Review on Contemporary Heat Transfer Enhancement Technologies in Conventional Heat Exchangers

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Abstract
This review examines modern approaches for improving heat transfer in heat exchangers, focusing on findings from 52 recent research papers. The strategies presented include nanofluids, surface modification techniques, the use of extended surfaces, and novel design combinations. Nanofluids, which contain nanoparticles such as Al_2O_3, CuO, and TiO_2, have higher thermal characteristics and greatly improve heat transfer efficiency over ordinary fluids. Surface changes, such as laser texturing, electrochemical deposition, and hydrophobic coatings, significantly reduce fouling while increasing boiling heat transfer. Extended surfaces with a variety of fin designs, including louvered, wavy, and helical fins, improve turbulence and thermal performance. Machine learning algorithms, genetic algorithms, and multi-objective optimization frameworks are examples of emerging technologies that improve heat exchanger performance under a variety of scenarios. Phase change and piezoelectric materials present innovative thermal management strategies. The existing review paper lacks individual enhancement methods, making it difficult to compare knowledge across categories. Moreover, recent innovations like hybrid nanofluids, fractal/biomorphic designs, surface modification techniques were missing in earlier reviews. This review highlights the significance of combining material science, surface engineering, and computational methodologies to improve heat exchanger efficiency and operational effectiveness.
Keywords: *Heat Exchangers, Nanofluids, Extended Surfaces, Innovative Design*

1. INTRODUCTION

Heat transfer can occur between a solid surface and a liquid, between solid particles and a liquid and more. Any conversion of energy from one type to another, as well as the transfer of energy from one device to another, is accompanied by the transition of a certain part of the energy to heat. Therefore, in almost all machines and apparatuses, heat transfer is important (Edreis & Petrov, 2020). Development of any new thermal technologies are needed in today's world to reduce the energy consumption and contribute towards global warming reduction. With the advancement of industries and the trend towards miniaturization, sustainability and higher energy efficiency of devices, compact heat exchangers become an urgent need in the wide range of heat transfer applications (Ajeeb & Murshed, 2022).

A heat exchanger is a heat transfer device that exchanges heat between two or more process fluids. They have widespread industrial and domestic applications. Many types of heat exchangers have been developed for use in steam power plants, chemical processing plants, building heat and air conditioning systems, transportation power systems, and refrigeration units (Zohuri, 2018). The heat exchangers are used both for cooling and heating processes. The fluids may come in contact with each other or may be separated by passing in tubes or pipes avoiding the mixing.

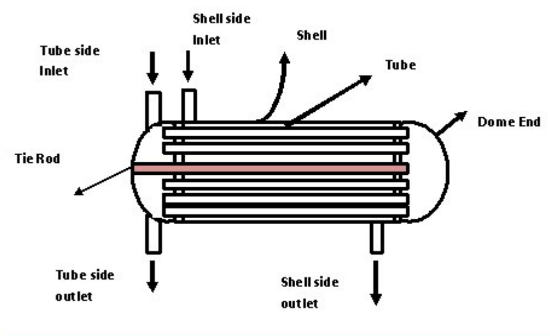

Fig. 1: *Shell and Tube Heat exchanger (Basic Chemical Engineering Operations, 2010).*

1.1. Classification of Heat Exchangers

According to constructional features

a. Shell and tube heat exchangers

These are also called surface condensers and are most commonly used for heating, cooling, condensation or evaporation applications. It consists of a shell and a large number of parallel tubes housing in it. The heat transfer takes place as one fluid flows through the tubes and other fluid flows outside the tubes through the shell(Rathore M. Mahesh, 2015).

b. Finned tube heat exchangers

When a high operating pressure or an enhanced heat transfer rate is required, the extended surfaces are used on one side of the heat exchangers. These heat exchangers are used for liquid to gas heat exchange(Rathore M. Mahesh, 2015). Fins are attached to the tubes by a tight mechanical (press) fit, tension winding, adhesive bonding, soldering, brazing, welding, or extrusion(Shah & Sekulib, 1998) .

c. Compact heat exchangers

Compact heat exchanger is a unique and special class of heat exchanger having a large heat transfer area per unit volume. These have been widely used in various applications in thermal fluid systems including automotive thermal fluid systems In addition, flat tubes are more popular in automotive applications due to the lower drag profile compared to round tubes(Huminic & Huminic, 2012).

The preliminary literature review showed that the prior research often focused on individual enhancement methods, making it difficult to compare knowledge across categories. Moreover, recent innovations like hybrid nanofluids, fractal/biomorphic designs were missing in earlier reviews. Similarly, surface modification techniques were often overshadowed by focus on nanofluids in the literature.

2. METHODOLOGY

This review adopts a systematic literature review approach to identify, evaluate, and categorize recent advancements in heat exchanger performance enhancement techniques. The primary objective of this study was to explore how nanofluids, surface modification techniques, and innovative heat exchanger configurations contribute to improved thermal performance and energy efficiency. To achieve this, three guiding research questions were established:

i) How do nanofluids influence heat transfer rates in heat exchangers?
ii) What roles do surface modifications and extended surfaces play in enhancing heat transfer performance?
iii) How can innovative configurations of heat exchangers improve overall thermal effectiveness in various heat transfer applications?

These questions provided a structured framework for organizing, analysing, and synthesizing findings from the literature.

2.1 Search Strategy

The literature search was conducted through Google Scholar, selected for its accessibility and broad indexing of peer-reviewed engineering research, including experimental, computational, and review-based studies. A targeted keyword strategy was employed to collect relevant publications. These keywords were drawn directly from the three research focus areas and included terms such as “nanofluids AND heat exchanger”, “surface modification AND heat transfer”, “extended surfaces AND heat exchanger”, “innovative design AND heat exchanger”, and “heat transfer enhancement techniques”. These keywords were searched in different combinations to retrieve relevant results from Google Scholar. The collected literature primarily ranged from the last two decades, aligning with the timeline during which research on nanofluids and high-efficiency exchanger designs has become particularly active.

2.2 Selection Criteria

Articles included in the review were limited to those written in English and indexed in databases accessible via Google Scholar. Only publications with full-text access were considered to allow for complete review of methodology and findings. The focus was on literature that presented experimental, numerical, or review-based data specifically related to enhancement techniques in heat exchangers. To ensure quality and relevance, only papers with measurable outcomes such as thermal conductivity enhancement, heat transfer coefficient increase, or thermal resistance reduction were retained.

By contrast, articles that did not provide quantitative results or engineering-focused insights were excluded. Studies that did not clearly discuss any form of material, fluid, or geometrical modification to the heat exchanger structure or operation were also filtered out. This ensured that only research directly contributing to engineering design knowledge was retained in the review.

2.3 Screening and Categorization Process

The initial pool of articles obtained from keyword searches was manually reviewed to assess suitability. Abstracts and conclusions were first skimmed to remove clearly irrelevant studies. For the remaining articles, the research objectives, identified problems, and key findings were extracted based on their abstracts, core findings, and conclusions. The focus was placed on performance metrics such as thermal resistance, pressure drop, efficiency, and heat transfer rate. This allowed each paper's contribution to be evaluated in terms of effectiveness and applicability.

Following this preliminary analysis, the studies were grouped into three major categories based on the primary enhancement strategy investigated. These categories were: nanofluids, surface modification techniques and extended surfaces, and innovative design configurations. Papers discussing nanofluids explored the use of CuO, Al_2O_3, TiO_2, Fe_3O_4, hybrid nanofluids, and MWCNTs in various heat exchanger geometries. Articles under surface modifications addressed fin geometries, coatings, textured surfaces, and fouling-resistant treatments. The third category comprised studies proposing geometric or topological changes to conventional heat exchanger configurations, such as fractal designs, oscillating heat pipes, vortex generators, capsule patterns, or helically coiled and microchannel structures. These categories were used to structure both the data extraction process and the discussion that followed.

2.4 Limitations

This review was conducted using only English-language publications and relied exclusively on indexed, peer-reviewed literature accessed through Google Scholar. As a result, high-quality studies published in other languages or not indexed in open-access academic platforms may have been excluded. Furthermore, the review was restricted to articles with accessible full texts, meaning subscription-based or proprietary industrial reports were not included.

3. LITERATURE REVIEW

3.1 Nanofluids:

(Khatoon et al., 2022) addressed the issue of low heat transfer in conventional fluids. A notable improvement in heat transfer rate was seen in shell and tube heat exchanger where CuO/Al_2O_3-water based nanofluid was used instead of conventional fluids. This shows that nanofluid gives excellent heat transfer coefficient than pure water (base fluid) so the result comes out in the form of reduced area for heat transfer with similar heat exchange capacity. Effect of nano-particles concentration on the values of Reynolds number (Re) and Prandtl number (Pr) was also observed, and was found that Re and Pr decreases with increasing value of particle concentration in the base fluid.

(Gupta et al., 2020) investigated thermal performance in mesh wick heat pipe using CuO as nanofluid. Experimental findings have confirmed 20.5% decrease in thermal resistance and 15.3% increment in thermal efficiency of the heat pipe compared to water. Maximum thermal efficiency (66.5%) of a heat pipe was obtained at 150 W and 1.0 vol.% of nanofluid in a horizontal position.

(Jajja et al., 2014) evaluated thermal management in high heat generating computer processors using multiwalled carbon nanotube nanofluid. It was found that base temperature decreased by reducing the fin spacing and using multiwalled carbon nanotube (MWCNT) nanofluid. The lowest value of heat sinks base temperature recorded was 49.7 °C at a heater power of 255 W by using a heat sink of 0.2 mm fin spacing and MWCNT nanofluid as a coolant. Moreover, as a result of reduced fin spacing and using MWCNT nanofluid as a coolant the value of overall heat transfer coefficient increased from 1200 W/m2K to 1498 W/m2K, translating to about a 15% increase. The value of thermal resistance also dropped by reducing the fin spacing and using MWCNT nanofluid.

(Rajak et al., 2023) explored the impact of ZnO nanoparticles on diesel fuel engine behaviour. The results demonstrated that DF + 0.1% ZnO increases BTE (Brake Thermal Efficiency) by 11.7% at 2500 rpm, while decreasing SFC (Specific Fuel Consumption) by 1.67%, exhaust gas temperature by 11.4%, and NOx emissions by 10.67%. CO2 emissions were reduced by 7.6% compared to 2500 rpm.

(Minea, 2017) studied the enhanced heat transfer and stability characteristics of hybrid nanofluids. It was noticed that all the nanofluids thermophysical properties are varying with the addition of nanoparticles and thermal conductivity is increasing by at least 12%. The viscosity uncertainty when using theoretical or experimental correlations was found to be very important. New Nu correlation for alumina nanofluids and their hybrids was developed.

(Khanlari et al., 2019) aimed to analyse heat transfer characteristics in the plate type heat exchanger experimentally and numerically. Computational fluid dynamics analysis has been used to simulate the problem by using the ANSYS fluent 16 software. Also, the effect of using TiO2/water nanofluid as working fluid was investigated. The obtained results showed that using TiO2/water nanofluid improved the overall heat transfer coefficient averagely as 6%, whereas maximum improvement in overall heat transfer coefficient was 10%.

(Ali & Arshad, 2017) examined the angle effect of fin heat sink channel on heat transfer performance using water-based graphene nanoplatelets nanofluids. Three heat sinks having channel angles, measured from positive x-axis, 22.5-degree, 45 degree and 90 degrees were used. Heat sink with 22.5-degree channel angle showed better thermal performance as compared to other tested heat sinks. For the same flow rate, 22.5-degree heat sink showed lowest convective thermal resistance as compared to other tested heat sinks.

(Sajawal et al., 2019) analysed thermal performance of finned tube-phase change material based solar air heater. The air heater was studied for three different configurations with no phase change materials (PCMs), RT44HC and RT18HC. It was revealed that the third configuration containing RT44HC and RT18HC in upper and lower passes respectively is the best among others for optimum heater performance.

(Khairul et al., 2013) analysed the use of three different types of nanofluids (CuO/water, Al_2O_3/water and ZnO/water) in a helical coil heat exchanger. Heat transfer coefficient and entropy generation rate of helical coil heat exchanger was analytically investigated considering the nanofluid volume fractions and volume flow rates. Analytical outcomes revealed that CuO/water nanofluids could increase the heat transfer coefficient and decrease the entropy generation about 7.14% and 6.14% respectively. Density and thermal conductivity are the most important parameters for efficiency improvement.

(Zheng et al., 2020) investigated heat transfer and fluid flow characteristics of various nanofluids in a corrugated plate heat exchanger in solar energy systems. By adding various nanoparticles (Al2O3-30 nm, SiC-40 nm, CuO-30 nm and Fe3O4-25 nm) into the base fluid, effects of nanofluid types and particle concentrations (0.05 wt.%, 0.1 wt.%, 0.5 wt.% and 1.0 wt.%) on the thermal performance of the plate heat exchanger were analysed at flow rates in the range of 3–9 L/min. red with DI-water, four nanofluids significantly improved the heat transfer performance of the plate heat exchanger. The Fe3O4-water nanofluid at mass fractions above 0.05 wt.% shows higher performance than the other nanofluids. By using 1.0 wt.% Fe3O4-water nanofluid as the working fluid, the heat transfer coefficient increased by 30.8% at 8 L/min compared to DI-water.

(Gürbüz et al., 2020) tested the Al_2O_3–CuO/water hybrid nanofluid in plate-type HEs (PHEs) with 8, 12 and 16 plates to determine the influence of number of plates on heat transfer improvement by hybrid nanofluid. Hybrid nanofluid increased the thermal performance in all PHEs with different number of plates. It was observed that increasing number of plates led to more increment in thermal performance by utilizing hybrid nanofluid. The highest increment in overall heat transfer coefficient was obtained as 12%, 19% and 20% in PHEs with eight, 12 and 16 plates, respectively. In addition, the highest enhancement in effectiveness was achieved as 10%, 11.7% and 16% in PHEs with eight, 12 and 16 plates, respectively.

(Ebrahimnia-Bajestan et al., 2016) investigated the laminar convective heat transfer of water-based TiO_2 nanofluid flowing through a uniformly heated tube. A maximum enhancement of 21% in average heat transfer coefficient was obtained using TiO2/water nanofluids. Convective heat transfer coefficient increased with an increase in nanoparticle concentration and flow Reynolds number, while particle size had an inverse effect.

(Saghir & Rahman, 2020) analysed forced convection of hybrid nanofluids of TiO_2–SiO_2, MWCNT–Fe_3O_4, and ND–Fe_3O_4 at different concentrations in porous media. The results revealed that the hybrid fluid contributed to heat enhancement, levied increased pumping power. However, the index of efficiency, obtained by combining the Nusselt number and pressure drop, indicated that the best hybrid fluid for such an application is ND–Fe3O4 in the water–ethylene glycol mixture.

(Farajollahi et al., 2010) measured the characteristics of γ-Al2O3/water and TiO2/water nanofluids in a shell and tube heat exchanger under turbulent flow condition. The effects of Peclet number, volume concentration of suspended nanoparticles, and particle type on the heat characteristics were investigated. The experimental results for both nanofluids indicated that the heat transfer characteristics of nanofluids improve with Peclet number significantly. TiO2/water and γ-Al2O3/water nanofluids possess better heat transfer behaviour at the lower and higher volume concentrations, respectively.

(Ajeeb et al., 2023) investigated the performance of a compact gasketed plate heat exchanger (PHE) employing Al2O3 nanofluids prepared for several low concentrations of Al2O3 (0.01, 0.05, 0.10, 0.15 and 0.20 vol%) and base fluids of distilled water (DW) and its mixture with ethylene glycol (15% and 30% of EG) for several flow rates (0.03–0.093 l/s). The results indicated a heat transfer enhancement with the increase of the nanoparticles' concentration reaching the maximum value of 27% at 0.2 vol% for DW based Al2O3 nanofluid and was accompanied by an increase in pressure drop of 8%. The heat transfer enhancement became lower with the increase of the EG percentage such as 19.1% at 0.2 vol% for 30% of EG based Al2O3 nanofluid. In addition, the energy efficiency factor increased by the addition of Al2O3 nanoparticles to the base fluids and with the increase of flow rates up to the value of 1.3 at the highest particles concentrations.

3.2 Surface Modification Techniques and Extended Surface Method

(Cheng et al., 2020) investigated the fishbone-patterned copper tubes for pool boiling heat transfer. The effect of laser-textured copper surfaces on pool boiling heat transfer in copper tubes was experimentally investigated by using deionized water as a working fluid under ambient environmental conditions. The picosecond laser system was used to apply fishbone patterns on cylindrical copper surfaces. Heterogeneous laser-textured surfaces exhibited better boiling heat transfer performance than plain copper surfaces.

(Wan et al., 2022) studied the impact of hydrophobic coatings on fouling mechanisms. Three types of coatings were coated on the inner surface of enhanced tubes with the same structure to obtain different surface characteristics. Compared with the original surface, the hydrophobicity of coated surfaces was improved, and their surface energy decreased by 18.48 %–45.32 %. It was found that for the enhanced tubes with lower surface energy, the foulants in the fluid will be more difficult to adhere to the heat transfer surface after coming into contact with the surface; but once adhering to the heat transfer surface, they will not be easily removed.

(X. Li et al., 2019) analysed the use of super hydrophilic porous surfaces to increase surface wick ability. Results showed that PDMS-co-PMHS@SP (a copolymer of polydimethylsiloxane and poly (methylhydrosiloxane)) possesses Superhydrophobic / superoleophilic (SHBOI) characteristics, high oil-adsorption capacity (up to 143 times its original weight) and excellent recyclability. PDMS-co-PMHS@FP can efficiently separate a series of immiscible oil/water mixtures in a single-step based on its high oil or organic solvents fluxes (about 2000–3000 $L.m^{-2}.h^{-1}$) and SHBOI characteristics.

(Kananeh et al., 2010) studied the reduction of milk fouling inside gasketed plate heat exchanger using nano-coatings. An antifouling coating with low surface energy (low wettability) led to a hydrophobic and oleophobic effect. Certain polyurethane-coated plates and tubes formed thinner deposit layer compared to standard uncoated stainless-steel plates and tubes. The cleaning time of the coated plates was 70% lower than stainless steel plates.

(T. Y. Zhang et al., 2022) investigated experimentally the condensation heat transfer and droplet dynamics on honeycomb-like superhydrophobic (HCLS) surfaces with hierarchical microporous structures, fabricated by an electrochemical method on four metallic substrates with different thermal conductivities, i.e., copper, brass H96, brass H65 and stainless steel SS316. It was seen that heat transfer is enhanced by almost 6 times through realizing the droplet-jumping condensation. The substrate with a higher thermal conductivity led to a higher condensation heat transfer coefficient as well as a higher droplet departure frequency at moderate degrees of subcooling, indicating the synergistic effect between the substrate thermal conductivity and droplet dynamics during FCT.

(Pradhan et al., 2020) approached through a powder metallurgy route for the synthesis of aluminium–graphene (Al–Gr) composite materials for commercially viable solar thermal collectors. The Al–Gr composite (with 1 wt. % of graphene filler content) recorded an enhanced thermal conductivity of ∼280 W/mK, which is higher than that of pristine Al (∼124 W/mK), at room temperature. These results suggested that the Al–Gr composites can be deployed as solar thermal collectors and heat sink materials for thermal dissipation.

(Ahn et al., 2019) aimed to develop a method for modifying SUS304 with micro/nanoscale holes using an electrical etching technique and evaluated its impact on the anti-fouling performance of chevron plate heat exchangers. The modified specimen had the highest pressure drop because the hole created by the electro chemical etching method increased the surface roughness. But the pressure drop was decreased after the specimens were treated by polymethyl methacrylate (PMMA) or boron nitride (BN). It was due to the holes were blocked by PMMA or the wall frictions were reduced by characteristic of BN. The overall heat transfer coefficient increased slightly than bare specimen due to the micro/nanoscale structures at the surface. But, at the BN-coated surface, the overall heat transfer coefficient decreased than bare specimen. This was because out-plane crystal of BN had a role like a thermal resistance.

(Boxler et al., 2014) addressed the effect of surface modification by plasma enhanced chemical vapor deposition (PECVD) on milk fouling in a plate heat exchanger. The results showed that surface modification directly affected the formation of deposits, their composition, as well as their adhesive strength. Lower protein content on diamond-like carbon (DLC) and Si-doped DLC (SICAN) (a-C:H: Si) and lower mineral deposition on SICAN were measured.

(Lin et al., 2020) discussed the influence of different surface properties, namely an unmodified copper fin surface and a modified hydrophobic fin surface, on the heat transfer effect of heat exchangers with air velocity ranging from 0.5 m/s to 2.5 m/s and relative humidity of 60% and 90%. The heat transfer and water removal rates of the two heat exchangers increased with an increase in wind velocity. When the inlet air velocity was increased from 0.5 to 2.5 m/s, the heat transfer and water removal rates of both heat exchangers were increased by approximately 90%. Compared with heat exchangers with unmodified copper fin surfaces, heat exchangers with hydrophobic surfaces exhibited a 5.56% higher heat transfer efficiency.

(Pandit et al., 2014) focused on effective techniques to enhance heat transfer on the hot side of the thermoelectric generator (TEG) in order to increase the total power output from the device. Pin fin performance was studied over a range of Reynolds numbers, calculated based on full channel height. Results showed that the diamond pin fins performed the best in enhancing heat transfer. Lower channel heights that caused pin fins to block 50% of the channel provide significantly higher heat transfer coefficients.

(Harris et al., 2024) evaluated the impact of pin fin 'top' geometrical features on the heat transfer coefficient (HTC) by combining computational fluid dynamics (CFD), experimental data, and machine learning. The results highlighted that the new pin fins saved 6.3 % to 14.3 % volume/material usage but produced around 1.5 to 1.7 times more heat transfer than conventional square/rectangular fins. Six machine learning models accurately predicted HTC using volume and surface area as key variables, achieving less than 5 % mean absolute percentage error (MAPE).

(H. Li et al., 2021) delved into the effect of perforated fins to enhance heat storage performance. The perforated fin structure was studied in detail by varying the hole diameter and hole location. The findings revealed that although the perforated fin is conducive to enhancing natural convection, it weakened thermal conduction compared with the solid-fin model. There is an optimal perforated-fin structure for achieving the maximum enhancement of the heat transfer. The structure, in which the hole diameter is 3 mm, hole location is L = 8 mm, and hole number is 6, reduced the complete melting time by 5.49% compared with the solid-fin model, and the heat storage capacity is commendably enhanced by 0.21%. Consequently, the perforated fins are worthy of being employed in the annular finned tube LHTES unit.

(L. Li et al., 2024) investigated the impact of different vibration parameters on heat transfer performance. Corrugated fins were chosen for investigation under vibration conditions, utilizing an orthogonal experimental approach to analyse the impact of fin structural parameters on heat exchanger performance. Findings indicate that vibration enhances the air side heat transfer coefficient of the heat exchanger, in experimental settings, the gas side heat transfer coefficient of the heat exchanger demonstrated a maximum increase of 12.28%. (Tokas et al., 2021) investigated the thermal performance of extended surfaces for a novel heat exchanger. The finite volume method was employed to discretize and solve the governing partial differential equations of heat conduction. The maximum effectiveness of copper fins is 304.62, whereas that for steel fin is 219.33 with the optimum dimensionless fin thickness reported to be $t^* = 0.1666$. Furthermore, the maximum overall efficiencies of fins were 99.98% and 99.62% for copper and steel fins, respectively.

(Hasan et al., 2023) investigated heat transfer enhancement in a double pipe heat exchanger embedded with an extended surface on the inner tube's outer surface with the addition of alumina nanofluid. The simulated results showed that the use of a finned tube heat exchanger resulted in an improvement ratio between (2.3) and (3.1). The coefficient of convective heat transfer increased numerically as the volume concentration and Reynolds number increased. The heat transfer coefficient and thermal conductivity rose by 20% and 4.7%, respectively, at a volume concentration of 5%.

(Nuntaphan et al., 2010) used oscillating heat pipe as extended surface in wire-on-tube heat exchanger for heat transfer enhancement. The experiments for this heat exchanger were performed in a wind tunnel by exchanging heat between hot water flowing inside the heat exchanger tubes and air stream flowing across the external surface. The results showed that the oscillating heat pipe technique for all working fluids could increase around 10% of the heat transfer rate obtained from that without the refrigerant flow in the capillary tube when the inlet water temperature is at 60 °C.

(Sahu et al., 2023) presented a comprehensive review of the work carried out to improve the thermal as well exergetic performance of the conventional smooth absorber plate solar air heater (SAH) duct by the use of the various configurations and arrangements of extended surfaces (fins) for the forced convection. It enhanced the performance of the conventional SAH by increasing the surface area and making flow turbulent by their presence.

(Hajabdollahi et al., 2022) aimed to investigate the influence of extended surface on the multi-objective optimization of a tubular heat exchanger network. The results showed the importance of constructal fins in improving the objective functions of heat exchangers. For instance, the simple fins case enhanced the effectiveness by up to 5.3% compared to that without fins (usual heat exchanger) while using constructal fins, in addition to the 7% increment of effectiveness, reduced the total heat transfer area by 9.47%.

3.3 Design Configuration

(Tuncer et al., 2021) proposed to enhance the performance of a shell and helically coiled heat exchanger by utilizing a new modification. A hollow tube was integrated into the shell side, and cold fluid entered the heat exchanger along this tube. The main objective of the simulation part of this study was to determine suitable configuration for shell and helically coiled tube heat exchanger to obtain high thermal performance. Overall heat transfer coefficient was obtained in the range of 1600–3150 W/m^2 K. Also, heat transfer coefficient of coil side in this study was obtained in the range of 5700–13,400 W/m^2 K. Moreover, average difference between simulation and experimental results was 8%. (Prabhanjan et al., 2002) determined the relative advantage of using a helically coiled heat exchanger versus a straight tube heat exchanger for heating liquids. Results showed that the heat transfer coefficient was affected by the geometry of the heat exchanger and the temperature of the water bath surrounding the heat exchanger. Use of a helical coil heat exchanger was seen to increase the heat transfer coefficient compared to a similarly dimensioned straight tube heat exchanger. Temperature rise of the fluid was found to be affected by coil geometry and by the flow rate.

(Jiang et al., 2020) proposed a new type of plate heat exchanger with symmetrically distributed capsules. Vortices and fluid impingement dominated the heat transfer enhancement. Longitudinal and transverse vortices were generated in capsule-type plate channels. The vortices promoted the swirl, disturbed the boundary layer and enhanced the heat transfer. Larger area coverage ratio of capsule region and higher capsule slope angle resulted in stronger vortices and fluid impingement.

(Kim et al., 2008) developed and tested multi-pass heat exchanger design because of uneven temperature distribution in single-pass heat exchanger. JF factor was investigated by varying the number of passes and the inlet diameter. JF factor was calculated as a function of the ratio of the inlet diameter to header height ratio. The optimal number of passes was two for an inlet diameter of 50 mm, and the performance based on the JF factor was improved by about 89% compared to a reference heat exchanger. Other design parameters, such as the inlet location, separator location, and header width were further optimized to improve the heat exchanger performance by an additional 20%.

(Dhumal & Havaldar, 2023) investigated various twist ratios for tape inserts and exterior helical tape in a counterflow setup using water as the working fluid. The analysis revealed that incorporating twisted tape inserts inside the pipe, along with helical tape on the exterior, significantly enhanced thermal characteristics. Compared to a plain pipe heat exchanger, Nusselt numbers increased by 219 %–315 % for the pipe with twisted tape inserts and helical tape. Friction factors were also higher, ranging from 4.4 to 8.7 times for pipe inserts with twist ratios of 6.77, 4.51, and 3.38.

(Khoshvaght-Aliabadi et al., 2015) studied the performance of plate-fin channel with rectangular wings as a transverse vortex-generator channel. It was found that the channel with the rectangular wings increased the heat transfer performance of the plate fin heat exchanger (PFHE) about 58.3% and 26.2% compared to the channels with the triangular and trapezoid wings, respectively. The heat transfer coefficient and pressured drop values enhanced as the wing's height, longitudinal wings pitch, and transverse wings pitch decreased and the wings width, channel length, and wings attack angle increased. Correlations were developed to predict Nusselt number of the conventional working fluids flow (water, oil, and ethylene glycol) inside the PFHEs with vortex-generator channels.

(Güllüce & Özdemir, 2020) studied the comprehensive optimization of rotary regenerative heat exchangers. A new design with the same budget was obtained by improving the effectiveness by 53.19% and reducing the entropy generation number by 18.95% in a volume which is 8.90% smaller. Similarly, a RHEX design to have approximately the same volume with the existing RHEX was possible with 50.64% increased effectiveness, 20.65% decreased entropy generation number and 23.35% reduced cost.

(Hrnjak et al., 2017) studied the performance of heat exchanger in frosting must be based on experiments with several cycles. The conclusion from these tests were that the heat exchanger with the largest louver angle had the most desirable behaviour after several refrosting periods with respect to both the overall heat transfer coefficient, pressure drop, and water movement. It showed shortcomings of the choices based on the only one frosting period, typical for many studies in this field. The selection of the high angle louver would not have been justifiably made based on the results of the first cycle.

(D. Zhang et al., 2022) analysed the flow and heat transfer process of the microchannel in detail. A new micro-channel heat transfer enhancement structure was designed and subjected to a comprehensive enhancement performance analysis including flow characteristics, heat transfer characteristics, pressure drop characteristics, comprehensive thermal strengthening performance and thermal strengthening performance aimed at energy saving. The result indicated that the microchannel with the triangular combined cavity exhibited the best heat transfer performance at a low Reynolds number. However, as the Reynolds number gradually increased the microchannel with 90° fan-shaped and triangular combined cavity presented more obvious advantages. Because of the combined effect of the boundary layer redevelopment and the cold and heat exchange of the fluid in the channel, the microchannel with cavity and the extended surface has better heat transfer and energy-saving performance than that of the traditional rectangular microchannel.

(Zhu et al., 2021) researched the effect of channel geometry on overall performance of microchannel heat sinks. Five types of silicon-based microchannel heat sinks were designed, and the periodic grooves arranged on channel sidewalls were rectangular, triangular, trapezoidal, water-droplet, and semicircular in shape. The results indicated that the overall performance can be greatly improved by arranging grooves on channel sidewalls. The significant improvement of overall performance can be achieved with all the groove shapes except rectangles. Water-droplet shaped grooves offered many advantages and improvements that make them the preferred choice for the development of microchannel heat sinks.

(Al zahrani et al., 2021) studied to improve the thermal performance of the existing conventional flat plate heat exchanger (FPHE). Two newly developed modified FPHEs are introduced ($FPHE_{m1}$ and $FPHE_{m2}$). The numerical results showed that $FPHE_{m2}$ has the best temperature uniformity and average temperature (the lowest values), and it has the highest Nu, JF, and turbulence intensity among all four HEs. Also, the f data of the $FPHE_{m2}$ are 18.7% to 33.2% lower than those of the $CPHE_C$. Thus, $FPHE_{m2}$ could be a probable replacement of its counterparts of both $FPHE_C$ and $CPHE_C$.

(Jafari, 2024) aimed at enhancing convection rate in a heat exchanger using heat blades. The proposed device comprised four mini-sized rectangular heat pipes i.e. heat blades. Each heat blade consisted of a hollow copper shell containing two pieces of copper foam, serving as the wick with acetone as base fluids. Three different blade angles were investigated i.e. 0, 45 and 90. It was found that the proposed turbulator significantly impacted the heat exchanger's thermal behaviour, enhancing the overall heat transfer rate by up to 50%. Comparing turbulators with different blade angles revealed that devices with a 90° blade angle offer the best convection enhancement. However, considering the associated increase in pressure drops, the device with a 45° blade angle demonstrated the best overall performance.

(Marzouk et al., 2023) investigated the effects of innovative fractal configuration in helically tubular heat exchangers on thermal and hydraulic performance. With Reynolds (Re) numbers ranging from 12,025 to 21,220, the overall heat transfer coefficient (U), pressure drop (ΔP), and performance factor (PF) were investigated. In comparison to the standard helically tube heat exchanger (HTHE), the results showed that the fractal tube heat exchanger (FTHE) was more favourable to heat transmission. The overall heat transfer coefficient enhancement ratio was around 289%. The exergy efficiency increased with the rise of the Re number where the fractal tube configuration has the highest exergy efficiency.

(Ishaq et al., 2021) discussed the enhancement of heat transfer in a diamond shaped design of extended fins for double-pipe heat exchangers (DPHE). Enhanced heat transfer was observed in a DPHE with proposed diamond-shaped fins, at a radii ratio of 0.25, for the cases i.e. 4 fins for a fin-height of 20% to 80% of the annulus, 8–12 fins for a fin-height of 80% of the annulus and 16–32 fins for a fin-height of 100% of the annulus. Considering frictional loss, heat transfer enhancement was seen in four fins for fin-height varying from 20% to 80% of the annulus, and eight fins for fin-height 100% of the annulus, at a radii ratio of 0.25.

4. RESULTS AND DISCUSSION

This section presents a comprehensive synthesis of research findings regarding the enhancement of heat exchanger performance. The reviewed literature was categorized into three thematic areas: nanofluid application, surface modification and extended surfaces, and innovative design configurations. Key patterns, effectiveness, and limitations observed in each category are discussed, followed by a comparative evaluation and identification of future research directions.

4.1 Nanofluids for Thermal Performance Enhancement

Nanofluids, suspensions of nanoparticles in base fluids, have demonstrated significant potential in enhancing the heat transfer capabilities of conventional heat exchangers. Several studies reported that replacing water or standard working fluids with nanofluids like CuO, Al_2O_3, TiO_2, Fe_3O_4, and hybrid nanofluids can improve the convective heat transfer coefficient (HTC) by 10% to 30%. For example, Khatoon et al. (2022) observed that CuO/Al_2O_3–water nanofluid in a shell and tube heat exchanger not only improved the heat transfer coefficient but also reduced the required heat transfer area. Similarly, Gupta et al. (2020) reported a 20.5% reduction in thermal resistance and a 15.3% rise in thermal efficiency using CuO nanofluid in mesh wick heat pipes. Zheng et al. (2020) noted a 30.8% enhancement in HTC using Fe_3O_4-water nanofluid in a corrugated plate heat exchanger. Hybrid nanofluids, as explored by Saghir and Rahman (2020), provided further improvements but at the expense of increased pumping power. Their findings indicated that among the tested hybrid fluids, ND–Fe_3O_4 in a water–ethylene glycol base was the most efficient, balancing heat transfer and pressure drop. However, nanofluid concentration plays a crucial role. While higher particle concentrations generally improve thermal performance, they also increase viscosity and potential agglomeration, which can negatively impact pressure drop and flow stability. Ajeeb et al. (2023) demonstrated a 27% improvement in heat transfer at 0.2 vol% Al_2O_3 concentration, but this was accompanied by an 8% increase in pressure drop. Table 1 summarized the findings of some of the papers of nanofluids

Table 1*: Analysis of Heat Exchanger with Hybrid Nanofluids*

Author	Nanofluids Used	Result / Performance
Khatoon et al. (2022)	CuO/Al_2O_3–Water (Hybrid)	Improved HTC and reduced heat transfer area

Gupta et al. (2020)	CuO–Water	20.5% reduction in thermal resistance and 15.3% increase in thermal efficiency
Zheng et al. (2020)	Fe_3O_4–Water	30.8% enhancement in convective HTC
Saghir & Rahman (2020)	ND–Fe_3O_4 in Water–Ethylene Glycol	Best balance between heat transfer and pressure drop; required more pumping power
Ajeeb et al. (2023)	Al_2O_3–Water (0.2 vol%)	27% improvement in HTC; 8% increase in pressure drop

Across the literature, the selection of nanoparticle material, size, base fluid, and volume fraction were identified as critical design parameters, necessitating optimization based on application requirements.

4.2 Surface Modifications and Extended Surface Techniques

Surface modification strategies such as coating, texturing, and the addition of extended surfaces have been instrumental in improving the performance of heat exchangers, particularly in boiling, condensation, and air-side applications. Cheng et al. (2020) reported enhanced boiling performance using fishbone-patterned copper tubes, while T. Y. Zhang et al. (2022) demonstrated that superhydrophobic honeycomb-like surfaces boosted condensation HTC by nearly sixfold through droplet jumping. In another study, Lin et al. (2020) found that hydrophobic fin surfaces improved heat transfer efficiency by 5.56% compared to unmodified copper fins under high humidity conditions. Finned and perforated structures have also shown substantial promise. Hasan et al. (2023) combined Al_2O_3 nanofluids with finned tubes in a double-pipe heat exchanger and achieved a 3.1-fold increase in the convective HTC. Similarly, Harris et al. (2024) employed machine learning to optimize pin fin geometry, achieving 1.5 to 1.7 times better thermal performance while reducing material use by up to 14.3%. Coatings such as PMMA, BN, and DLC have been used to reduce fouling and improve surface longevity. Kananeh et al. (2010) reported a 70% reduction in cleaning time using hydrophobic coatings inside plate heat exchangers. However, some coatings such as BN may act as thermal resistors, leading to slightly decreased thermal performance despite their anti-fouling advantages (Ahn et al., 2019). Table 2 indicates the role of extended surface modification techniques in heat transfer enhancement

Table 2: *Enhancement of heat transfer using surface modification techniques*

Author	Extended Surface Type / Method	Result / Performance
Hasan et al. (2023)	Finned tube + Alumina nanofluid in double-pipe heat exchanger	Convective HTC increase up to 3.1 times; thermal conductivity increased by 4.7%
Tokas et al. (2021)	Copper & steel fins with optimal geometry	Effectiveness: Copper = 304.62, Steel = 219.33; 99%+ fin efficiency
Pradhan et al. (2020)	Al–Graphene composite fins via powder metallurgy	Conductivity increased to ~280 W/mK (vs 124 for Al)
Nuntaphan et al. (2010)	Oscillating heat pipe as extended surface	Heat transfer increased by ~10% at 60°C inlet water
L. Li et al. (2024)	Corrugated fins under vibration	HTC increased by 12.28% under optimal vibration settings
Cheng et al. (2020)	Fishbone-patterned copper tubes via picosecond laser texturing	Boiling heat transfer coefficient (HTC) improved
Zhang et al. (2022)	Superhydrophobic honeycomb surfaces on metals using electrochemical etching	Up to 6 times improvement in condensation HTC
Lin et al. (2020)	Hydrophobic modification of copper fins	5.5% increased heat transfer efficiency at high humidity

Thus, surface engineering offers a balance between performance enhancement, fouling resistance, and manufacturability, but careful selection of material and method is essential to avoid compromising thermal conductivity.

4.3 Innovative Heat Exchanger Design Configurations

Design geometry has a profound impact on fluid dynamics and heat transfer characteristics. Innovative configurations ranging from helical coils to fractal tubes and microchannels have demonstrated substantial improvement in Nusselt number, heat transfer coefficient, and thermal effectiveness.

Tuncer et al. (2021) achieved HTC values as high as 13,400 W/m²·K on the coil side of a shell-and-coil heat exchanger by introducing a hollow tube for cold fluid injection. Marzouk et al. (2023) demonstrated a 289% improvement in the overall HTC using a fractal tubular design. Dhumal and Havaldar (2023) enhanced the Nusselt number by up to 315% using twisted tape inserts and exterior helical tapes. Microchannel enhancements were notable as well. Zhang et al. (2022) and Zhu et al. (2021) confirmed that incorporating triangular cavities or water-droplet shaped grooves in microchannels substantially improved convective heat transfer at low Reynolds numbers. Additionally, plate-fin geometries with vortex generators (Khoshvaght-Aliabadi et al., 2015) and capsule-patterned channels (Jiang et al., 2020) induced vortex formation and boundary layer disturbance, improving fluid mixing and overall performance. Table 3 presents the summary of innovative heat exchanger design for the enhancement of heat exchanger.

***Table 3**: Heat Transfer Enhancement using Innovative Heat Exchanger Design*

Study	Innovation	Key Outcomes
Tuncer et al. (2021)	Integrated a hollow cold fluid tube into a shell-and-coil HEX	Achieved overall heat transfer coefficient U = 1600–3150 W/m²·K while coil-side HTC up to 13,400 W/m²·K
Kim et al. (2008)	Developed a multi-pass HEX design	JF factor increased by 89%, further 20% with layout refinement
Marzouk et al. (2023)	Used fractal geometry in helically coiled tubes	Enhanced surface area & turbulence led to HTC increment ~289%, better exergy efficiency at high Re
Jafari (2024)	Added mini heat blades (45° angle) inside HEX	Boosted convection by up to 50%, with balanced pressure drop
Güllüce & Özdemir (2020)	Optimized rotary regenerative HEX	Achieved 53% better effectiveness and 23% cost savings with smaller volume and less entropy generation

Despite these improvements, a common challenge remains: most design innovations lead to higher pressure drops and are more complex to manufacture. Balancing these aspects with thermal gains is essential for practical implementation.

5. CRITICAL ANALYSIS

While nanofluids provide measurable gains in thermal performance (up to 60%) of heat exchangers, challenges like increase in pressure drop remains as a major concern. The rise in pressure drop can undermine the system efficiency unless optimized fluid concentrations are used. Similarly, results from lab-scale studies often lack transformation to large-scale system.

Surface modification techniques enhance heat transfer up to 300% but can be harder to manufacture at scale. Moreover, the long-term durability of coatings and their impact on thermal resistance need further investigation. The cost of manufacturing also remains a major factor.

Innovative design configurations show promising improvement in heat exchanger with compactness and better efficiency, but complex geometries demand higher precision, tolerance and increased maintenance. Higher pumping power may be required.

6. LIMITATIONS AND FUTURE RESEARCH DIRECTIONS

While the reviewed studies demonstrate significant potential for improving heat exchanger performance, several limitations persist like most findings are from controlled lab environments and lack validation under real-world operating conditions. There's a scarcity of studies evaluating degradation, maintenance needs, or cost-performance trade-offs. Similarly, combining nanofluids, surface engineering, and advanced geometries in a single system remains complex. Future research should focus on multi-objective optimization balancing heat transfer, pressure drop, manufacturability, and maintenance requirements. The development of standardized testing protocols and real-world pilot studies is essential to transition from promising lab-scale results to industrial applications.

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