Journal of Advanced Research in Fluid Mechanics and Thermal Sciences

Journal homepage:
https://semarakilmu.com.my/journals/index.php/fluid_mechanics_thermal_sciences/index
ISSN: 2289-7879

A Comprehensive Evaluation of Recent Studies Investigating Nanofluids Utilization in Heat Exchangers

Shital Yashwant Waware[1], Sukhadip Mhankali Chougule[2], Rahul Shivaji Yadav[3], Ramdas Biradar[4], Prashant Patil[5], Kashinath Haribhau Munde[6], Nitin Babanrao Kardekar[7], Ajitkumar Gulab Nimbalkar[3], Anant Sidhappa Kurhade[1,*], Govindarajan Murali[8], Sandeep Sadashiv Kore[9]

[1] Department of Mechanical Engineering, Dr. D. Y. Patil Institute of Technology, Sant Tukaram Nagar, Pimpri, Pune, 411018, Maharashtra, India
[2] Department of Mechanical Engineering, Pimpri Chinchwad College of Engineering and Research, Ravet, Pune, 412101, Maharashtra, India
[3] Department of Mechanical Engineering, Marathwada Mitra Mandal's College of Engineering, Karvenagar, Pune, 411052, Maharashtra, India
[4] School of Engineering & Technology, PCET's Pimpri Chinchwad University, Sate, 412106, Pune, Maharashtra, India
[5] Department of Mechanical Engineering, Abhinav Education Society's College of Engineering & Technology, Satara, 412801, Maharashtra, India
[6] Department of Mechanical Engineering, KES Rajarambapu Institute of Technology, Lohagaon, Pune, 411047, Maharashtra, India
[7] Department of Mechanical Engineering, Bhivarabai Sawant College of Engineering and Research, Pune, 411041, Maharashtra, India
[8] Department of Mechanical Engineering Koneru Lakshmaiah Education Foundation Green Fields, Vaddeswaram, Guntur (Dt) Andhra Pradesh 522502, India
[9] Department of Mechanical Engineering, BRACT's Vishwakarma Institute of Information Technology, Pune ,411048, Maharashtra, India

ARTICLE INFO

Article history:
Received 25 March 2024
Received in revised form 28 June 2024
Accepted 13 July 2024
Available online 30 July 2024

ABSTRACT

This comprehensive review critically examines recent research concerning the application of nanofluids in heat exchangers. The utilization of nanofluids, which are colloidal suspensions of nanoparticles in a base fluid, has garnered significant attention in enhancing heat transfer performance. Various studies have explored the potential benefits and challenges associated with incorporating nanofluids into heat exchanger systems. Through a systematic analysis of recent literature, this review assesses the effectiveness of nanofluids in improving heat transfer efficiency and overall performance of heat exchangers. Key parameters such as nanoparticle concentration, size, and type are thoroughly evaluated to understand their influence on heat transfer characteristics. Additionally, factors such as stability, flow behavior, and thermal conductivity enhancement are scrutinized to provide a comprehensive understanding of nanofluid behavior in heat exchangers. The review also addresses potential limitations and areas requiring further investigation to optimize the utilization of nanofluids in heat exchanger applications. By synthesizing recent findings, this review aims to contribute to the advancement of knowledge in the field of heat exchanger technology and nanofluid applications. Ultimately, the insights provided in this review offer valuable guidance for researchers and engineers seeking to enhance heat transfer processes through the implementation of nanofluid-based heat exchangers. Nanofluids offer advantages like enhanced thermal conductivity and tailored properties, promising optimized heat exchanger designs, leading to energy efficiency and reduced costs. However, challenges remain, such as nanoparticle dispersion and cost-effectiveness, necessitating further research for refinement. Interdisciplinary collaboration is crucial for advancing nanofluid

* *Corresponding author.*
E-mail address: a.kurhade@gmail.com

https://doi.org/10.37934/arfmts.119.2.160172

Keywords:
Nanofluids; heat exchangers; recent studies; nanoparticles; heat transfer enhancement

applications, fostering innovation to meet demands for sustainable heat transfer solutions.

1. Introduction

Heat exchangers are essential apparatuses extensively utilized across industrial, residential, and commercial sectors to exchange thermal energy between multiple fluids at distinct temperatures. They serve a pivotal function in heating, cooling, and energy retrieval operations, enabling efficient heat transfer while reducing energy usage and operational expenditures.

The principal purpose of a heat exchanger is to enable the transfer of thermal energy between fluids while preventing their mixing. This transfer can take place via conduction, convection, or radiation, depending on the heat exchanger's design and operational conditions. By moving heat from a hotter fluid to a cooler one, or vice versa, heat exchangers facilitate temperature regulation and thermal management in numerous systems and processes.

Heat exchangers are available in diverse configurations and designs, each tailored to specific applications and operating environments. Common varieties include shell-and-tube, plate-and-frame, finned-tube, and compact heat exchangers, each offering unique benefits in terms of efficiency, space utilization, and maintenance requirements.

The design and performance of a heat exchanger are influenced by factors such as fluid properties, flow rates, temperature differentials, surface area, and overall system demands. Engineers must meticulously consider these factors when selecting, designing, and operating heat exchangers to ensure optimal functionality and dependability.

Advancements in heat exchanger technology persist, driven by the imperative for heightened energy efficiency, environmental sustainability, and cost-effectiveness. Ongoing research endeavors concentrate on innovations in materials, geometries, manufacturing methodologies, and computational modeling to enhance heat exchanger performance and tackle emerging challenges across various industries.

The investigation of nanofluids has garnered significant interest [1-10]. Kore *et al.,* [11] examine the impact of a single dimple with an arch-type turbulator on heat transfer and fluid friction. Researchers have scrutinized various aspects within this field, covering topics such as nanofluids role in boiling heat transfer, convective heat transfer, friction factor correlations, particle migration behavior, magnetic properties, entropy production, and mass transfer characteristics [12-17]. Kore *et al.,* [18] studied numerical and computational analysis of improving heat transfer rate in heat exchangers employing obstructing geometries such as Circular Ring, Circular Ring with clearance, and Hexagonal ring tabulators with different pitch diameter ratios (PDR). Irabatti *et al.,* [19] discussed comprehensive review of spiral heat exchanger for diverse applications. Khot Rahul *et al.,* [20-24] explain the investigation on Laser Welding Parameters on the Strength of TRIP Steel. Gadekar *et al.,* [25], Kamble *et al.,* [26], and Gadekar and Kamble [27] explain Experimental Study on Gear EP Lubricant Mixed with Al_2O_3/SiO_2/ZrO_2 Composite Additives to Design a Predictive System.

Heat exchangers are fundamental parts of any system that deals with temperature control. They're like workhorses, silently transferring heat from one fluid to another. These systems encompass various applications where temperature control is critical. This could be anything from regulating a car engine's temperature to heating a building or even large-scale industrial processes. Heat exchangers act as the middle ground, allowing heat to flow between two fluids with different temperatures. They are crucial for maintaining desired temperatures in various systems. Heat exchangers have diverse applications. They can be used for traditional heating and cooling purposes, like radiators in cars or air conditioners in buildings. Additionally, they play a vital role in energy recovery, capturing waste heat from one process and using it for another, improving overall efficiency. By understanding how heat exchangers work and the factors affecting their performance, engineers can design them to be more efficient. This translates to less energy wasted during heat transfer. Efficient heat exchangers contribute significantly to reducing overall energy consumption in various industries. This not only saves costs but also benefits the environment. As industrial processes become more complex and environmental regulations stricter, heat exchanger technology needs to adapt. Understanding the latest advancements is crucial to meet these evolving demands. The nanofluids offer exciting possibilities for enhancing heat exchanger performance. While challenges remain, research is ongoing to unlock their full potential for various thermal management applications.

2. Plate Heat Exchangers

Numerous research studies have explored the integration of nanofluids into Plate Heat Exchangers (PHEs) due to their significant role across diverse industries and the unique properties of nanofluids. In their investigation, Barzegarian *et al.,* [28] specifically examined the use of TiO_2-water nanofluid to improve heat transfer and reduce pressure drop in a brazed PHE utilized in a residential hot water system. The nanofluids were formulated with TiO_2 nanoparticles at concentrations of 0.3%, 0.8%, and 1.5% by weight. The experimental analysis focused on assessing the influence of Reynolds number and nanoparticle concentration on heat transfer characteristics. The addition of nanoparticles to distilled water resulted in a significant enhancement of convective heat transfer coefficient, with the most substantial improvements observed at concentrations of 0.3%, 0.8%, and 1.5%.

Kabeel *et al.,* [29] designed an experimental setup to explore various thermal characteristics of Plate Heat Exchangers (PHEs), including heat transfer coefficient, effectiveness, power transmission, and pressure drop, across different concentrations of Al_2O_3 nanomaterial in pure water. Notably, both transmitted power and heat transfer coefficient showed noticeable increases as the concentration of nanoparticles increased.

Similarly, Behrangzade and Heyhat [30] evaluated the efficiency improvement of a commercial corrugated PHE by employing a silver-water nanofluid. Their experimental apparatus measured the pressure drop and heat transfer rate of the nanofluid. Results revealed an enhancement in the overall heat transfer coefficient ranging from 6.18% to 16.79% for a 100 ppm silver nanofluid, with no significant change in pressure drop values. Additionally, variations in process temperatures and flow rates notably impacted the utilization of nanofluids in PHEs.

Goodarzi *et al.,* [31] conducted research into the effects of different functional covalent groups on the thermophysical properties of a fluid containing carbon nanotubes. To explore this further, they chemically altered the surfaces of multiwalled carbon nanotubes (MWCNT) with cysteine (Cys) and silver (Ag) (see Figure 2). Using a counter-flow corrugated Plate Heat Exchanger (PHE), they analyzed the thermal characteristics of various water-based nanofluids, including silver (FMWCNT-Ag), cysteine-functionalized MWCNT (FMWCNT-Cys), and gum arabic-coated MWCNT. Results indicated that increasing Reynolds number, Peclet number, or volume percentage improved nanofluid properties for heat transfer. Particularly noteworthy was the increase in heat transfer coefficients by 41.3073% and 41.3058% at the lowest and highest Peclet values, respectively, at a 1% concentration.

The investigation of Plate Heat Exchangers (PHEs) underscores the remarkable heat transmission capabilities of nanofluids. Analysis of the data collected suggests a direct relationship between increasing volume fraction and the enhancement of the heat transmission coefficient. This phenomenon can be attributed to enhancements in thermophysical properties at higher nanofluid concentrations. Contrary to some less common studies suggesting otherwise, it is suggested that lower nanofluid concentrations along with higher Reynolds and Peclet numbers result in improved heat transfer efficiency.

In a study by Khoshvaght-Aliabadi [32], the efficacy of plate-fin heat exchangers was examined regarding the influence of vortex-generator (VG) and Cu/water nanofluid flow. A meticulously designed test loop ensured precise measurement of pressure drop and heat transfer properties. Results showed a significant increase in heat transfer rate when transitioning from a plain channel to a VG channel. Additionally, the performance of the plate-fin heat exchanger with the VG channel exceeded that with nanofluid alone. Combining these optimization techniques resulted in a thermal-hydraulic performance gain of up to 1.67.

Abed *et al.,* [33] investigated heat transfer with nanofluids in trapezoidal PHEs, analyzing Al_2O_3, CuO, SiO_2, and ZnO nanoparticles at various volume fractions. The study explored the impact of trapezoidal channel geometry, including wavy amplitudes and longitudinal pitch. Results showed SiO_2 yielding the highest Nusselt number. While pressure loss slightly increased with decreasing nanoparticle diameter, heat transfer enhancement correlated positively with concentration. Notably, the average Nusselt number rose for 20 nm nanoparticles, achieving up to a 35% improvement over water. Some investigations have also focused on how the chevron angle affects PHE thermal characteristics.

Aldabesh and Tlili [34] noticed that the heat transfer rate was improved by the presence of the injection parameter and the permeability of the porous space. Sajjad *et al.,* [35] examines the effectiveness of a finned heat exchanger when using various nanofluids. The findings indicate that adding graphene oxide (GO) and Al_2O_3 nanoparticles to the base fluid improves heat transfer performance, with GO-based nanofluids demonstrating superior performance compared to Al_2O_3-based ones. Smida *et al.,* [36] proposed a new ternary nanofluid heat transfer model using different physical constraints using the impressive effects of thermal radiations, surface convection and saddle/nodal points.

In their research, Chen *et al.,* [37,38] evaluated the performance of a lithium bromide (LiBr) solution with and without nanoparticles in a Plate Heat Exchanger (PHE), considering different chevron angles and mass flow rates. Notably, the effectiveness of the PHE with a 60°/60° chevron configuration was about 70% higher than that with a 30°/30° configuration, with the heat transfer rate and overall heat transfer coefficient almost doubling. The addition of nanoparticles significantly improved heat transmission performance across all chevron PHEs, with the heat transfer rate of 3 vol% nanofluids increasing by approximately 3-8% compared to pure LiBr solution. Particularly, the 60°/60° PHE utilizing 3 vol% nanofluids achieved the highest heat transfer rate and efficacy.

Kurhade *et al.,* [38-41] discuss material selections and Computational Fluid Dynamics (CFD) approaches for thermal cooling. Patil *et al.,* [42] and Waware *et al.,* [43] provide critical reviews on heat transfer and Heat Transfer Enhancement in Tubular Heat Exchangers with Jet Impingement.

Maré *et al.,* [44] conducted experimental comparisons on the thermal performance of two commercial nanofluids at low temperatures within a PHE. The first nanofluid comprised aqueous carbon nanotube suspensions, while the second contained alumina dispersed in water. Both alumina and carbon nanotube (CNT) nanofluids exhibited significant enhancements in the laminar convective heat transfer coefficient compared to pure water, with improvements of approximately 42% and 50%, respectively. The study highlights the importance of considering viscosity and pressure reduction effects at low temperatures before utilizing nanofluids in heat exchangers. Additionally,

Figure 1 illustrates the heat transfer coefficient ratio for various nanoparticles at a 0.5% concentration relative to Reynolds number.

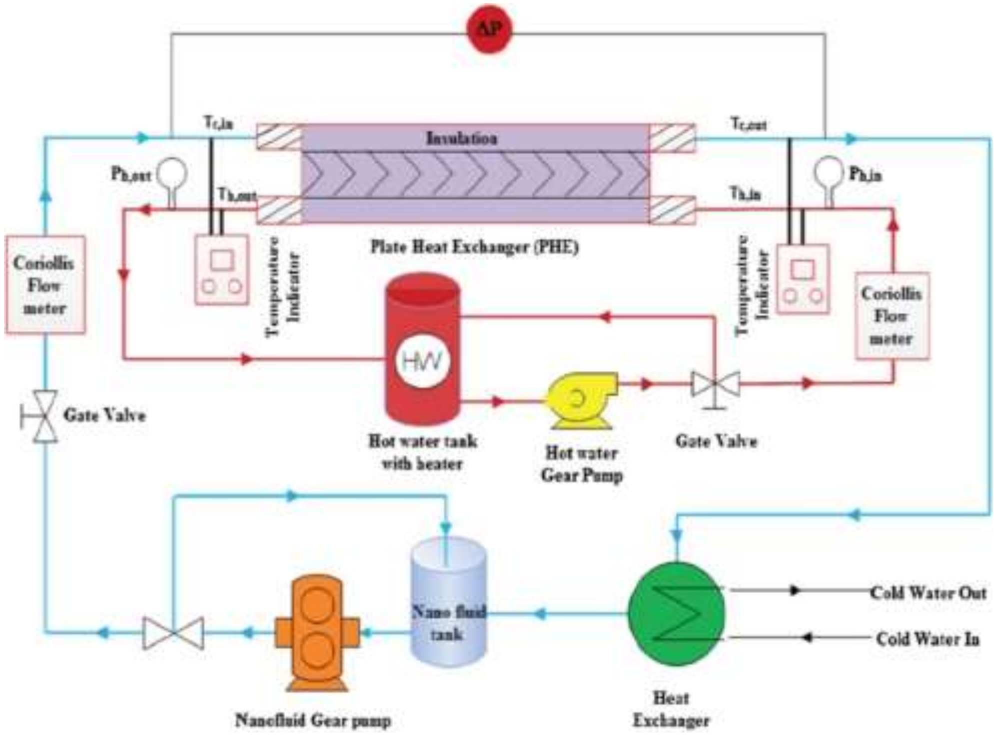

Fig. 1. Schematic of experimental apparatus [23]

In their investigation, Wu *et al.,* [45] explored the heat transfer and pressure drop properties of Al_2O_3/water and multi-walled carbon nanotube (MWCNT)/water nanofluids within a chevron-shaped PHE. Results showed that using nanofluids at constant Reynolds numbers tended to enhance heat transfer, but marginal increases were observed at constant flow velocities. MWCNT/water nanofluid exhibited more significant degradation in heat transfer compared to Al_2O_3/water nanofluid. Moreover, the pressure drops of nanofluids notably exceeded that of water, escalating with concentration due to increased viscosity. However, at low concentrations, the pressure drop of nanofluids didn't significantly differ from that of water. Al_2O_3 exhibited an enhancement value of 8.1%, whereas CNT showed a value of 0.42%.

In their experiment, Pandey and Nema [46] examined the impact of using pure water and Al_2O_3-water nanofluids as coolants on heat transfer, frictional losses, and energy loss within a counter-flow corrugated PHE. Heat transmission improved with rising Reynolds and Peclet numbers, coupled with decreasing nanofluid concentration. Pumping power requirements escalated with increasing concentration under a given heat load. Interestingly, non-dimensional exergy loss remained constant for water, while non-dimensional energy loss was minimized for 2 vol% nanofluid at a flow rate of 3.7 lpm among the considered coolants. Furthermore, the average PHE efficiency on an energy basis was 84% for water and 87% for nanofluid.

Khairul *et al.,* [47] conducted an evaluation comparing water and CuO/water nanofluid regarding their effects on various parameters of a corrugated PHE, including heat transfer coefficient, heat transfer rate, frictional loss, pressure drop, pumping power, and exergy destruction. The study revealed that compared to water, the CuO/water nanofluid exhibited a notable increase in heat transfer coefficient ranging from 18.50 to 27.20% with a concentration rise from 0.50 to 1.50%. Moreover, utilizing nanofluids as heat transfer media resulted in a 24% reduction in exergy loss compared to traditional fluids. Furthermore, a volume percentage of 1.5% demonstrated a 34% improvement in exergetic heat transmission efficiency.

The primary concern in PHE operation lies in fouling deposits, which escalate heat resistance and pressure loss, impacting both initial and ongoing costs. In 1985, corrosion and fouling costs in the US industry ranged from $3 to $10 billion, motivating engineers and scientists to investigate fouling characteristics and develop effective mitigation methods. Researchers have meticulously examined fouling development mechanisms, focusing on variables such as operation duration, geometric structure, hydrodynamic circumstances, flow temperature, and surface material. It's noteworthy that fouling exacerbates in PHEs employing nanofluids, potentially leading to nanoparticle fouling. Despite limited research on fouling in nanofluid-utilizing PHEs, Sarafraz *et al.,* [48] conducted an experiment investigating heat transport and pressure drop properties of MWCNT nanofluids within a PHE while considering CNT fouling. Results suggested that increasing flow velocity and nanoparticle concentration might enhance the heat transfer coefficient, with a 14% increase observed at a 1% concentration compared to water.

Furthermore, it was noted that with increasing flow rate and mass concentration, the pressure drop became more pronounced. Although MWCNT/water nanofluids exhibited a higher pressure drop compared to the base fluid, they demonstrated superior thermal performance overall. Substantial fouling resistance was also observed under prolonged operating conditions, with this resistance being enhanced by higher concentrations.

Fouling formation poses a challenge when particle-laden fluids flow through heat exchange mediums, particularly with MWCNT nanofluids, where nanotube clustering can exacerbate fouling. In the study by Nikkhah *et al.,* [49], the PHE was continuously operated for approximately 720 working hours, with fouling resistance continually monitored. Figure 2 illustrates the fouling resistance parameter's linear behavior with varying slopes, worsening with operating time and increasing MWCNT concentration. The authors emphasized that metal oxides exhibit fouling resistance roughly ten times greater in magnitude compared to MWCNT when compared to metal oxides.

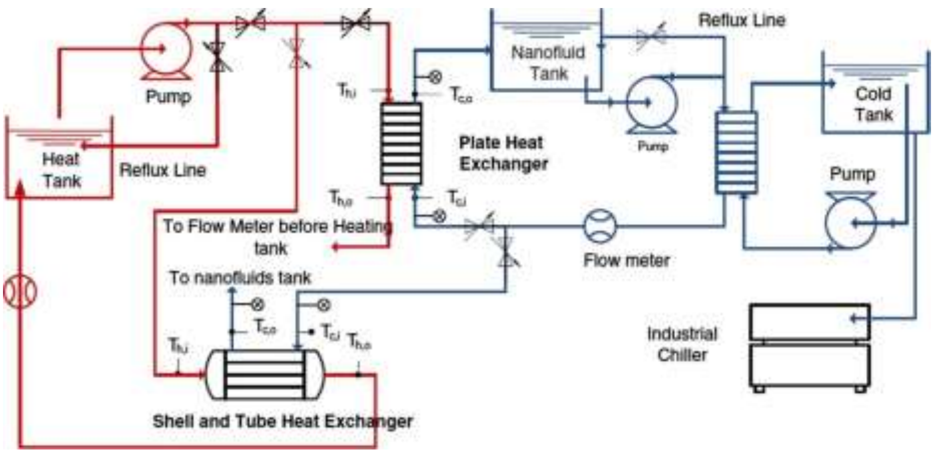

Fig. 2. Schematic of the experimental setup use [51]

In a separate investigation, Anoop *et al.,* [50] analyzed the thermal performance of SiO_2-water nanofluids in an industrial PHE. Depending on nanofluid flow velocity and concentration, experimental results displayed variations in the heat transfer coefficient, showcasing both enhancements and reductions. Scientists attributed this phenomenon to the interplay between fouling on PHE contact surfaces and alterations in fluid thermophysical properties. They highlighted that besides the reduced specific heat values of nanofluids at higher concentrations; particle deposition fouling on heat exchanger surfaces could diminish heat transfer performance when employing nanofluids. Notably, a maximum heat transfer enhancement of approximately 5% was observed for 2% concentrations at the lowest flow rate. Earlier studies investigating nanofluid use in microchannels reported a similar decline in heat transfer efficiency [51].

To achieve more precise outcomes, certain scholars have investigated dual-phase methodologies for nanofluids, taking into account various factors like gravity, Brownian motion, fluid-particle friction, thermophoresis, sedimentation, and dispersion inherent in nanofluids. Despite the complexity involved, only a few studies have employed dual-phase techniques to replicate nanofluid characteristics within Plate Heat Exchangers (PHEs).

In their study, Khoshvaght-Aliabadi *et al.,* [51] utilized single-phase (homogeneous) and two distinct two-phase (mixed and Eulerian) models to examine forced convective heat transfer in copper-water nanofluid flowing through a vortex-generator plate-fin heat exchanger. Findings revealed that the mixed model produced convective heat transfer coefficient estimations closest to experimental data compared to the homogeneous and Eulerian models. Intriguingly, both the homogeneous and Eulerian models underestimated the Nusselt number. For fins with heights of 2.5 mm, 5.0 mm, and 7.5 mm, heat transfer coefficients at 0.3% concentrations were roughly 19.1%, 16.3%, and 14.4% higher than those of the base fluid, respectively. Finally, correlations were established linking geometrical parameters, Reynolds number, nanoparticle weight fraction, Colburn factor, and Fanning friction factor.

3. Double-pipe Heat Exchangers

Double-pipe heat exchangers are recognized as the most basic type in terms of geometry and are widely used across various industries. Consequently, numerous experiments have been carried out using different nanofluids in these exchangers. In this section, we analyze and assess studies conducted on double-pipe heat exchangers employing nanofluids across various categories. Each paragraph addresses the relevant challenges and opportunities.

Darzi *et al.,* [52] conducted an experimental inquiry to evaluate the influence of Al_2O_3 nanofluid on the heat transfer, pressure drop, and thermal efficiency of a double-pipe heat exchanger. Their findings indicated that incorporating nanoparticles within a studied range, where significant pressure drop penalties are absent, presents considerable potential for improving the thermal performance of the heat exchanger. Furthermore, they developed an empirical correlation for Nusselt number based on Reynolds number and concentration, resulting in enhancements of up to 20% at a 1% concentration.

Moreover, Duangthongsuk and Wongwises [53] performed an experimental investigation on forced convective heat transfer of a nanofluid consisting of water and TiO_2 nanoparticles under turbulent conditions. They examined the heat transfer coefficient and friction factor of the nanofluid flowing in a double-pipe counter-flow heat exchanger. Their findings revealed that the convective heat transfer coefficient of the nanofluid exceeded that of the base liquid by approximately 6–11%.

4. Shell and Tube Heat Exchangers

Bahrehmand and Abbassi [54] conducted a study investigating the flow of Al_2O_3 nanofluid in shell and helical tube heat exchangers to analyze heat transfer characteristics. Their results indicated that volume concentrations of 0.2% and 0.3% enhanced heat transfer rates by approximately 14% and 18% respectively. Furthermore, increasing concentration led to elevated coil-side, shell-side, and total heat transfer coefficients. Notably, nanofluid exhibited significantly improved heat transfer rates compared to water at the same mass flow rate, with marginal enhancements observed with further concentration increases. Additionally, enhancing concentration, tube diameter, and coil diameter while reducing mass flow rate augmented effectiveness.

Similarly, Shahrul *et al.,* [55] assessed the performance of a nanofluid-operated Shell and Tube Heat Exchanger (STHE). Their findings revealed that the convective heat transfer coefficient of nanofluids exceeded that of water by 2–15%. Moreover, nanofluid energy effectiveness increased by approximately 23-52%, with ZnO-water nanofluid exhibiting maximum energy effectiveness and SiO_2-water nanofluid demonstrating the lowest due to the interdependency between the density and specific heat of working fluids.

Elias *et al.,* [56] examined the influence of various particle shapes on the total heat transfer coefficient, heat transfer rate, and entropy production in a STHE with diverse baffle angles and segmental baffles. Nanoparticles shaped cylindrically with segmental baffles exhibited the highest heat transmission coefficient among other shapes. Specifically, for a 1 vol% concentration of Boehmite alumina, cylindrical particles with a 20° baffle angle displayed a 12%, 19.9%, 28.23%, and 17.85% improvement in the total heat transfer coefficient compared to 30°, 40°, 50° baffle angles, and segmental baffles, respectively. Moreover, a 20° baffle angle demonstrated superior heat transfer rates for cylindrical shapes compared to other baffle angles and segmental baffles.

Elias *et al.,* [57] analytically investigated the influence of different nanoparticle shapes on the performance of a STHE operating with nanofluid. They mixed Boehmite alumina nanoparticles of various shapes with ethylene glycol and water, observing enhanced thermodynamic performance and heat transmission in the system. Particularly, cylindrical nanoparticles exhibited superior heat transmission compared to other shapes. At a 1% concentration, cylindrical nanoparticles showed a 2.4% improvement in heat transfer coefficient over spherical ones. However, nanofluids containing cylindrical nanoparticles demonstrated higher entropy production compared to other nanoparticle shapes.

Lotfi *et al.,* [58] explored enhancing heat transfer in an MWCNT-water nanofluid within a horizontal STHE. They utilized catalytic chemical vapor deposition to synthesize CNTs on a Co, Mo, and MgO nanocatalyst, followed by a three-step purification process. The introduction of COOH functional groups rendered the nanotubes hydrophilic, enhancing nanofluid stability. Results indicated improved heat transmission compared to the base fluid, with nanoparticles increasing the overall heat transfer coefficient from 30 to 32 W/m^2K in the heat exchanger.

Hosseini *et al.,* [59] demonstrated the efficacy of CNT-water nanofluid as a cooling medium in an LPG absorber tower's shell and tube intercooler. They observed an approximate 14.5% increase in both the total heat transfer coefficient and heat transfer rate compared to water, particularly at the highest CNT volume percentage of 0.278%. This enhancement potentially reduces the heat exchanger's surface area, leading to cost savings in manufacturing. While the pressure drop caused by suspended nanoparticles in water was minimal, the exit temperature of the hot fluid decreased with increasing volume percent of the fluid.

Similarly, Kumar *et al.,* [60] investigated the heat transfer and pressure drop characteristics of a shell and helically coiled tube heat exchanger using Al_2O_3/water nanofluids. They found that the pressure drop increased by 4%, 6%, and 9% for nanofluid concentrations of 0.1%, 0.4%, and 0.8%, respectively, compared to water. Additionally, the experimental Nusselt number on the tube side increased by 28%, 36%, and 56% for the corresponding nanofluid concentrations, attributing these improvements to the nanofluid's enhanced thermal conductivity, improved fluid mixing, and generation of robust secondary flows in the coiled tube. Moreover, the thermal performance factor exceeded one, signifying improved thermal performance.

Utilizing Computational Fluid Dynamics (CFD) modeling, Kumar *et al.,* [61] explored the pressure drop and heat transfer coefficient of an Al_2O_3/water nanofluid-handling helically coiled tube heat exchanger. They found that the maximum pressure drops exceeded water by 9%. Moreover, with increasing volume concentration and Dean number, both pressures drop and Nusselt number rose. Comparing pressure drop values to experimental and theoretical data, CFD proved accurate in forecasting pressure drop in the heat exchanger. Additionally, the nanofluid's Nusselt number surpassed water by 30%.

In a Shell and Tube Heat Exchanger (STHE) with helical baffles, Bahiraei *et al.,* [62] evaluated the hydrothermal properties of water- Al_2O_3 nanofluid. Increasing nanoparticle concentration, baffle overlapping, and reducing the helix angle enhanced heat transmission and pressure loss. A 4.8% and 2% improvement in convective heat transfer coefficient was observed with concentration increments from 1% to 2% and from 4% to 5%, respectively. Employing a neural network model optimized conditions for maximum heat transfer and minimal pressure drop, indicating the potential for using high nanofluid concentrations even when minimal pressure drop is essential.

Azad and Azad [63] explored the utilization of alumina nanofluid to enhance the effectiveness of a STHX while reducing energy consumption and overall costs. The nanofluid increased the heat exchanger's heat transfer coefficient, thereby shortening the required tube length and reducing pressure drop. In the studied scenario, a remarkable 185% improvement in the tube side heat transfer coefficient facilitated a 94% decrease in pressure drop by reducing the heat exchanger's length and flow rate. Consequently, the overall cost of the heat exchanger was reduced by over 55%. The authors advocate for the adoption of this technology to optimize the design of STHXs, given the significant benefits observed from nanofluid utilization.

In their research, Hussein and Alaiwi [64] employed titanium dioxide (TiO_2) nanoparticles in water and observed a substantial enhancement in heat transfer efficiency during their experiments. The most favorable outcomes were observed at a concentration of 0.3%, where efficiency increased by as much as 23%, suggesting that TiO_2/water nanofluid holds considerable promise for applications in heat exchangers. Patil *et al.,* [65] used a water-based Al_2O_3 nanofluid was used in this work to grind materials due to its outstanding convective heat transfer and thermal conductivity qualities.

5. Conclusion

The present study endeavours to provide a comprehensive analysis of research conducted on the utilization of nanofluids in heat exchangers. Many investigations have explored the efficacy of nanofluids in heat exchangers owing to their favourable characteristics. The consensus among both experimental and computational studies suggests that nanofluids exhibit improved heat transfer rates, particularly with increased concentrations and Reynolds numbers. This review highlights the following key points.

i. Recent studies indicate the considerable potential of nanofluids in enhancing heat transfer efficiency across diverse industries, highlighting their growing importance in heat exchanger technology.
ii. Findings consistently demonstrate the effectiveness of nanofluids in improving heat transfer rates and overall system performance compared to traditional heat transfer fluids, showcasing their practical advantages.
iii. Nanofluids offer several advantages, including enhanced thermal conductivity, improved heat transfer coefficients, and the ability to tailor properties through nanoparticle manipulation, thus presenting opportunities for optimized heat exchanger design and operation.

iv. The attributes of nanofluids present opportunities for increasing energy efficiency, reducing operating costs, and enhancing system reliability in heat exchange applications.
v. Despite advancements, challenges such as nanoparticle dispersion, stability, and cost-effectiveness persist, requiring further research and development efforts to address these issues effectively.
vi. Interdisciplinary collaboration among researchers in materials science, fluid dynamics, and thermodynamics is crucial for advancing the understanding and application of nanofluids in heat exchanger technology.
vii. Collaborative efforts and innovation are essential for overcoming existing barriers and maximizing the potential of nanofluids to meet the demand for efficient and sustainable heat transfer solutions in various industries.

References

[1] Bahiraei, Mehdi, Khashayar Gharagozloo, Masoud Alighardashi, and Nima Mazaheri. "CFD simulation of irreversibilities for laminar flow of a power-law nanofluid within a minichannel with chaotic perturbations: An innovative energy-efficient approach." *Energy Conversion and Management* 144 (2017): 374-387. https://doi.org/10.1016/j.enconman.2017.04.068
[2] Sidhappa, Kurhade Anant, Miss Sonal S. Hande, Mr Swarup B. Patil, and Mr Vivekanand R. Mask. "Heat Transfer Enhancement by using Twisted Tape Inserts with circular holes in forced convection." *International Journal of Innovations in Engineering Research and Technology* 3, no. 3 (2016): 1-7.
[3] Gravndyan, Qumars, Omid Ali Akbari, Davood Toghraie, Ali Marzban, Ramin Mashayekhi, Reza Karimi, and Farzad Pourfattah. "The effect of aspect ratios of rib on the heat transfer and laminar water/TiO_2 nanofluid flow in a two-dimensional rectangular microchannel." *Journal of Molecular Liquids* 236 (2017): 254-265. https://doi.org/10.1016/j.molliq.2017.04.030
[4] Bahiraei, Mehdi, and Morteza Hangi. "An empirical study to develop temperature-dependent models for thermal conductivity and viscosity of water-Fe_3O_4 magnetic nanofluid." *Materials Chemistry and Physics* 181 (2016): 333-343. https://doi.org/10.1016/j.matchemphys.2016.06.067
[5] Behnampour, Ali, Omid Ali Akbari, Mohammad Reza Safaei, Mohammad Ghavami, Ali Marzban, Gholamreza Ahmadi Sheikh Shabani, and Ramin Mashayekhi. "Analysis of heat transfer and nanofluid fluid flow in microchannels with trapezoidal, rectangular and triangular shaped ribs." *Physica E: Low-Dimensional Systems and Nanostructures* 91 (2017): 15-31. https://doi.org/10.1016/j.physe.2017.04.006
[6] Bahiraei, Mehdi, and Morteza Hangi. "Numerical investigation and optimization of flow and thermal characteristics of nanofluid within a chaotic geometry." *Advanced Powder Technology* 27, no. 1 (2016): 184-192. https://doi.org/10.1016/j.apt.2015.11.016
[7] Bahiraei, Mehdi, Raouf Khosravi, and Saeed Heshmatian. "Assessment and optimization of hydrothermal characteristics for a non-Newtonian nanofluid flow within miniaturized concentric-tube heat exchanger considering designer's viewpoint." *Applied Thermal Engineering* 123 (2017): 266-276. https://doi.org/10.1016/j.applthermaleng.2017.05.090
[8] Rezaei, Omid, Omid Ali Akbari, Ali Marzban, Davood Toghraie, Farzad Pourfattah, and Ramin Mashayekhi. "The numerical investigation of heat transfer and pressure drop of turbulent flow in a triangular microchannel." *Physica E: Low-dimensional Systems and Nanostructures* 93 (2017): 179-189. https://doi.org/10.1016/j.physe.2017.06.013
[9] Mashayekhi, Ramin, Erfan Khodabandeh, Mehdi Bahiraei, Leyli Bahrami, Davood Toghraie, and Omid Ali Akbari. "Application of a novel conical strip insert to improve the efficacy of water-Ag nanofluid for utilization in thermal systems: a two-phase simulation." *Energy Conversion and Management* 151 (2017): 573-586. https://doi.org/10.1016/j.enconman.2017.09.025
[10] Heshmatian, Saeed, and Mehdi Bahiraei. "Numerical investigation of entropy generation to predict irreversibilities in nanofluid flow within a microchannel: effects of Brownian diffusion, shear rate and viscosity gradient." *Chemical Engineering Science* 172 (2017): 52-65. https://doi.org/10.1016/j.ces.2017.06.024
[11] Kore, Sandeep Sadashiv, Manoj Kumar Chaudhary, Parimal Sharad Bhambare, and Dinesh Keloth Kaithari. "The Heat Transfer and Fluid Flow Investigations of Single Dimple with Straight and Curved Arch Turbulator within in a Duct." *Journal of Advanced Research in Fluid Mechanics and Thermal Sciences* 115, no. 1 (2024): 206-216. https://doi.org/10.37934/arfmts.115.1.206216
[12] Heydari, Ali, Omid Ali Akbari, Mohammad Reza Safaei, Masoud Derakhshani, Abdullah A. A. A. Alrashed, Ramin Mashayekhi, Gholamreza Ahmadi Sheikh Shabani, Majid Zarringhalam, and Truong Khang Nguyen. "The effect of

attack angle of triangular ribs on heat transfer of nanofluids in a microchannel." *Journal of Thermal Analysis and Calorimetry* 131 (2018): 2893-2912. https://doi.org/10.1007/s10973-017-6746-x
[13] Wu, J. M., and Jiyun Zhao. "A review of nanofluid heat transfer and critical heat flux enhancement-research gap to engineering application." *Progress in Nuclear Energy* 66 (2013): 13-24. https://doi.org/10.1016/j.pnucene.2013.03.009
[14] Sundar, L. Syam, and Manoj K. Singh. "Convective heat transfer and friction factor correlations of nanofluid in a tube and with inserts: a review." *Renewable and Sustainable Energy Reviews* 20 (2013): 23-35. https://doi.org/10.1016/j.rser.2012.11.041
[15] Bahiraei, Mehdi. "Particle migration in nanofluids: a critical review." *International Journal of Thermal Sciences* 109 (2016): 90-113. https://doi.org/10.1016/j.ijthermalsci.2016.05.033
[16] Bahiraei, Mehdi, and Morteza Hangi. "Flow and heat transfer characteristics of magnetic nanofluids: a review." *Journal of Magnetism and Magnetic Materials* 374 (2015): 125-138. https://doi.org/10.1016/j.jmmm.2014.08.004
[17] Mahian, Omid, Ali Kianifar, Clement Kleinstreuer, Al-Nimr Moh'd A, Ioan Pop, Ahmet Z. Sahin, and Somchai Wongwises. "A review of entropy generation in nanofluid flow." *International Journal of Heat and Mass Transfer* 65 (2013): 514-532. https://doi.org/10.1016/j.ijheatmasstransfer.2013.06.010
[18] Kore, Sandeep Sadashiv, Manoj Kumar Chaudhary, Adhikrao Sarjerao Patil, and Vijay Dilip Kolate. "Computational study and enhancement of heat transfer rate by using inserts introduced in a heat exchanger." *Journal of Advanced Research in Fluid Mechanics and Thermal Sciences* 103, no. 1 (2023): 16-29. https://doi.org/10.37934/arfmts.103.1.1629
[19] Irabatti, Vedant, Yash Patil, Sandeep Kore, Vaishnavi Barangule, and Abhishek Kothe. "Comprehensive review of spiral heat exchanger for diverse applications." *Materials Today: Proceedings* 72 (2023): 1328-1334. https://doi.org/10.1016/j.matpr.2022.09.308
[20] Khot Rahul, S., and Prasanna Rajendra Kadam. "Structural behavior of fillet weld joint for bimetallic curved plate using finite element analysis (FEA)." In *6th International Conference on Advanced Research in Arts, Science, Engineering & Technology, Organized By DK International Research Foundation*, Perambalur, Tamilnadu , ICARASET - 2021 Proceedings, pp. 23-28. 2021.
[21] Khot Rahul, S., and T. Venkateswara Rao. "Investigation of mechanical behaviour of laser welded butt joint of transformed induced plasticity (TRIP) steel with effect laser incident angle." *International Journal of Engineering Research and Technology* 13, no. 11 (2020): 3398-3403. https://doi.org/10.37624/IJERT/13.11.2020.3398-3403
[22] Khot Rahul, S., T. Venkateshwara Rao, Harshad Natu, H. N. Girish, Tadashi Ishigaki, and Puttaswamy Madhusudan. "An investigation on laser welding parameters on strength of TRIP steel." *Strojniski Vestnik/Journal of Mechanical Engineering* 67, no. 1-2 (2021): 45-52. https://doi.org/10.5545/sv-jme.2020.6912
[23] Khot Rahul, S., and T. Venkateshwara Rao. "Effect of Quenching Media on Laser butt Welded Joint on Transformed -Induced Plasticity (TRIP) Steel." *International Journal of Emerging Trends in Engineering Research* 8, no. 10 (2020): 7686-7691. https://doi.org/10.30534/ijeter/2020/1588102020
[24] Khot Rahul, S., T. Venkateswara Rao, Abhishek Keskar, H. N. Girish, and Puttaswamy Madhusudan. "Investigation on the effect of power and velocity of laser beam welding on the butt weld joint on TRIP steel." *Journal of Laser Applications* 32, no. 1 (2020): 012016. https://doi.org/10.2351/1.5133158
[25] Gadekar, Tushar D., Dinesh N. Kamble, and Nitin H. Ambhore. "Experimental Study on Gear EP Lubricant Mixed with $Al_2O_3/SiO_2/ZrO_2$ Composite Additives to Design a Predictive System." *Tribology in Industry* 45, no. 4 (2023): 579. https://doi.org/10.24874/ti.1461.03.23.07
[26] Kamble, Dinesh N., Tushar D. Gadekar, and Devendra P. Agrawal. "Experimental study on gearbox oil blended with composite additives." *Jurnal Tribologi* 33 (2022): 1-19.
[27] Gadekar, Tushar, and Dinesh Kamble. "Tribological investigation on oil blended with Additive using Response surface methodology." In *E3S Web of Conferences*, vol. 170, p. 01025. EDP Sciences, 2020. https://doi.org/10.1051/e3sconf/202017001025
[28] Barzegarian, Ramtin, Mostafa Keshavarz Moraveji, and Alireza Aloueyan. "Experimental investigation on heat transfer characteristics and pressure drop of BPHE (brazed plate heat exchanger) using TiO_2-water nanofluid." *Experimental Thermal and Fluid Science* 74 (2016): 11-18. https://doi.org/10.1016/j.expthermflusci.2015.11.018
[29] Kabeel, A. E., T. Abou El Maaty, and Y. El Samadony. "The effect of using nano-particles on corrugated plate heat exchanger performance." *Applied Thermal Engineering* 52, no. 1 (2013): 221-229. https://doi.org/10.1016/j.applthermaleng.2012.11.027
[30] Behrangzade, Ali, and Mohammad Mahdi Heyhat. "The effect of using nano-silver dispersed water based nanofluid as a passive method for energy efficiency enhancement in a plate heat exchanger." *Applied Thermal Engineering* 102 (2016): 311-317. https://doi.org/10.1016/j.applthermaleng.2016.03.051
[31] Goodarzi, Marjan, Ahmad Amiri, Mohammad Shahab Goodarzi, Mohammad Reza Safaei, Arash Karimipour, Ehsan Mohseni Languri, and Mahidzal Dahari. "Investigation of heat transfer and pressure drop of a counter flow

corrugated plate heat exchanger using MWCNT based nanofluids." *International Communications in Heat and Mass Transfer* 66 (2015): 172-179. https://doi.org/10.1016/j.icheatmasstransfer.2015.05.002

[32] Khoshvaght-Aliabadi, Morteza. "Thermal performance of plate-fin heat exchanger using passive techniques: vortex-generator and nanofluid." *Heat and Mass Transfer* 52, no. 4 (2016): 819-828. https://doi.org/10.1007/s00231-015-1603-6

[33] Abed, Azher M., M. A. Alghoul, K. Sopian, H. A. Mohammed, and Ali Najah Al-Shamani. "Design characteristics of corrugated trapezoidal plate heat exchangers using nanofluids." *Chemical Engineering and Processing: Process Intensification* 87 (2015): 88-103. https://doi.org/10.1016/j.cep.2014.11.005

[34] Aldabesh, Abdulmajeed D., and Iskander Tlili. "Thermal enhancement and bioconvective analysis due to chemical reactive flow viscoelastic nanomaterial with modified heat theories: Bio-fuels cell applications." *Case Studies in Thermal Engineering* 52 (2023): 103768. https://doi.org/10.1016/j.csite.2023.103768

[35] Sajjad, Ramisha, Muzamil Hussain, Sami Ullah Khan, Abdul Rehman, Muhammad Jahangir Khan, Iskander Tlili, and Sami Ullah. "CFD analysis for different nanofluids in fin waste heat recovery prolonged heat exchanger for waste heat recovery." *South African Journal of Chemical Engineering* 47, no. 1 (2024): 9-14. https://doi.org/10.1016/j.sajce.2023.10.005

[36] Smida, Kamel, Muhammad Umer Sohail, Iskander Tlili, and Asma Javed. "Numerical thermal study of ternary nanofluid influenced by thermal radiation towards convectively heated sinusoidal cylinder." *Heliyon* 9, no. 9 (2023). https://doi.org/10.1016/j.heliyon.2023.e20057

[37] Chen, Ting, Jinhyun Kim, and Honghyun Cho. "Theoretical analysis of the thermal performance of a plate heat exchanger at various chevron angles using lithium bromide solution with nanofluid." *International Journal of Refrigeration* 48 (2014): 233-244. https://doi.org/10.1016/j.ijrefrig.2014.08.013

[38] Kurhade, Anant Sidhappa, T. Venkateswara Rao, V. K. Mathew, and Naveen G. Patil. "Effect of thermal conductivity of substrate board for temperature control of electronic components: A numerical study." *International Journal of Modern Physics C* 32, no. 10 (2021): 2150132. https://doi.org/10.1142/S0129183121501321

[39] Kurhade, Anant, Virendra Talele, T. Venkateswara Rao, Archana Chandak, and V. K. Mathew. "Computational study of PCM cooling for electronic circuit of smart-phone." *Materials Today: Proceedings* 47 (2021): 3171-3176. https://doi.org/10.1016/j.matpr.2021.06.284

[40] Kurhade, Anant Sidhappa, and G. Murali. "Thermal control of IC chips using phase change material: A CFD investigation." *International Journal of Modern Physics C* 33, no. 12 (2022): 2250159. https://doi.org/10.1142/S0129183122501595

[41] Kurhade, Anant Sidhappa, G. Murali, and T. Venkateswara Rao. "CFD Approach for Thermal Management to Enhance the Reliability of IC Chips." *International Journal of Engineering Trends and Technology* 71, no. 3 (2023): 65-72. https://doi.org/10.14445/22315381/IJETT-V71I3P208

[42] Patil, Suhas Prakashrao, Sandeep Sadashiv Kore, Satish Suresh Chinchanikar, and Shital Yashwant Waware. "Characterization and Machinability Studies of Aluminium-based Hybrid Metal Matrix Composites-A Critical Review." *Journal of Advanced Research in Fluid Mechanics and Thermal Sciences* 101, no. 2 (2023): 137-163. https://doi.org/10.37934/arfmts.101.2.137163

[43] Waware, Shital Yashwant, Sandeep Sadashiv Kore, and Suhas Prakashrao Patil. "Heat Transfer Enhancement in Tubular Heat Exchanger with Jet Impingement: A Review." *Journal of Advanced Research in Fluid Mechanics and Thermal Sciences* 101, no. 2 (2023): 8-25. https://doi.org/10.37934/arfmts.101.2.825

[44] Maré, Thierry, Salma Halelfadl, Ousmane Sow, Patrice Estellé, Steven Duret, and Frederic Bazantay. "Comparison of the thermal performances of two nanofluids at low temperature in a plate heat exchanger." *Experimental Thermal and Fluid Science* 35, no. 8 (2011): 1535-1543. https://doi.org/10.1016/j.expthermflusci.2011.07.004

[45] Wu, Shen-Chun, Dawn Wang, Wei-Jhih Lin, and Yau-Ming Chen. "Investigating the effect of powder-mixing parameter in biporous wick manufacturing on enhancement of loop heat pipe performance." *International Journal of Heat and Mass Transfer* 89 (2015): 460-467. https://doi.org/10.1016/j.ijheatmasstransfer.2015.05.074

[46] Pandey, Shive Dayal, and V. K. Nema. "Experimental analysis of heat transfer and friction factor of nanofluid as a coolant in a corrugated plate heat exchanger." *Experimental Thermal and Fluid Science* 38 (2012): 248-256. https://doi.org/10.1016/j.expthermflusci.2011.12.013

[47] Khairul, Mohammad A., Mohammad A. Alim, Islam M. Mahbubul, Rahman Saidur, Arif Hepbasli, and Altab Hossain. "Heat transfer performance and exergy analyses of a corrugated plate heat exchanger using metal oxide nanofluids." *International Communications in Heat and Mass Transfer* 50 (2014): 8-14. https://doi.org/10.1016/j.icheatmasstransfer.2013.11.006

[48] Sarafraz, M. M., and F. J. E. T. Hormozi. "Heat transfer, pressure drop and fouling studies of multi-walled carbon nanotube nano-fluids inside a plate heat exchanger." *Experimental Thermal and Fluid Science* 72 (2016): 1-11. https://doi.org/10.1016/j.expthermflusci.2015.11.004

[49] Nikkhah, V., M. M. Sarafraz, F. Hormozi, and S. M. Peyghambarzadeh. "Particulate fouling of CuO-water nanofluid at isothermal diffusive condition inside the conventional heat exchanger-experimental and modeling." *Experimental Thermal and Fluid Science* 60 (2015): 83-95. https://doi.org/10.1016/j.expthermflusci.2014.08.009

[50] Anoop, Kanjirakat, Jonathan Cox, and Reza Sadr. "Thermal evaluation of nanofluids in heat exchangers." *International Communications in Heat and Mass Transfer* 49 (2013): 5-9. https://doi.org/10.1016/j.icheatmasstransfer.2013.10.002

[51] Khoshvaght-Aliabadi, M., F. Hormozi, and A. J. A. T. E. Zamzamian. "Effects of geometrical parameters on performance of plate-fin heat exchanger: Vortex-generator as core surface and nanofluid as working media." *Applied Thermal Engineering* 70, no. 1 (2014): 565-579. https://doi.org/10.1016/j.applthermaleng.2014.04.026

[52] Darzi, A. A. Rabienataj, Mousa Farhadi, and Kurosh Sedighi. "Heat transfer and flow characteristics of Al_2O_3-water nanofluid in a double tube heat exchanger." *International Communications in Heat and Mass Transfer* 47 (2013): 105-112. https://doi.org/10.1016/j.icheatmasstransfer.2013.06.003

[53] Duangthongsuk, Weerapun, and Somchai Wongwises. "Heat transfer enhancement and pressure drop characteristics of TiO_2-water nanofluid in a double-tube counter flow heat exchanger." *International Journal of Heat and Mass Transfer* 52, no. 7-8 (2009): 2059-2067. https://doi.org/10.1016/j.ijheatmasstransfer.2008.10.023

[54] Bahrehmand, S., and A. Abbassi. "Heat transfer and performance analysis of nanofluid flow in helically coiled tube heat exchangers." *Chemical Engineering Research and Design* 109 (2016): 628-637. https://doi.org/10.1016/j.cherd.2016.03.022

[55] Shahrul, I. M., I. M. Mahbubul, R. Saidur, S. S. Khaleduzzaman, and M. F. M. Sabri. "Performance evaluation of a shell and tube heat exchanger operated with oxide based nanofluids." *Heat and Mass Transfer* 52 (2016): 1425-1433. https://doi.org/10.1007/s00231-015-1664-6

[56] Elias, M. M., I. M. Shahrul, I. M. Mahbubul, R. Saidur, and N. A. Rahim. "Effect of different nanoparticle shapes on shell and tube heat exchanger using different baffle angles and operated with nanofluid." *International Journal of Heat and Mass Transfer* 70 (2014): 289-297. https://doi.org/10.1016/j.ijheatmasstransfer.2013.11.018

[57] Elias, M. M., M. Miqdad, I. M. Mahbubul, R. Saidur, M. Kamalisarvestani, M. R. Sohel, Arif Hepbasli, N. A. Rahim, and M. A. Amalina. "Effect of nanoparticle shape on the heat transfer and thermodynamic performance of a shell and tube heat exchanger." *International Communications in Heat and Mass Transfer* 44 (2013): 93-99. https://doi.org/10.1016/j.icheatmasstransfer.2013.03.014

[58] Lotfi, Roghayeh, Ali Morad Rashidi, and Azadeh Amrollahi. "Experimental study on the heat transfer enhancement of MWNT-water nanofluid in a shell and tube heat exchanger." *International Communications in Heat and Mass Transfer* 39, no. 1 (2012): 108-111. https://doi.org/10.1016/j.icheatmasstransfer.2011.10.002

[59] Hosseini, S. Masoud, Leila Vafajoo, and B. H. Salman. "Performance of CNT-water nanofluid as coolant fluid in shell and tube intercooler of a LPG absorber tower." *International Journal of Heat and Mass Transfer* 102 (2016): 45-53. https://doi.org/10.1016/j.ijheatmasstransfer.2016.05.071

[60] Kumar, P. C. Mukesh, J. Kumar, R. Tamilarasan, S. Sendhil Nathan, and S. Suresh. "Heat transfer enhancement and pressure drop analysis in a helically coiled tube using Al_2O_3/water nanofluid." *Journal of Mechanical Science and Technology* 28 (2014): 1841-1847. https://doi.org/10.1007/s12206-014-0331-z

[61] Kumar, P. C. Mukesh, K. Palanisamy, J. Kumar, R. Tamilarasan, and S. Sendhilnathan. "CFD analysis of heat transfer and pressure drop in helically coiled heat exchangers using Al_2O_3/water nanofluid." *Journal of Mechanical Science and Technology* 29 (2015): 697-705. https://doi.org/10.1007/s12206-015-0129-7

[62] Bahiraei, Mehdi, Morteza Hangi, and Mahdi Saeedan. "A novel application for energy efficiency improvement using nanofluid in shell and tube heat exchanger equipped with helical baffles." *Energy* 93 (2015): 2229-2240. https://doi.org/10.1016/j.energy.2015.10.120

[63] Azad, Abazar Vahdat, and Nader Vahdat Azad. "Application of nanofluids for the optimal design of shell and tube heat exchangers using genetic algorithm." *Case Studies in Thermal Engineering* 8 (2016): 198-206. https://doi.org/10.1016/j.csite.2016.07.004

[64] Hussein, Diyar F., and Yaser Alaiwi. "Efficiency Improvement of Double Pipe Heat Exchanger by using TiO_2/water Nanofluid." *CFD Letters* 16, no. 1 (2024): 43-54. https://doi.org/10.37934/cfdl.16.1.4354

[65] Patil, Prashant, Nitin Kardekar, Rahul Yadav, Anant Kurhade, and Dhanapal Kamble. "Nanofluids: An Experimental Study for MQL Grinding." *Journal of Mines, Metals and Fuels* 71, no. 12 (2023): 2751-2756. https://doi.org/10.18311/jmmf/2023/41766