced Convective Heat Transfer in a Coiled Flow Inverter Using TiO_2–Water Nanofluid	TiO_2/Water	Experimental	0.2 – 1.0 % and 0.2 – 1.5 %	Turbulent	The findings demonstrated how the coiled flow inverter's (CFI) curved geometry and heat exchanger's geometry affected the reinforcement through a series of bends and coils in addition to enhancing heat transfer as indicated by an improvement in the working fluid's thermophysical characteristics. (1400–9550)
8	Sunu et al., 2020 [49] Journal of Physics: Conference Series	Study of thermal effectiveness in shell and helically coiled tube heat exchanger with addition nanoparticles	Al_2O_3 /Water (cold fluid) R-22 (Hot fluid)	Experimental	0.10%	Laminar flow	The results showed the effect of nanoparticles on the tube coiled inside the heat exchanger to promote heat transfer by convection negatively and logarithmic temperature difference (LMTD) Also under the influence of nanoparticles, in addition to increasing the efficiency of the heat exchanger up to 2.2%

No.	Author (year, journal)	Title	Nanomaterial	Type of study	Volume concentration	Flow regime	Results
9	Abdullah & Alsaffawi, 2020 [20] International Journal of Thermal Engineering	Enhancement of Heat Exchanger Effectiveness by Using Water- Al_2O_3 as a working substance	Al_2O_3/water	Experimental and Numerical	0.50%	Turbulent	The investigation showed that improvement in the performance of the heat exchanger of the double tube type with the opposite flow, the maximum efficiency rate obtained was 31%, and using the ANSYS FLUENT program to estimate the effectiveness of the HE
10	Hozien et al., 2021 [34] Journal of Molecular Liquids	Experimental study on thermophysical properties of TiO_2, ZnO and Ag water base nanofluid	TiO_2, ZnO, and Ag/water	Experimental	0.25%.	Laminar flow	The results showed increases of 32%, 21%, and 16% in the heat transfer coefficient, These improvements were accompanied by rises in the Nu of 27.31%, 16.03%, and 10.38%.
11	Mukesh Kumar & Chandrasekar, 2021 [35] Journal of Thermal Analysis and Calorimetry	Heat transfer and friction factor analysis of MWCNT nanofluids in double helically coiled tube heat exchanger	MWCNT/water	Experimental	0.2%–0.6%	Laminar flow	The investigation showed that the nanofluid with 0.6% MWCNTs, containing water, achieved a 35% convective heat transfer efficiency under specific conditions.
12	Chandra & Reddy, 2021 [47] Turkish J. of Comput. and Mathematics Education	Experimental analysis of heat transfer coefficient in counter flow shell and helical coil tube heat exchanger with hybrid nanofluids to enhance heat transfer rate using in food processing industries	Cu-Ni/Water	Experimental	0.02%,0.04% and 0.06 %	Laminar flow	The investigation showed that the Cu-Ni/H2O solution with a 0.04% concentration could be quite beneficial for maintaining constant temperatures, especially in food preservation. The relationship between pressure drop and heat transfer coefficient in the counter-flow spiral tube highlights its operational efficiency.
13	Maghrabie et al., 2021 [37] Applied Thermal Engineering	Performance assessment of a shell and helically coiled tube heat exchanger with variable orientations utilizing different nanofluids	Al_2O_3 and SiO_2/Water	Experimental	0.1 %, 0.2 %, and 0.3%	Laminar-turbulent	The inclination angle (θ) impact on the performance of the shell heat exchanger and spirally coiled tube (SHCT-HE) with increasing the angle enhances the Nu and effectiveness of the SHCT-HE, and reduce pressure and improve Nu by 11–7.5%.

No.	Author (year, journal)	Title	Nanomaterial	Type of study	Volume concentration	Flow regime	Results
14	Bashtani et al., 2021 [50] Journal of the Taiwan Institute of Chemical Engineers	Effects of water-aluminum oxide nanofluid on double pipe heat exchanger with gear disc turbulators: A numerical investigation	Al_2O_3/water	Numerical	1%, 4%, and 6%	Turbulent	The collision of fluid with turbulator surfaces and boundary layer disruption notably increases heat transfer and local Nu by approximately 70%. Additionally, incorporating nanoparticles in the heat exchanger along with turbulators further boosts the average Nu, showcasing promising enhancements in heat transfer efficiency.
15	Kavitha et al., 2022 [38] Materials Today: Proceedings	Heat transfer enhancement in a double pipe heat exchanger with copper oxide nanofluid: An experimental study	CuO/Water	Experimental	0.002%, 0.003% and 0.004%	Laminar	The investigation showed that the Copper oxide nanoliquids appear heat transfer in the heat exchanger, particularly at high thermal and volumetric nanoparticle concentrations. Additionally, using a parallel flow arrangement in a double pipe heat exchanger leads to an increase in the average heat transfer coefficient.
16	Ghaderi et al., 2022 [39] International Journal of Thermophysics	Experimental and Numerical Study of Thermal Efficiency of Helically Coiled Tube Heat Exchanger Using Ethylene Glycol-Distilled Water Based Fe_3O_4 Nanofluid	Fe_3O_4/Water - Ethylene Glyco	Experimental and Numerical	0.10%	Turbulent	The investigation showed that revealed that incorporating copper oxide nanofluids at various concentrations of thermocouple and volumetric nanoparticles improves heat transfer in the heat exchanger. Furthermore, employing a parallel flow arrangement in a two-pipe heat exchanger leads to an increased average heat transfer coefficient.

No.	Author (year, journal)	Title	Nanomaterial	Type of study	Volume concentration	Flow regime	Results
17	Basit Shafiq et al., 2022 [40] Journal of Thermal Analysis and Calorimetry	Thermal Performance Enhancement of Shell and Helical Coil Heat Exchanger Using Mwcnts/Water Nanofluid	MWCNT/water	Numerical	0.1%, 0.3% and 0.5%	Turbulent	Numerical experiments showed improvement in combining the two opposite methods, performing numerical simulations, and taking into account the flow of cold liquid through the shell and hot liquid through the spiral coil, which led to improved thermal performance of the heat exchangers. The results indicated an increase in the flow of Neslate fluid through the coil with a higher Reynolds number (Re) of the coil and a concentration of nanofluid volume, while the maximum pressure decreased by 40.5%.
18	Chtourou et al., 2022 [41] International Journal of FluidMechanics Research	Numerical Analysis of Fe_3O_4 Nanofluids Flow in Plate Heat Exchangers Fitted with Fractal Y-Shaped Obstacles	Fe_3O_4/water	Numerical	0.2 %–1%	Laminar	Convection heat transfer rate, and fluid flow properties, revealing a 5.85% and 2.36% reduction in pressure drop.
19	Bairagi et al.,2023 [42] Journal of Thermal Science and Engineering Applications	Heat Transfer Enhancement in Laminar Pipe Flow Using Al_2O_3–Water Nanofluid and Twisted Tape Inserts	Al_2O_3	Numerical	5%	Laminar	A significant improvement in energy transfer and heat transfer efficiency when combined with nanofluid, with an increase in friction factor proportional to the nanoparticles' size ratio. The optimal thermo-hydraulic performance was achieved with nanofluids..

No.	Author (year, journal)	Title	Nanomaterial	Type of study	Volume concentration	Flow regime	Results
20	Izadi et al., 2023 [43] Engineering Analysis with Boundary Elements	Numerical study on forced convection heat transfer of TiO_2/water nanofluid flow inside a double-pipe heat exchanger with spindle-shaped turbulators	TiO_2/water	Numerical	0.01%	Turbulent	The findings indicate that incorporating nanoparticles at a volumetric fraction of 0.01 into the original fluid enhances the heat transfer coefficient by 11.45% at Re 4000 and 11.91% at Re 7000, compared to the base fluid's performance.
21	Kia et al., 2023 [44] International Journal of Thermal Sciences	Experimental and numerical investigation on heat transfer and pressure drop of SiO_2 and Al2O3/oil-based nanofluid characteristics through the different helical tubes under constant heat fluxes	SiO_2, Al_2O_3	Experimental and numerical	0.05%, 0.1%, 0.3%, and 0.5%	laminar flow	The study found that nanofluid increased heat transfer factor and pressure drop over base fluid, with Al2O3 nanofluid showing a higher enhancement in heat transfer coefficient compared to SiO_2 nanofluid. Peak heat transfer rates were observed at 0.5% mass concentrations for Al2O3 and SiO2 nanofluids, resulting in 41.4% and 27.3% improvements over base oil, respectively. Using a helical tube increased heat transfer by 19.5%.
22	Liu et al., 2023 [45] International Journal of Refrigeration	Experimental investigation on the use of CuO/water nanofluid in horizontal spiral-coil ground heat exchanger	CuO/water	Experimental	0.5%-1 %		The study found that a 1% volumetric fraction of When compared to water, the CuO/water nanofluid enhanced the HSGHE's heat exchange rate by 9.4%. Its viscosity has less of an effect on the HSGHE's performance than this heat transfer enhancement. However, the 1% volume fraction was deemed unsuitable due to a performance efficiency coefficient (PEC) of less than 1, with the optimal volume fraction of 0.5% achieving the highest PEC value of 1.025.

No.	Author (year, journal)	Title	Nanomaterial	Type of study	Volume concentration	Flow regime	Results
23	Abdullah &Hussein, 2023 [46] Thermal Science	Impact Of Coil Pitch on Heat Transfer Enhancement of A Turbulent Flow of - Al_2o_3/Dw Nanofluid Through Helical Coils	AL2O3/DW	Experimental and numerical	0.1%.	Turbulent	Increased temperature led to an improvement in heat transfer efficiency. there is a link between the Nu associated with the flow of nanofluids inside a coil and the curvature of such coil.
24	Ghaderi et al., 2022 [47] International Journal of Thermophysics	Experimental and Numerical Study of Thermal Efficiency of Helically Coiled Tube Heat Exchanger Using Ethylene Glycol-Distilled Water Based Fe3O4 Nanofluid	Fe3O4/ Ethylene glycol (EG)	Experimental and numerical	0.03%, 0.06%, & 0.1%	Turbulent	The heat transfer coefficients and Nu increase with the nanofluid flow rate. The rate of heat transfer improvement increased by around 60% at a volume concentration of 0.1% (Ø) of nanoparticles. The Nu rises by 22%.
25	Bhattad, Sarkar, and Ghosh 2019 [48] Applied Thermal Engineering	Experimentation on effect of particle ratio on hydrothermal performance of plate heat exchanger using hybrid nanoflui	Al_2O_3–MWCNT	Experimental	0.01 %		The enhanced performance of Al_2O_3-MWCNT/Water hybrid nanofluid over Al_2O_3/Water nanofluid is attributed to the higher thermal conductivity of MWCNT compared to Al_2O_3. The heat transfer coefficient for MWCNT nanofluid shows a notable improvement of 15.2%, accompanied by a minimal 0.02% increase in pump work and a 2.96% boost in the performance index under hydrothermal conditions
26	Returi et al. 2019 [51] Wiley	Heat transfer enhancement using hybrid nanofluids in spiral plate heat exchangers	Al_2O_3-CuO/H_2O Al_2O_3-TiO_2/H_2O	Numerical	4%		Maximum 16%–27% increase in heat transfer rate using hybrid nanofluids, performance of (SPHE) in comparison with the use of nanofluids
27	Nabi et al., 2022 [52] Case Studies in Thermal Engineering	Increasing heat transfer in flat plate solar collectors using various forms of turbulence-inducing elements and CNTs-CuO hybrid nanofluids	SWCNT-CuO/H_2O	Numerical	1, 3, and 5%	Turbulent	Elevated concentrations of SWCNT-CuO/water result in higher heat transfer coefficients and friction factors. Specifically, at the lowest Rey of 4000, the friction factor rises by 2.7%, 7.7%, and 12.3%.

No.	Author (year, journal)	Title	Nanomaterial	Type of study	Volume concentration	Flow regime	Results
28	Singh Sokhal et al., 2022 [53] Materials Today: Proceedings	Role of hybrid nanofluids on the performance of the plate heat exchanger: Experimental study	Al_2O_3 - CuO	Experimental	0.1 % to 0.5 %		Maximum heat transfer coefficient at the nanofluid inlet's highest temperature and Re. Also, 30% enhancement in the heat transfer coefficient upon the introduction of nanoparticles.
29	Bantan et al., 2023 [54] Alexandria Engineering Journal	Heat transfer improvement of hybrid nanofluid with use of twisted tapes within a heat exchanger	(MWCNT + Al2O3) / H2O	Numerical	0.04%	Laminar	Operating at Re of 200 with increased permeability, there's a decrease of approximately 3.03% and 87.15% in Nu and pressure drop, higher pressure drop results in an increase of about 6.87% and 89.01% in Nu and Dp, respectively.
30	Nadeem et al., 2023 [55] Case Studies in Thermal Engineering	Numerical investigation of the influence of hybrid nano-fluid on heat transfer in semi-annular channel	SWCNT and MWCNT	Numerical	0.01% to 0.1%		Lower curved walls exhibit more efficient convection heat transfer and raising the volume percentage of nanoparticles leads to increased pressure