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Numerical and Experimental Studies of the Nanofluid Characteristics that Effects on Heat Transfer Enhancement: Review and Comparison

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ABSTRACT

This review describes and compare the recent studies for numerical and experimental researches in the improvement of Nanofluid on flow, thermal conductivity, and heat transfer for various heat exchanger applications. The Nanofluid consists of two parts which are nanoparticles and base fluid. This study investigated nanoparticles' and base fluid's effects separately—the main preparation techniques and latest heat exchanger applications that used nanofluid technology, which has been touched upon. Nanofluid technology is one of the hot topics and high Impact that researchers have worked on in the latest decades. Therefore, this review paper investigated and collected the data from the latest results in this area based on nanofluid characteristics and effects of particle material, volume concentration, particle size, particle shape, fluid temperature, acidity, magnetic field, and electrical pulsing individually. Many recent studies were recast using a common parameter to settle comparisons of data between the research group in the same study and conditions to identify its thermal enhancement. The latest trends of nanofluid technology have been stated in this research alongside the recommendations for future studies that present the leaks in each area of study. Heat transfer enhancement has been increased in different nanofluids, metallic, non-metallic, organic, inorganic and hybrid, by up to 300%.

1. Introduction

The latest trends of technological development in mechanical and thermal systems refer to the necessity of increasing the thermal efficiency in these systems. Thus, many researchers have studied the heat transfer enhancement inactive, passive, or hybrid methods. The first found of nanotechnology in Mesopotamia, and artists they used that for a glittering effect on the surface of the pots [1]. Medieval artisans used a suspension of gold nanoparticles for their windows to make deep red colours without knowing their secrets. In the 15th century in Italy, ceramicists used metallic nanoparticles dispersed in a liquid to make shininess pottery [2]. The term "nanofluid" was stated by Sus [3]; he refers to a liquid containing a dispersion of submicronic solid particles (nanoparticles) with

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a particle size of 1–50 nm. Nanofluid is a suspension of nanometer-sized particles or fibers in a liquid called (base fluid). These additional particles will effect on physical properties of the base fluid, e.g., density, viscosity, specific heat, and thermal conductivity. Lately, many researchers studied the changing of base fluid from pure Water to a liquid more efficiently by adding a liquid, like ethylene glycol, to create a high thermal conductivity fluid. Many review papers agreed that the addition of nanoparticles and the changing of base fluid gave the systems high performance, but those review papers didn't make a comparative analysis between the experimental and simulation studies in this field or didn't mention the characteristics that effect of the heat transfer enhancement of these thermal applications [4-8] Many studies determined the thermal conductivity of different nanoparticles in various fluids with volume concentrations between (0.1-4%) they found an enhancement in the system of 4.9-50% compared to its base fluid. Convection I the study of heat transport processes effected by the flow of fluids [9]. Convection has three types; natural convection is a phenomenon in which the fluid motion is driven by buoyancy forces due to the variation in density by temperature difference [10]. Force convection means that an external force device, such as a pump, is used to promote the fluid motion for the process. Mixed convection is a unique case of the convective transportation phenomenon; it's a mixing of natural and forced convection, which occurs in heat exchangers, solar panel systems, and most electronic cooling systems.

Nanofluid is liquid content of metallic (Fe_2O_3, Au, Ag Al_2O_3), non-metallic (silica, ceramic, glass), organic (proteins, sugars), inorganic (calcium phosphates), friendly environmental (roots, stems, leaves, bulbs) or hybrid nanoparticles ($MgFe_2O_4$, Al_2O_3+Cu) with a 0.1-100nm size suspended in a base fluid, such as water, ethylene glycol, glycerine, acetone, etc. [11-13]. In recent years, it has been noticed that the addition of nanosized particles to the base fluid can improve its thermal conductivity. This research presents the latest enhancement in each character that can change the thermal conductivity and the heat transfer quantity; this research aims to aggregate the latest research on the nanofluid technology to simplify to the researchers about the latest trends and the recommendations for new researchers based on authors' knowledge. Many researchers applied this magnificent fluid in many heat exchanger applications that will enhance the heat transfer coefficient, which increases the heat exchanger efficiency [14]. Several review papers have been published concerning the synthesis and applications of the usage of nanofluids [15]. The Nanofluid is regarded as a novel class technique to optimize the heat transfer efficiency of the heat exchangers owing to the high dispensability of the nanoparticles within the base fluid and the high stability of the suspension. Figure 1 shows the Nusselt number increasing for different nanofluids. Bazdar *et al.,* [16] studied the effects of changing the wavelength of the sinusoidal microchannel and CuO nanofluid on flow and heat transfer properties. The flow was simulated at Reynolds numbers range of 3000-7500 with volume fractions of 0, 1.5, and 3%. Figure 1 presented the Nu result of this study. Table 1 shows the heat transfer enhancement or thermal conductivity of many studies in the nanofluid area.

Bisheh *et al.,* [17] investigated the Impact of hybrid nanofluids (Ag-TiO_2/Water) at 1.5-3-6% concentration with10000-18000 Re on improving the performance of a heat exchanger with turbulent induction elements and concluded that the heat transfer coefficient had increased by 52% at 6% of Ag-TiO_2/ Water. Elfaghi *et al.,* [18] studied the Forced Convection Heat Transfer Enhancement in Pipes numerically Using Al_2O_3/Water Nanofluid with (0.5-1-2% of concentration) in the Reynolds number range from 6000 to 12000. The Nusselt number results are shown in Figure 1. Hybrid DWCNT-TiO2 /water nanofluid has been investigated by Zheng *et al.,* [19] on the influence of the shape of the vortex generator on fluid flow and turbulent heat transfer in a channel. The results show that the heat transfer gains higher performance with the usage of the hybrid nanofluid.

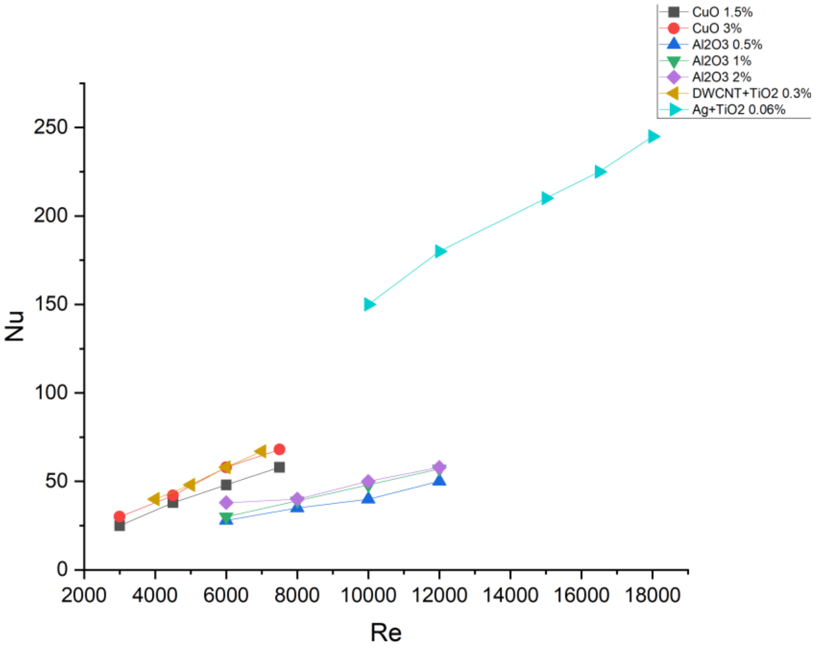

Fig. 1. Nusselt number increase for different nanofluids

Table 1
Heat transfer enhancement or thermal conductivity of many studies in the nanofluid area

Reference	Method	Nanoparticles	Base fluid	Geometry and Flow	Enhancement
Ataei *et al.,* [20]	Experimental	Al_2O_3:TiO_2 (0.5%)	Water	Minichannel/laminar	16.97% HT
Ahmad *et al.,* [21]	Experimental	ZnO (0.1-0.4%)	Water	Car radiator/laminar	70% HT at 0.2%
Chopkar *et al.,* [22]	Experimental	Al-Cu 70:30 (0.19-2.50%) (20-40nm)	ethylene glycol	Turbulent	2.25 TC ratio
Alshehri *et al.,* [23]	Simulation	Al_2O_3-TiO_2 (2.5:1.5, 5:3%)	W-EG 70:30	Circular pipe/ turbulent	52% HT
Li and Peterson [24]	Experimental	Al_2O_3(2-10%, 36nm), CuO (2-6%, 29nm)	Water (28.9-34.7C)	Laminar	1.51 TC ratio at CuO-W (33.4C)
Bayat and Nikseresht [25]	Simulation	Al_2O_3(0-10%)	EG-W 60:40	circular tube/Turbulent	33.9% HT
El Bécaye Maïga *et al.,* [26]	Simulation	Al_2O_3 (1-10%)	Water	Circular tube/Turbulent	50% HT
Vandrangi *et al.,* [27]	Simulation	SiO_2, Al_2O_3 (1%)	W-EG 40:60, 60:40	Circular tube/ laminar	52.9% HT
Bianco *et al.,* [28]	Simulation	Al_2O_3 (1-6%)	Water	Circular tube/ turbulent	30% HT
Usri *et al.,* [29]	Experimental	Al_2O_3 (0-0.6%) (13nm)	EG-W 40:60	Turbulent	14.6% HT
Kumar *et al.,* [30]	Simulation	CuO, Al_2O_3, SiO_2 (0.2-0.6%)	Water	Circular tube/ turbulent	58.79% HT at (Al_2O_3 0.6)
Liu *et al.,* [31]	Experimental	Cu (0.1-0.2%) (50-500nm)	Water	Laminar	1.24 TC ratio
Devireddy *et al.,* [32]	Experimental	TiO_2 (0-0.5%) (21nm)	EG-W 40:60	Turbulent	37% HT
Xie *et al.,* [33]	Experimental	Al_2O_3 (5%) (60.4nm)	Water, EG, pump oil, glycerol		Pump oil>EG> G> W in TC ratio

Selimefendigil and Oztop [34]	Simulation	CuO (0-0.035%)	Water	Face step/ laminar	30% Nu
Hamid *et al.,* [35]	Experimental	TiO_2 (0.5-1.5%) (50nm)	EG-W 40:60	Turbulent	29% HT
Kherbeet *et al.,* [36]	Experimental	SiO_2(0-1%)	Water	Face step/ laminar	66% HT
Di Ilio *et al.,* [37]	Simulation	Al_2O_3, CuO (0-10%)	Water	Wavy wall/ laminar	20% HT (Al_2O_3)
Sun *et al.,* [38]	Experimental	Fe_3O_4(0.1-0.5%)	Water	Circular tube/laminar	9.16% HT
Gupta *et al.,* [39]	Experimental	$ZnFe_2O_4$ (0.02-0.5%)	Water	Circular tube laminar	43% TC
Li *et al.,* [40]	Experimental	C (0.25-1%)	Acetone	Microchannel/ laminar	73% HT
Manay and Sahin [41]	Experimental	TiO_2	Water	Rectangular microchannel	39.7 HT
Saffarian *et al.,* [42]	Simulation	Al_2O_3, CuO (1-4%)	Water	Wavy, spiral pipes /turbulent	78.25% HT
Behnampour *et al.,* [43]	Experimental	Ag	Water	Trapezoidal, Rectangular, Triangular microchannel	100% HT
Irandoost *et al.,* [44]	Simulation	Al_2O_3 (2,4,6%) (10,30,50,70nm)	Water	Microchannel/ laminar	1.98 PEC
Fayadh *et al.,* [45]	Simulation	CuO (1-3-5%)	Water	Solar collector	1.155 K
Gholizadeh *et al.,* [46]	Experimental and Simulation	Ag+Fe_3O_4(1-5%)	Water	Diesel engine / shell and tube	47.12 HT

Initial research and development technology demonstrated the potential of the heat transfer nanofluid for applications in industrial sections and research institutes all over the world to keep the effort in research and development in this field. Lately, that effort has increased and taken much attention from researchers [47].

In 2010, the nanofluid-related publications were 2720, And that number can be seen increasing each year, which shows the importance of this field. Its success led to being applied in several applications and systems. In 2019, there were more than 14600 Publications published and indexed in the Google Scholar search engine. Figure 2 shows the number of publications in the Google Scholar search engine from 2010-2022. The nanofluid research has increased worldwide because nanofluid increases the performance of the application that reduces energy consumption which leads to reduced operational costs. Hence can maintain the whole system and increase its lifespan.

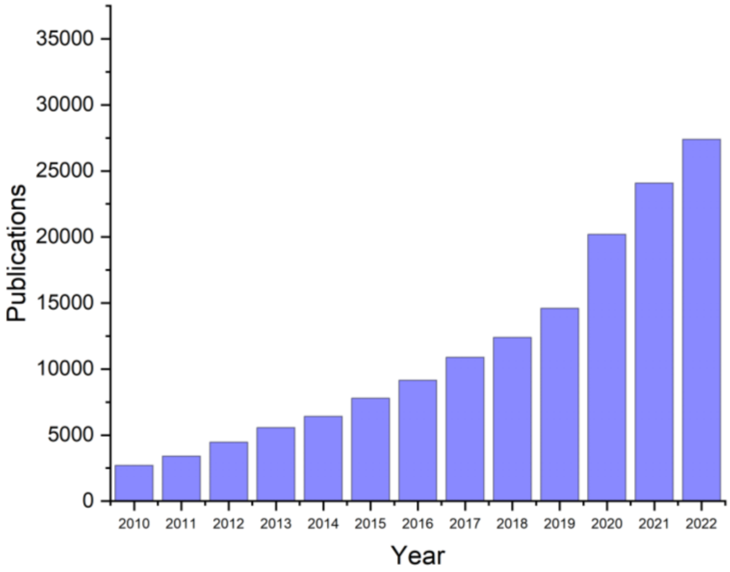

Fig. 2. Shows the number of publications in the Google Scholar search engine from 2010-2022

2. Preparation Methods for Nanofluids

Nanofluids contain two parts Nanosized particles and base fluid. To maintain the thermal properties of the Nanofluid should reach a high stability suspension of nanoparticles in the base fluid; some fluids require special treatment to reach that stability without changing their chemical properties. There are two main techniques for the preparation of nanofluids: the single-step method (SSM) and the two-step method (TSM) [48-51].

2.1 Single-Step Method (SSM)

The single-step method concurrently produces and disperses the nanoparticles into the base fluid; this method can give stability to metallic nanofluids [52]. The aggregation can be reduced with the direct evaporation condensation method. In this stage of preparation, the condensation forms of nanoparticles through directly contacted between the vapor and base fluid; the continuous circulation of base fluid can reduce the agglomeration of the nanoparticles [53,54] This technique is preferable because it prevents oxidation of the particles; this method is suitable for research purposes, can produce small quantities, also can produce ultra-thin coated nano layers (2-10nm) which give more stability in the liquid.

2.2 Two-Step Method (TSM)

The two-step method is the most common and economical method for nanofluids preparation, especially for large-scale production, that can be used in nanotubes, Nanofibers, or nanomaterials such as metallic, non-metallic, and hybrid Nanosized particles [55]. The nanoparticles are in a powder form by physical or chemical methods of preparation, then that nano powder is suspended in a base fluid like water, ethylene glycol, engine oil, etc., in successive processing steps using ultrasonication method or surfactants to reach higher stability and can keep its thermal properties longer, this technique is suitable for producing large quantities, this method required higher concentrations with the usage of oxide nanoparticles compared with the SSM [56-58]

3. Applications of Nanofluids

Nanofluids can be used to optimize heat transfer and energy efficiency in various applications. Industrial systems and devices that need high thermal efficiencies like micro-manufacturing, chemical sectors, metallurgical, heating, and air-conditioning to reduce and distribute the heat from these systems or devices to the air to prevent overheat and failures in the systems [59]. Tsai *et al.,* [60] investigated experimentally for an electrical application the thermal resistance of heat pipes using gold nanoparticles in water liquid, they found a significant reduction in the temperature by 40% and 37%.

Many industrial researchers studied the addition of nanoparticles in engine oils and coolants, and they found a magnificent enhancement in efficiency and sustainability; after that, they experienced that technique in gear oils, lubricants, and transmission fluids in vehicles [61-63]. Yu *et al.,* [64] and Paramane *et al.,* [65] determined the improvement of adding nanoparticles to the power transformers cooling system oil [66] They studied the heat transfer enhancement in a flat plate solar collector using different nanofluids. Nanotechnology has enhanced the nuclear system cooling to face the high heat flux that is convicted from the nuclear core. Recently nanotechnology has taken part in many devices like Central Processing Unit (CPU) coolers in the computer, especially the supercomputers CPU and the same value with the microprocessors [67-69]. Studied the heat transfer of a microchannel heat sink in forced convection with a supercomputer circuit board. This technology has been involved in many areas like solar collectors, space applications, radars, heavy military vehicles, chemicals, oil, gas, food industry, drinking products, paper, printing process, textiles, and biomedical applications [70-73]. The National Aeronautics and Space Administration (NASA) applied this magnificent technology in various applications and systems, and they announced they gain many benefits from that technique starting from reducing the vehicle mass in their missions' vehicles outside the planet and to improve the functionality and durability furthermore, to enhance power generation, storage and propulsion for rovers and EVA suits [74]. Nanotechnology played an important role in various applications, especially the huge systems like nuclear reactors in their cooling [75,76]. Recently modern military radars applied nanotechnology in the cooling system of the radar, and found that the efficiency of the waste heat recovery heat exchanger increased for nanofluids, that huge among of heat can be calcified as pollution, therefore, many researchers and environmental activists trying to reduce and minimize thermal pollution and recover the energy waste [77-79].

4. The Heat Transfer in Nanofluids

The heat transfer in heat exchanger channels represents energy transportation along the channel. In general, there are three types of flows in heat exchanger channels: laminar, transition, and turbulent [38,79]. These flows Reynold's number can be calculated by:

$$Re = \frac{\rho\, V_{avg}\, D}{\mu} \tag{1}$$

4.1 Laminar Flow

When the fluid particles flow in smooth paths in layers with an expected path and no mixing, the Reynolds number < 2300. Zhang *et al.,* [80] and Li *et al.,* [81] studied the heat transfer evaluation of a micro heat exchanger cooling with spherical carbon nanoparticles suspended in acetone as a base fluid in Reynolds number range 256-1376, the thermal performance index results that increase with the increase in volume fraction and Reynolds number Figure 3 shows the results and Table 2 summarizes the enhancements of various types of nanofluids in laminar flow conditions:

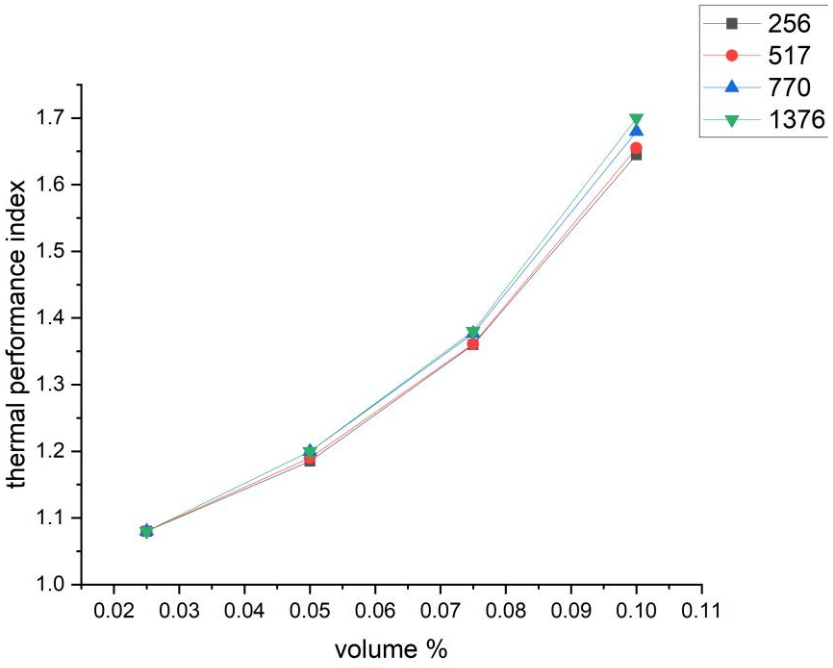

Fig. 3. Present the increase in thermal performance with the increase in volume fraction and Reynolds number

Table 2
Summarizing enhancements of various types of nanofluids in laminar flow conditions

Author	Method	Nanoparticles	Base fluid	Geometry	Enhancement
Pahlevaninejad *et al.,* [82]	Simulation	Al_2O_3 0.5-1.5%	Water	Wavy microchannel	21%↑ Pd
Yildiz *et al.,* [83]	Experimental	Graphite 0.5-2%	Water	Microchannel	25% HT
Yang *et al.,* [84]	Simulation	Cu/CuO/ Al_2O_3 0-5%	Water	Wavy channel	9% Nu
Jaferian *et al.,* [85]	Simulation	Al_2O_3 0-4%	Water	Trapezoidal, sinusoidal, stepped microchannel	3.6 PEC
Ahmed *et al.,* [86]	Simulation	Cu 0-5%	Water	Wavy channel	25% Nu avg
Hussein *et al.,* [87]	Experimental	TiO_2 SiO_2 1-2.5%	Water	Flat tube	61% Nu
Hussein *et al.,* [88]	Experiment	SiO_2 1-2.5%	Water	Flat tube	50% HT
Firlianda *et al.,* [89]	Experiment	$MnFe_2O_4$ 0.02-0.075%	Ethylene glycol	Mini heat exchanger shell and tube	50% Nu
Amini *et al.,* [90]	Simulation	Al_2O_3 0.5%	Water	Microchannel with rotating vortex	15.5% Nu
Jung *et al.,* [91]	Experimental	Al_2O_3 0.6-1.8%	Water	Microchannel	150% HT

4.2 Turbulent Flow

Turbulent flow is a type of fluid flow in which the fluid undergoes irregular fluctuations and mixing, with the Reynolds number Re>4000. Hussein *et al.,* [92] Studied numerically on turbulent forced convective heat transfer using nanofluids TiO_2 with Water as a base fluid in a range of (10000-100000 Re) in different volume fraction range 1-4%. Figure 4 presents the average Nusselt number

(Nu_{avg}) results, which means the increase in the Reynolds number and volume fraction increases the average Nusselt number. Table 3 summarizes the enhancements of various types of nanofluids in turbulent flow conditions:

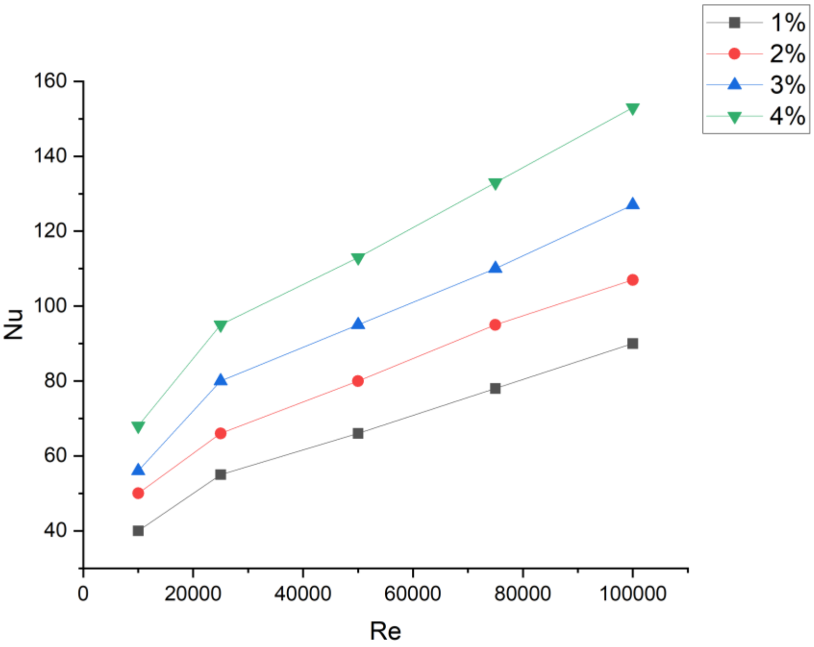

Fig. 4. Present the increase of Nusselt number with the increase in Reynolds number and volume fraction [92]

Table 3

Summarizing enhancements of various types of nanofluids in turbulent flow conditions

Author	Method	Nanoparticles/ concentration	Base fluid	Geometry	Enhancement
Yang *et al.,* [93]	Simulation	SiC 4%	EG/Water 50/50	Sinusoidal	1.67 PEC
Hussein *et al.,* [92]	Simulation	TiO_2 1-4%	Water	Flat tube	20% HT
Salman [94]	Simulation	Al_2O_3, CuO, SiO_2, ZnO 1-4%	Water	Flat with ribs	66% HT
Pendyala *et al.,* [95]	Simulation	Al_2O_3, CuO, SiO_2 1-5%	EG/Water 60/40	3D car radiator	110% HT
Ahmed *et al.,* [96]	Experimental	ZnO, Al_2O_3 0.1-0.4%	Water	Car radiator	70% HT
Ali *et al.,* [97]	Experimental	ZnO 0.01-0.3%	Water	Car radiator	46% HT
Leong *et al.,* [98]	Simulation	Cu 0-2%	EG	Car radiator	45.2% HT
Kaska *et al.,* [99]	Simulation	Hybrid AIN-Al_2O_3 1-4%	Water	Flat tube	50% HT
Bazdar *et al.,* [100]	Simulation	CuO 0-3%	Water	Wavy microchannel	90% Nu 1.95 PEC
Manavi *et al.,* [101]	Simulation	Al_2O_3 1-5%	Water	Wavy channel	30% Nu
Farag *et al.,* [102]	Simulation	Sio2, Al2O3, CuO 1-5%	Water	Lobed swirl generator pipe	87% HT

5. The Characteristics that Effect on Nanofluids Heat Transfer

Several parametric effects on the nanofluids' heat transfer have been studied in this review, particle material, volume concentration, particle size, particle shape, fluid temperature, acidity, magnetic field and electrical pulsing. Those characteristics can enhance the nanofluid heat transfer enhancement ratio up to 3.00 compared to its base fluid [103,104].

5.1 Effect of Particle Material

The effect of particle material on the heat transfer enhancement is shown in Figure 5 in different nanoparticles (Al_2O_3, TiO_2, ZnO, SiO_2) with water as the base fluid. From that figure can be analysed that the addition of ZnO nanofluid to the horizontal flat tube radiator conditions got the highest increase in heat transfer enhancement among other nanofluids, and SiO_2 gets the lowest value due to its low thermal conductivity [105]. Table 4 present the thermal properties for some nanoparticle materials [106-112].

Table 4

Present the thermal properties of some nanoparticle materials and base fluids

Material	Density Kg.m^3	Specific heat J/Kg.K	Thermal conductivity W/m^2 K
Water	998	4182	0.606
Ethylene glycol	1115	2430	0.253
Kerosene	783	2090	0.15
RT-50	800	2000	0.2
ZnO	5600	4108.6	50
Al_2O_3	3980	773	38.5
TiO_2	3900	697	11.8
$MnFe_2O_4$	4870	857	12.522
Engine oil	884	1910	0.114
SWCNT	2600	425	6600
DWCNT	2600	519	2000
CWCNT	2600	425	6600
MoS_2	5060	904.4	0.39721
Ag	10490	429	0.235
Cu	8978	381	377
CuO	6500	540	18
Fe_3O_4	5180	670	9.7

Khan and Ahmed [105] analysed numerically the performance of four different nanoparticles (Al_2O_3, TiO_2, ZnO, SiO_2) suspended in water in a horizontal flat tube radiator. The result shows that the ZnO nanofluid enhanced the radiator by up to 19.35% of its thermal properties compared to distilled Water. Figure 6 presents the increase in heat transfer performance of the nanofluids in different volume concentrations.

Bubbico *et al.,* [113] studied experimentally the heat transfer efficiency of TiO_2, ZrO_2, SiC, and Al_2O_3 suspended in water, tasted that in a heated and instrumented pipe with 4mm hydraulic diameter and 200mm length, Al_2O_3 showed higher heat transfer coefficients than other nanofluids and water.

Pendyala *et al.,* [95] analysed numerically the heat transfer performance of a three-dimensional (3D) car radiator consuming CuO, Al_2O_3, and SiO_2 in ethylene glycol- water mix fluid (60:40) in various volume concentrations 1%-5%, Al_2O_3 nanofluid resulted in high heat transfer coefficient compared to other nanofluids and base fluid up to 90%.

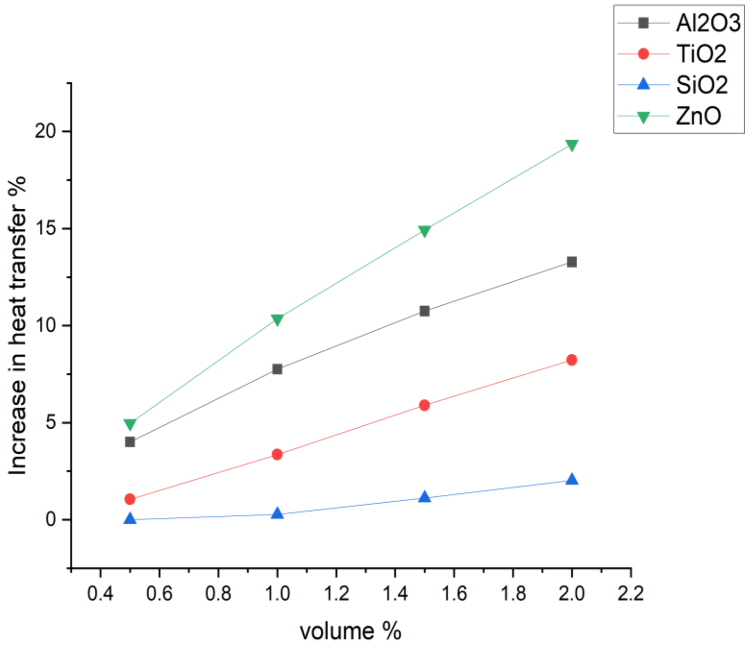

Fig. 5. Present the increase in heat transfer performance of the nanofluids in different volume concentrations

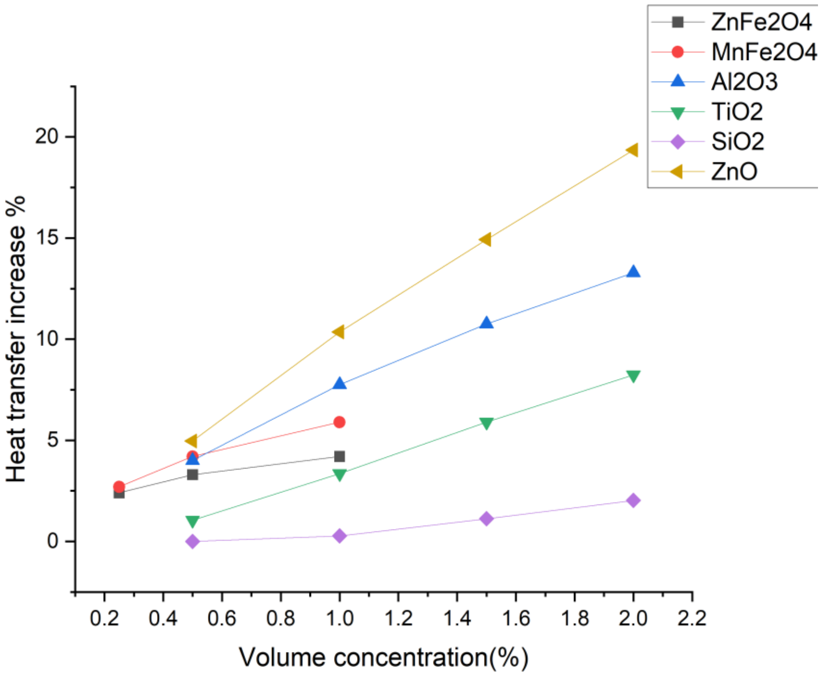

Fig. 6. Present the increase of heat transfer performance of different nanofluids materials in different volume concentrations [105,115]

As noticed from the results above, each material has its specific thermal properties that are different from one material to another; not all materials have been studied either experimentally or in simulation; we recommend that future studies focus on uncommon nanoparticle materials or try to combine suitable hybrid nanoparticles.

5.2 Effect of Particle Volume Concentration

The effect of particle volume concentration is shown in Figure 7 for different nanofluids with different volume concentrations in heat transfer efficiency; the nanoparticles can increase the heat transfer with the increase in nanoparticles volume concentrations; several works in the literature review studied its work with different volume concentrations. Generally, the Nanofluid can increase the heat transfer coefficient with the increase of the nanoparticles volume concentrations [114].

Manay *et al.,* [115] studied the thermophysical properties of nano ferrofluids in water experimentally as a base fluid, $MnFe_2O_4$ and $ZnFe_2O_4$ nanoparticles have been dispersed in pure water in different volume fractions (0.25,0.5, 1%) to study the gradient of thermal conductivity enhancement effectively.

Khan and Ahmed [105] studied numerically in automobile radiators the thermal properties and performance analyses of (Al_2O_3, TiO_2, ZnO, and SiO_2) in four different volume concentrations (0.5, 1, 1.5, 2%).

Kaska *et al.,* [99] studied hybrid nanoparticles in water as a base fluid by mixing AlN with Al_2O_3 at four-volume fractions (1, 2, 3, 4%) to enhance the heat transfer significantly; results showed the best enhancement in heat transfer at 3% of volume concentration 50% compared to pure water.

In this research, most of the researchers agreed that the heat transfer enhancement increase with the increase in the volume concentration; the results above show there are limits to that increase of heat transfer enhancement. Therefore, we recommend in future studies increasing the percentage range of the volume concentration to reach the maximum limit of heat transfer enhancement with volume concentration, especially for the hybrid nanofluids.

5.3 Effect of Particle Size

The effect of particle size on thermal conductivity enhancement has been studied by a few researchers; they agreed that the particle size could enhance the Nanofluid; the bigger size, the highest the thermal conductivity. The nanoparticle size is measured as (nm), and the nanosized is differently measured from one shape to another; the usual size particle for a spherical shape is around (2-80nm), and for a cylindrical shape, around (600nm) [116]. The nanoparticle commercially is found as nano powder. Therefore, that can be sized and measured by using a TEM micrograph [117].

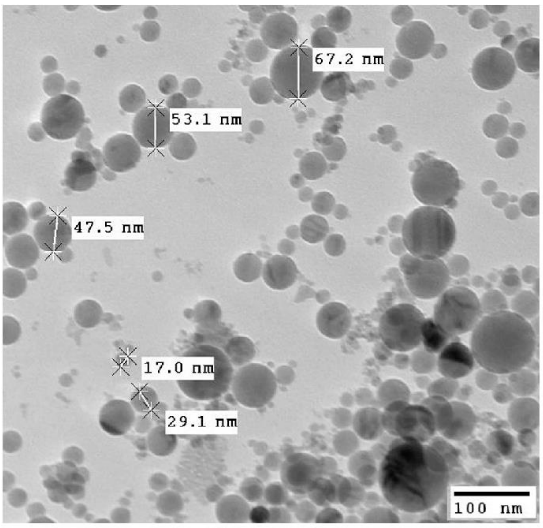

Fig. 7. TEM test for Al_2O_3 nanoparticles [118]

Pahlevaninejad *et al.,* [119] calculated the average Nusselt's number in Al2O3 numerically with water as base fluid with three different nanoparticles diameters (25, 45, 100 nm), the results of how that the 100nm got the highest Nu_{avg}.

Yang *et al.,* [120] studied the SiC nanofluid with ethylene glycol and Water as a base fluid in a sinusoidal heat exchanger channel in four different particles size (16, 28, 66, 90nm) with water and with EG/H_2O, from Figure 8, can agree with Pahlevaninejad *et al.,* [119] that the thermal conductivity enhancement increase with the increase of the nanoparticle size.

Salman [121] investigated the effect of nanoparticles size in SiO2 with water as a base fluid in a range 30-60nm in different Reynolds numbers numerically, the results show an increase in the Nusselt number with the increase in the Reynolds number and an increase in the Nusselt number with the decrease of nanoparticle size, the heat transfer results reveal that the SiO_2 with 30nm got the highest value of the enhancement Figure 9.

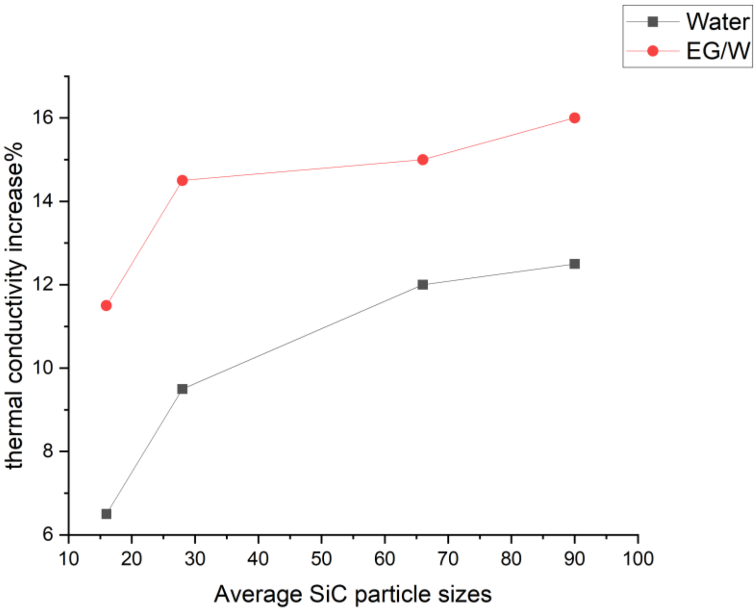

Fig. 8. The thermal conductivity enhancement for SiC nanofluid in different particle sizes in water and ethylene glycol as base fluid

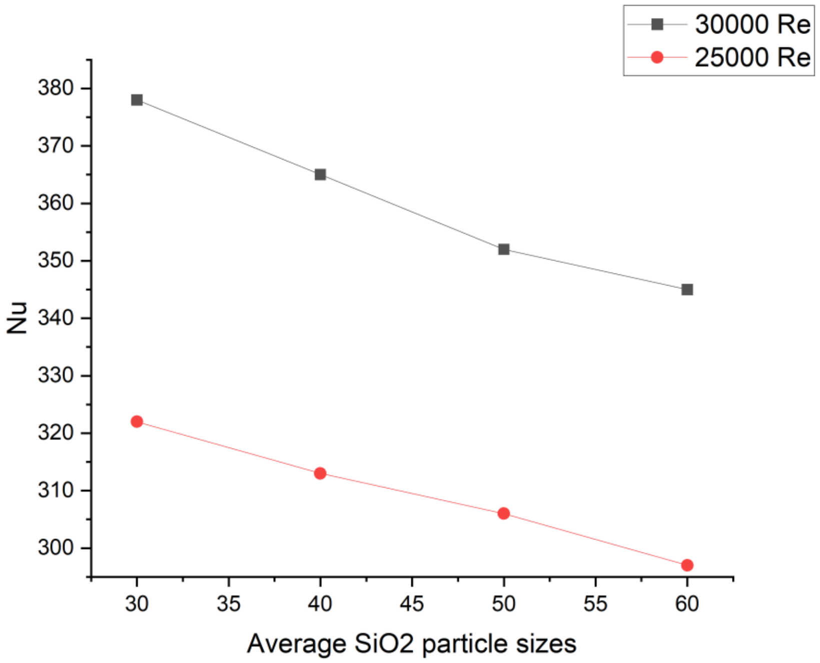

Fig. 9. The enhancement in Nusselt number in different SiO_2 nanoparticles size

Few studies have been recorded on the effect of nanoparticles size on thermal conductivity; from the results above, we can agree with the researchers that the increase in the particle size leads to an increase the thermal conductivity.

5.4 Effect of Particle Shape

Many researchers studied the effect of different particle shapes (spherical, cylindrical, platelet, Brick, blades, rods, etc.) on the thermal conductivity of the nanofluids [122]. Murshed *et al.,* [123] studied the thermal conductivity enhancement for two different TiO_2 nanoparticles shapes (15nm sphere, 10*40 nm rod) suspended in water with volume concentration range (0.5-5%), rod nanoparticle shape got the highest enhancement ratio up to 1.33 compared with pure water.

Bhattad and Sarkar [124] studied the effect of nanoparticles shape on the thermohydraulic performance of plate evaporator experimentally using different hybrid nanofluids (Alumina + Cu, CuO + Cu, Titania+ Cu, Silica + Cu); the researcher studied different types of nanoparticles shapes (brick, cylindrical, platelet, spherical), the thermal performance factor show that the brick type got the highest value then spherical and cylindrical lastly the platelet type as shown in Figure 10.

Amin *et al.,* [125] investigated the effect of nanoparticles shape on an Al2O3 with water and ethylene glycol as base fluid nanofluid in a based flat plate solar collector application efficiency numerically; in this research, different types of nanoparticles shapes have been studied (blades, platelets, cylinders, bricks, spherical) with different nanoparticle concentration (1-5%), the blades type got the highest thermal conductivity enhancement among other shapes, followed by platelets, cylinders, bricks, and spherical shape, Figure 11 presents the thermal conductivity enhancement of alumina nanofluids for different particle shapes.

Xie *et al.,* [126] studied the effect of SiC nanoparticle's cylindrical and spherical shape suspended in Water as base fluid on nanofluid thermal conductivity; the results show the cylindrical shape enhanced the thermal conductivity of the Nanofluid up to 37.5%, that enhancement resulted because the cylindrical shape got 600nm size compared to the spherical 26nm, and we agreed obviously that the particle size effect on the nanofluid thermal conductivity increasing with the increase in the particle size.

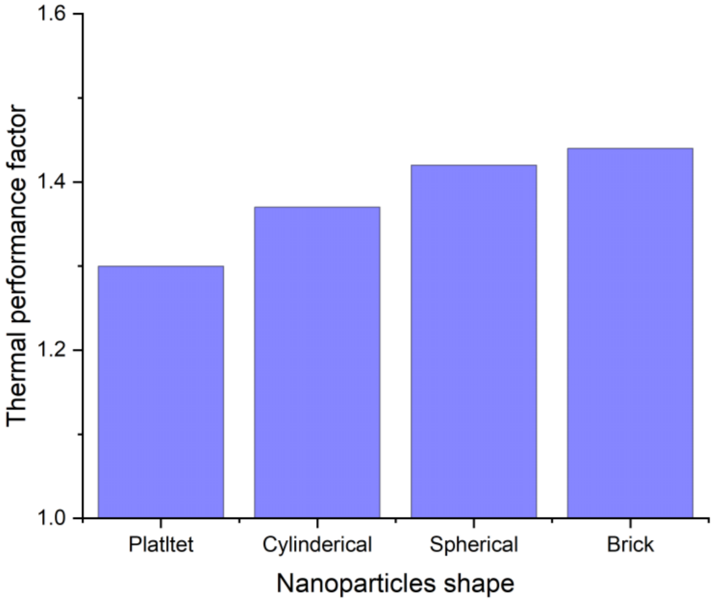

Fig. 10. Thermal performance factor for CuO-Cu hybrid fluid in different particle shapes

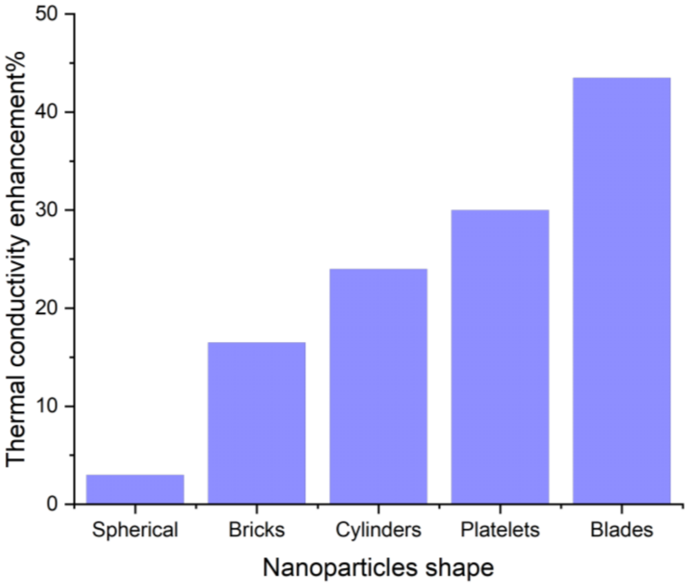

Fig. 11. Thermal conductivity enhancement for different particle shapes

Limited studies experimentally or numerically have investigated the effect of nanoparticles shape; there is a leak in this area of study because there is no agreement between the studies on the arrangement of the best particle shape on thermal conductivity, and the area of the shape plays a role in that enhancement as we explained previously. Therefore, we agree that there is a need to increase the experimental studies on this effect, and that will be a novel study.

5.5 Effect of Fluid Temperature

The thermal conductivity of the nanoparticles is more affected by temperature-sensitive than its base fluid. All the studies in the literature review agreed that the value of the heat transfer increase with the increase in the fluid temperature in its 'limits'. Figure 12 presents the heat transfer enhancement for SiO_2- Water nanofluid in different fluid temperatures experimentally and numerically.

Hussein *et al.,* [87] studied experimentally and numerically the heat transfer enhancement for three different fluid temperatures (60, 70, 80 C) in automotive cooling system application, SiO_2 nanoparticles were suspended in pure Water in a volume concentration range (1-2.5%), observed from the results the heat transfer enhancement increases with the increase of fluid temperature Figure 12.

Gupta *et al.,* [117] analysed the heat transfer in a circular tube using $ZnFe_2O_4$ at different concentrations (0.02-0.5%) with different temperatures (30-80C). The researchers studied the effect of the nanofluid temperature on the thermal conductivity, the thermal conductivity at (30C was 0.625 W/m.K), and at (80C was 0.75 W/m.K); hence, the thermal conductivity increased with the increase of the nanofluid temperature.

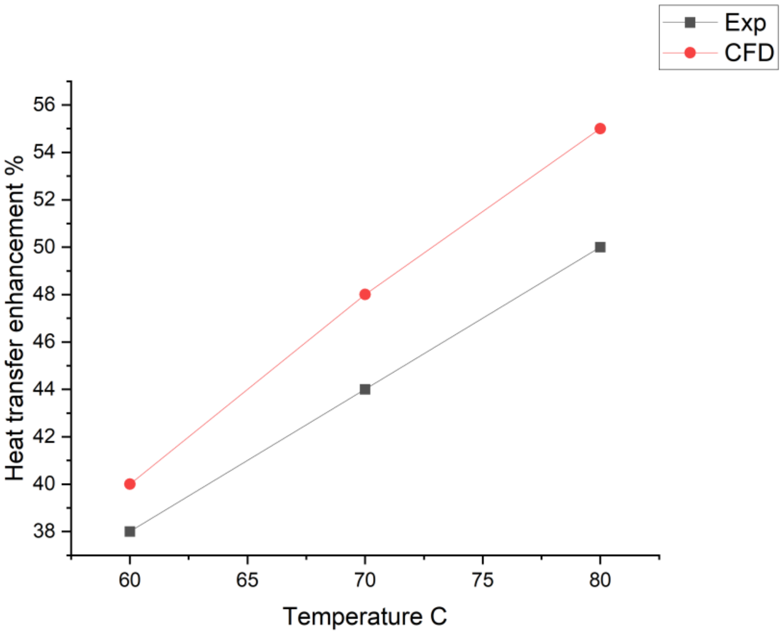

Fig. 12. Heat transfer enhancement for SiO_2- water nanofluid in different fluid temperatures experimentally and numerically

From the studies above, all the researchers agreed that the heat transfer increase with the increase of fluid temperature; that increase is different from one material to another, so we encourage future studies to study experimentally or simulate the effect and enhancement of different nanofluids and compare the differences from fluid to another.

5.6 Effect of Acidity

Few researchers have studied the effect of fluid acidity on the nanofluid thermal conductivity Lee *et al.,* [127] studied the acidity effect on CuO-Water nanofluid (0.03-0.3%) of volume concentration and (25nm) of particle size and (3,6 pH), the results present that the (3pH) Nanofluid got 1.12 thermal conductivity enhancement ratio compared to its base fluid and the (6pH) Nanofluid got 1.07 thermal conductivity enhancement ratio.

Ali *et al.,* [97] investigated the convective heat transfer augmentation for car radiator experimentally using ZnO with water nanofluid, the researcher prepared the nanofluid solution in different volume concentrations (0.08-0.3%), and the acidity value maintained too (2.2 pH) the lower value, the higher thermal conductivity enhancement.

The studies on the acidity effect have settled that when fluid acidity increases, the thermal conductivity increase.

5.7 Effect of the Magnetic Field and Electrical Pulsing

Many researchers lately investigated the effect of the magnetic field on nanofluids; those studies resulted that the nanofluids can be affected under a specific amount of (G) in its thermal conductivity; Figure 13 can be noticed that while the magnetic increase the nanofluid thermal conductivity increase.

Kharat *et al.,* [128] studied the evaluation of the thermal conductivity of NiFe2O4 with Water under the influence of the magnetic field experimentally; results show the thermal conductivity increase with the increase of the magnetic field, as shown in Figure 13.

Amani *et al.,* [129] measured the thermal conductivity of spinel-type $MnFe_2O_4$ nanoparticles suspended in Water as a base fluid in a uniform magnetic field. Figure 13 presents the results; the increase in the magnetic field raises the thermal conductivity, hence increasing the thermal enhancement of the nanofluid and the system.

Karimi *et al.,* [130] investigated the effect of magnetic field on Fe3O4 and CoFe2O4 Nanofluid's thermal conductivity in a range of (0-500G) and different nanoparticles volume fraction (0-4.8%) experimentally, the conclusion set that the increase in the magnetic field increases the thermal conductivity match the results of the previous studies.

Xu *et al.,* [131] applied pulsating flow on graphene oxide nanoparticles experimentally with Water in a pin-fin microchannel, then analysed the heat transfer; the pulsing range was (1-5Hz) and (272,407, 544 Re) with a mass fraction (0.02, 0.05, 0.1, 0.15, 0.2%), the low frequency ($f < 2$ Hz) pulsating flow has no significant effect on nanofluid heat transfer enhancement compared to higher frequencies.

The previous studies on the effect of the magnetic field show that the thermal conductivity increase with the increase of the magnetic field (G) and increases with the increase in electrical pulsing.

This type of study is fully needed in many applications which use nanofluids that effect by a magnetic field or electrical waves.

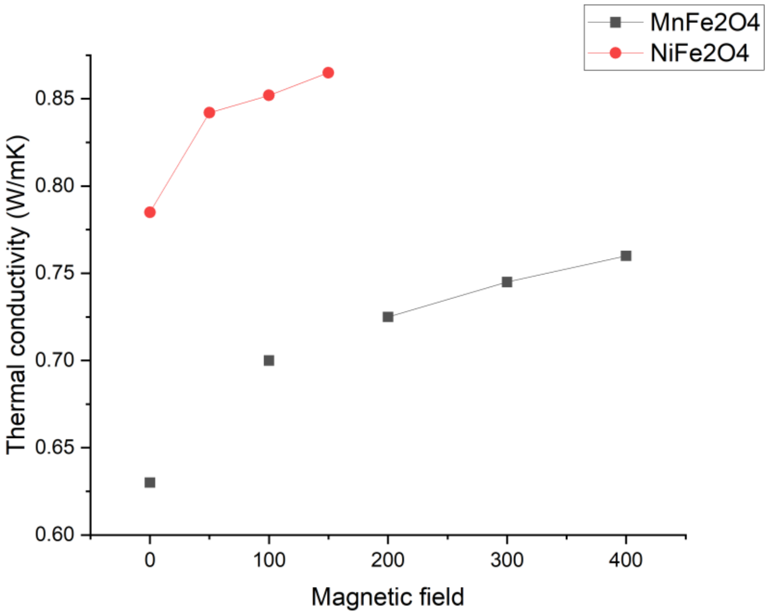

Fig. 13. The enhancement of the thermal conductivity while increasing the magnetic field for $MnFe_2O_4$ and $NiFe_2O_4$

6. Heat Transfer Enhancement in Ethylene Glycol and Water as Base Fluid

The studies in the enhancement of the base fluid for nanofluids does not have less important in the heat transfer optimization; many publications have studied the heat transfer enhancement in different base fluids like water, ethylene glycol, glycerine, acetone, pump oil, etc. or even combination between them in specific quantities [132,133]. Table 5 summarizing some publications on the thermal optimization of the addition ethylene glycol.

Heat transfer enhancement using $MnFe_2O_4$ – ethylene glycol has been studied experimentally in a mini shell and tube heat exchanger by Firlianda *et al.,* [89] has been successfully carried out; the researchers studied the effect of adding $MnFe_2O_4$ to ethylene glycol as base fluid; the results of heat transfer analysed by using LMTD method, the highest value was obtained at 0.075% of nanoparticles concentration of $MnFe_2O_4$.

Rao and Ravibabu [134] investigated the enhancement of adding Al2O3-Water+ ethylene glycol in an automobile radiator experimentally; the volume fraction range was (0.01 to 0.08%), the nanofluid after preparation was stable, and the research found the heat transfer performance increased by 48% compared to pure water at 0.08% of volume fraction which leads to increase the overall automobile radiator performance.

Li *et al.,* [135,136] investigated experimentally thermophysical properties of ZnO nanoparticles in (50-50) EG-W and with EG in different volume concentrations; they agreed that the performance had been increased by up to 30% compared to its base fluid.

Lee *et al.,* [137] studied the comparative thermal conductivity enhancement ratio for CuO and Al_2O_3 nanoparticles in Water and ethylene glycol in the concentration range (1-4%) for CuO and (1-5%) for Al_2O_3 in the two-step method, the results show the ethylene glycol fluids thermal conductivity enhancements value higher than the pure water as base fluid.

Recently, researchers studied mixing ethylene glycol with water to give the base fluid a higher thermal conductivity, therefore Vandrangi *et al.,* [138] studied the fluid dynamic of ethylene glycol-water mixture numerically to predict the nanofluid heat transfer coefficients and mixed it with Al_2O_3 and SiO_2 nanoparticles in different Reynolds number (5000, 80000 Re).

Table 5
Summary of thermal optimization in ethylene glycol studies

Reference	Method	Nanoparticles	Base fluid	Geometry	Enhancement
Yang *et al.,* [139]	Simulation	SiC 4%	EG-W, 50:50	Sinusoidal mini tube	37% PEC
Leong *et al.,* [140]	Simulation	Cu 0- 2%	EG	Car radiator	12% HTC
Shah *et al.,* [141]	Experimental	Graphene oxide (0.02-0.05%)	EG		11.3% TC
Pendyala *et al.,* [95]	Simulation	CuO, Al_2O_3, SiO_2(1,3,5%)	EG-W 60:40	3D car radiator	90%HTC (Al_2O_3 5%)
Subhedar *et al.,* [142]	Experimental	Al_2O_3(0.2-0.8%)	W-Mono EG 50:50	Car radiator	30% HTC
Delavari and Hashemabadi [143]	Simulation	Al_2O_3 (0-1%)	W, EG	Car radiator	114% HTC

7. Discussion

This study presents and investigates the latest studies that investigate nanofluid technology, starting from the importance of nanofluid technology on thermal performance and the preparation techniques, then sight the applications that include nanofluid technology as an important addition to enhance its thermal efficiency and present the nanofluid technology coefficient in the heat transfer applications. This work investigated the important characteristics that affect the nanoparticle and nanofluid enhancement in the latest studies, like the effect of particle material, particle volume concentration, particle size, particle shape, inlet fluid temperature, fluid acidity, magnetic field, and electrical pulsing. Furthermore, analyse the latest studies in the addition of ethylene glycol as base fluid and compare it with water in different nanoparticles Table 5 presents studies that investigated the thermal conductivity enhancement in ethylene glycol base fluid compared to Water. This study aims to provide researchers with a wide range of information about this magnificent technology and to present the leaks in each step and the recommendations for their future studies about the uncertain data in this area of study, either experimentally or numerically.

8. Conclusion and Recommendations

Based on the studies above and the authors' knowledge of nanofluid technology found there is a leak in specific studies in this technology as below:

i. Expand the thermal applications that the nanotechnology used in and try to apply and investigate the thermal performance experimentally and numerically.
ii. Study the difference between the single-step method (SSM) and the Two-step method (TSM) for different nanofluids in metallic, non-metallic, and hybrid fluids.
iii. Investigate experimentally and numerically the heat transfer enhancements in new hybrid fluid nanoparticles.
iv. Study the nanofluid heat transfer enhancement in a higher range of volume concentration to find the peak limit of the enhancement considering the pressure as a loss and calculate the performance evaluation criteria (PEC) to certain the enhancement evaluation method for the experimented application.

v. Based on the studies above, there is a leak in the experimental studies about the effect of particle shape on thermal conductivity.
vi. The nanofluid studies so far not all has been investigated the effect of inlet temperature on the heat transfer coefficient.
vii. The latest trends in nanofluid technology are changing the common base fluid (pure Water) with other liquids that have more thermal effectiveness, like (ethylene glycol, acetone, and glycerine) and making a comparative study on its thermal enhancement.

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