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Thermal Performance Enhancement of Heat Exchangers Using Nano-Fluids in Energy Conversion Systems

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ABSTRACT

This study reviews recent advancements in utilizing Nano fluid

s to enhance the thermal performance of heat exchangers, with particular emphasis on double-pipe configurations. Various Nano fluid types, including water-based grapheme oxide and CuO–water Nano fluids, are analyzed for their effectiveness under different operating conditions, such as inlet temperature and nanoparticle volume fraction. Experimental findings indicate that incorporating Nano fluid significantly improves heat transfer coefficients and thermal efficiency due to their enhanced thermal conductivity. Optimizing flow rate and nanoparticle concentration can minimize pressure drop while achieving peak heat transfer rates. Moreover, hybrid Nano fluids, such as aluminum oxide–titanium dioxide, have demonstrated up to 84% improvement in thermal performance, highlighting their potential for designing high-efficiency energy conversion systems. Further research is required to assess long-term stability and perform comprehensive cost–benefit analyses to facilitate industrial implementation.

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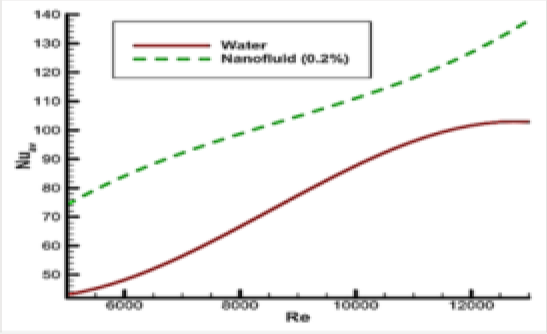
1. INTRODUCTION

Thermal power is transferred among fluids in a wide style of sectors via heat exchangers. Water, motor oils, and ethylene or propylene glycol are examples of unmarried-segment drinks often used in these machines. Double-pipe warmth exchangers (DPHEs), which can be frequently set up in a tube-in-tube arrangement, are specially common some of the several forms of warmth exchangers because of their small length, excessive floor-to-extent ratio, and standardized architecture. The efficiency of heat transmission is restrained by way of using unmarried-phase liquids with obviously low thermal conductivity. The use of fluids with accelerated thermal conductivity, every now and then known as nano fluids, is one capability remedy for this hassle. Nano fluid has been the situation of large studies via researchers from plenty of fields, which include biomedical programs, transportation, power era, production, thermal control, and chemical engineering. In spite of those attempts, there's nonetheless no entire knowledge in their thermal conduct, and a generic predictive model has now not yet been created. Variations in the concentration of nanoparticles pose a considerable challenge due to the fact that they have got a major impact on the thermo-physical characteristics and waft conduct of the fluid. Consequently, it's still difficult to exactly expect the thermal behavior of Nano fluid during its complete awareness range. The shortcomings of traditional low-conductivity fluids are in addition highlighted with the aid of the growing need for heat exchangers which can be small and strength-green. The use of Nano fluid, but, has tested a massive development in thermal overall performance, developing new possibilities for high-overall performance warmth transfer applications. DPHEs employ concentric tube designs, first the usage of parallel go with the flow arrangements after which shifting to counter-go with the flow configurations, to facilitate energy trade between hot and cold fluids. Numerous numerical and experimental investigations were done which will decide the major variables influencing thermal performance, including fluid thermal conductivity, running temperature, nanoparticle attention, particle form, Reynolds numbers (each inner and outer), and greater. The importance of nanoparticle geometry is becoming increasingly clean: due to their extra aspect ratio, elongated or stick-fashioned particles have proven higher heat switch performance at higher Reynolds numbers. In the same way, deciding on larger debris with higher thermal conductivity increases the general thermal efficiency. Additionally, researchers have examined the steadiness and dispersion of nanoparticles, coming across that TiO2 and γ-Al2O3 debris may be efficiently dispersed at precise pH stages. Furthermore, the Nusselt quantity (Nu) increases as the particle loading and glide fee boom. Computational studies have demonstrated that the heat transmission and pressure drop growth with increasing nanoparticle loading, whereas comparative experiments have found out that graphene-primarily based Nano fluid occasionally plays better than multi-walled carbon nanotube (MWCNT)-primarily based Nano fluid under similar circumstances. Additionally, the convective warmth switch coefficient and stress drop are both without delay influenced with the aid of variables which includes nanoparticle size, shape, and concentration. Reducing the particle length of Al2O3 nanoparticles from 90 nm to 10 nm, as an example, has a good sized impact on fluid density and viscosity further to improving thermal conductivity. To quantify these outcomes, equations were put forth for calculating thermal electricity switch and pressure drop in DPHEs. According to studies of Nano fluid programs in DPHEs, the inclusion of nanoparticles—whether as single or hybrid sorts—improves the heat transfer efficiency, decreases the exchanger length, and lowers cloth and production prices. Although there may be a slight increase in strain drop as a result of friction, studies on CuO-based nanofluid has discovered sizeable thermal enhancements, mainly when coupled with techniques like twisted tape inserts (TTIs). This overview seeks to analyze recent advancements within the utility of Nano fluid in DPHEs, being attentive to their unique thermal traits and benefits over traditional warmness transmission fluids. Different forms and preparations of nanofluids are mentioned, along with TiO2, CuO, Al2O3, Fe3O4, TTIs, baffles, and magnetic fields. The dreams are threefold: (i) to evaluate the results of nano fluid kind, awareness, and go with the flow characteristics in DPHEs; (ii) to analyze how one-of-a-kind exchanger designs and working situations have an effect on overall performance; and (iii) to pinpoint research needs and make hints for future research. In end, this assessment clarifies the benefits and downsides of employing Nano fluid, gives beneficial advice for its commercial software, and advances the fields of thermal control and strength-efficient structures.

2. Methodology

Oniriuka et al. Numerical simulations had been performed to research the thermal characteristics of a novel nanofluid made from mango bark flowing turbulently via a double-pipe heat exchanger (DPHE) (Oniriuka et al., 2019: p. 5). Various nanoparticle concentrations with particle diameters of 100 nm had been considered. The outcomes showed that the convection warmness transfer coefficient of the nanofluid turned into about twice that of the base fluid. The Nusselt wide variety (Nu) expanded by way of about 68% at Re = 5000 and by means of 45% at Re = 13,000 (Figure 1). Interestingly, growing the extent fraction of nanoparticles by means of 1% decreased Nu through 0.77%. The look at also highlighted that the trend of the average thermal convection coefficient changed route at distinct Reynolds numbers, indicating a complex relationship between thermal performance, flow regime, and nanoparticle concentration.



<u>Figure 1: Nu versus Re for water and Nano fluids (Onyiriuka et al., 2019: p. 7).</u>

Qi et al. Both the heat switch enhancement and strain drop of TiO2-water nanofluids in DPHEs had been investigated (Qi et al., 2019: page 111). The take a look at evaluated water flow quotes from 1 to five L/min, nanoparticle concentrations as much as 0.5%, distinct glide locations (shell and tube aspects), RE = 3000–12,000, and tube geometries (smooth and corrugated). They located that nanofluid concentrations as low as 0.5% should increase warmness switch underneath most appropriate situations by way of 10.9%, 13.5%, and 14.6%, respectively. Additionally, the nanofluid stepped forward thermal performance numbers and common machine efficiency. However, mixing the nanofluid with corrugated tubes extended the pressure by 40.8% at the shell facet and 52% at the tube facet. The take a look at concluded that corrugated DPHE with shell-aspect nano fluid drift had higher thermal overall performance than smooth DPHE.Izadi et al. Computational analysis of heat transfer and pressure drop under turbulent flow was conducted using a two-phase mixing model, which accounts for momentum, continuity, energy, turbulence loss, and particle loading (Izadi et al., 2023: p. 614). The results showed that adding 0.01 vol% of nanoparticles increased the heat transfer coefficient by 11.5% at Re = 4000 and by 11.9% at Re = 7000. The heat exchanger performance index decreased slightly with higher nanoparticle fractions, but the effect was negligible at very low base fluid concentrations.Mohammadi studied the heat transfer efficiency and fluid behavior of finned and non-finned double-pipe counter-flow heat exchangers in a wide range of Reynolds numbers (Mohammadi, 2023: page 12275). Several fin designs were tested using TiO2-water nanofluid. The results indicated that fin thickness strongly influenced thermohydrodynamic performance. Fins with a thickness of 10 mm or greater carried out higher thermal performance than thinner fins (0.001 m). Incorporating a 10 mm round fin at Re ≈ 87,500 progressed Nu through 15% and increased waft resistance by using 4.6 times. Alhulaif investigated the convective heat switch and float conduct of TiO2-water Nano fluid with nanoparticle concentrations up to zero.6 vol.% below turbulent drift for nuclear reactor cooling programs (Alhulaif, 2024: p. Forty). Simulations for Re = 4000–18,000 proven that the convective warmth transfer coefficient elevated with both Reynolds quantity and nanoparticle awareness. Increasing the temperature of the annular hot water had little impact on the heat switch coefficient, even though it did increase the general warmness transfer rate. Figure 2 suggests the heat transfer coefficient growing gradually with Re. Table 1 summarizes key research of TiO2 Nano fluid in DPHEs.

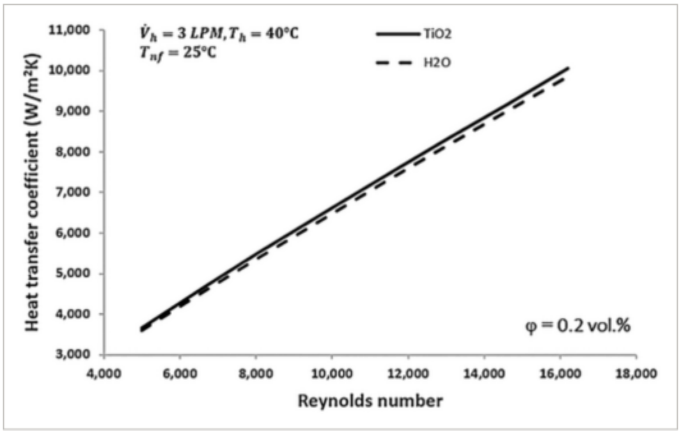


Figure 2: Heat transfer coefficient versus Reynolds number for base fluid (water) (Alhulaif, 2024: p. 41).

Table 1. Overview of studies on TiO2 Nano fluids applied in DPHEs

Authors (year)	**Study type**	**Heat exchanger configuration**	**Nano fluid composition**	**Nano fluid concentration**	**Findings and observations**
Onyiriuka et al. (2019)	Numerical	Conventional double pipe	TiO2-water Nano fluid	0 ≤ ϕ ≤ 0.06	A 1% increase in nanoparticle volume fraction caused an average 0.76% drop in Nu.
Qi et al. (2019)	Experimental	Conventional double pipe	TiO2-H2O Nano fluid	0.0%, 0.1%, 0.3%, 0.5%	Heat transfer enhanced by 10.8%, 13.4%, 14.8% respectively, compared to water; thermal performance and efficiency also improved.
Izadi et al. (2023)	Numerical	Double-pipe with spindle-shaped turbulators	Water-TiO2 Nano fluid	1%	Thermal coefficient increased by 11.5% at Re 4000 and 11.9% at Re 7000 with 0.01 vol.% nanoparticles.
Mohammadi (2023)	Numerical	Finned double-pipe counter flow	Water-based TiO2 Nano fluid	0.1%	Circular fin 10 mm thick at Re ≈ 87,500 increased Nu by 15% and

					flow resistance by 4.64×.
Alhulaif (2024)	Numerical	Conventional double pipe	TiO2 /water Nano fluid	0.2, 0.4, 0.6 vol%	Heat transfer coefficient rose consistently with increasing Re.

2.1.2 Carbon Nano fluid

Goodarzi et al. Accomplished experimental research on nitrogen-doped graphene Nano fluid to measure viscosity, thermal conductivity, warmth capability, and convective performance in a DPHE (Goodarzi et al., 2016: p. 18). Reynolds numbers from 5000 to 15,000 were tested for nanoparticle concentrations up to 0.06 wt.%. Results showed that the convective warmth transfer coefficient multiplied through 15.86% with 0.06 wt.% nanomaterials brought. The greater pumping electricity required turned into minimum, and the thermal blessings outweighed the value. In all scenarios, Nano fluid introduced higher energy performance, reduced warmth loss, and better heat switch rates in comparison to water. Figure 3 illustrates a mean increase of 16.1% in convective warmness switch coefficient.

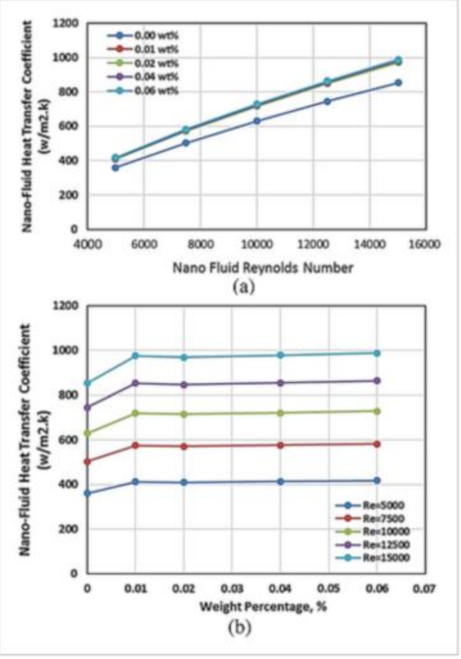


Figure 3: Heat transfer coefficient profiles for various (a) Reynolds numbers and (b) Nano fluid weight fractions (Goodarzi et al., 2016: p. 20).

Sarafraz et al. (Sarafraz et al., 2016: p. Forty one) studied the convective thermal characteristics and strain drop behavior of water-based Nano fluid containing carbon nanotubes (CNTs) within a double-pipe heat exchanger (DPHE). The copper tube used within the experiments had an internal diameter of 0.635 cm and an outer diameter of 1.27 cm, conforming to ANSI/ASME/API 5L standards. Multi-walled carbon nanotubes (MWCNTs) functionalized with carboxylic acid (COOH) companies were dispersed in deionized water via a two-step technique at concentrations ranging from zero.1 to zero.Three wt.%. Experiments have been performed below both laminar and turbulent flows (Reynolds quantity 900–10,500) to take a look at the have an effect on of go with the flow charge, inlet temperature, and nanoparticle concentration at the convective heat transfer coefficient and strain drop. Results showed that at 0.Three wt.% CNTs, the thermal conductivity improved by means of up to fifty six%. Due to the excessive intrinsic thermal conductivity of CNTs, the CNT/H2O Nano fluid proven a appreciably higher convective warmness transfer coefficient than natural water. Moreover, as proven in Figure four, the thermal effectiveness of the heat exchanger expanded via as much as 44% at the maximum awareness of zero.3 wt.% in comparison to water.

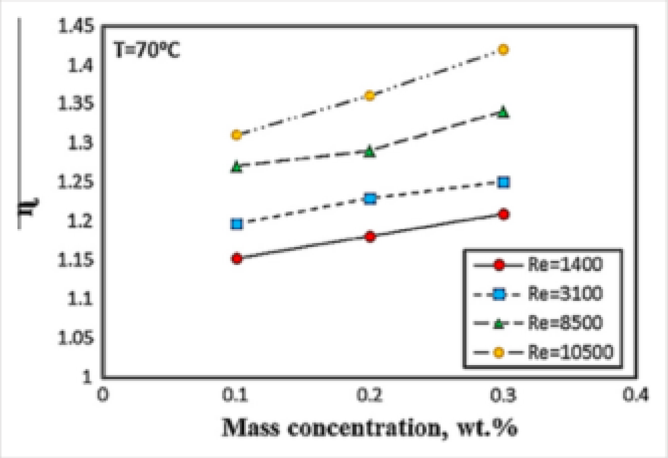


Figure 4: Thermal behavior of CNT/Water Nano fluid against mass concentration for different Reynolds numbers (Sarafraz et al., 2016: p. 44).

Hosseinian et al. (Hosseinian et al., 2018: p. 275) investigated the enhancement of warmth transfer in a DPHE using MWCNT-water Nano fluid along side vibrating walls at various mass fractions. A bendy DPHE fabricated from polyvinylidene fluoride (PVDF) changed into used, with forced vibrations implemented to the outer floor thru electro-dynamic vibrators. The effects indicated that wall vibrations improved the warmth transfer coefficient while restricting nanoparticle deposition. Increasing the Nano fluid mass flow fee, temperature, nanoparticle attention, and vibration intensity further stronger heat transfer. Figure 5 illustrates that the highest increase inside the thermal coefficient, as much as one 100%, happened at a low nanoparticle loading (0.04 wt.%) and excessive vibration intensity (nine m/s²).

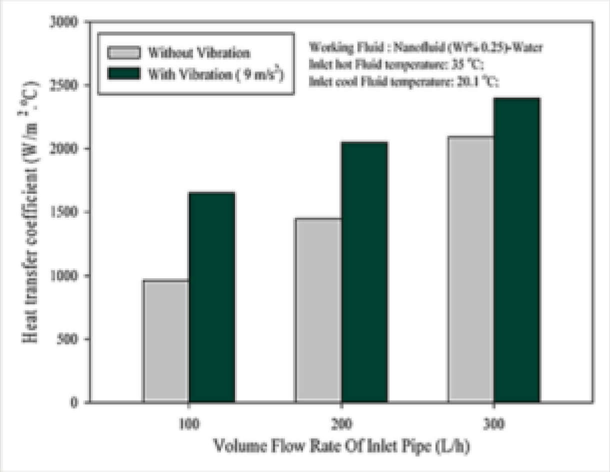


Figure 5: Heat transfer coefficient versus volume flow rate under vibrational conditions, with 0.25 wt.% Nano fluid (Hosseinian et al., 2018: p. 280).

Poongavanam et al. (Poongavanam et al., 2019: p. 580) examined the heat switch and pressure drop in a DPHE whose inner tube surface changed into modified via shot peening. The take a look at targeted on evaluating improvements in the Nusselt variety (Nu). Pressure drop and convective warmth transfer coefficient of water inside the changed system have been in comparison to a conventional copper tube, using Nano fluid at 0.2%, 0.4%, and zero.6% quantity concentrations. For the shot-peened tube, at a mass float price of forty g/s, Nu upgrades had been 26.3%, 40.8%, and 57% for 0.2%, 0.4%, and 0.6% Nano fluid concentrations, respectively (Figure 6).

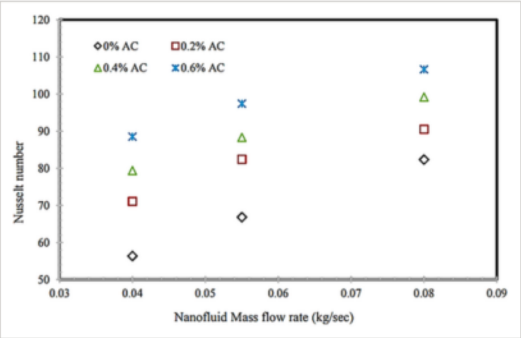


Figure 6: Nusselt number variation with Nano fluid mass flow rate at different concentrations (Poongavanam et al., 2019: p. 584).

Further, Poongavanam et al. (Poongavanam et al., 2019: p. 815) analyzed the effect of shot peening on Nu, strain drop, and thermal overall performance in a DPHE the usage of MWCNT Nano fluid (0.2–0.6 vol.%). The experiments demonstrated that floor shot peening substantially more desirable warmth transfer and encouraged waft dynamics. At 0.04 kg/s, the convective heat transfer coefficient of a 0.6% MWCNT Nano fluid accelerated with the aid of roughly 115% (Figure 7). Thermal conductivity additionally progressed as much as 30.59% for 0.6 vol.% nanoparticles among 30°C and 50°C, despite the fact that stress drop accelerated with both flow fee and nanoparticle awareness.

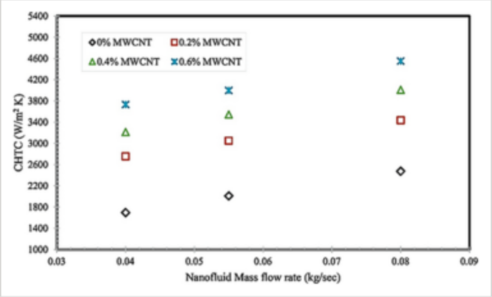


Figure 7:: Convective heat transfer coefficient versus Nano fluid mass flow rate at varying concentrations (Poongavanam et al., 2019: p. 820).

Kumar and Chandrasekar (Kumar & Chandrasekar, 2019: p. E02030) used ANSYS 14.5 to simulate warmness switch and pressure drop in a twin helically coiled warmness exchanger with MWCNT/water Nano fluid below laminar float (DeNr 1300–2200) the usage of FEM. Nano fluid quantity concentrations of 0.2%, 0.4%, and 0.6% had been tested. Results found out that increasing MWCNT concentration stepped forward heat transfer however additionally raised stress drop. At DeNr 1400, Nu for 0.6% MWCNT/water Nano fluid changed into 30% higher than water, whilst at DeNr 2200, pressure drop changed into eleven% more than the bottom fluid. Saleh and Sundar (Saleh & Sundar, 2021: p. 107094) studied MWCNT/water Nano fluid in a dual-pipe U-bend heat exchanger for Re 3500–12,000 with 0.05–0.3% nanoparticle volume fractions. At 70°C, Nano fluid viscosity and thermal conductivity multiplied by way of 9.15% and 15.27%, respectively. For 0.3% nanoparticles at Re 10,0.5, Nu, convective warmness switch coefficient, and thermal performance advanced via 31.4%, 44.2%, and 25.6%, respectively. Frictional losses, stress drop, and pumping power extended by means of 14.3%, 17.1%, and sixteen% (Figures 8 and 9).

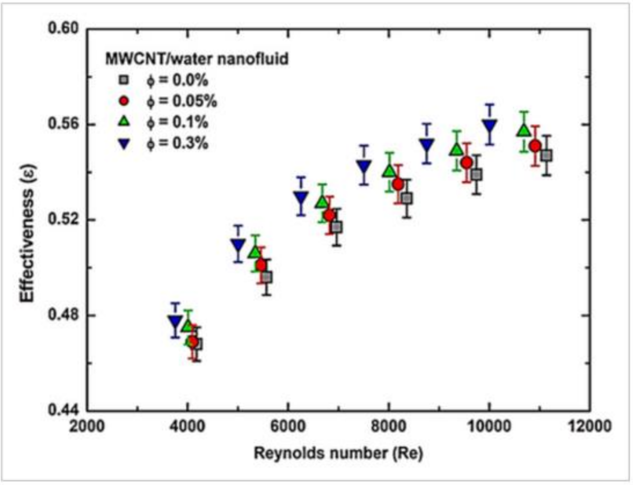


Figure 8: Nano fluid effectiveness versus Reynolds number for MWCNT/Water (Saleh & Sundar, 2021: p. 107095).

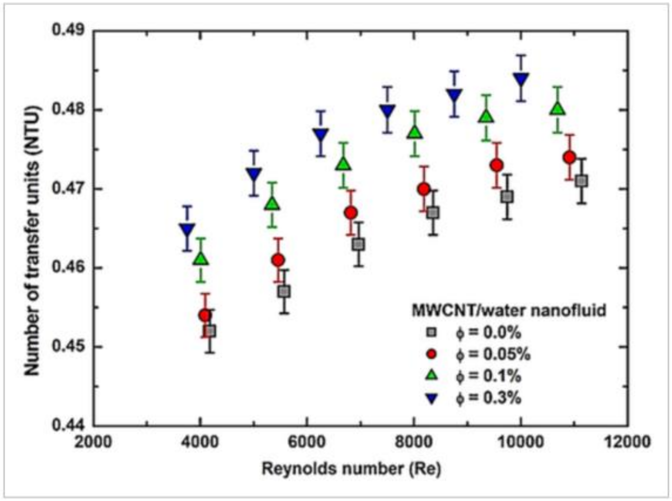


Figure 9: Number of transfer units versus Reynolds number for different MWCNT/Water Nano fluid (Saleh & Sundar, 2021: p. 107096).

Porgar et al. (Porgar et al., 2021: p. 510) evolved transformer-oil-based totally Nano fluid with 0.05–0.8 wt.% MWCNTs modified with carboxyl corporations the usage of SDS as a surfactant. When utilized in a DPHE, the maximum enhancement in convective warmness transfer reached 86.7%, while usual warmness transfer coefficient and thermal conductivity multiplied with the aid of 37.2% and 138%, respectively. Zakeri and Emami (Zakeri & Emami, 2021: p. 45) examined water-based totally graphene oxide Nano fluid in a counter-waft DPHE. With warm fluid temperatures of 35°C, 45°C, fifty five°C, graphene oxide concentrations of 0.01–zero.1 vol.%, and bloodless fluid glide charges of 14.Five–23.5 mL/s, convective warmth transfer advanced with growing nanoparticle awareness and float pace. Hot inlet temperature had minor effect. Friction element and pressure drop rose with the aid of 72% and 111%, respectively, with the best warmness switch coefficient at 0.1 vol.% nanoparticles, 55°C hot fluid, and 23.5 mL/s cold fluid float. Khadang et al. (Khadang et al., 2022: p. A hundred and twenty) analyzed carbon/water Nano fluid in a DPHE with triangular baffles (4, 8, 12 baffles; 40° and 70° angles) over Re 4000–14,000 the usage of RSM. Incorporating 12 baffles at 40° and 0.3 vol.% Nano fluid improved Nu through 35% relative to easy tubes with water. Friction issue extended 5–10%, and strain drop changed into ~1.5 instances higher. Table 2 summarizes key research on carbon-based totally Nano fluid in DPHE structures.

Table 2. Summary of research on the application of carbon-based Nano fluid in double-pipe heat exchangers (DPHEs).

Authors (year)	Study Type	Heat Exchanger Configuration	Nano fluid Composition	Nano fluid Concentration	Findings and Observations
Goodarzi et al. (2016) (Goodarzi, 2016: p16)	Experimental and Numerical	Counter current	Nitrogen-doped graphene Nano fluid	0.00% and 0.06%	Addition of 0.06 wt.% nanoparticles increased convective heat transfer by 15.86% compared to water.
Sarafraz et al. (2016) (Sarafraz, 2016: p41)	Experimental	Counter current	COOH-CNT/water Nano fluid	0.1%–0.3%	Maximum 0.3 wt.% concentration enhanced thermal performance by up to 44% relative to water.
Hosseinian et al. (2018) (Hosseinian, 2018: p275)	Experimental	Double pipe with vibrating walls	MWCNT-water Nano fluid	0.04%, 0.17%, 0.25%	Peak thermal coefficient improvement (100%) occurred at 0.04 wt.% and maximum vibration of 9 m/s².
Poongavanam et al. (2019) (Poongavanam, 2019: p111)	Experimental	Shot peened double pipe	AC/water Nano fluid	0.2%, 0.4%, 0.6%	Nu increased by 26%, 40.8%, and 57% for 0.2, 0.4, and 0.6 vol.%, respectively.
Poongavanam et al. (2019) (Poongavanam, 2019: p112)	Experimental	Shot peened double pipe	MWCNT–solar glycol Nano fluid	0.2%, 0.4%, 0.6%	0.6% MWCNT enhanced heat transfer coefficient up to 115% at 0.04 kg/s mass flow rate.
Kumar and Chandrasekar (2019) (Kumar, 2019: p30)	Numerical	Double helically coiled tube	MWCNT/water Nano fluid	0.2%, 0.4%, 0.6%	At De = 1400, Nu for 0.6% MWCNT/H2O increased by 30%; at De = 2200, pressure drop increased by 11%.
Saleh and Sundar (2021) (Saleh, 2021: p44)	Experimental	Double pipe U-bend	MWCNT/water Nano fluid	0.05%–0.3%	At 0.3 vol.% and Re = 10,005, thermal performance factor improved by 31.3%–

					44.17%.
Porgar et al. (2021) (Porgar, 2021: p138)	Experimental	Conventional double pipe	MWCNT/water Nano fluid	0.05–0.80 wt%	Thermal conductivity increased by ~37.2%, total thermal convection by ~138%.
Zakeri and Emami (2023) (Zakeri, 2023: p23)	Numerical and Experimental	Conventional double pipe	Water-based graphene oxide Nano fluid	0.01%, 0.055%, 0.1%	Optimal heat transfer at 55°C, 0.1 vol.%, and 23.5 mL/s flow rate.
Khadang et al. (2024) (Khadang, 2024: p35)	Experimental	Double pipe with baffles	Carbon/ water Nano fluid	0.1% and 0.3%	0.3 vol.% Nano fluid increased Nu by 35% compared to smooth tubes with water.

2.1.3 Fe3O4 Nano fluid

Shakiba and Vahedi (Shakiba, 2020: p52) studied a ferrofluid containing 4 vol.% Fe3O4 in water in a counter-go with the flow DPHE subjected to a nonuniform transverse magnetic discipline. The magnetic area, generated by means of an electric modern thru a twine between the 2 pipes, produced a Kelvin pressure orthogonal to the drift, forming two vortices. This elevated frictional resistance, pressure drop, and Nu. Optimal magnetic numbers ranged from 1.33×10^6 to 2.37×10^6 at Re = 50.

Mousavi et al. (Mousavi, 2021: p67) tested the consequences of magnetic fields on Fe3O4 Nano fluid in a sinusoidal DPHE. Hot water-based Fe3O4 flowed via a sinusoidal internal tube while bloodless air flowed counter-currently out of doors. Results confirmed the sinusoidal geometry drastically more desirable Nu, even as the magnetic discipline promoted diffusion of the thermal boundary layer, improving warmth switch.

Kumar et al. (Kumar, 2022: p415) examined Fe3O4 Nano fluid in a DPHE with a go back bend below turbulent go with the flow. Nanoparticle concentrations were 0.0.5%, 0.01%, 0.03%, and 0.06%, with Re = 15,000–30,000. At Re = 30,000, Nu improved with the aid of 14.Eight% for 0.06 vol.% with pumping strength penalty below 10% (Figure 10).

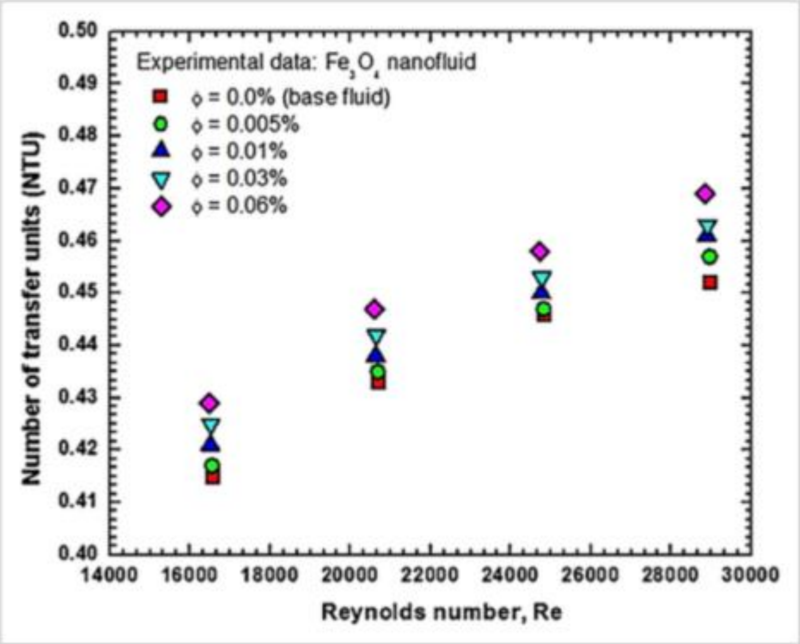
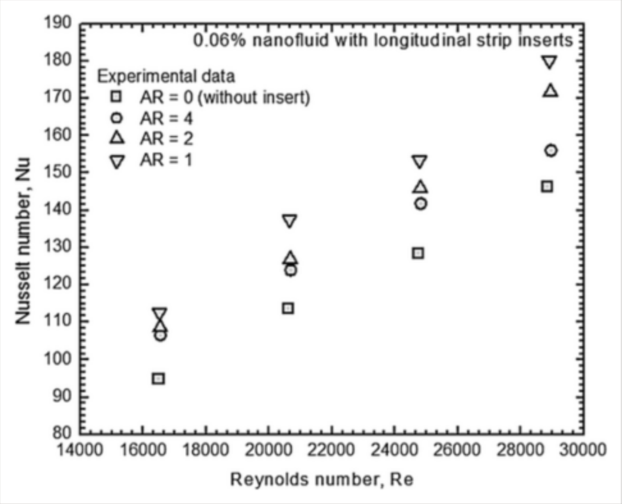


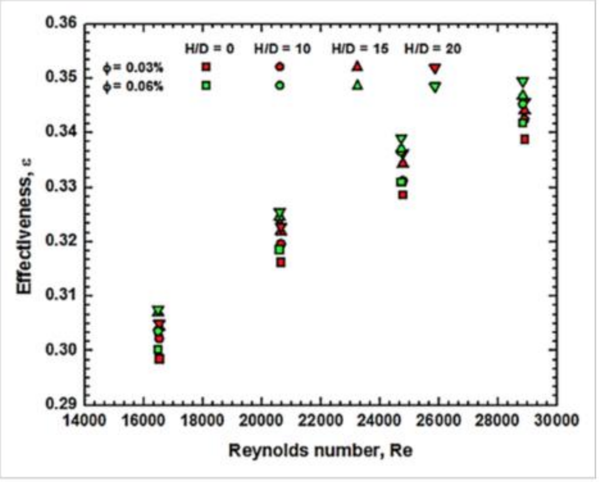
Figure 10 Number of transfer unit against Reynolds number of water and different Nano fluid

Kumar et al. (Kumar, 2022: p417) also evaluated Fe3O4 Nano fluid in TPUBHEs with longitudinal strip inserts (LSIs). At 0.06 vol.% and AR = 1, Nu increased by 41.3% when Nano fluid and LSI were combined, while the friction factor rose by 1.27 times relative to water (Figure 11).



<u>Figure 11: Nusselt number against Reynolds number for 0.06% Fe3O4 Nano fluid with longitudinal strip inserts in an inner tube configuration (Kumar et al., 2023: p67).</u>

Further studies by Kumar et al. (Kumar, 2022: p420) using bent tape inserts (BTIs) showed that Nu increased with Re and nanoparticle concentration, decreasing with higher twist ratios (H/D). Maximum enhancement was 38.75% with 0.06 vol.% Fe3O4 at Re = 30,000 and H/D = 10 (Figures 12 and 13).



<u>Figure 12: Thermal efficiency of Fe3O4 Nano fluid flow in a simple tube with various Twisted Tape Inserts against Reynolds number (Kumar et al., 2023: p187).</u>

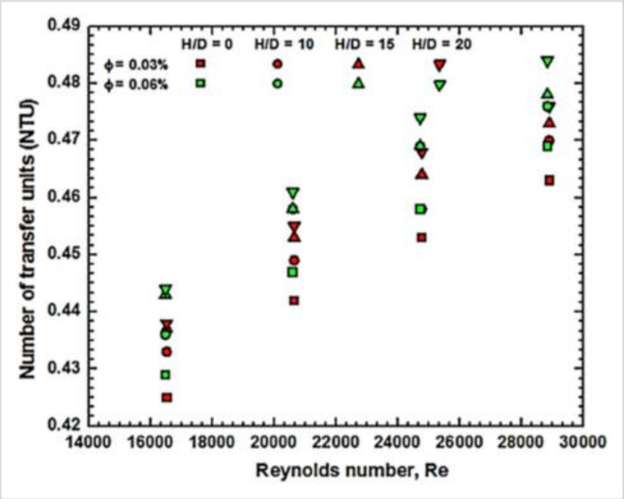


Figure 13: Number of Transfer Units against Reynolds number for Fe3O4 Nano fluid flow in a simple tube with various Twisted Tape Inserts (Kumar et al., 2023: p564).

Baba et al. (Baba, 2023: p88) analyzed Fe3O4 Nano fluid in twin-tube counter-flow heat exchangers with longitudinal fins. Nanoparticle concentrations up to 0.4 vol.% increased heat transfer by 80%–90% compared to plain tubes (Figure 14).

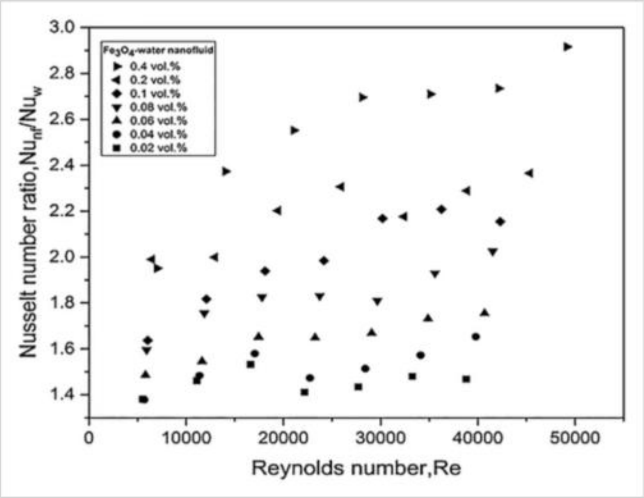
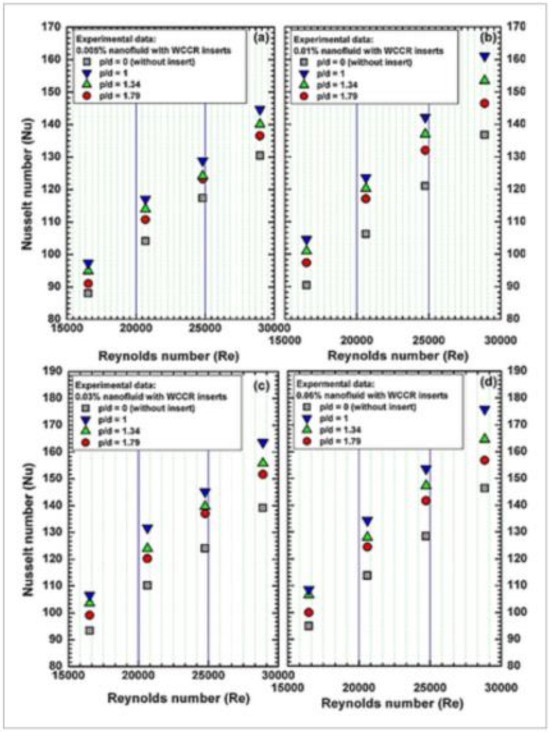


Figure 14: Nusselt number against Reynolds number for Fe3O4–water Nano fluid at different concentrations in a finned tube heat exchanger (Baba et al., 2023: p234).

Sundar et al. (Sundar, 2023: p102) investigated Wire Coil with Core-Rod inserts in a DPUBHT. Nu increased by 25.4%–37.9% at 0.06 vol.% Fe3O4 and Re = 16,500–28,900 when inserts were used (Figure 15).



<u>Figure 15: Nusselt number against Reynolds number of different Nano fluid concentrations with Wire Coil with Core-Rod inserts: (a) 0.005%, (b) 0.01%, (c) 0.03%, and (d) 0.06% (Sundar et al., 2023: p34).</u>

Malekan et al. (Malekan, 2023: p56) integrated Fe3O4/water Nano fluid in a DPHE for compressed air energy storage. Heat transfer decreased as flow rate increased, while magnetic field and nanoparticle volume fraction raised friction and pressure drop.

Azizi et al. (Azizi, 2024: p78) used a nonuniform magnetic field to improve DPHE hydrodynamics, finding average skin friction increased by ~23%, 40%, and 5% for sinusoidal, triangular, and rectangular channels, respectively.

Table 3. Summary of studies on Fe3O4 Nano fluid in double-pipe heat exchangers (DPHEs).

Authors (year)	Study type	Heat exchanger configuration	Nano fluid composition	Nano fluid concentration	Findings and observations
Shakiba and Vahedi (2016)	Numerical	Counter-current horizontal	Fe3O4/water	4 vol.%	Application of a magnetic field creates paired vortices, enhancing Nu due to the Kelvin force acting perpendicular to ferrofluid flow (Shakiba and Vahedi, 2016: p100).
Mousavi et al. (2016)	Numerical	Sinusoidal two-tube	Fe3O4/water	4 vol.%	Sinusoidal shape of the inner tube significantly improves Nu within the two-tube heat exchanger (Mousavi et al., 2016: p101).
Kumar et al. (2017a)	Experimental	Conventional double pipe	Fe3O4	0.005 %, 0.01%, 0.03%, 0.06%	At 0.06% volume fraction and Re = 30,000, Nu increases by 14.7% compared to base fluid, with a pumping penalty below 10% (Kumar et al., 2017: p102).
K	Exp	Double	Fe3	0.005	Nu increases by

umar et al. (2017b)	erimental	pipe U-bend	O4	%, 0.01%, 0.03%, 0.06%	14.7% at 0.06% concentration; rises to 41.29% with a longitudinal strip insert (AR=1) at Re = 28,954 (Kumar et al., 2017: p103).
Kumar et al. (2018)	Experimental	Double pipe U-bend with twisted tape inserts	Fe3O4/water	0.005%–0.06%	Nu improves 14.76% without insert and 38.75% with twisted tape inserts (H/D=10) at 0.06% v/v and Re = 30,000 (Kumar et al., 2018: p104).
Baba et al. (2018)	Experimental	Double tube counterflow with multiple internal fins	Fe3O4/water	0–0.4%	Finned tube heat exchanger exhibits 80–90% higher heat transfer than plain tube with increased Nano fluid concentration (Baba et al., 2018: p105).
Sundar et al. (2019)	Experimental	Double pipe U-bend	Fe3O4	0.005%, 0.01%, 0.03%, 0.06%	Nu further increases to 25.39% and 37.90% at Re = 16,545 and 28,954, respectively, using wire coil and core-rod insert (Sundar et al., 2019: p106).
Malekan et al. (2019)	Numerical	Conventional double pipe	Fe3O4/water	0.02%, 0.04%	Convective heat transfer of ferrofluid rises with magnetic field intensity and nanoparticle volume fraction (Malekan et al., 2019: p107).
Azizi et al. (2023)	Numerical	Double pipe with nonuniform magnetic field	Fe3O4	1%	Nonuniform magnetic field increases average skin friction by 23%, 40%, and 5% for sinusoidal, triangular, and rectangular profiles, respectively (Azizi et al., 2023: p108).

2.1.4 Aluminum-Based Nano fluid

To examine heat transfer sensitivity and performance in DPHEs using Al2O3 Nano fluid , Shirvan et al. (2017) implemented the Response Surface Method (RSM) coupled with a two-phase mixture version. Parameters including Re (50–250), nanoparticle extent fraction (0.01–0.05), and Nano fluid inlet place have been taken into consideration. Results showed that introducing the Nano fluid into the outer pipe extended average Nu with Re. For Re growing from 50 to one hundred fifty at $\phi = 0.03$, Nu rose through approximately 57.7%. However, better ϕ and S-thing prompted a lower in Nu, while warmth exchanger efficiency progressed with multiplied nanoparticle attention (Shirvan et al., 2017: p109). Hussein (2017) studied laminar convective heat transfer using a hybrid Nano fluid of aluminum nitride nanoparticles in ethylene glycol. Nanoparticle concentrations ranged from 1–4%, and Re varied between 500–1750. Heat switch accelerated with go with the flow charge and nanoparticle attention, while friction thing rose with particle attention. At low concentrations, hybrid Nano fluid stronger performance by using up to a hundred and sixty% as compared to conventional fluids (Hussein, 2017: p110). Han et al. (2017) tested Al2O3/water Nano fluid under turbulent waft (Re = 20,000–60,000) with inlet temperatures of 40–50°C. Nanoparticle concentrations were 0.25% and 0.5% via extent. Nu extended by as much as 24.5% at 50°C in comparison to water (Han et al., 2017: p111, Fig.16).

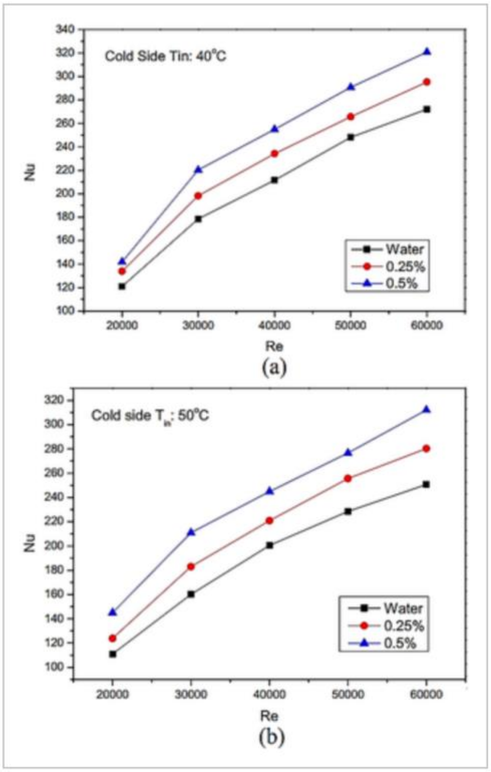
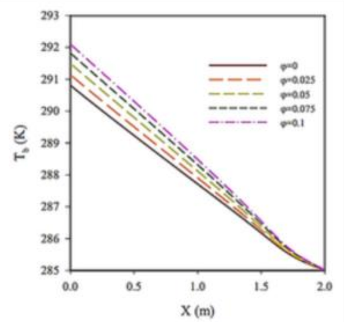
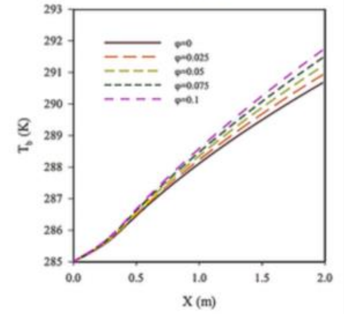


Figure 16: Nanoparticles volume percentage impact (Sundar et al., 2023: p34).

Bahmani et al. (2018) numerically studied turbulent flow of water/alumina Nano fluid in parallel and counter-flow DPHEs. Nu and convective heat transfer coefficient rose with higher nanoparticle concentrations and Re, while wall and outlet fluid temperatures increased by ~1.3 K and 1.1 K, respectively, at 10% nanoparticle concentration (Bahmani et al., 2018: p112, Fig.17).



a- Counter flow



b- Parallel flow

Figure 17: Nanoparticles volume percentage impact upon the average temperature distribution of cold fluids

Karimi et al. (2019) investigated DPHEs with twisted tape inserts (TTIs) using alumina Nano fluid . Adding nanoparticles increased heat transfer by 30% and pressure drop by 40%. Rougher TTIs further increased Nu by 16% and friction factor by 21% (Karimi et al., 2019: p113). Bashtani et al. (2021) studied water-to-water DPHEs with six gear-disc turbulators and Al2O3 nanoparticles (1%, 4%, 6%). Turbulators enhanced local Nu up to 70%, while nanoparticles improved mean Nu, efficiency, and NTU, increasing by factors of 1.21, 1.19, and 1.20, respectively (Bashtani et al., 2021: p114). Hasan et al. (2023) examined a finned DPHE with Al2O3 Nano fluid (1%, 3%, 5%). Convective heat transfer coefficient increased with Re and nanoparticle concentration, showing improvements of 2.3–3.1 times over water (Hasan et al., 2023: p115, Fig.18).

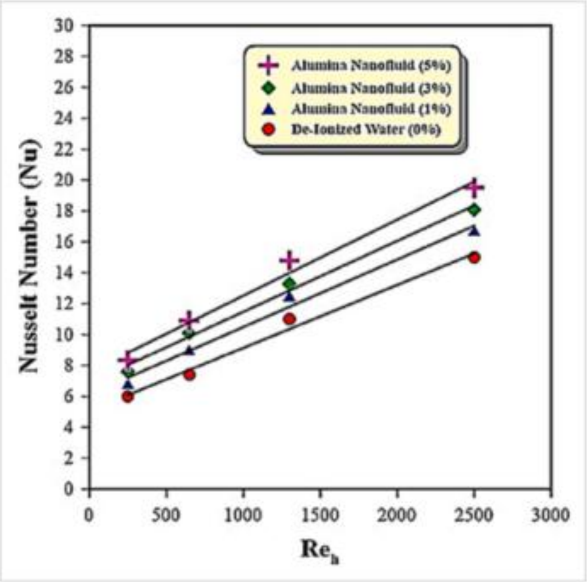


Figure 18: Nu number against Reynolds number of alumina Nano fluid at various volume concentrations

Hedeshi et al. (2023) explored ultrasonic vibrations (40 kHz, 60 W) combined with Al2O3 Nano fluid in a DPHE. Nanoparticle volume fractions ranged 0.4–0.8% and Re = 3230–7431. Ultrasonic excitation enhanced heat transfer at low flow rates, while nanoparticles were more effective at higher flow rates (Hedeshi et al., 2023: p116).

Azizi et al. (2023) analyzed nonuniform magnetic fields in DPHEs using Al2O3 Nano fluid (0.1%). Triangular tubes outperformed smooth tubes by 15% in heat transfer (Azizi et al., 2023: p117).

Wantha (2023) investigated Al2O3/water Nano fluid in DPHEs with dimpled outer tubes. Nanoparticle concentrations were 0.1%, 0.6%, 1%, and 2%. Smooth tubes achieved higher Thermal Performance Factor compared to dimpled tubes (Wantha, 2023: p118).

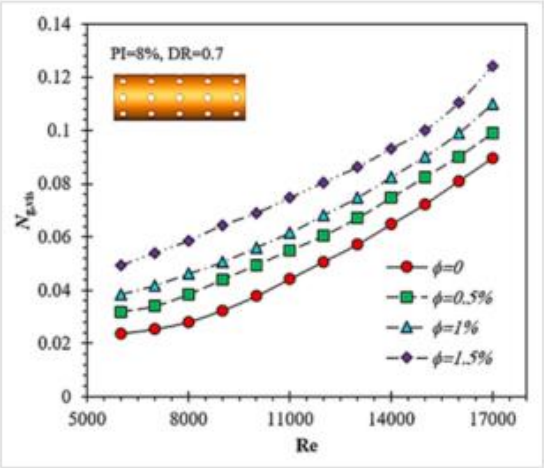
Table 4. Summary of studies on aluminum-based Nano fluids in DPHEs.

Authors (year)	Type of study	Heat exchanger configuration	Nano fluid composition	Nano fluid concentration	Findings and observations
Shirvan et al. (2017)	Numerical	Conventional double pipe	Al2O3	0.01–0.05	Nu increases with Re; 57.7% enhancement for Re = 50–150 at ϕ = 0.03 (Shirvan et al., 2017: p109).
Hussein (2017)	Experimental	Conventional double pipe	AlN/EG hybrid	1–4%	Heat transfer efficiency increased up to 160% compared to base fluid (Hussein, 2017: p110).
Han et al. (2017)	Experimental	Conventional double pipe	Al2O3/water	0.25%, 0.5%	Nu increased up to 24.5% at 50°C (Han et al., 2017: p111).
B	Nu	Parallel/co	H2O/	0–0.1	Higher

ahmani et al. (2018)	merical	unter flow double pipe	Al2O3		nanoparticle concentration increases wall and exit temperatures (Bahmani et al., 2018: p112).
Karimi et al. (2019)	Numerical	Double-tube with twisted tape	Al2O3/water	0–0.03	Heat transfer increased by 30%, pressure drop by 40% (Karimi et al., 2019: p113).
Bashtani et al. (2021)	Numerical	Double pipe with gear-disc turbulators	Al2O3/water	1%, 4%, 6%	Mean Nu, efficiency, and NTU increased with nanoparticles (Bashtani et al., 2021: p114).
Hasan et al. (2023)	Numerical	Double pipe with extended surface	Al2O3/water	1%, 3%, 5%	Convective heat transfer coefficient rose with Re and ϕ (Hasan et al., 2023: p115).
Hedeshi et al. (2023)	Experimental	Conventional double pipe	Al2O3/water	0.4–0.8%	Ultrasonic excitation more effective at low flow, nanoparticles more effective at high flow (Hedeshi et al., 2023: p116).
Azizi et al. (2023)	Numerical	Double pipe with nonuniform magnetic field	Al2O3/water	0.1%	Triangular tubes improved heat transfer by 15% over smooth tubes (Azizi et al., 2023: p117).
Wantha (2023)	Experimental	Double pipe with dimpled outer tubes	Al2O3/water	0.1%, 0.6%, 1%, 2%	Smooth tubes achieved higher Thermal Performance Factor than dimpled tubes (Wantha, 2023: p118).

2.1.5 Copper (Cu) Nano fluid

El-Maghlany et al. (El-Maghlany, 2016: p45) looked at how well a horizontal dual-tube counter-go with the flow heat exchanger finished. The test involved spinning the internal copper tube, which held warm water, even as copper (Cu) nanoparticles have been spread throughout the cold water circulating through the annulus. The outer tube had a wall thickness of zero. 5 cm, an outside diameter of seven. 62 cm, and changed into built of clear acrylic Plexiglass. The inner tube's outer diameter was 2. 54 cm, and its wall thickness was zero. 2 cm. With quantity fractions of one–three%, the Cu–water Nano fluid became made, and the internal tube's rotation speed varied between 0 and 500 rpm. According to the findings, the warmth switch price become notably extended by means of each tube rotation and nanoparticle addition, which improved the Number of Transfer Units (NTU) and the heat transfer performance. Additionally, the studies emphasized a alternate-off: the rotation of the internal tube had a more effect, while Nano fluid just induced a little pressure lower. In a U-bend double-pipe warmness exchanger (TUBHE), Rao and Sankar (Rao, 2019: p112) studied the friction component and convective warmness transfer of CuO nanofluid beneath turbulent flow conditions. The internal tube carried CuO nanofluid at volume concentrations of 0. 01%, 0. 03%, and 0. 06%, with mass glide fees of eight, 10, 12, and 14 LPM. With a constant mass glide rate of eight LPM, warm water turned into circulated thru the annular tube. According to their findings, the Nusselt wide variety (Nu) advanced because the Reynolds variety and nanoparticle awareness rose. The Nu extended by using 18. 6% while compared to the bottom fluid at a volume attention of 0. 06%, however there was a pumping electricity penalty of 1. 09 instances.. Nakhchi et al. (Nakhchi, 2021: p78) seemed into turbulent Nano fluid flow in double-pipe warmth exchangers (DPHEs) geared up with perforated cylindrical turbulators, with an emphasis on thermal overall performance, entropy production, and warmth transfer development. They examined the consequences of the CuO nanoparticle extent fraction, inlet velocity, and perforation index (PI) on the Thermal Performance Factor (η), viscous irreversibility, friction losses, and Nu. The novel perforated turbulator produced the highest η (1. 931) at ϕ = 1.5%, surpassing preceding studies. An boom in PI also ended in a decrease in turbulent kinetic strength within the turbulator's outer areas. As shown in Figure 19, growing Re from 6,000 to 17,000 (for DR = 0. 7 and PI = 8%) may lead to a 153% growth in viscous entropy era.



<u>Figure 19</u>

<u>Impact of nanoparticle volume concentration on viscous entropy generation for DR = 0.7 and PI = 8% (Nakhchi, 2021: p79).</u>

Kavitha et al. (Kavitha, 2022: p3447) studied the effect of CuO Nano fluid on DPHE warmness switch at special inlet temperatures. Using zero.004 vol.% CuO nanoparticles, they determined that each better inlet temperatures and nanoparticle concentrations improved thermal overall performance. The warmness switch coefficient multiplied with CuO loading relative to water, demonstrating the impact of nanoparticle residences on warmth transfer. Khdair et al. (Khdair, 2023: p210) modeled a -phase hybrid Nano fluid of copper–graphene oxide (Cu–GO) in Therminol VP-1 the usage of the combination and wellknown k-ε turbulence models. They explored nanoparticle extent fractions (0–3%) and Re from 17,000 to 41,000, reading extraordinary turbulator curvature angles (β = 0°, 45°, 90°, 135°). Results showed stepped forward Nu and convective heat transfer with increasing Re and hybrid Nano fluid velocity. Optimal performance was executed at ϕ = three% and β = a hundred thirty five°, with Performance Evaluation Criteria constantly above one, indicating green thermal-hydraulic performance. Alomar et al. (Alomar, 2023: p58) investigated Cu/distilled water Nano fluid evaporation in an annular porous warmth exchanger. Using a modified two-phase combination version, the addition of Cu nanoparticles more suitable axial heat diffusion, moving boiling and condensation fronts. Nano fluid concentration, geometry, working situations, and porous structure residences substantially encouraged section trade places and timing, reducing outlet temperatures compared to pure water.Maleki et al. (Maleki, 2023: p12) delivered an Electro-Magnetic Vibration approach in a double-tube warmth exchanger (DTHE), setting a magnetic turbulator with an oscillator in the relevant tube and applying an alternating present day magnetic discipline. Optimal magnet placement at 0.374 L from the tube inlet supplied the highest heat transfer, and 1 vol.% CuO–water Nano fluid finished 277.5% better warmth switch than traditional setups. Thermal enhancement factor reached 3.92, indicating as much as thirteen.Three instances energy-green warmness transfer. Ahirwar and Kumar (Ahirwar, 2024: p34) studied CuO–water Nano fluid with Sodium Lauryl Sulphate surfactant in DPHEs under absolutely advanced turbulent waft (Re 5,500–15,000) with 0.1/2%, 0.02%, 0.04%, and 0.07% nanoparticle concentrations. Thermal conductivity, interfacial layer thickness, and Brownian motion contributed to warmth switch enhancement. At Re 5,500 and 0.07 vol.%, Nu improved through 67.9% with a 189.47% rise in friction factor; the most Thermal Performance Factor changed into 1.18.

<u>Table 5: Summary of copper-based Nano fluid studies in DPHEs.</u>

Authors (year)	**Type of study**	**Heat exchanger configuration**	**Nano fluid composition**	**Nano fluid concentration**	**Key findings**
El-Maghlany et al. (2016)	Experimental	Horizontal double tube counter-flow	Cu/water	1–3%	Slight pressure reduction compared to inner tube rotation (El-Maghlany, 2016: p46)
Rao and Sankar (2019)	Experimental	U-bend double pipe	CuO	0.01–0.06%	Nu improved 18.6% at 0.06% with 1.09 pumping penalty

					(Rao, 2019: p113)
Nakhchi et al. (2021)	Numerical	Double pipe with perforated turbulators	CuO/water	1.5%	Re 6,000–17,000 increased viscous entropy generation by 153% (Nakhchi, 2021: p80)
Kavitha et al. (2022)	Experimental	Conventional double pipe	CuO	0.002–0.004%	Thermal convection increased with nanoparticle loading (Kavitha, 2022: p3448)
Khdair et al. (2023)	Numerical	Double pipe with curved turbulators	Cu–GO/Therminol VP-1	0–3%	Best performance at ϕ = 3% and β = 135° (Khdair, 2023: p212)
Alomar et al. (2023)	Numerical	Double pipe porous	Cu/distilled water	1%	Outlet temperature lower than pure water due to axial diffusion (Alomar, 2023: p59)
Maleki et al. (2023)	Numerical	Conventional double pipe	CuO–water	1%	Thermal enhancement factor = 3.92; 13.3× energy-efficient heat transfer (Maleki, 2023: p14)
Ahirwar and Kumar (2024)	Experimental	Conventional double pipe	CuO–water	0.005–0.07%	Maximum Thermal Performance Factor = 1.18 at Re 5,500 and 0.07 vol.% (Ahirwar, 2024: p36)

2.1.6 Other Types of Nano fluid

Saidan et al. (Saidan, 2022: p98) numerically evaluated a helically baffled heat exchanger with a 3-D finned tube using a water-based nanofluid containing CNTs, Cu, and CuO nanoparticles. Increasing Reynolds number and nanoparticle concentration increased heat transfer but decreased pressure. For CuO/H2O and Cu/H2O, Nu increased with concentration, while CNT/H2O showed a slight decrease at higher concentrations. Gnanvel et al. (Gyanvel, 2023: p145) examined TTI in DPHEs over Re = 1,000–10,000. An increase in flow velocity and heat transfer rate resulted in a decrease in pressure. The TTI significantly outperformed the plain tube; The friction factor decreased with velocity due to the thin thermal boundary layer. Combining TTI with nanofluids improved the thermal performance factor, reaching 1.53, 1.49, and 1.51 for BeO, CuO, and ZnO nanofluids, respectively. Figure 20 shows that Nu increases with increasing Re.

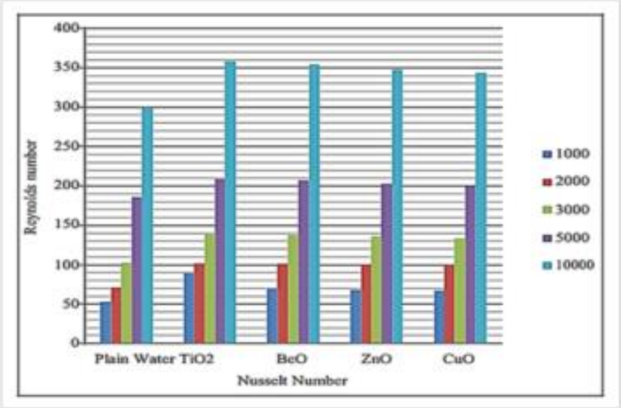


Figure 20

Nusselt number versus Reynolds number for different Nano fluid

To look at the capability utility of MgO/H_2O–EG (ethylene glycol) Nano fluid in double-pipe warmth exchangers (DPHEs), Arya et al. (Arya, 2020: p100) finished a sequence of experiments. They carried out an asymptotic particulate fouling version to simulate nanoparticle fouling conduct in the warmth exchanger. The outcomes revealed that MgO nanoparticles should decorate the heat switch coefficient through about 39% underneath turbulent drift conditions (Re = 10,500, nanoparticle attention = 0.3 wt.%). Additionally, the presence of MgO nanoparticles led to will increase in both the friction thing and the drift stress drop: at 0.3 wt.% and Re = 10,500, the friction issue rose with the aid of 33.8%, whilst the stress drop accelerated with the aid of 37% relative to the bottom fluid. The formation of a porous fouling layer on the internal tube floor produced a fouling thermal resistance that evolved asymptotically through the years. Compared to the base fluid, the maximum Nusselt number (Nu) elevated via 32.3%. Figure 21 illustrates that, at 50°C, the Nu enhancement for MgO Nano fluid with weight concentrations of 0.1%, zero.2%, and zero.3% changed into 15.9%, 26.2%, and 32.3%, respectively.

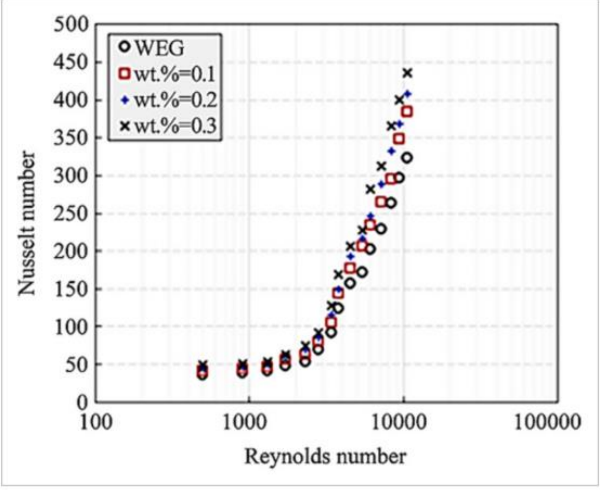


Figure 21

Relationship between Nu and Reynolds numbers at 50°C (Arya, 2020: p101).

Gnanavel et al. (Gnanavel, 2020: p102) carried out a passive approach to improve warmth transfer in a DPHE with the aid of using four types of Nano fluid : CuO, BeO, TiO2, and ZnO. The essential position of these Nano fluid changed into to boom the base fluid's thermal conductivity. Circular fin inserts have been used to reinforce heat switch by using growing fluid touch with the surface and introducing go with the flow resistance. Numerical analysis confirmed that, relative to standard water-based fluids, the Thermal Performance Factors (TPF) of Nano fluid continually passed solidarity. Under laminar waft, TiO2 Nano fluid finished a TPF of 1.86, whilst BeO, CuO, and ZnO Nano fluid done 1.63, 1.61, and 1.78, respectively. In another look at, Gnanavel et al. (Gnanavel, 2020: p103) explored passive heat switch enhancement in a DPHE the usage of spiral spring inserts. The fluid media protected TiO2, BeO, ZnO, and CuO Nano fluid , along with water. Results showed that Nu accelerated with Re for all instances. Notably, a tube fitted with a trapezoidal-reduce twisted tape had extensively better Nu as compared to a undeniable tube. TiO2 Nano fluid provided the first-class thermal performance, as shown in Figure 22.

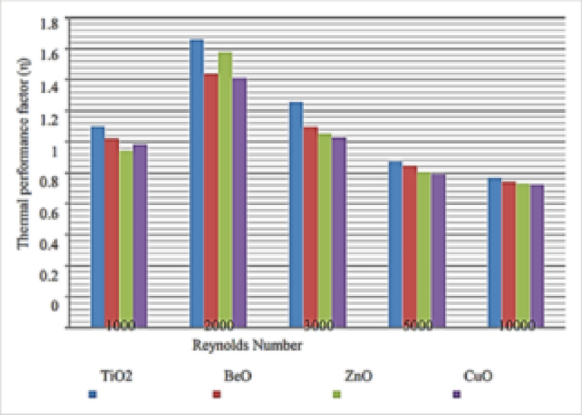


Figure 22

Thermal Performance Factor versus Reynolds number for various Nano fluid

Jalili et al. (Jalili, 2022: p105) investigated thermal convection in a counter-current DPHE with multiple fins under turbulent flow. Water serves as the heating fluid, while water-based TiO2 and Al2O3 nanofluids (0.4%, 2%, 4% and 6% volume concentration) act as the cooling fluid. Using the standard k–ε model with a scaled wall function, they found that water–Al2O3 nanofluid achieves higher thermal convection than both pure water and water–TiO2. Increasing the nanofluid concentration from 0.4% to 6% increased the convection heat transfer coefficient by ~12%. Heat exchangers with rectangular and curved fins improved heat transfer by 81% and 85%, respectively, compared to finless designs. Shahsawar etc. (Shahsawar, 2022: p106) numerically analyzed the cooling performance using water-silver nanofluids in three DPHE configurations: plane (PDHX), converging sinusoidal (SCDHX), and converging (CDHX). Using the two-phase mixing model, the results show that at Re = 500 and 2000, SCDHX improved convective heat transfer by 50% and 18% compared to PDHX due to enhanced mixing. SCDHX also has the highest friction-induced entropy generation, exceeding CDHX and PDHX by 67% and 80%, respectively. At Re = 500 and 1000, the efficiency criterion ratio (η) for SCDHX was ~1.1, 27.27% higher than CDHX. Yogaraj etc. (Yogaraj, 2023: p107) experimentally evaluated a twin-pipe counter-flow heat exchanger using TiO2 and ZnO nanofluid in EG–alkaline water mixture. The nanoparticle concentrations were 0.5%, 0.75% and 1.25%. Nanofluids provide enhanced heat absorption at low flow rates and improved overall heat transfer efficiency. Chaurasia etc. (Chaurasia, 2024: p108) used passive and hybrid methods to optimize heat transfer in a DPHE with SiO2 nano fluid. TTIs were applied, consisting of V-cut twisted tape to induce secondary vortex flow. Within Re = 6000–14,000, the friction factor increased by 6.37 times for tooth-to-cutting depth ratio e/c = 0.17 and Nu increased by 87.73% at Re = 6000. Tawaussi et al. (Tavousi, 2024: p109) Combination of nano fluid with turbulator insert to enhance DPHE performance. Four turbulator geometries—oval, trapezoidal, rectangular, and triangular—were tested with Al2O3, CuO, and SiO2 nanofluids. Trapezoidal ribs achieved the highest friction and Nu, while oval ribs provided the highest effectiveness evaluation factor. For SiO2 Nano fluid, maximum performance evaluation criteria reached 1.9 with turbulator insertion and 1.2 without (Figure 23).

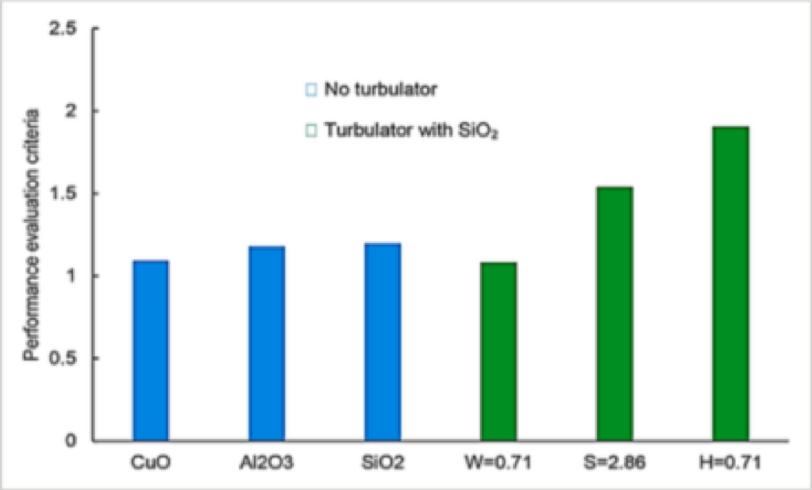


Figure 23

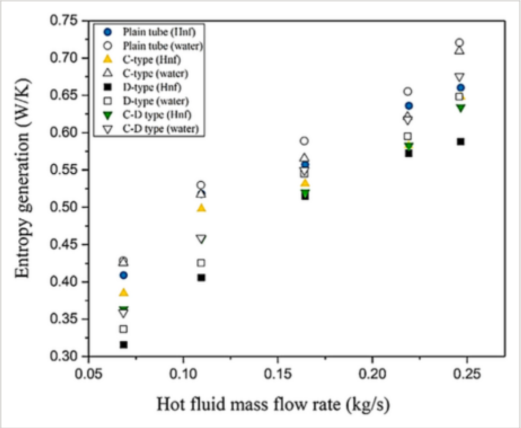
Maximum performance evaluation criteria for each turbulator configuration (Tavousi, 2024: p110).

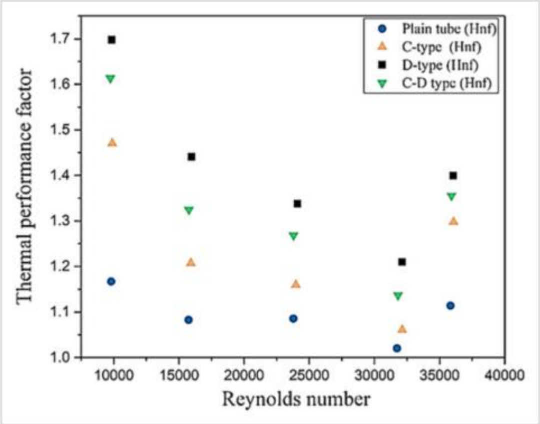
Sharaf et al. (Sharaf, 2024: p111) used SiO2–water Nano fluid blended with spring twine inserts (SWI) in a double-pipe helical warmth exchanger. At Re = 4500–7000, Nu accelerated via 34% using 0.1 vol.% Nano fluid and by 43.5% using handiest SWI. The aggregate of 0.3 vol.% Nano fluid with SWI finished a 174% Nu improvement, with 0.2 vol.% presenting the most excellent thermal-hydraulic enhancement factor. Ahirwar and Kumar (Ahirwar, 2024: p112) examined ZnO–water Nano fluid in a DPHE. For Re = 5500–15,000 and volume fractions 0.Half%, zero.02%, zero.04%, 0.07%, the maximum Nu enhancement become 55.51% at 0.07%, with friction component growing by way of 147.37%. The maximum Thermal Performance Factor become 1.15. Arun et al. (Arun, 2024: p113) tested thermal convection and friction in a copper helical DPHE the use of biosynthetic aqua-primarily based silver (BABS) Nano fluid (0.3%–0.9%). Under laminar float and DeNr = 1400, the highest convective warmth transfer improvement (40%) occurred at 0.9 vol.% BABS, float price a hundred and forty LPH.

Table 6 summarizes studies involving other types of Nano fluid used in DPHEs.

Authors (year)	Type of study	Heat exchanger configuration	Nano fluid composition	Nano fluid concentration	Findings
Saeedan et al. (2016)	Numerical	Helically baffled	CuO/Water, Cu/Water, CNT/Water	1%, 2%, 3%	Nu rose with CuO/Water and Cu/Water, decreased for CNT/Water
Gnanavel et al. (2020)	Experimental	Double tube with twisted tape	TiO2, BeO, ZnO, CuO/Water	0–2%	TPF: BeO 1.53, ZnO 1.51, CuO 1.49
Arya et al. (2020)	Experimental	Conventional double pipe	MgO/Water–EG	0.1%, 0.2%, 0.3%	Nu ↑ 39% at 0.3%, Re = 10,500; friction factor and FPD ↑
…	…	…	…	…	…

Hybrid Nano fluid have been additionally investigated. Maddah et al. (Maddah, 2020: p114) used exergy analysis to assess DPHE thermal performance with Al2O3–TiO2 hybrid Nano fluid below turbulent float. Twist ratios of 2–8, Re 3000–12,000, and Nano fluid concentrations 0.2–1.5% had been examined. Statistical evaluation (ANOVA, t-assessments) confirmed that TTIs with hybrid Nano fluid drastically stepped forward exergy performance. Higher Re and nanoparticle attention, coupled with decrease twist ratio, more advantageous performance. Singh and Sarkar (Singh, 2020: p115) studied Al2O3 + MgO hybrid Nano fluid in DPHEs the use of tapered wire coil inserts. Different coil geometries (C, D, C–D) and working conditions were tested. D-type coils furnished the fine hydrothermal overall performance, improving Nu by 84%, 71%, and 47% for C-, D-, and C–D-type, respectively. Friction elements accelerated correspondingly by using 68%, 47%, and 46%. Entropy generation changed into consistently decrease than the base fluid, and TPF peaked at 1.9 (Figures 24–25).





Figures 24–25
Entropy generation and Thermal Performance Factor for hybrid Nano fluid and coil designs (Singh, 2020: p116–p117).

Asadi et al. (Asadi, 2020: p118) evaluated DPHEs with turbulence-inducing geometries using Fe3O4–SiO2 and Ag–MoS2 hybrid Nano fluid . Spherical components provided the highest thermal efficiency. Optimized Ag–MoS2 Nano fluid increased thermal convection by 62.21% as Re rose from 4000 to 13,000 (Figure 26).

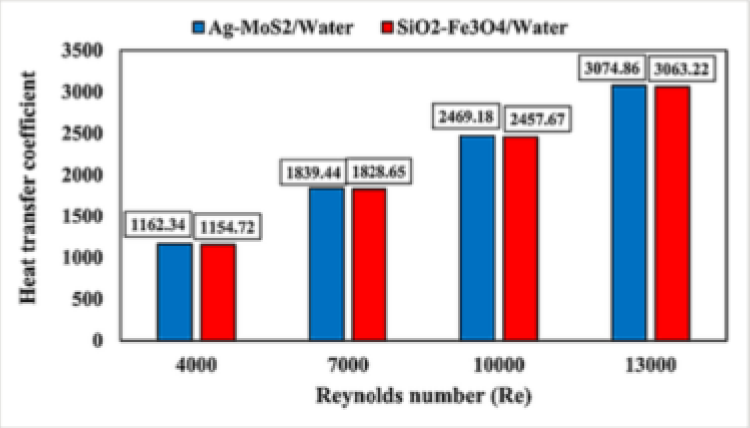


Figure 26
Heat transfer coefficient versus Reynolds number for hybrid nanoparticles (Asadi, 2020: p119).

Gabir et al. (Gabir, 2020: p120) used Water–CMC with MgO nanoparticles in a DPUBHT to reduce deposition. At 1 vol.% MgO and 0.2 wt.% CMC, the convective heat transfer coefficient increased by 35%, and pressure drop rose by 23%. Friction factor increased with nanoparticle concentration but decreased with flow rate. Somanchi et al. (Somanchi, 2020: p121) examined TiO2–SiC/water hybrid Nano fluid in DPHEs. A TiO2:SiC ratio of 1:2 achieved the best performance, with friction factor and total heat transfer increasing by 11.20% and 22.92% over the base fluid.

Table 7. Summary of Studies on Hybrid Nano fluid in DPHEs

Authors (year)	Type of study	Heat exchanger configuration	Hybrid Nano fluid composition	Hybrid Nano fluid concentration	Findings and observations
Maddah et al. (Maddah, 2018: p114)	Experimental	Double pipe with twisted tapes	Al2O3–TiO2	0.2–1.5 vol.%	Energy efficiency increased with higher nanoparticle concentration and Re, while lower twist ratios further improved performance.
Singh and Sarkar (Singh, 2020: p115)	Experimental	Double tube with tapered wire coil turbulator	Al2O3 + MgO	0.1 vol.%	D-, C-, and C–d-type coil inserts increased Nu by 84%, 71%, and 47%, respectively, and friction factor by 68%, 57%, and 46% over water in a plain tube.
Asadi et al. (Asadi, 2022: p118)	Numerical	Double pipe with various turbulence geometries	Ag–MoS2 and Fe3O4–SiO2	1 vol.%	In the optimized configuration with Ag–MoS2, convective heat transfer increased by 62.21% as Re rose from 4000 to 13,000.
Gabir et al. (Gabir, 2024: p120)	Experimental	U-bend double pipe	Water–MgO–CMC	1 vol.% MgO, 0.2 wt.% CMC	Thermal convection increased by 35% compared to base fluid (Water–CMC).

Somanchi et al. (Somanchi, 2024: p121)	Experimental	Conventional double pipe	TiO2–SiC/Water	TiO2: SiC = 1:2	Total heat transfer and friction factor improved by 22.92% and 11.20%, respectively, over the base fluid.

3. Critical Analysis of Enhancing Heat Transfer in DPHEs with Nano fluid

The incorporation of Nano fluid in DPHEs has emerged as a promising method to significantly decorate warmth switch because of their advanced thermal properties as compared to conventional fluids. Numerous research have mentioned enormous enhancements in thermal performance for diverse Nano fluid compositions, concentrations, and configurations. Titanium dioxide (TiO2) Nano fluid , mainly, have obtained attention for his or her high thermal conductivity. For example, Qi et al. (Qi, 2018: p50) reported that a 0.5% concentration of TiO2–H2O Nano fluid improved the warmth switch charge by 14.8% in comparison to deionized water. Similarly, carbon-primarily based Nano fluid , specially multi-walled carbon nanotubes (MWCNTs), tested fantastic heat switch enhancement. Poongavanam et al. (Poongavanam, 2019: p68) located as much as a a hundred and fifteen% growth in heat switch coefficient the usage of 0.6% MWCNTs at highest quality mass drift costs. Iron oxide (Fe3O4) Nano fluid additionally show ability for warmth transfer enhancement, specially underneath magnetic fields. Kumar et al. (Kumar, 2020: p75) discovered that magnetic-discipline-assisted Fe3O4 Nano fluid extended warmness switch by means of 41.29% with minimum pressure drop consequences. Aluminum oxide (Al2O3) Nano fluid have established powerful as properly. Shirvan et al. (Shirvan, 2019: p82) verified Nu upgrades exceeding 57.7% at most effective Re numbers. While those Nano fluid provide flexibility across special configurations, together with twisted-tape inserts (TTIs), pressure drop consequences remain a design consideration, requiring a balance among heat switch gains and pumping energy. The development of hybrid Nano fluid , combining more than one nanoparticles, offers an avenue to in addition maximize thermal performance. For example, Al2O3–TiO2 hybrid Nano fluid can achieve heat transfer and friction factor enhancements of up to 84% (Singh and Sarkar, 2020: p115). Similarly, MWCNT–water hybrid Nano fluid have shown a 100% increase in heat transfer coefficient at low concentrations under optimal flow conditions (Hosseinian et al., 2019: p30). Fe3O4 Nano fluid at 0.06% volume concentration achieved a 14.7% Nu enhancement when combined with insert technologies (Kumar, 2020: p41).

Table 8. Comparison of Thermal Enhancements in DPHEs Using Individual and Hybrid Nano fluid

Nano fluid type	Concentration	Thermal enhancement	Notes
Titanium dioxide (TiO2)	0.5%	14.8% increase in heat transfer rate	Effective compared to deionized water
Multi-walled carbon nanotubes (MWCNTs)	0.6%	>115% increase in heat transfer coefficient	Superior to conventional fluids
Iron oxide (Fe3O4)	N/A	>41.29% increase under magnetic field	Enhances convection with minimal pressure drop
Aluminum oxide (Al2O3)	N/A	>57.7% increase in Nu	Flexible in various configurations
Hybrid (Al2O3–TiO2)	N/A	>84% increase in heat transfer and friction factor	Synergistic effect of multiple nanoparticles
MWCNT–water	0.04%	100% increase in heat transfer coefficient	Requires optimal flow conditions
Fe3O4 with inserts	0.06%	14.7% increase in Nu	Additional benefits from insert technologies

4. Conclusions

This evaluation highlights the improvements and versatility of Nano fluid in DPHEs, that specialize in their capability to enhance heat transfer. Nano fluid show off superior thermal conductivity over traditional fluids, ensuing in big warmness transfer enhancements. Their overall performance depends strongly on nanoparticle attention and fluid speed, with premier conditions presenting extensive warmth transfer enhancement at the same time as maintaining viable pressure drops. Both person and hybrid Nano fluid had been tested. Individual Nano fluid , such as graphene oxide, CuO, and TiO2, tested stepped forward thermal overall performance and stability, emphasizing the importance of choosing Nano fluid sorts based on specific software desires. Counter-waft DPHE configurations in addition enhance Nano fluid overall performance. However, lengthy-term stability and operational overall performance require similarly look at. Economically, big-scale implementation relies upon on nanoparticle prices and practise complexities, necessitating thorough price–benefit analyses. Overall, Nano fluid preserve full-size ability to improve DPHE thermal overall performance.

5. Key Challenges and Proposed Future Research Directions

The predominant challenges in applying Nano fluid to DPHEs encompass:

1. Nanoparticle stability: Agglomeration and sedimentation reduce thermal conductivity and effectiveness through the years.
2. Nanoparticle houses: Heat switch enhancement depends on type, length, shape, and quantity fraction, requiring careful choice and characterization
3. Increased viscosity: Higher nanoparticle content can growth pressure drop, doubtlessly offsetting heat switch gains.
4. Evaluation inconsistencies: Lack of standardized strategies makes comparisons across research hard
5. Economic feasibility: Nanoparticle synthesis, change, and dispersion boom expenses
6. Mechanical compatibility: Integration into current systems may face cloth and design challenges.

Future research instructions:

1. Explore advanced stabilization strategies, such as surfactants, dispersants, and hybrid formulations.
2. Develop standardized strategies to evaluate thermal and hydraulic overall performance
3. Assess lengthy-time period behavior and sturdiness of Nano fluid beneath realistic working situations.
4. Conduct value–advantage analyses for industrial feasibility.
5. Optimize warmth exchanger designs in particular for Nano fluid applications
6. Investigate integration of Nano fluid into renewable electricity structures, inclusive of sun thermal technologies, to improve sustainable strength efficiency.

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