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Historical Perspective

The promise of nanofluids: A bibliometric journey through advanced heat transfer fluids in heat exchanger tubes

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ABSTRACT

Thermal management is a critical challenge in advanced systems such as electric vehicles (EVs), electronic components, and photoelectric modules. Thermal alleviation is carried out through the cooling systems in which the coolant and the heat exchangers are the key components. The study examines recent literature on nanofluids and heat exchanger tubes along with state-of-the-art concepts being tested for heat transfer intensification. The performance of nanofluids in several common heat transfer tubes' geometries/configurations and the effectiveness of novel heat transfer augmentation mechanisms are presented. Promising results have been reported, showing improved heat transfer parameters with the use of nanofluids and intensification mechanisms like turbulators, fins, grooves, and variations in temperature and flow velocity. These mechanisms enhance dispersion stability, achieve a more uniform temperature distribution, and reduce the boundary layer thickness, resulting in lower tube wall temperatures. Moreover, introducing flow pulsations and magnetic effects further enhances particle mobility and heat exchange. However, there are limitations, such as increased frictional losses and pressure drop due to magnetic effects. The combination of nanofluids, novel heat exchanger tube geometries, and turbulators holds great promise for highly efficient cooling systems in the future. The study also presents a bibliometric analysis that offers valuable insights into the impact and visibility of research in the integration of nanofluids into heat transfer systems. These insights aid in identifying emerging trends and advancing the field towards more efficient and compact systems, paving the way for future advancements.

1. Introduction

Nobody can dispute the fact that as the industrial sector expands, there is a growing demand for small and lightweight devices with improved capabilities. It is a fact that, achieving sustainable growth requires prioritizing the efficient production, conversion, and consumption of energy. Heat transfer devices are the essential part of almost all devices that consume or generate energy used in various industrial and commercial sectors. Researchers are focused on making these devices more compact while also exploring advanced thermal coolants with enhanced thermal characteristics that can transfer heat more effectively like ionic liquids, nanofluids, superfluid helium, graphene-based coolants, phase change material, etc. Nanoparticles suspended fluids are one of the promising candidates grabbing the attention of researchers because of their improved thermal properties. Nanofluids are mixtures of base fluid with metallic or non-metallic nano sized particles typically having a size <100 nm in at least one dimension. The uniformly suspended particles enable them to exhibit improved thermal properties, which can lead to more efficient heat transfer in the heat exchanger.

The concept of nanofluids was first proposed by Choi [1] in the mid-1990s, the study suggested that suspending nanoparticles in a base fluid could enhance heat transfer properties. Later on, Choi and Eastman [2] suspended various metallic particles in different fluids and found that each study resulted in an improvement in performance. It was found that nanofluids had significantly higher thermal conductivity than the base fluid, stimulating interest in their potential applications. The early research in the field of nanofluids focused on developing methods for synthesizing stable nanoparticle suspensions and characterizing their thermal and rheological properties. In this effort, Zhu et al. [3]

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introduced the chemical method for preparing the ethylene glycol (EG) based copper nanofluid while Choi and Eastman [2] proposed the vapour deposition technique to prepare the nanofluid in one step inside a chamber. A substantial amount of research has been carried out since the early 2000s on the synthesis, characterization, and application of nanofluids. The focus was to understand the mechanisms behind the enhanced properties of nanofluids and develop methods to optimize their performance for specific applications. Xuan and Roetzel [4] proposed the correlations to predict the heat transfer coefficient (HTC) of nanofluids treating the fluid as a single phase and multiphase solid-liquid. In 2004, Eastman et al. [5] compiled a comprehensive study on the thermal characteristics of nanofluids summarizing the numerous heat transfer mechanisms. The authors came to the conclusion that more investigation would be required in the upcoming years to fully comprehend the transfer of heat at the atomic level. The study shed a light on the impact of several factors, such as particle size, surface morphology, agglomeration, and fluid temperature, on the thermal transport capacity of nanofluids. On the basis of a considerable number of studies, it was concluded that the particle size, surface treatment, and temperature significantly affected the thermal characteristics, while the formation of particles clusters is undesirable.

Researchers also explored various types of materials and started investigating the impact of parameters like shape, size, concentration, etc. on their thermal and rheological properties. Over the next decade, the study of nanofluids continued to gain even more attention, particularly in applications such as heat exchangers, energy storage, thermal management of electronics, and biomedical equipment. Researchers focused their efforts on exploring the potential of nanofluids in these areas, recognizing their promising prospects and the impact they could have on enhancing performance and efficiency [6,7].

After 2010, the focus of the investigation starts shifting gradually towards more practical applications, such as developing nanofluid-based compact heat transfer devices, enhancing heat transfer in solar thermal systems, and improving the efficiency of power generation and industrial processes [8]. This transition has paved the way for innovations in nanofluid technology, with companies worldwide actively engaging in the development and deployment of these advanced fluids to address pressing challenges in various industries. A Korean company named Zalman introduced nanofluids as a cooling agent in two of their products, the Reserator 3 Max and Reserator 3 Max Dual. There is another company named Ice Dragon Cooling supplying nanofluids to several industrial sectors for use in diverse applications. Hydromx, a USA-based company with global reach, specializes in commercializing nanofluids for heating and cooling applications. Their revolutionary heat transfer nanofluid, powered by Nano-Thermo™ technology, accelerates heat transfer through suspended nano-particles. This results in significant energy savings and cost efficiency for clients. In this effort, Synano is working to bring this nanofluid innovation to market to meet the considerable cooling challenges faced in data centres and other electronics thermal management applications. Synano claims they are developing nanofluids that have a thermal conductivity value >20% higher than the base fluid, without a substantial increase in viscosity. Their nanofluids technology seeks to maintain the favourable flow properties of the base fluid while significantly boosting its heat transfer capabilities. An Italian company TCT Nanotech has developed a nanofluid product called HTF Compact that contains copper oxide nanoparticles suspended in a fluid with corrosion inhibitors. Characterized by nanoparticles measuring 3-7 nm, this nanofluid is specifically crafted to enhance the efficiency of HVAC/R systems when introduced into established closed water loops such as chilled water or hot water loops. Notably, this nanofluid presents an opportunity to reduce or eliminate the need for antifreeze glycols, substances that typically hinder heat transfer, resulting in a further enhancement of overall efficiency. A demonstration of the fluid took place at a Pfizer research facility in New York, where it was integrated into the glycol-based heat recovery loop, chilled water loop, and hot water loop. Remarkably, at a 5% mix ratio with the existing fluid, the nanofluid showcased a notable improvement in heating/cooling efficiency, leading to reported electricity savings of 14.1% and fuel savings of 7.8%, as reported by the vendor. Werner Finley, a company functioned in India, has developed a nanofluid named Nanofluid-99, asserting that their heat-transferring fluid can contribute to a minimum electricity savings of 20%. Beyond its potential for energy conservation, this nanofluid offers the additional benefits of being corrosion-resistant and providing protection against freezing. Collectively, these companies represent a global movement towards harnessing the potential of nanofluids, demonstrating their efficacy in optimizing thermal processes and heralding a new era in heating and cooling system efficiency.

In recent years, nanofluids have also been found to be very effective in other applications, such as antimicrobial activity [9], improved lubrication [10], and desalination [11]. However, some challenges have prevented their widespread commercial adoption. One major issue is nanoparticle aggregation and sedimentation over time, which compromises stability [12]. Market uncertainties, unclear health implications, high production costs, and potential environmental impacts contribute to the hesitancy of companies to invest in nanofluid production. Additionally, the high maintenance expenses and corrosion issues of nanofluid-based systems, coupled with uncertainties in thermophysical properties and complex system performance predictions, further complicate widespread adoption [13]. Despite extensive research efforts since 2000, stability remains a significant hurdle to the commercialization of nanofluids, posing alarming and persistent challenges for investigators. However, it's essential to note that stability is not the sole barrier; other issues further impede the widespread adoption of nanofluids in various applications.

Heat transfer in heat exchangers using nanofluids has become an area of active research due to the potential benefits offered by these fluids. The suspension of nanometer-sized particles in working fluid could potentially act as a "heat bridge" between the coolant and the heat exchanger surface, supporting more effective heat transmission. Another way that nanofluids can enhance heat exchanger performance is by increasing the convective HTC. The fluid can experience turbulent flow because of the nanoscale particles, resulting in an increase in heat transfer from the fluid to the heat exchanger surface. At the nanoscale, the particles introduce additional complexity to the fluid dynamics. As they move through the fluid, these nanoparticles disrupt the normal flow patterns, creating localized turbulence. This turbulence, in turn, intensifies the mixing and interaction between the fluid and the heat exchanger surface [14,15]. Moreover, the turbulent flow induced by nanoscale particles helps in breaking down thermal boundary layers that may develop on the heat exchanger surface. This breakdown further improves the overall heat transfer efficiency by preventing the formation of stagnant fluid layers that could impede the transfer of thermal energy. While nanofluids can significantly improve heat transfer rates, it is important to note the trade-off with pumping power. Optimizing this balance is essential for practical and energy-efficient applications.

According to the stats of the Scopus database, there has been a growing interest regarding the utilization of nanofluids in heat exchangers. A considerable number of studies have been undertaken to delve into the potential advantages and limitations of nanofluids in greater depth, approaching the subject from various perspectives. These investigations intend to gain a comprehensive understanding of nanofluids and their suitability for enhancing heat exchanger performance. In this regard, significant progress has been made in this field, encompassing a deeper understanding of the mechanisms responsible for enhanced heat transfer, the formulation of new nanofluids, optimization of flow parameters, utilization of advanced manufacturing techniques, and efforts towards scale-up and commercialization. The presented study aims to provide critical insights into the current state of knowledge about the use of nanofluids in heat exchangers and identify areas for further study. Notable, a comprehensive bibliometric analysis has been conducted to discern emerging research trends, identify primary contributors, and pinpoint areas that demand further exploration within this field.

2. Bibliometric analysis

A method of evaluating scientific output known as bibliometry involves the use of mathematical and statistical methods [16]. In this study, the Scopus database was used as it contains a wider range of publications in the field of engineering compared to Web of Science, to facilitate the research process [17,18]. The bibliometric analysis is performed to evaluate the impact and productivity of research, spot trends and patterns in research output, and identify research gaps for potential new areas of investigation. Additionally, it would also be helpful to provide valuable information for funding agencies, academic institutions, researchers seeking collaborations, and those looking to inform future research directions. The methodology adopted to conduct this study involves searching the Scopus database using the query string "(TITLE-ABS-KEY("heat exchanger") AND TITLE-ABS-KEY('nanofluid')". The data collection was conducted in May 2023, from the invention of nanofluid to 2022. The search returned 1940 documents, which included a variety of publication types such as original articles, books, review studies, conference papers, book chapters, conference reviews, errata, letters, and editorials.

The evaluation of the publications involved utilizing bibliometric analysis methodologies found in the relevant literature [18–20]. These methodologies suggested categorizing the publications based on various criteria such as publication type, language, yearly distribution, country and institution distribution per year, subject area, authors, journals, and keywords utilized. The analysis of correlations between authors and keywords was conducted using VOSviewer, a program designed for visualizing and constructing bibliometric networks. VOSviewer is a powerful tool for presenting comprehensive bibliometric maps in a user-friendly and comprehensible manner [21]. Fig. 1 illustrates the sequential process undertaken to carry out a bibliometric study.

Fig. 2 depicts the quantitative visualization of the research trend based on the year of publication, as determined by the data obtained from Scopus. The graph also presents the annual count of experimental studies and numerical or theoretical studies. It is crucial to highlight that statistics for experimental and numerical studies were collected by filtering results with the terms "experimental" and "numerical or theoretical," respectively. The substantial surge in publications related to nanofluids in heat exchangers was first observed after 2008. This may be due to a number of factors, including the increasing availability of high-performance computing resources, formulation of new nanofluids, the development of innovative nanofluid synthesis methods, and realization of the potential benefits of nanofluids for heat exchanger applications.

Analyzing the data, the first study was published in 1996, just after the invention of nanofluids in 1995, the number of documents increased steadily from 1996 to 2022, with some fluctuations along the way. It is noted that, the number of publications remained comparatively low from 1996 to 2011, ranging from 1 to 78 documents per year. However, starting from 2012, there has been a noticeable increase in the number of publications. The years 2021 and 2022 exhibit the highest number of publications, with 308 and 370 documents, respectively.

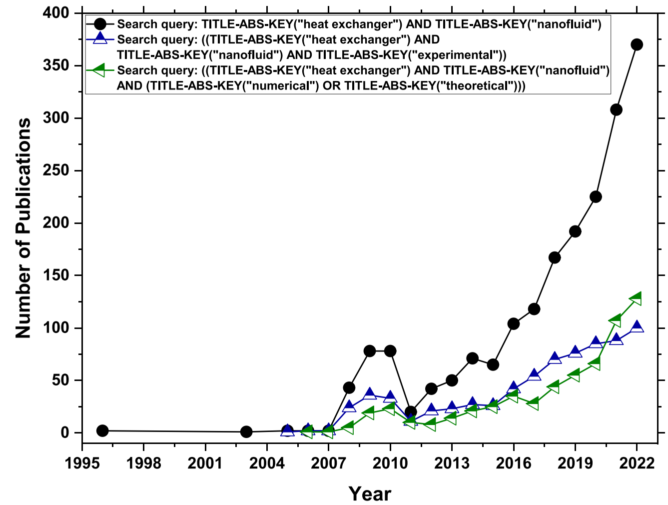

Fig. 2. Number of publications over time (Scopus database).

This data suggests a growing interest and research activity in the field, particularly in recent years. The substantial increase in publications from 2012 onwards indicates an accelerating research trend and emphasizes the importance and relevance of the topic. However, it is important to note that this analysis is limited to the Scopus database, and other factors, such as the extent and inclusiveness of the database, may influence the results. Fig. 3 represents the distribution of publications based on their types. This analysis provides insights into the diverse types of publications which often serve distinct purposes and contribute to the overall scholarly discourse. The majority of publications were in the form of articles, while conference papers and reviews also constituted a significant portion.

Fig. 4(a) sheds light on the research productivity of the institutions based on the number of publications associated with each. Several institutions are renowned for their research contributions, here we mentioned the top ten. Universiti Malaya has the highest number of publications followed closely by Islamic Azad University and King Abdulaziz University. Performing such an analysis helps researchers identify areas where research on a particular topic is highly stimulated, as well as areas where a certain stagnation or limited activity can be observed. Fig. 4(b) highlights the involvement of various funding bodies in supporting research endeavours. This analysis indicates the financial support provided by these funding bodies for research activities. The involvement of these funding bodies underscores their commitment to promoting scientific research and development in their respective regions. The data of these funding bodies helps researchers by providing valuable information on available funding sources and guiding them in aligning their research proposals with the funding priorities, increasing their chances of securing financial support for their work.

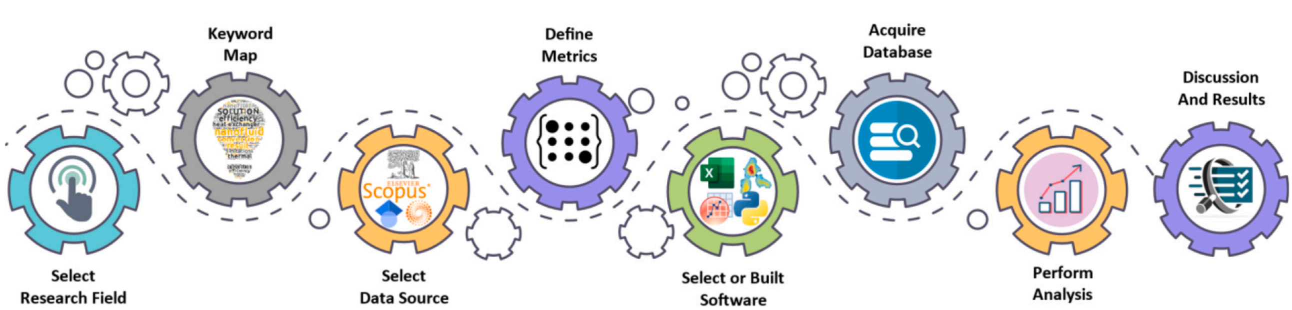

Fig. 1. Stages of methodology for conducting a bibliometric study.

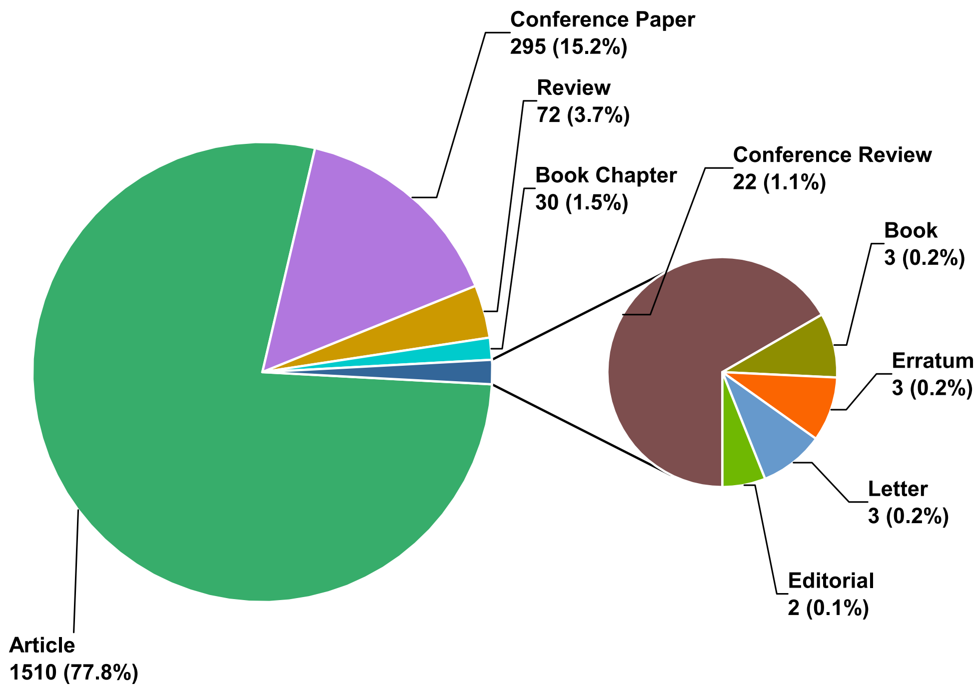

Fig. 3. Type of documents.

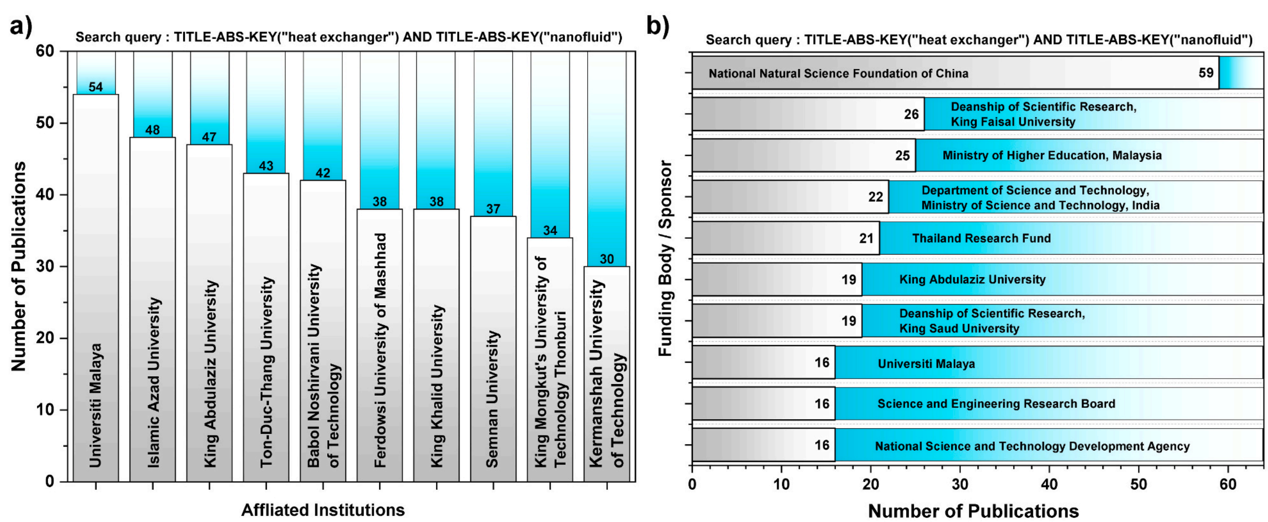

Fig. 4. Stats of the top ten institutes and funding bodies.

Fig. 5(a) depicts the distribution of research publications across different countries. The data indicates that research efforts are being made by several countries across the globe. India emerges as the leading country with 525 publications, followed by Iran (450), China (214), Saudi Arabia (167), and the United States (159). The stats provide valuable insights into the research productivity of various countries and highlight their contributions to the scholarly landscape. It underscores the global nature of research and the commitment of researchers worldwide to advancing knowledge and innovation in their respective fields.

Fig. 5(b) provides insights into the relationship between countries publishing on the topic, revealing a strong interconnectedness among them. It is noteworthy that countries with significant contributions are not only conducting research in the field but also engaging in global collaborations to effectively leverage nanofluids for enhancing heat exchanger performance. This highlights the collaborative nature of research and the collective efforts towards advancing knowledge and applications in this domain.

Fig. 6 illustrates the distribution of research publications across various subject areas, highlighting the multidisciplinary nature of the field. Engineering emerges as the leading subject area with 1026 publications, followed by Physics and Astronomy with 811, and Chemical Engineering with 765. Next to it, there are a significant number of documents in the field of Chemical Engineering and Materials Science further emphasizing the pivotal role in the development and characterization of nanofluids. The analysis proved the diverse range of subject areas involved in research related to the topic, highlighting the significance of interdisciplinary collaboration and the potential for cross-pollination of ideas and methodologies across multiple fields.

The list of leading journals producing research on the subject is illustrated visually in Fig. 7(a), which also reflects the multidisciplinary nature of the field. According to the stats, the research related to the

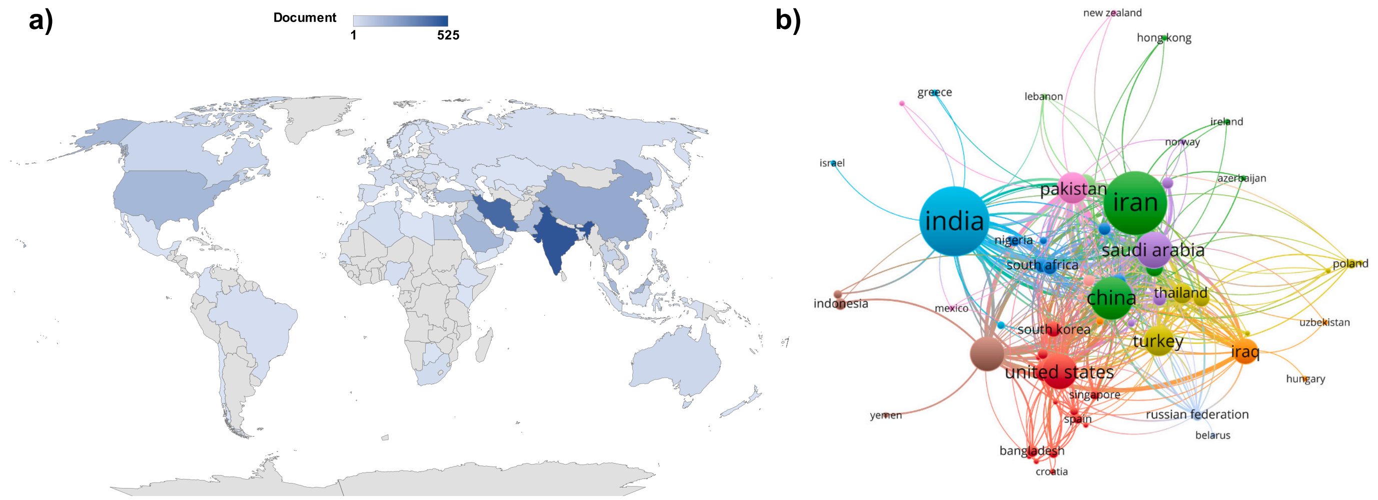

Fig. 5. Global dissemination of published research and the interconnectedness of countries engaged in collaborative scientific efforts.

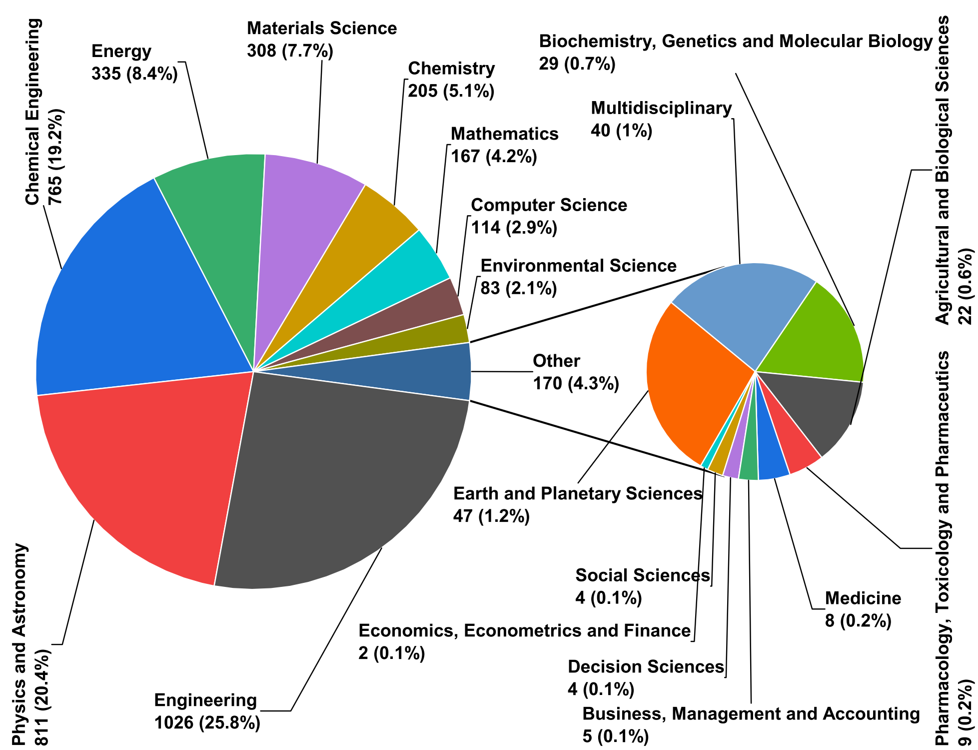

Fig. 6. Distribution of publications across different subject areas.

topic is being published across a wide range of high-impact journals with a strong emphasis on thermal and fluid sciences. The "International Communications in Heat and Mass Transfer, which has been classified as a Q1 journal by SJR (Scimago Journal & Country Rank), holds the record for the highest number of publications with a total of 92 articles, followed closely by "Journal of Thermal Analysis and Calorimetry" with 89 publications. Other notable journals include "International Journal of Heat and Mass Transfer" (59), "Case Studies in Thermal Engineering" (40), and "International Journal of Thermal Sciences" (37). Additionally, these top ten journals represent 36.33% of all the published documents and 2.12% of all the published sources. Fig. 7(b) presents an overlay visualization created using VOSviewer. The size of each circle corresponds to the number of documents published in that particular journal, while the colour coding distinguishes the publication year of the articles. Earlier-stage researchers can use this information to identify the leading publications in the field and target their research for publication in the most impactful and relevant journals.

To gain a deeper understanding of the relationship between the scientific content and the discussed bibliometric trends, a network analysis of keywords was conducted. Fig. 8 illustrates the relationships and frequency of different keywords within the subject under investigation. The most frequent keyword in the literature on nanofluids is "nanofluid," occurring in 698 publications. The keywords "heat transfer" (291), "nanofluids" (284), "heat exchanger" (238), and "heat transfer enhancement" (135) are also frequently used by the authors. Interestingly, "hybrid nanofluid" (113) appears to be a significant keyword, indicating the growing interest in combining different types of nanoparticles in nanofluids to achieve enhanced thermal properties.

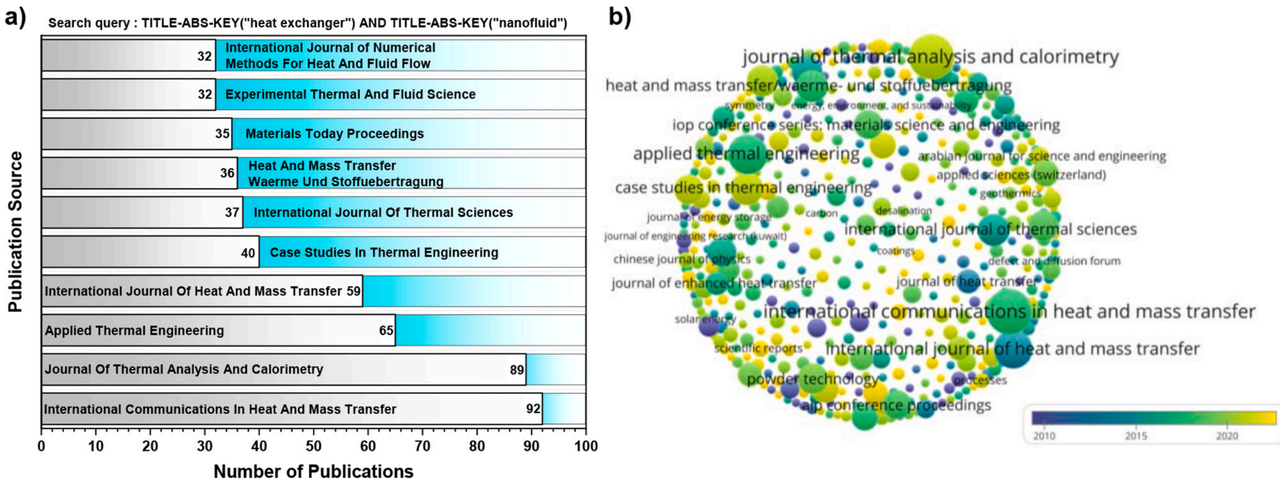

Fig. 7. Number of publications in various journals around the world.

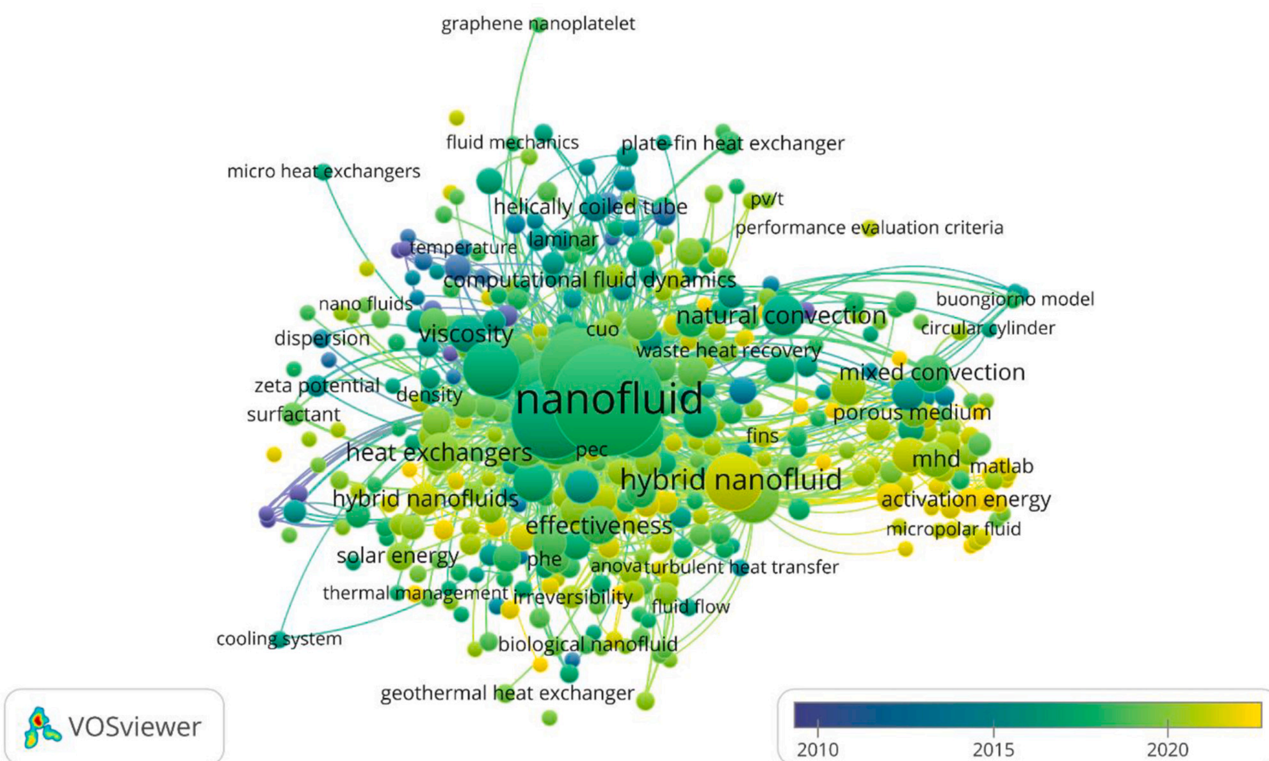

Fig. 8. *Co*-occurrence and interconnection of keywords.

Other important keywords include "pressure drop" (112), "thermal conductivity" (107), "Nusselt number" (103), "entropy generation" (84), and "heat transfer coefficient" (80). The use of numerical simulations is evident from the appearance of "CFD", "finite element method", and "artificial neural network" as keywords. The keywords like "experimental study", "experimental", and "correlation" suggest the significance of experimental studies. The importance of thermal properties of nanoparticles is also evident from the keywords "thermal resistance" and "thermal conductivity". In summary, the analysis demonstrates the emphasis on the fundamental understanding and practical applications of nanofluids in heat transfer systems.

Fig. 9(a) presents a comprehensive overview of the most cited sources in the field. The top-ranked journal is the International Journal of Heat and Mass Transfer, with a substantial citation count of 9158, indicating its significant impact in the field. The results suggest a high interest in the topic of nanofluids and their applications in heat exchangers within the thermal sciences and engineering community. These journals serve as reputable sources of research in the study of nanofluids' role in heat exchangers, as evidenced by the substantial number of citations they have received. The analysis of journal citations can be important for readers as it provides insights into the influence and impact of different journals in a specific field of research, such as the role of nanofluids in heat exchangers. By examining the number of citations received by journals, readers can gauge the level of recognition and trustworthiness associated with these journals. Highly cited journals often indicate that their published papers have been widely referenced and acknowledged by the research community, suggesting their relevance and quality.

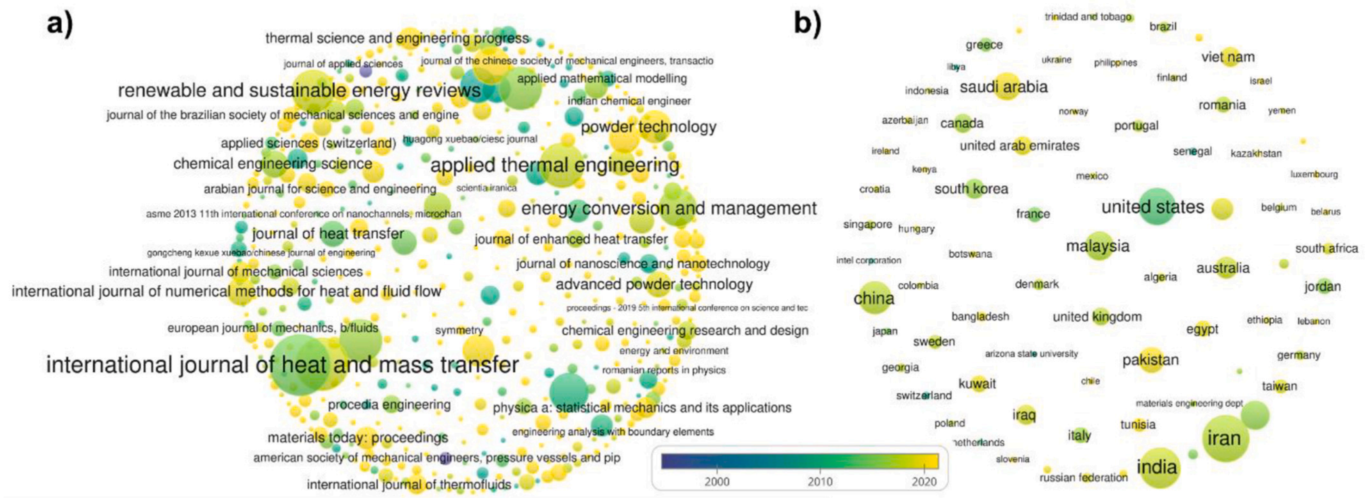

Fig. 9. *Co*-citation stats for a diverse range of journals and countries.

The country-wise citations received by papers on the role of nanofluids in heat exchangers reveal interesting patterns, graphically illustrated in Fig. 9(b). Iran emerges as the leading country with 19,752 citations, followed by India with 13,562 citations. The United States and China also have significant citation counts, with 10,135 and 7776 citations respectively. Thailand, Malaysia, Saudi Arabia, and Pakistan also demonstrate notable citation impact in this research area.

These findings suggest that countries in the Middle East and Asia, particularly Iran, India, and China, have been actively contributing to and receiving recognition in the field of nanofluids in heat exchangers. The presence of these countries highlights their significant research efforts and contributions to advancing knowledge and innovation in this domain. It is worth noting that the list includes countries from different continents, indicating the global nature of research in this field. The data can be used to identify potential collaborators or research partners in specific regions and can also inform policymakers and funding agencies about the countries that have made significant contributions to the field, which may influence decisions related to funding and resource allocation.

Fig. 10 presents the co-citation statistics of the top fifteen authors in the field of nanofluids in heat exchangers, based on the Scopus database. The co-citation analysis provides insights into the influential authors within the research community. The presence of multiple authors from various institutions suggests collaborative research efforts and the exchange of ideas within the scientific community. Their research output contributes to advancing knowledge and understanding in the field, and their expertise can be valuable for researchers seeking authoritative references or collaboration opportunities. SUS Choi emerges as the most highly cited author, known for introducing the concept of nanofluids and has conducted pioneering research in this area. His research has focused on enhancing thermal conductivity and understanding the behaviour of nanofluids. Furthermore, he has collaborated on studies investigating the effects of various parameters on nanofluid thermal conductivity and the role of interfacial layers in enhancing thermal conductivity. Choi's research has contributed to the development of fundamental understanding and application of nanofluids in heat transfer, establishing him as a key figure in the field.

Somchai Wongwises is the second one on the list, a researcher from

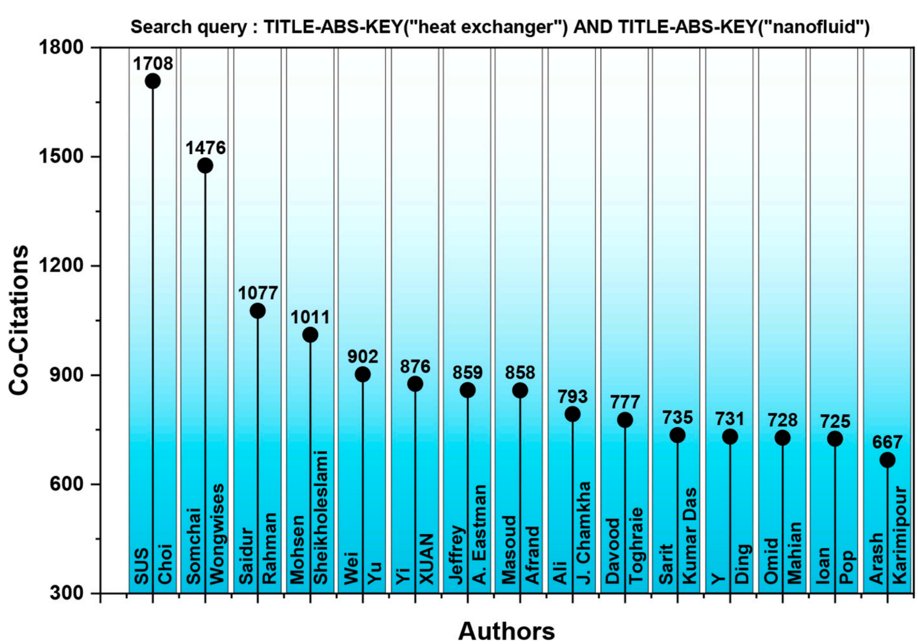

Fig. 10. *Co*-citation matrices of the top 15 investigators around the world.

the Department of Mechanical Engineering at King Mongkut's University of Technology Thonburi, has made significant contributions to the field of nanofluids and related areas. He has authored numerous articles that centre around the utilization of nanofluids in diverse domains such as solar energy, improving heat transfer, and enhancing heat exchangers. Wongwises' research has covered a wide range of topics, including the thermal conductivity and viscosity measurements of nanofluids, heat transfer characteristics, and the effects of nanofluids on evaporation rates and boiling heat transfer. He has conducted experimental studies, critical reviews, and modelling investigations to explore the behaviour and potential applications of nanofluids. Wongwises has conducted extensive research on heat transfer enhancement using nanofluids in heat exchangers. They have investigated the effects of different parameters, such as nanoparticle size, tube roughness, and thermophysical properties, on heat transfer efficiency and pressure drop. Wongwises' work also includes reviews of the current state of knowledge in areas such as flow and heat transfer characteristics in curved tubes, entropy generation in nanofluid flow, and electrohydrodynamic enhancement of heat transfer. Ranked third on the list, Saidur Rahman is a prolific author in the field of renewable and sustainable energy. Their research group has published numerous articles and reviews on a wide range of topics, including nanofluids, biomass fuel, solar energy, wind energy, energy savings strategies, and electrical motors. Their work covers various aspects of energy research, including applications, challenges, policy, analysis, and technology development. Saidur Rahman's research on nanofluids explores their applications and challenges, as well as their stability properties and characterization. Nanofluid-based coolants in automotive car radiators and the use of nanofluids as absorbers in direct solar collectors have also been investigated in their studies.

Next on the list is Mohsen Sheikholeslami, a highly accomplished author in the field of heat transfer and nanofluid dynamics. Sheikholeslami's research explores the impact of thermal radiation, magnetic fields, Lorentz forces, and porous media on nanofluid flow and heat transfer. Their research group developed innovative computational approaches and numerical simulations to analyze the behaviour of nanofluids and their application in diverse systems. His studies have examined the influence of magnetic fields on forced convection, natural convection, and free convection heat transfer in different geometries.

In addition to nanofluids, Sheikholeslami has also investigated the behaviour of ferrofluids, convective heat transfer in semi-annulus enclosures, and the use of innovative heat transfer enhancement methods. Their research has provided valuable insights into the mechanisms governing heat transfer and fluid flow, and has practical implications for designing efficient and sustainable energy systems.

Wei Yu is an accomplished author affiliated with Shanghai Second Polytechnic University, specializing in the field of advanced thermal materials, especially graphene-based thermal interface materials, silicone-based thermal greases with graphene additives, phase change materials, thermal gels, cooling films, and various types of nanofluids [22–27]. Professor Yu has also explored the influence of nitrogen doping on the thermal conductivity of carbon nanotubes, shedding light on the intricate relationship between doping, defects, and phonon scattering. Additionally, he has investigated modified graphene papers with alkaline earth metal ions, showcasing substantial improvements in thermal conductivities through ion chelating mechanisms. Collaborating with Xie and other colleagues, Yu has published numerous articles focusing on the preparation, stability mechanisms, and applications of nanofluids. Yu and the team have studied the influence of various nanoparticles, including TiO_2, SnO_2, MgO, diamond, and Ag/MWNT composites, on thermal transport and heat transfer performances. Additionally, Yu extends beyond nanofluids to include the synthesis and characterization of different nanomaterials, such as copper colloids, heterostructured nanofibers, and nanocomposites for photocatalytic applications.

Jeffrey A. Eastman is a materials scientist who worked alongside SUS Choi to introduce the concept of nanofluids. He has worked extensively at the Argonne National Laboratory in Illinois, United States. Eastman and Choi have collaborated on several research articles exploring the thermal properties and applications of nanofluids. Their seminal paper, published in 1995 [1] introduced the concept of using nanoparticles to improve the thermal properties of fluids. This work opened up new possibilities for enhancing heat transfer in various industrial processes and thermal management applications. His expertise spans a wide range of materials science and engineering areas, and his contributions have been widely cited by the scientific community.

Masoud Afrand is a researcher known for his work on heat exchangers and nanofluids. He leads a highly active research group that has made significant contributions to the field. Afrand has investigated how various hybrid nanofluids behave rheologically and their impact on heat transfer. His work sheds light on the benefits and challenges of utilizing nanofluid potential in heat transfer systems. In multiple studies, he investigated the effect of temperature, nanoparticle concentration, and volume fraction on the viscosity and flow characteristics of nanofluids. These findings can help in designing more efficient heat exchangers by considering the fluid dynamics and flow properties of nanofluids. Afrand's research also involves the development of correlations and models for predicting the thermal and rheological properties of nanofluids. By establishing these correlations, engineers can estimate the heat transfer and fluid flow characteristics of nanofluids without extensive experimentation, facilitating the design and optimization of heat exchanger systems. However, given the diverse nature of nanofluids and the various influencing factors, such as preparation techniques, particle characteristics, base fluid properties, and stability, it is important to note that the correlations developed by Afrand's group may not universally apply. In a more nuanced approach, it is suggested that employing a consistent preparation method and using the same particles could enhance the reliability of these correlations when predicting properties.

The work of Ali J. Chamkha encompasses various aspects of heat transfer, including natural convection, mixed convection, and forced convection in different fluid media and geometries. Chamkha has made contributions to the field of magnetohydrodynamics (MHD) and its applications to heat transfer [28–30]. Chamkha's work extends to the modelling and simulation of heat transfer processes in porous media, offering valuable insights into their ubiquitous presence in nature and wide-ranging engineering applications. He has studied the MHD flow of fluids in the presence of magnetic fields, heat generation/absorption, and chemical reactions. His research has elucidated the mechanisms of heat transfer in porous media, including conduction, convection, boundary layer formation, and phase change, and has led to the development of improved analytical and numerical methods for analyzing these processes [31–33].

The group of investigators, including Davood Toghraie, Sarit Kumar Das, Yulong Ding, Omid Mahian, Ioan Pop, and Arash Karimipour, along with the broader research community worldwide, are diligently working towards the comprehensive integration of nanofluids in heat exchangers. Their collective efforts aim to enhance the efficiency and compactness of heat transfer systems.

The bibliometric analysis conducted on the research efforts in the field of integrating nanofluids in heat exchange systems has yielded several significant advantages. The analysis helps in assessing the impact and visibility of research in this domain, aiding in the evaluation and recognition of the contributions made by researchers. In addition, such kind of analysis can aid policymakers and industry stakeholders in understanding the impact and potential applications of nanofluid-based heat transfer systems, leading to informed decision-making and investment strategies. It would be valuable for the identification of emerging trends and potential areas for further exploration. Ultimately, the study acts as a catalyst for advancing the integration of nanofluids in heat transfer systems, leading to enhanced efficiency and compactness, and paving the way for further advancements in the field.

3. Heat transfer in heat exchangers

The efficiency of heat transfer in heat exchange devices is predominantly influenced by factors such as the choice of coolant or working fluid, the geometric configuration, and the material composition of the heat exchangers [34]. Researchers have explored and tested a diverse array of both traditional and contemporary thermal fluids, as well as different heat exchanger channel geometries, intending to identify optimal configurations for various applications. However, to improve heat transfer, various approaches can be adopted. These techniques have been classified as passive and active methods [35,36]. Passive techniques in heat exchangers refer to methods that enhance heat transfer without the need for external energy input and typically involve structural modifications, specific material selections, or the exploitation of natural phenomena to facilitate the heat exchange process. Passive techniques might not be adequate for high-heat generating systems or in high-temperature environments but can be effective in certain applications. The passive method mainly focuses on the geometry of the heat exchangers and the material of heat exchanger pipes and fins since the efficacy of the working fluids is not that impressive.

Active methods of heat transfer involve the deliberate application of external energy to enhance the efficiency of heat exchange processes. Unlike passive methods that rely on inherent properties or natural phenomena, active techniques provide a proactive approach to heat transfer improvement. In these systems, a cooling agent, typically air or liquid, is actively circulated to remove heat from the source. This method is advantageous in terms of flow control, allowing for customized flow modifications based on the system's requirements. For instance, the utilization of a magnetic field is particularly effective in controlling ferrofluid [37]. Other active methods include the implementation of pulsating flow, the vibration of heat transfer surfaces, and the application of an electric field, among others. Historically, active methods predominantly relied on water and air as primary coolants in heat transfer devices. However, the intrinsic thermal transportation and flow characteristics exhibited by these conventional fluids often fall short of meeting the intricate demands posed by contemporary thermal transport devices. Therefore, notable advancements have been made in improving the geometry of heat exchanging sections and the development of modern thermal fluids. These advancements aim to overcome the challenges associated with temperature control and ensure optimal performance of the devices.

Scientists from various research laboratories have dedicated years to advancing the field of thermal fluids, with a focus on developing highly efficient solutions. Among the cutting-edge developments in thermofluids, nanofluids have emerged as a remarkable innovation, showcasing exceptional thermal transportation properties surpassing those of conventional fluids. This progress is particularly significant in the context of heat exchange devices, where the intricacies of geometrical designs and manufacturing challenges have contributed to increased costs. To enhance the performance of heat exchangers and effectively navigate the intricacies of their designs, it becomes imperative to adopt a synergistic approach that combines forced convection heat transfer mechanisms with advanced thermal fluids like nanofluids, ionic liquids, superfluid helium, phase change material, graphene-based coolants, etc. The use of these thermal coolants, particularly in conjunction with forced convection, not only streamlines the cooling process but also underscores a commitment to pushing the boundaries of thermal management systems. This integrated approach addresses the dual challenges of intricate design complexities and the need for efficient heat transfer. As investigators and manufactures continue to explore and implement such synergistic solutions, the potential for innovation in heat exchanger technologies becomes increasingly promising.

The effectiveness of heat transfer devices is intricately influenced by several key factors, as illustrated in Fig. 11. It is crucial to give meticulous consideration to the flow channel, geometry, and effective surface area during the design of these devices. These elements play a vital role in optimizing the heat transfer process. Another essential aspect that requires careful attention is the thermal and rheological characteristics of the flowing fluid. Properties like heat capacity, conductivity, and viscosity of the fluid have a substantial impact on the overall efficiency of heat transfer. Hence, a thorough understanding of both the structural and fluid-related factors is indispensable for the effective design and performance of heat transfer devices.

4. Nanofluid

Nanofluids exhibit enhanced thermal properties compared to traditional thermal fluids, a distinction attributed to heightened thermal conductivity resulting from the colloidal suspension of metallic particles within the base fluid. The spectrum of nanofluids encompasses simple, ionic, magnetic, hybrid, and organic nanofluids, each contributing unique attributes to the enhancement of thermal performance. The superior thermal characteristics of nanofluids are intricately linked to the properties of nanoparticles employed in their formulation. These nanoparticles play a pivotal role in determining the overall effectiveness of nanofluids. Fig. 12 illustrates the diverse types of nanoparticles utilized in preparing nanofluids, encapsulating a range of materials that contribute to the improved thermal properties. In the continuous exploration of this field, significant strides have been made in understanding and harnessing the full potential of nanofluids. Researchers have delved into novel synthesis techniques, optimizing nanoparticle properties and exploring innovative applications. Advanced studies

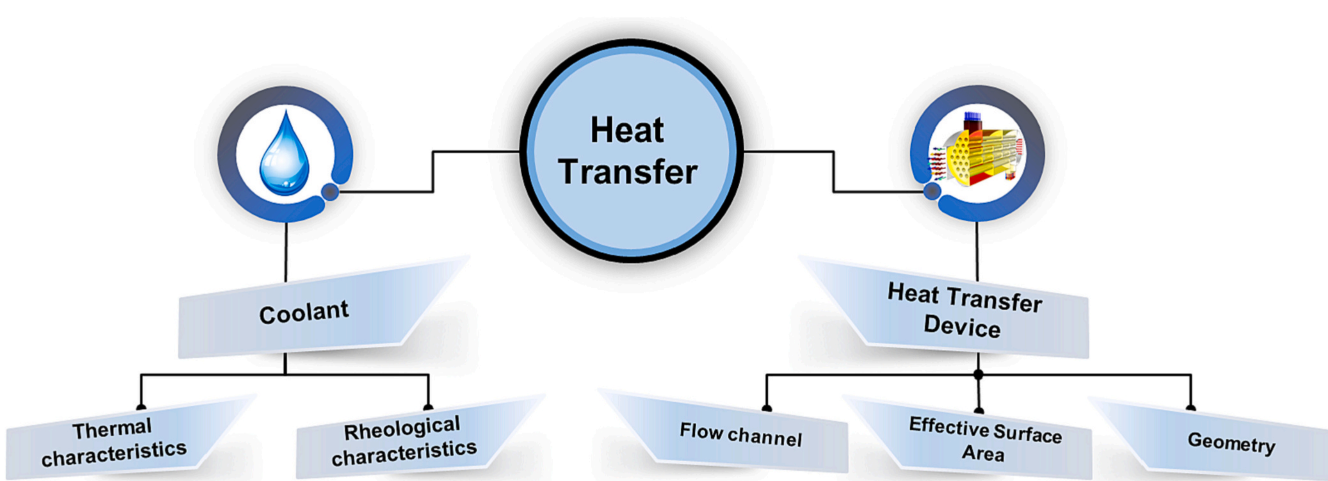

Fig. 11. Key factors affecting heat transfer efficiency in nanofluid based heat transfer devices.

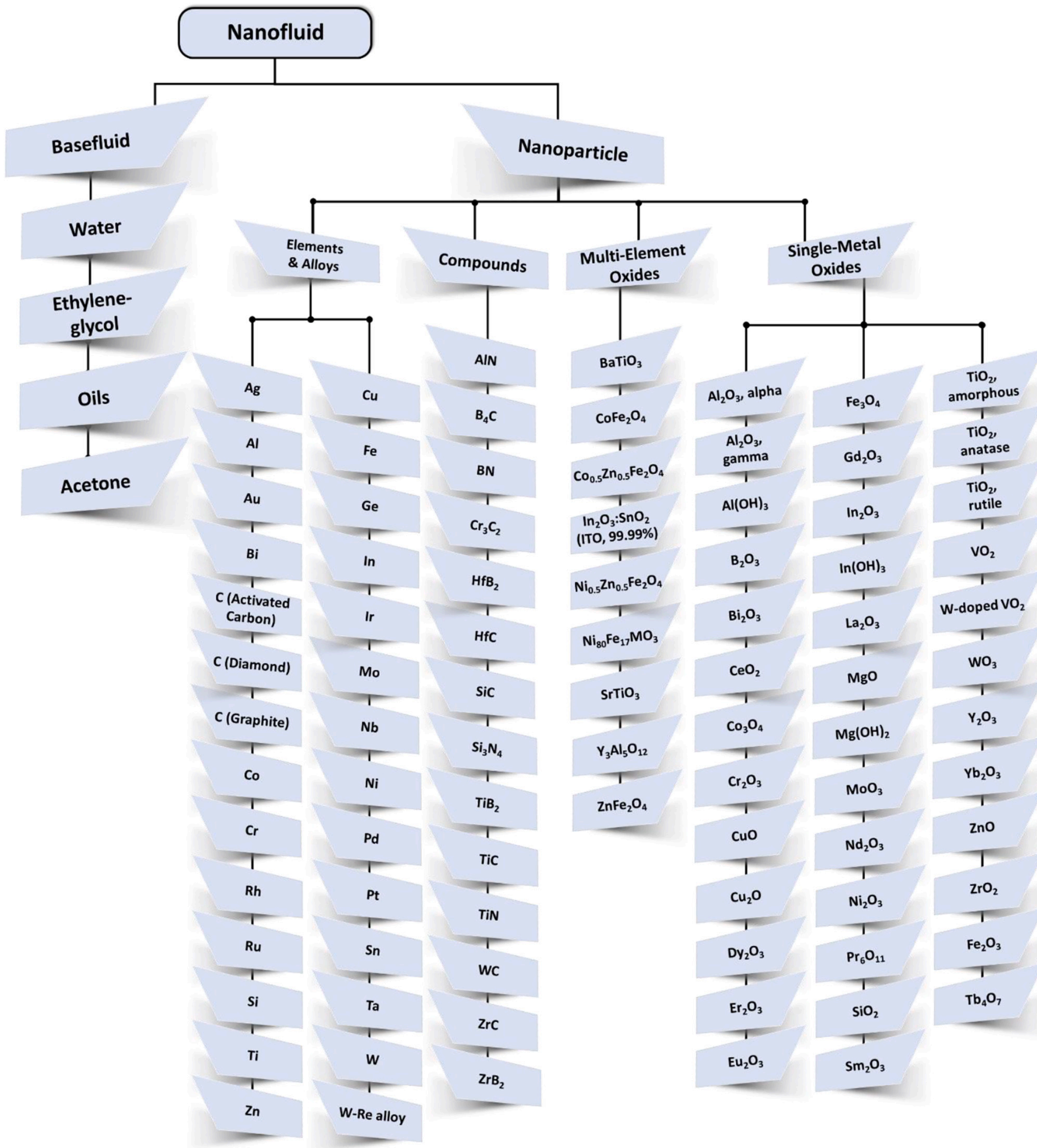

Fig. 12. Nanoparticles used in nanofluids' preparation.

have focused on tailoring nanofluid compositions to specific thermal requirements, paving the way for customized solutions in diverse industrial and technological domains [38–40]. Moreover, ongoing research endeavours aim to unravel the intricate interplay between nanoparticle characteristics and their influence on nanofluid performance. This deeper understanding opens avenues for the precision engineering of nanofluids, allowing for the creation of tailored thermal solutions that address specific challenges in heat transfer and thermal management.

The preparation of nanofluids is achieved by two different methods named single-step and two-step methods. These methods are categorized based on the number of stages involved in the preparation process. Fig. 13 provides a graphical illustration of these two techniques used for nanofluid preparation. In the single-step method, the nanoparticle synthesis and nanofluid production are carried out simultaneously using the hotwire method. In the two-step synthesis approach, the generation of nanoparticles involves initial processes employing diverse mechanical methods for nano-powder production. Subsequently, the nanofluid is prepared through the implementation of suspension creation techniques. This methodical two-step procedure allows for the precise control and customization of both the nanoparticle and fluid phases, thereby enhancing the overall versatility and applicability of the synthesized materials.

A single-step approach involves the production of particles and

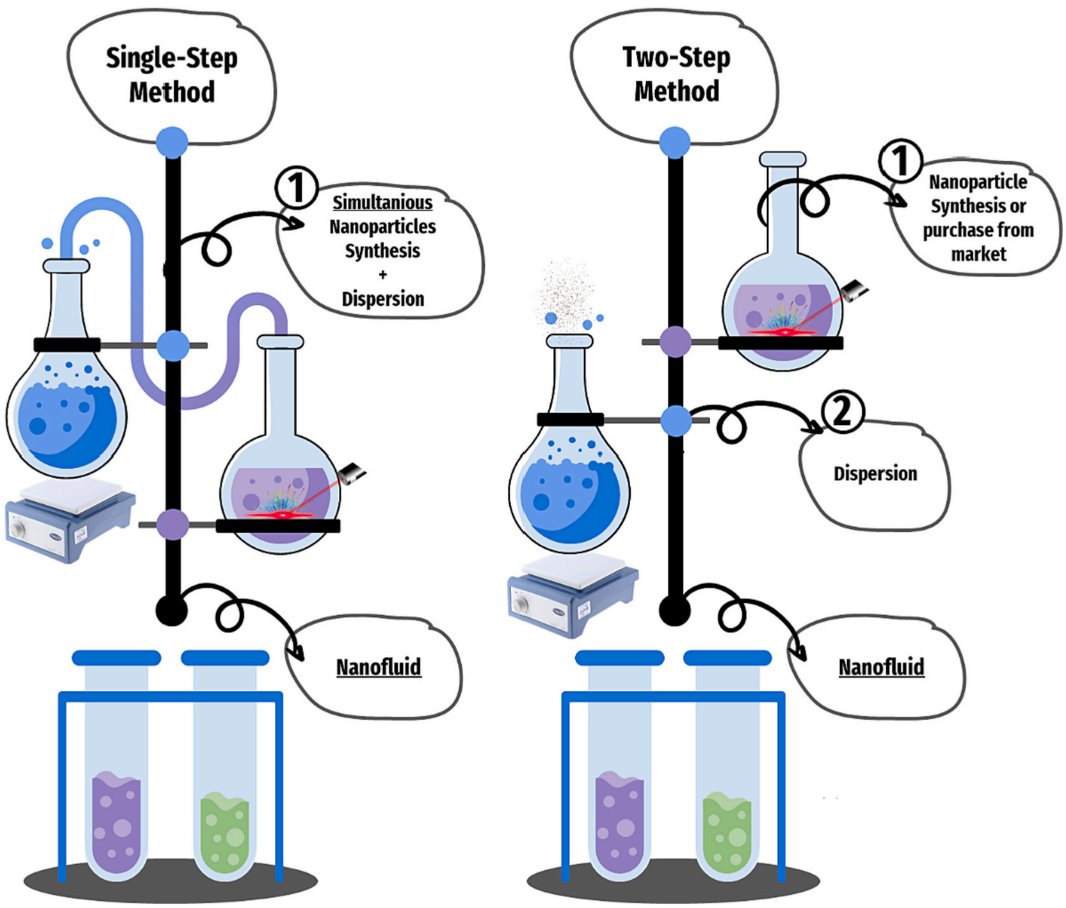

Fig. 13. Illustration of Nanofluid Preparation Methods (a) Single-step approach and (b) Two-step approach.

nanofluid in a single step, rather than requiring multiple steps or different processing stages. In this method, the nanoparticles are produced in a chamber under extreme pressure and heat, and the resulting suspension is subsequently cooled to produce the nanofluid. The two-step process, which requires the separate production and dispersion of nanoparticles, is more popular since it can provide a more stable solution but is also more expensive [41,42]. For small-scale manufacturing, the one-step technique is favoured; however, the two-step method is preferred for industrial or bulk production of nanofluids.

4.1. Mechanism of heat transfer in nanofluids

Heat transfer in nanofluids refers to the process by which thermal energy is transferred within a suspension of nanoparticles in a base fluid. These nanoscale suspensions exhibit unique thermophysical properties that can significantly impact heat transfer mechanisms. The addition of nanoparticles to the base fluid alters its thermophysical properties. Some of the important characteristics of nanoparticles that play a decisive role in the overall performance of the nanofluids include the particle size, shape, thermal conductivity of nanofluids, and intermolecular attraction/clustering effect.

The size and morphology of nanoparticles within a nanofluid play a pivotal role in shaping the efficiency of convection heat transfer, as the available surface area for thermal transport is intricately tied to these two critical factors. Notably, the rate of heat transfer is significantly influenced by the size and shape of the nanoparticles. Additionally, the formation of clusters, driven by intermolecular attractive forces, contributes to an amplification of heat transfer mechanisms. It is crucial to acknowledge, however, that while this cluster formation enhances heat transfer, it concurrently introduces the potential challenge of nanoparticle sedimentation. Transitioning from the considerations of nanoparticle characteristics, it is essential to explore the broader mechanisms that govern heat transfer within nanofluids. Heat transfer in nanofluids is primarily governed by three mechanisms: conduction, convection, and radiation. Understanding the mechanisms of heat transfer in nanofluids is crucial for various applications, including thermal management in electronics, energy conversion systems, and advanced cooling technologies [43].

- Conduction is the process by which heat is transferred between particles directly. Conduction occurs in nanofluids not just between the nanoparticles but also between the nanoparticles and the surrounding fluid.
- Convection is the transfer of heat by the movement of a fluid. In nanofluids, heat can be transferred by convection when the nanoparticles suspended in the fluid are in motion, either due to natural convection (e.g., due to differences in density caused by temperature gradients) or due to forced convection (e.g. when the fluid is pumped through a system).
- The transport of heat by electromagnetic waves is known as radiation. Radiation can happen in nanofluids between the nanoparticles and the environment.

The heat transfer dynamics exhibit variations between stationary and flowing nanofluids. In the case of stationary nanofluids, the predominant mode of heat transfer revolves around conduction. However, in the context of moving nanofluids, the interplay of conduction, convection, and additional transport phenomena introduces a more intricate and dynamic heat transfer mechanism. The literature describes several mechanisms involved in conduction heat transfer within nanofluids, including nanoparticle Brownian motion, nanoparticle clustering, nano-layering effect, nonlocal effect, thermophoretic effect, ballistic transport, and near-field radiation [44], illustrated in Fig. 14.

The overall heat transfer coefficient rises as a result of the collisions between the fluid molecules and the randomly moving nanoparticles caused by their thermal motion. This effect, referred to as "enhanced Brownian motion," can improve the nanofluid's overall heat transfer performance.

In addition to enhanced Brownian motion, another mechanism by which nanofluids can enhance heat transfer is through the formation of nanoparticle clusters. When nanoparticles are suspended in a fluid, they may aggregate or cluster together due to various factors such as van der Waals forces, Coulombic forces, or hydration forces. The formation of these clusters can affect the heat transfer properties of the nanofluid. Murshed et al. [45] examined the impact of nanoparticle clustering on the thermal conductivity of aqueous nanofluids containing TiO_2 and Al_2O_3 nanoparticles. According to the findings, the cluster size grows along with nanoparticle concentration, which reduces the augmentation of the thermal conductivity of the nanofluids.

In nanofluids, nano-layering effect is the propensity of nanoparticles to gather at the interface between a fluid and a solid surface, such as the wall of a heat exchanger. The gradual aggregation of nanoparticles at the fluid-solid interface can lead to the formation of a thin layer of nanoparticles on the solid surface, which can enhance the heat transfer performance of the nanofluid or in some cases it can impact adversely. As time progresses, this layer becomes increasingly thicker, further influencing the heat transfer process.

Thermophoretic effect is a phenomenon that occurs when particles suspended in a fluid are transported by temperature gradients due to a temperature-dependent diffusivity. The thermophoretic effect can lead to the separation or concentration of nanoparticles in certain regions of the fluid. Mehdi Bahiraei [46] studied the impact of thermophoresis on the distribution of nanoparticles in a TiO_2-water nanofluid flowing through a circular tube. It was found that thermophoresis has a significant effect on the distribution of particles in basefluid, and as the particle size increases, the non-uniformity of the concentration distribution also increases. The results also revealed that thermophoresis increases the concentration distribution's non-uniformity, with the effect being most pronounced at higher mean concentrations. The study conducted by Malvandi et al. [47] on concentric vertical annulus employing Al_2O_3-water nanofluids observed that the thermophoretic force pushed the particles towards the adiabatic wall, leading to an increase in nanoparticle concentration near the adiabatic wall and a decrease near the heated wall.

The ballistic transport effect and the nonlocal effect are phenomena influenced by the size of nanoparticles. The ballistic transport effect refers to the transport of heat by nanoparticles through the base fluid via ballistic phonon transport, while the nonlocal effect refers to the nonlocal nature of heat transport by nanoparticles due to their small size. These effects can lead to an enhancement in HTC of the nanofluid [48].

In a nanofluid, the nanoparticles can act as "hot spots" that emit near field radiation due to their small size and high surface-to-volume ratio. Near field radiation, sometimes referred to as near field thermal radiation, is the electromagnetic radiation that can be exchanged between two bodies when they are in close proximity. The absorption of this radiation by the base fluid or another nanoparticle can enhance the heat transfer coefficient.

Chen et al. [49] investigated the thermal radiation characteristics of nanofluids with nanoparticle aggregation theoretically and experimentally. To conduct the study, titanium dioxide/silver plasmonic nanofluids were prepared in distilled water, and their spectrum transmittance was assessed with different levels of aggregation. According to the findings, nanoparticle aggregation has a substantial impact on the thermal radiation characteristics of nanofluids in the long wavelength band.

A variety of factors such as the size and concentration of the nanoparticles, the kind of base fluid, and the system temperature, determine how much thermal transportation mechanisms affect a nanofluid's ability to transfer heat. In order to exploit nanofluids for heat transfer applications to their maximum potential, it is crucial to properly take into account these parameters.

However, in the moving nanofluids, the cause of heat transfer is the convection heat transfer mechanism. Convection heat transfer, a crucial mechanism in fluid dynamics, is governed by several key factors that significantly impact the efficiency of heat exchange within a fluid medium. These critical elements include the effective surface area, flow rate, and channel geometry. An increase in surface area increases the heat transfer performance of the system. The increase in surface area can be achieved by increasing nanoparticles size, promoting cluster formation, and increasing the number of nanoparticles, if the size of the nanoparticles is small in magnitude. Flowrate of the nanofluid increases the heat transfer rate due to increasing intermolecular interaction and particle interaction with the channel's surface. Importantly, increasing the flow rate not only leads to a higher thermal transportation rate but also amplifies the turbulence within the fluid. Channel coefficient geometry also plays a critical role in heat transfer augmentation in nanofluids since the surface and geometry of the channel have a direct impact on convective heat transfer.

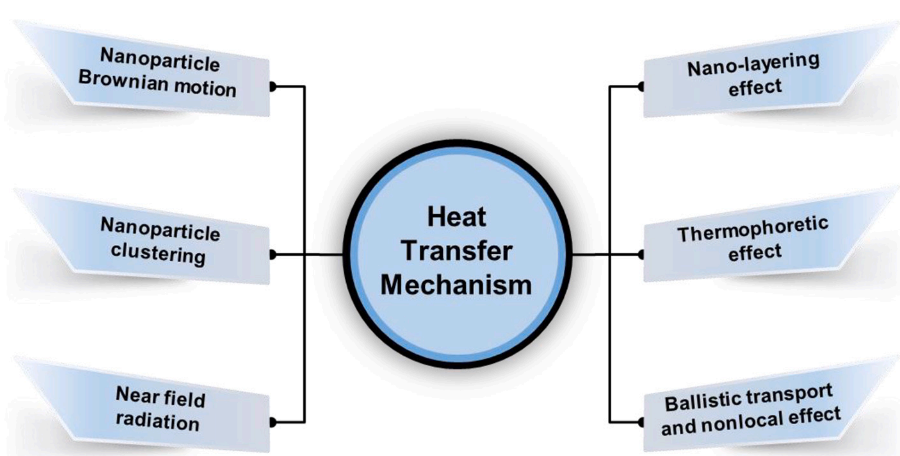

Fig. 14. Conduction-based Heat Transfer Mechanisms in Nanofluids.

4.2. Thermal transportation characteristics of nanofluids

The distinctive molecular chain behaviour of nanofluids urged the investigators to study this advanced class of coolants as a potential substitute for traditional fluids in heat exchangers, as they have potential applications in various fields. The objective is to attain the highest possible thermal conductivity at the smallest possible concentration of nanoparticles. It notes that conventional fluids such as water and mineral oils have poor thermal characteristics, and that the use of nanoparticles suspended in these fluids has shown promise in improving thermal properties. The significance of these advancements is further underscored by the comprehensive presentation of key nanofluid characteristics in Fig. 15, shedding light on the evolving trends and interests in nanofluid research over time. Fig. 16 shows the number of publications over time for different properties of nanofluids, based on the Scopus database. The data was obtained by searching with the keyword "nanofluid" and then filtering the results by the property of interest.

The publications on thermal conductivity have shown remarkable growth over the years. The numbers have increased significantly, reflecting the importance of understanding and optimizing thermal conductivity in nanofluids. This could be attributed to the crucial role thermal conductivity plays in enhancing heat transfer efficiency. Closely followed to thermal conductivity, the number of publications on viscosity has steadily increased, indicating a growing recognition of its importance in the stability and flow characteristics of nanofluids. The rise in publications may signify efforts to address challenges related to viscosity in practical applications. While density publications have not seen as rapid an increase as thermal conductivity and viscosity, there is a consistent upward trend. The growing interest in density suggests a recognition of its impact on buoyancy and specific heat in nanofluids. Heat capacity, though the least studied property, has witnessed a gradual rise in publications. The increasing attention to heat capacity indicates a growing awareness of its significance in influencing thermal energy storage and heat transfer rates in nanofluids. A comparative analysis across properties reveals that thermal conductivity consistently receives the highest number of publications, followed by viscosity, density, and heat capacity. This order aligns with the perceived importance of these properties in various applications, such as heat transfer and energy conversion.

4.2.1. Thermal conductivity of nanofluids

Nanofluids, colloidal suspensions of nanoparticles in base fluids, have emerged as a promising frontier in the realm of thermal conductivity enhancement [50]. The manipulation of nanoscale materials within fluids has led to significant improvements in thermal properties, sparking intense research across various scientific disciplines. Due to their small size, nanoparticles experience significant Brownian motion, which leads to enhanced mixing and improved heat transfer

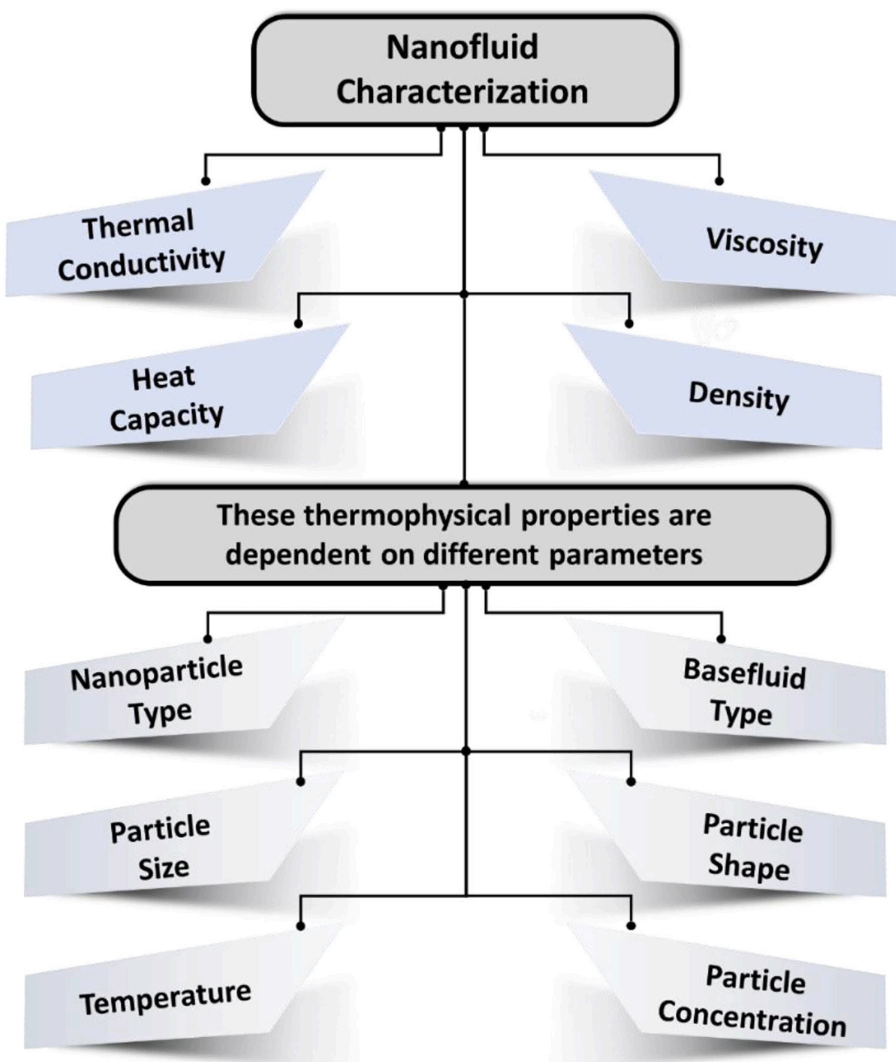

Fig. 15. Nanofluid characteristics.

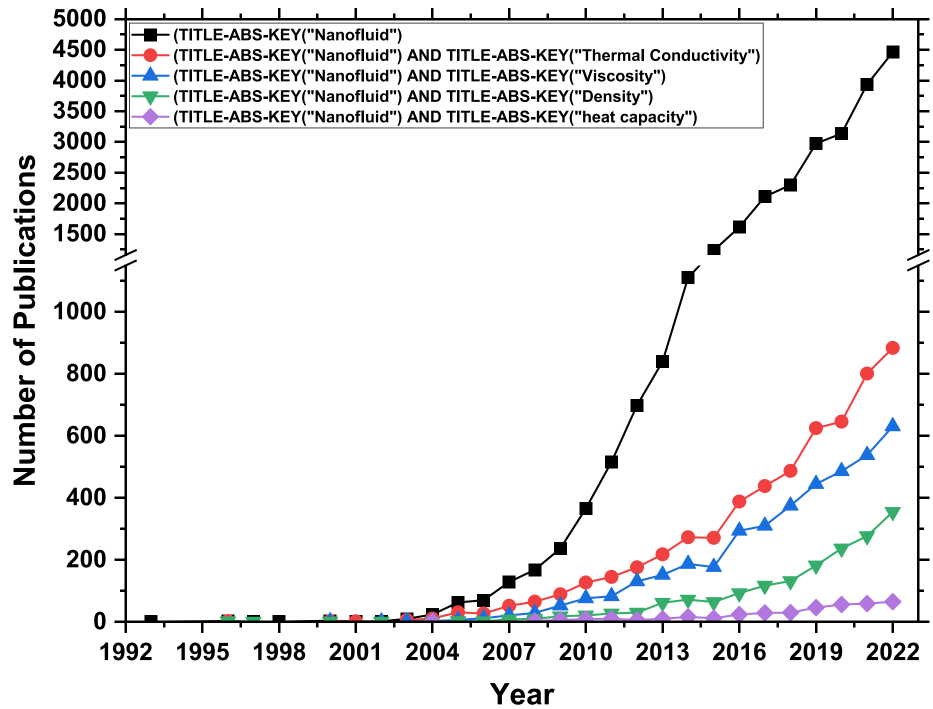

Fig. 16. Evolution of published studies over time investigating key thermophysical properties of nanofluids (Scopus database).

characteristics. The motion of nanoparticles creates more interactions between the particles and the fluid molecules, increasing the energy transfer and promoting thermal conductivity. Their viability as advanced heat transfer fluids could revolutionize cooling solutions for microelectronics, lasers, and data centres to manage escalating thermal loads [51]. Additionally, nanofluid-based technologies present opportunities to radically improve the efficiency of industrial heat exchangers and energy systems for significant energy savings and reduced emissions [52].

Several critical parameters exert significant influence on the thermal conductivity of nanofluids, encompassing base fluid properties, nanofluid temperature, fluid flow rate, nanoparticle concentration, Brownian motion of nanoparticles, and nanoparticle size. The choice of base fluid emerges as a pivotal determinant, showcasing a substantial impact on thermal conductivity. Distinct base fluids exhibit varying degrees of thermal conductivity enhancement, attributed to chemical interactions and inherent competence. Timofeeva et al. [53] conducted a study on the thermal conductivity of water-based and ethylene glycol/water-based (50:50) silicon carbide (SiC) nanofluids. The findings revealed that at the same particle concentrations and sizes, the addition of nanoparticles to ethylene glycol/water resulted in 4-5% higher thermal conductivity enhancements than in water, as illustrated in Fig. 17.

In navigating the intricate realm of coolants for various applications, there's a considerable body of research dedicated to the ethylene glycol as a base fluid, despite the fact that water exhibits nearly double the thermal conductivity. Water, a reliable and widespread coolant, undoubtedly carries its thermal weight, but possesses certain limitations, including a low boiling point and a high freezing point. In contrast, ethylene glycol, as a liquid coolant, offers a higher boiling point and a lower freezing point than water, making it a more suitable option for applications requiring a broader temperature range. This makes ethylene glycol better suited for applications needing to operate below water's freezing point or above its boiling point. The high boiling point allows ethylene glycol to remove more heat before turning into a gas, while the low freezing point prevents it from solidifying at low temperatures where water would freeze.

Particles loading is another important parameter that significantly

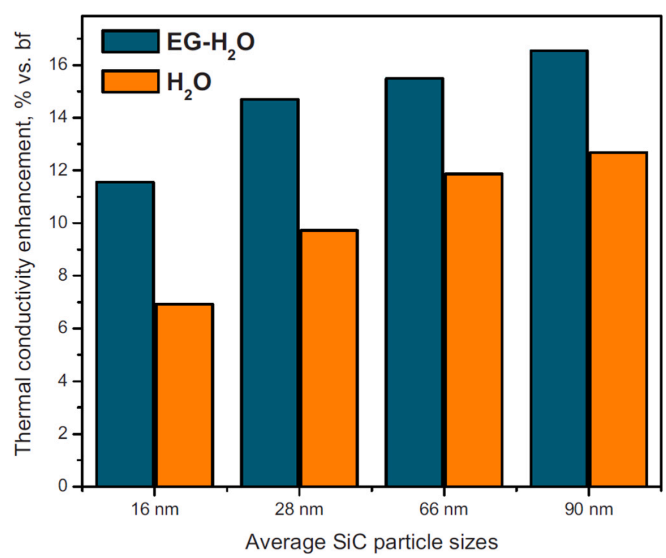

Fig. 17. Effect of base fluid on thermal conductivity of the nanofluid [53].

affects the thermal conductivity of the fluid. Increasing the particle loading means more number of nanoparticles, which in turn, enhances the thermal conductivity of the nanofluids. Moreover, as the nanoparticle concentration increases, there is greater molecular interaction, which further contributes to the improvement of thermal conductivity. The effect of concentration on nanofluid thermal conductivity has been presented in Fig. 18.

The impact of particle size on nanofluids' thermal conductivity is multifaceted, with conflicting findings. The study conducted by Ambreen and Kim [55] analyzed the impact of particle size on the thermal properties of nanofluids. It was found that while the thermal conductivity generally increases with decreasing particle size, the effect is not consistent across all nanofluids. Additionally, the magnitude of the enhancement also depends on the volume fraction and size distribution

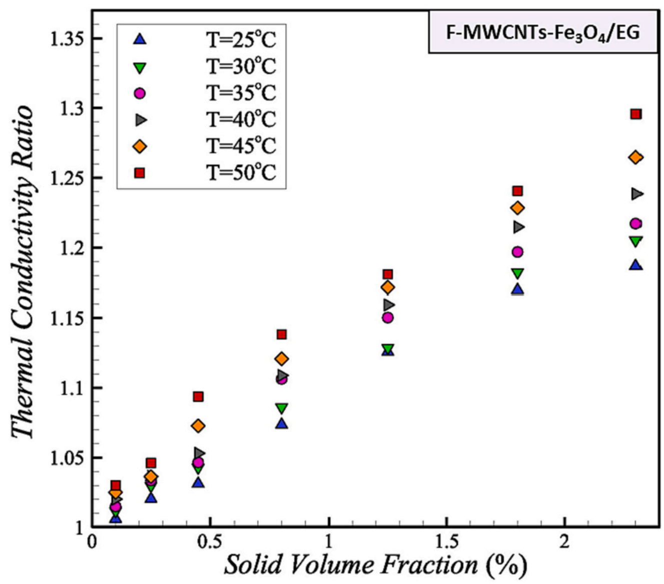

Fig. 18. Effect of nanoparticle concentration on thermal conductivity of the nanofluid (Harandi et al. [54]).

of the particles. A large part of the literature reported higher thermal conductivity with smaller particles and others with larger particles.

The cost also needs to be considered while selecting the particles for a particular application. Nanoparticles with sizes smaller than 50 nm tend to be relatively more expensive. Therefore, the cost implications should be carefully considered alongside other factors when deciding on the particle size for a given application. In this regard, Alirezaie et al. [56] conducted a study on ethylene glycol based nanofluids consisting various sized nanoparticles of iron (Fe) and magnesium oxide (MgO). The findings indicated that particles with smaller sizes delivered better thermal conductivity values with a penalty of higher production costs, resulting in a lower price-performance ratio. It was concluded that the trade-off between increased thermal conductivity and higher cost must be carefully considered when deciding which particle size to use in different applications. The effect of nanoparticle size on the thermal conductivity of a nanofluid is shown in Fig. 19.

The nanofluid has a higher effective thermal conductivity as a result of the increased nanoparticle mobility and interaction brought on by the temperature increase. This trend has been observed in a different type of nanofluids, including those containing metal or oxide nanoparticles suspended in water, oil, or other base fluids. The rate at which the thermal conductivity increases with temperature can depend on a number of factors like the morphological and thermal properties of the particles and thermal and rheological behaviour of fluid. Sundar et al. [57] investigated the influence of temperature on the thermal conductivity of Fe_3O_4/water + EG nanofluid was investigated. The researchers observed that as the temperature of the nanofluid increased, there was a corresponding enhancement in its thermal conductivity. Kole and Day [58] conducted a study on the thermal conductivity of lubricating oil-based copper oxide (CuO) nanofluid at various fluid temperatures. Their results indicated a significant augmentation of 10% and 12% in thermal conductivity at temperatures of 30 °C and 80 °C, respectively, specifically for a nanofluid with a volume fraction of 2.5%.

The thermal conductivity of certain nanofluids can exhibit a maximum value at a specific temperature, beyond which it starts to decline, a phenomenon referred to as thermal conductivity saturation. This behaviour is commonly attributed to nanoparticle aggregation at elevated temperatures, leading to a reduction in their effectiveness as thermal conductors.

The shape of nanoparticles also has a significant effect on thermophysical characteristics. Various nanoparticle shapes, such as spherical, triangular, rod-like, plate-like, and others, exhibit distinct thermal and transport properties [59], as shown in Fig. 20. Tailoring the nanoparticle shape can provide opportunities for optimizing nanofluid performance in various applications, including cooling systems, energy storage, and heat exchangers.

Nine et al. [60] investigated the thermal conductivity of Al_2O_3-MWCNT hybrid nanofluid prepared with different weight concentrations ranging from 1% to 6%. The findings showed that compared to those with spherical nanoparticles, nanofluids with cylindrical nanoparticles showed a larger improvement in thermal conductivity. Spherical nanoparticles are commonly used in many nanofluid applications due to their favourable thermophysical properties.

Timofeeva et al. [61] explored the influence of particle shape on the thermophysical properties of alumina nanofluids. The samples were prepared in an equal percentage of water and EG suspending alumina nanoparticles with different shapes, including bricks, platelets, blades, cylindrical, and plates-like structures, Fig. 21. The thermal conductivity measurements of the nanofluids revealed that particle shape

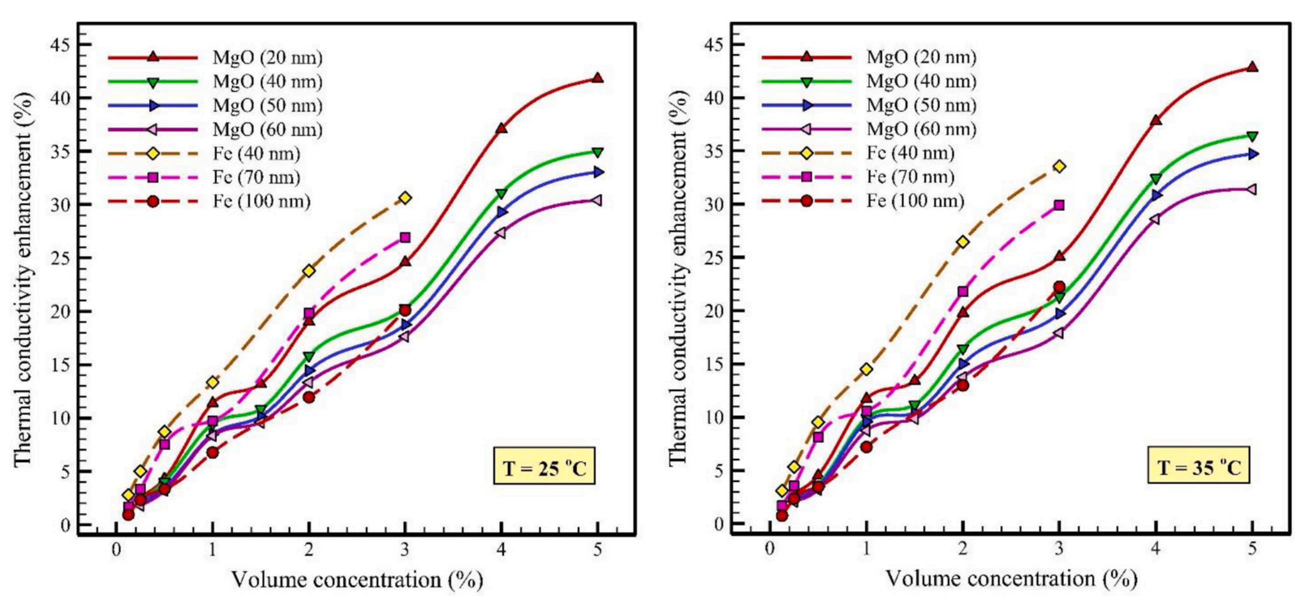

Fig. 19. Effect of nanoparticle size on thermal conductivity of nanofluid [56].

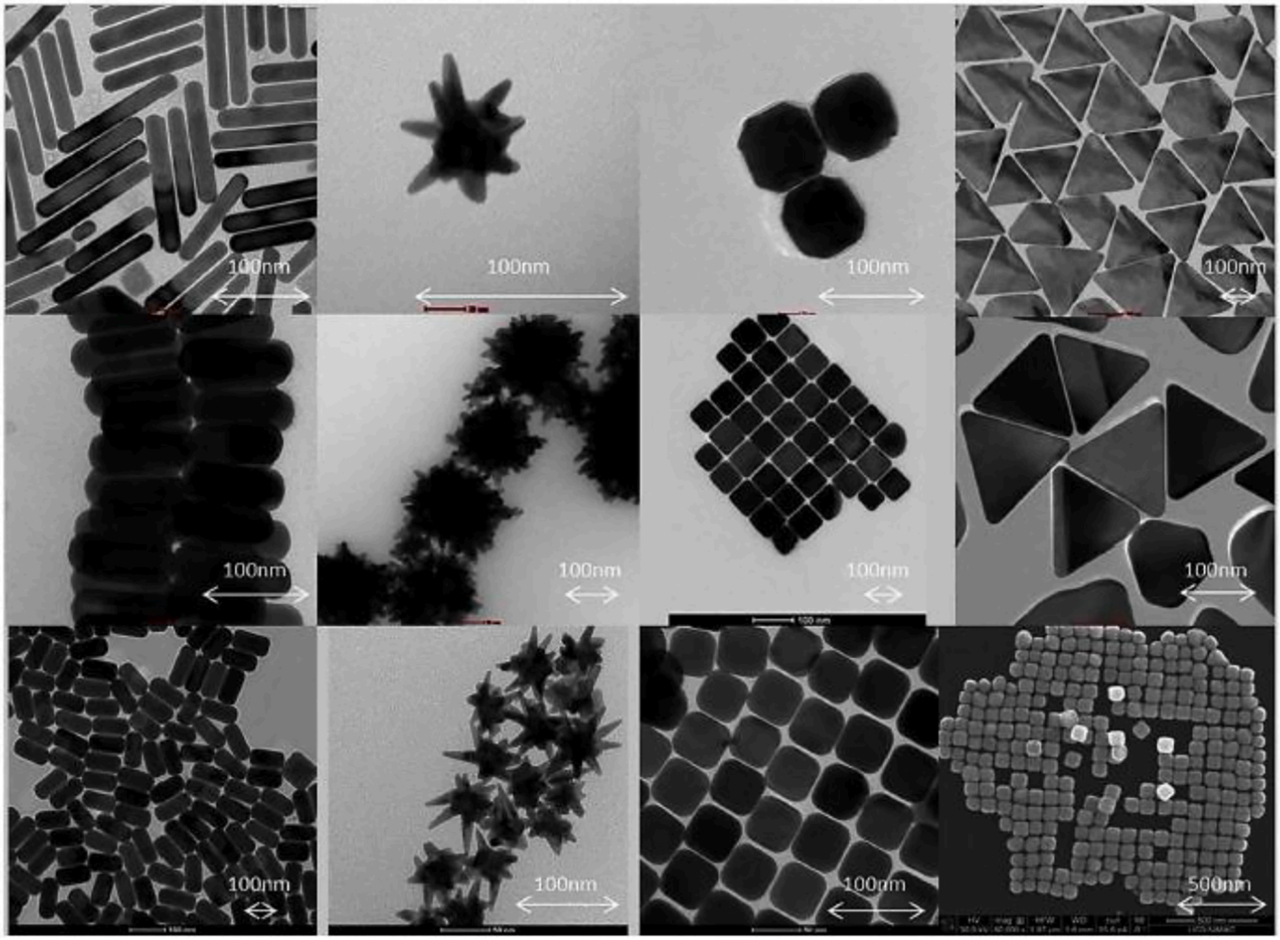

Fig. 20. Shapes of nanoparticles and shape factor value [59].

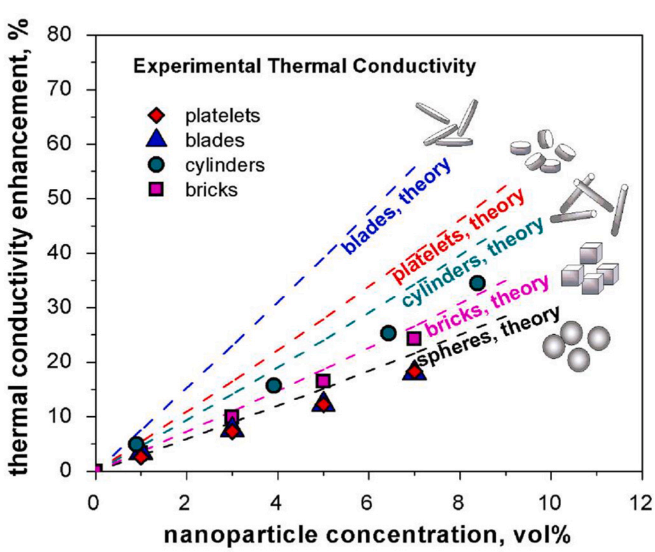

Fig. 21. Nanoparticle shape effect on thermal conductivity of nanofluids [61].

significantly affects the enhancement in thermal conductivity. The results showed that nanofluids containing blades-shaped nanoparticles exhibited the highest thermal conductivity enhancement compared to the others. The findings from this study highlight the importance of considering particle shape when selecting nanofluids for thermal systems.

Importantly, it has been observed in various studies that the observed thermal conductivity values from experimental studies have exhibited discrepancies when compared to the predicted values derived from conventional theoretical models [62–64]. The divergence between experimental and theoretical predictions underscores the complexity of thermal transport phenomena, urging researchers to reassess existing models and explore additional factors that may influence heat transfer. The realization that conventional theoretical frameworks may not fully capture the intricacies of the thermal behaviour in certain conditions has spurred a reevaluation of the governing principles. Researchers are scrutinizing factors such as nanoscale effects, interfacial interactions, and the impact of particle size distribution, recognizing that these intricacies may play pivotal roles in influencing thermal conductivity.

The comprehensive body of literature pertaining to various nanofluid types underscores a notable lack of uniformity in outcomes. This inconsistency is evident not only across distinct nanofluid categories but also within the same nanofluid composition. Establishing reliable and consistent values for thermal conductivity becomes a formidable task in light of these variations. Numerous factors contribute to this disparity, including diverse preparation techniques, stability of nanofluids, particle characteristics, properties of the base fluid, uncertainties in equipment, and the presence of measurement errors. Surfactants, pH levels, and Brownian motion introduce other variables that impact the results. These multifaceted influences collectively underscore the complexity inherent in obtaining accurate and consistent thermal conductivity data for nanofluids. Proposed models based on Brownian motion, liquid layering, ballistic phonon transport, and nanoparticle clustering aim to explain experimental observations but a unified theory remains elusive. As nanofluids bridge across disciplines of colloid science, materials engineering, physics, and nanotechnology, developing a universal model for thermal conductivity prediction remains an open quest in the field.

4.2.2. Viscosity of nanofluids

Viscosity plays a crucial role in the flow characteristics of fluids, which is a measure of a fluid's resistance to flow. It significantly impacts various aspects such as pumping power, pressure drop in laminar flow, and convective heat transfer. The practical utilization of nanofluids in thermal management systems relies on striking a balance between their high thermal conductivity and the low viscosity associated with factors such as nanoparticle type, loading, shape, size, and fluid temperature. The rheology of nanofluids is essential in understanding their flow behaviour and its impact on pressure drop in flow systems like heat exchangers [65]. Accurately determining the rheological behaviour involves examining the relationship between shear rate and shear stress, that is viscosity. Newtonian fluids demonstrate a direct and consistent correlation between shear stress and shear rate, exhibiting a constant apparent viscosity. In contrast, for non-Newtonian fluids shear stress and shear rate did not correlate linearly.

Studies on nanofluid viscosity reveal that these fluids can exhibit both Newtonian and non-Newtonian flow behaviour depending on various factors and conditions. Factors such as base fluid properties, nanoparticle concentration, temperature, shear stress, shear rate, as well as the type and size of nanoparticles, influence the rheological characteristics. These factors influenced the viscosity significantly.

- Size and shape of the nanoparticles: Smaller and more spherical nanoparticles tend to have a lower effect on the viscosity of the nanofluid compared to larger and more irregularly shaped nanoparticles.
- Concentration of the nanoparticles: As the concentration of nanoparticles increases, the viscosity of the nanofluid generally increases.
- Type of base fluid: Different types of base fluids can have different viscosities and can affect the overall viscosity of the nanofluid.
- Surface properties of the nanoparticles: The surface properties of the nanoparticles, such as their surface charge and surface roughness, can affect the way they interact with the base fluid and thus affect the viscosity of the nanofluid.
- Temperature: The viscosity of a nanofluid generally decreases with increasing temperature.
- Shear rate: The viscosity of a nanofluid can also be affected by the shear rate, or the rate at which the fluid is deformed due to an applied force. The viscosity of nanofluid tends to decrease with an increase in shear rate.
- Preparation method: The viscosity of nanofluids is not solely dictated by their composition but is also significantly influenced by the methods employed during the preparation process. Various preparation techniques such as laser ablation, vapour deposition, mechanical stirring, submerged arc method, and ultrasonication play a crucial role in shaping the rheological properties of nanofluids, thereby adding an additional layer of complexity to the understanding of their viscosity behaviour.

Li et al. [66] were among the pioneers in exploring the transport properties of nanofluids. Their investigation revealed that viscosity was influenced not only by volume concentration but also by the size of nanoparticles. The surge in research on convective heat transfer involving nanofluids prompted numerous studies focusing on viscosity. In the early stages, Pozhar [67] made theoretical and simulation efforts to predict the viscosity of nanofluids. Timofeeva et al. [61] studied the impact of nanoparticle shape on the viscosity of ethylene glycol/water based alumina nanofluids. It was observed that the rheological behaviour was significantly influenced by the shape and aspect ratio of the nanoparticles. Specifically, higher viscosity was observed for agglomerated and elongated particles at the same volume fraction, attributed to structural constraints on transitional and rotational Brownian motions. The study recommended the use of spherical particles or spheroids with lower aspect ratios. Additionally, the research demonstrated a notable 31% reduction in the viscosity of alumina nanofluids by adjusting the pH of the nanofluid suspension, attributed to the alteration of surface charge on nanoparticles, influencing particle-particle interactions and agglomeration dynamics. Jeong et al. [68] investigated the viscosity of ZnO nanofluids containing different nanoparticle shapes, including nearly rectangular and spherical particles, at various volumetric concentrations. They found that the viscosity significantly increased with increasing particle concentration, from 5.3% to 68.6% for the nearly rectangular particles and 5.9% to 59.0% for the spherical particles as the concentration varied from 0.5 vol% to 5.0 vol%. Notably, the viscosity of the nanofluid with the nearly rectangular shape particles was higher by 7.7% compared to the nanofluid with the spherical particles. To validate their findings, the experimental viscosity data was compared with predictions from multiple models. The Batchelor [69] and Brinkman [70] models were observed to underestimate the results, while the Timofeeva model tended to over-predict. In contrast, the Chen model [71], which considers particle aggregation, demonstrated favourable agreement with mean deviations falling within the range of 1.7–2.2%.

Zhou et al. [72] conducted a comprehensive experimental analysis of the viscosity of several common surfactant solutions under varying conditions. They found that the non-ionic surfactant PVP showed a rapid increase in viscosity at low concentrations, with the zero-shear viscosity at 4 wt% being about twice that of water. In contrast, the viscosity of the ionic surfactants SDS and SDBS did not increase substantially except at higher concentrations where larger micelles formed. The viscosity of all surfactant solutions decreased markedly with increasing temperature, especially for PVP where it dropped by 50% from 20 °C to 50 °C. At higher temperatures, the viscosity of PVP approached closer to that of the ionic surfactants and water. It was concluded that using PVP surfactant at higher temperatures results in more stable nanoparticle suspensions while also yielding lower fluid viscosity. Li et al. [73] investigated the viscosity of Cu-H_2O nanofluids, comparing formulations prepared with and without the dispersant SDBS. Their findings underscored temperature and SDBS concentration as pivotal factors influencing nanofluid viscosity. In contrast, the impact of Cu nanoparticle mass fraction was observed to be less prominent within the explored experimental range. Specifically, the apparent viscosity exhibited a decrease with rising temperature and a slight increase with higher SDBS dispersant concentrations. Moreover, viscosity remained largely unchanged with varying Cu mass fractions from 0.04% to 0.16%. At higher nanoparticle loadings beyond this range, viscosity would be expected to increase more substantially. Mahbubul et al. [74] noted a significant decrease in the viscosity of alumina-water nanofluid as the temperature increased from 10 °C to 50 °C. This phenomenon was attributed to the weakening of interparticle adhesion forces at elevated temperatures. Additionally, the researchers observed a reduction in nanofluid viscosity with longer ultrasonication duration during the preparation process. The decrease was particularly rapid during the initial hour of ultrasonication, slowing down with extended ultrasonication periods. Interestingly, at lower temperatures, a longer ultrasonication time was required to achieve the minimum viscosity level compared to higher temperatures. These viscosity reductions over ultrasonication duration were linked to improved nanoparticle dispersion and the breakdown of agglomerates, leading to a decrease in flow resistance. Tiwari et al. [75] studied the impact of different surfactants, sonication times, and temperatures on the viscosity of hybrid nanofluids made of CeO_2 and MWCNT nanoparticles dispersed in various base fluids like water, silicone oil, ethylene glycol, and Therminol VP-I. The findings revealed a nuanced impact of different surfactants, sonication times, and temperatures on nanofluid viscosity. It was noted that viscosity initially decreased with increasing sonication time, reaching an optimal duration that varied for each base fluid, followed by a gradual increase thereafter. Furthermore, viscosity exhibited a linear increase with higher nanoparticle concentrations but underwent a significant decrease as temperatures rose from 55 °C to 80 °C. Among the tested base fluids, the nanofluid formulated with deionized water demonstrated the least viscosity enhancement. The study also developed a correlation to predict the viscosity of the CeO_2-MWCNT/water hybrid nanofluid, considering temperature and nanoparticle concentration. The optimized nanofluid, composed of CeO_2-MWCNT in deionized water with the Benzalkonium chloride (BAC) surfactant, demonstrated long-term stability and minimal viscosity enhancement, making it suitable for heat transfer applications. He et al. [76] found that the TiO_2 nanofluids exhibited shear thinning behaviour, with the shear viscosity decreasing rapidly with increasing shear rate until reaching around 100 s^{-1}, above which the viscosity approached a constant value. The constant viscosity was found to increase with both increasing particle concentration and increasing particle size. At a given particle size, the increase of viscosity with concentration was highly non-linear, deviating significantly from the Einstein equation prediction for dilute suspensions. This indicates strong particle interactions in the nanofluids. Compared to particle size, particle concentration had a more significant effect on viscosity. The reasons for the non-linear concentration dependence were unclear, but the authors hypothesized that different nanofluid structures at varying concentrations could play a role. The authors recommend directing readers to recent comprehensive review studies that specifically delve into the intricate aspects of nanofluid viscosity [77–81]. These reviews offer an in-depth exploration and analysis of the latest findings and advancements in the field, providing valuable insights into the complex behaviour of nanofluids. Engaging with these studies is highly recommended for those seeking a thorough understanding of the current state of research on nanofluid viscosity.

The measurement of viscosity can be done through two approaches: experimental measurement and the use of classical or empirical models. Experimentally it is measured using the viscometers or rheometers which have been extensively reported in various studies [82–84]. Alternately, there are several models that have been developed to predict the viscosity of nanofluids there is currently no universally accepted model available that can precisely estimate the viscosity of nanofluids. Researchers commonly used the classical or empirical models based on their experimental data [85]. These models need to be verified as their accuracy can vary depending on the specific conditions of the nanofluid and the assumptions made in the model. The Einstein model [86], a seminal and pioneering approach, stands out as a classic in the field and holds the distinction of being extensively cited and modified. Despite its widespread use, the applicability of the Einstein model is constrained to low concentrations, specifically below 2 vol%. This limitation arises from the model's foundation on the assumption of hard-sphere particles, neglecting particle interactions. The expression for the Einstein model is given by Eq. (1).

$$\mu_{nf} = \left(1 + 2.5\varphi_{np}\right)\mu_{bf} \tag{1}$$

Here, μ_{nf} represents the viscosity predicted by the Einstein model, μ_{bf} is the viscosity of the base fluid, and φ denotes the volume fraction of particles. It's crucial to note that the model's accuracy diminishes at higher concentrations due to its inherent simplifications. Consequently, advancements and modifications have been made to address these limitations and enhance the model's applicability in a broader range of concentration regimes.

Following Einstein's pioneering work, subsequent researchers have endeavoured to refine and extend the model through various amendments. One notable enhancement was put forth by Brinkman in 1952 [70], expanding the applicability of the Einstein model to slightly higher volume fractions, up to 4%. Brinkman's modification is expressed through Eq. (2).

$$\mu_{nf} = \frac{\mu_{bf}}{\left(1 - \varphi_{np}\right)^{2.5}} \tag{2}$$

Taking into account the Brownian motion within an isotropic suspension of rigid spherical particles and recognizing the impact of particle interactions, Batchelor in 1967 [69] proposed a model that goes beyond the simplifications of earlier formulations, Eq. (3).

$$\mu_{nf} = \left(1 + 2.5\varphi_{np} + 6.5{\varphi_{np}}^2\right)\mu_{bf} \tag{3}$$

In addition to the aforementioned correlations, several models have been proposed that diverge from the approach of enhancing the Einstein model. These alternative models employ different methodologies or take into account additional influencing factors [87–89]. Each model brings its unique strengths and applicability, addressing specific challenges or phenomena. The emergence of nanofluids has led to the development of numerous empirical models also, often represented as simple mathematical correlations derived from fitting experimental data. A current trend gaining significant attention involves utilizing artificial intelligence such as artificial neural networks for constructing models that predict various properties. In light of these advancements, the authors propose an integration of the latest tools to formulate a comprehensive model capable of accommodating diverse nanofluids. The development of such a general model is envisioned as a substantial contribution to the field, offering a valuable tool for predicting viscosity across a broad spectrum of nanofluid compositions and applications. This pursuit aligns with the evolving methodologies in nanofluid research, paving the way for enhanced predictive capabilities and insights.

4.2.3. Density

The density of nanofluids plays a significant role in influencing various heat-transferring properties, including the pumping power,

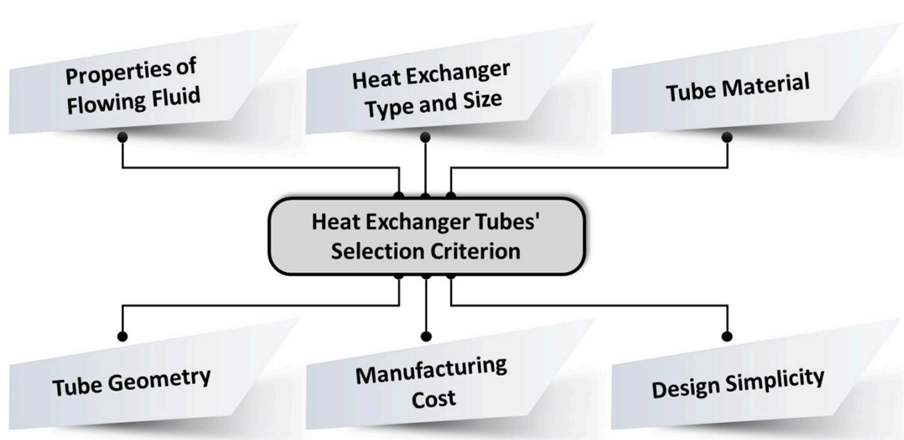

Fig. 22. The selection criterion of heat exchanger tubes.

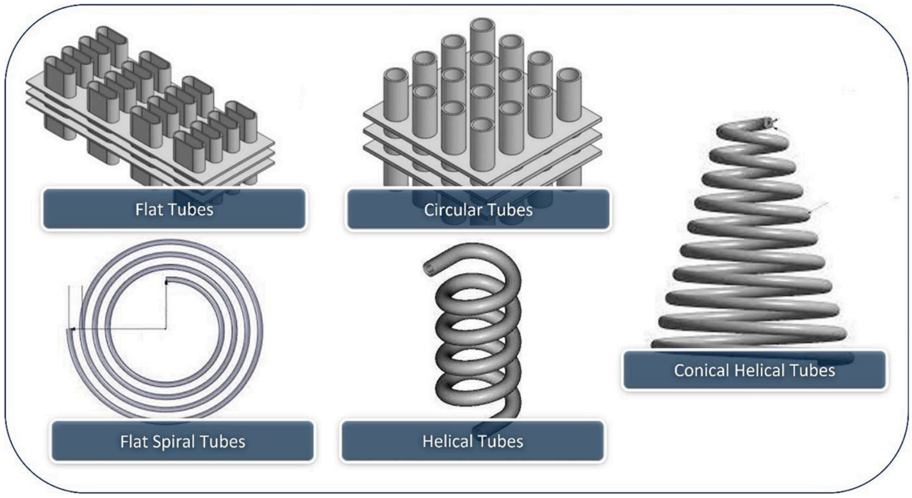

Fig. 23. Geometries of heat exchanger tubes.

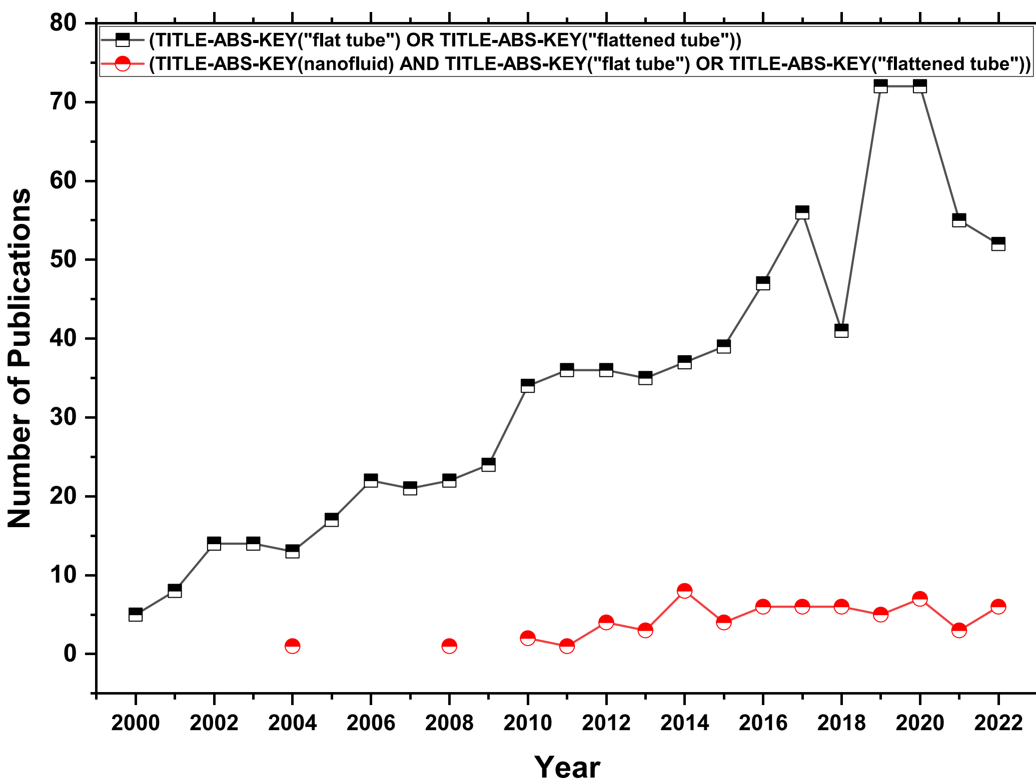

Fig. 24. Number of publications on flat tube heat exchangers from 2000 to 2022 (Scopus database).

frictional factor, Reynolds number, and stability. It is considered one of the most crucial thermophysical properties in this regard. The density of a nanofluid depends on the density of the base fluid and the concentration and size of the suspended nanoparticles. The model developed by Pak and Cho [90] is most commonly employed to estimate the value of density, Eq. (4). This model considered the effect of particle concentration, density, and the density of basefluid. The model has been employed in numerous investigations and found to be effective at predicting values within acceptable error bounds.

$$\rho_{nf} = \varphi_{np}\rho_{np} + \left(1 - \varphi_{np}\right)\rho_{bf} \tag{4}$$

Vajjha et al. [91] conducted a study to investigate the density of different nanofluids, including alumina (Al_2O_3), zinc oxide (ZnO), and antimony-tin oxide (Sb_2O_5:SnO_2) in a water:EG (60:40) base fluid. They looked at how temperature change affected the density of prepared samples using an Anton Paar digital density meter with a temperature control bath. The outcomes demonstrated good agreement with the Pak and Cho model. In a study conducted by Ganeshkumar et al. [92], the impact of adding MWCNT in a W/EG basefluid on density was investigated by adopting the flask method and the results were compared with Eq. (1). The results indicated that the nanofluid density rose proportionally with the volume concentration of MWCNT. It was observed that the experimentally measured data and the values predicted by the equation exhibited a good agreement with the values predicted using the equation, particularly at lower particle concentrations. However, for nanofluid containing 1.5 wt% MWCNT, the density was overpredicted by the equation. The density of nanofluids generally increases with increasing nanoparticle concentration, although the specific effect can vary depending on the type of nanoparticles and the base fluid. Nanofluids exhibit anomalous density behaviour, where the addition of nanoparticles can either increase or decrease the fluid's density compared to the base fluid. This characteristic opens up possibilities for applications in heat transfer and cooling systems, where higher density nanofluids can improve efficiency, as well as in buoyancy-related industries, where lower density nanofluids can enhance vessel performance. The study of nanofluids' density behaviour remains a vibrant research field with the potential to revolutionize diverse industries and lead to disruptive technological advancements.

Abbasi et al. [93] conducted molecular dynamics simulations to investigate how particle shape and the type of base fluid impact the density of nanofluids, taking into consideration the formation of an interfacial nanolayer around nanoparticles. Their findings revealed that liquid argon formed a thicker nanolayer around silver nanoparticles (1.3 nm) compared to water (0.9 nm), attributing this difference to stronger silver-argon interactions and increased fluctuation freedom of argon atoms. Analysis of various nanoparticle shapes indicated that planar particles exhibited the highest nanolayer density due to their expansive surface area, while nanorods with higher aspect ratios also contributed to increased nanolayer density. Furthermore, the density of nanofluids containing planar and spherical nanoparticles was observed to decrease with an increase in particle diameter. Utilizing an innovative ternary mixture model that accounted for the nanolayer led to significantly improved predictions of nanofluid density compared to traditional binary models, particularly for non-spherical particles. These results offer valuable insights into how the choice of base fluid and the design of nanoparticle shapes can be leveraged to fine-tune nanofluid density through interfacial effects. Karimi and Yousefi [94] devised a sophisticated hybrid model that integrates a back-propagation neural network (BPN) with a genetic algorithm (GA) to predict the density of four distinct nanofluids. This prediction is contingent on variables such as temperature, nanoparticle volume fraction, base fluid density, and the density ratio between the base fluid and nanoparticles. The model underwent training using experimental density data derived from nanofluids containing ZnO, Al_2O_3, Sb_2O_5/SnO_2, and CuO nanoparticles suspended in water/ethylene glycol mixtures within the temperature range of 273-323 K, with volume fractions reaching up to 10%. During testing, the hybrid model exhibited remarkable accuracy, showcasing an impressive mean absolute relative error of merely 0.13% and a correlation coefficient of 0.999 when compared to experimental values. Comparative assessments against radial base function neural network and Pak-Cho models underscored the superiority of the BPN-GA approach, yielding error reductions of 64% and 95%, respectively. This substantiated the higher precision of the BPN-GA model across all studied nanofluids. The researchers concluded that this hybrid model reliably predicts nanofluid density, effectively capturing the impact of temperature fluctuations and nanoparticle loading.

It is worth noting that there is limited data available in the literature regarding the measurement of nanofluid density, particularly for base

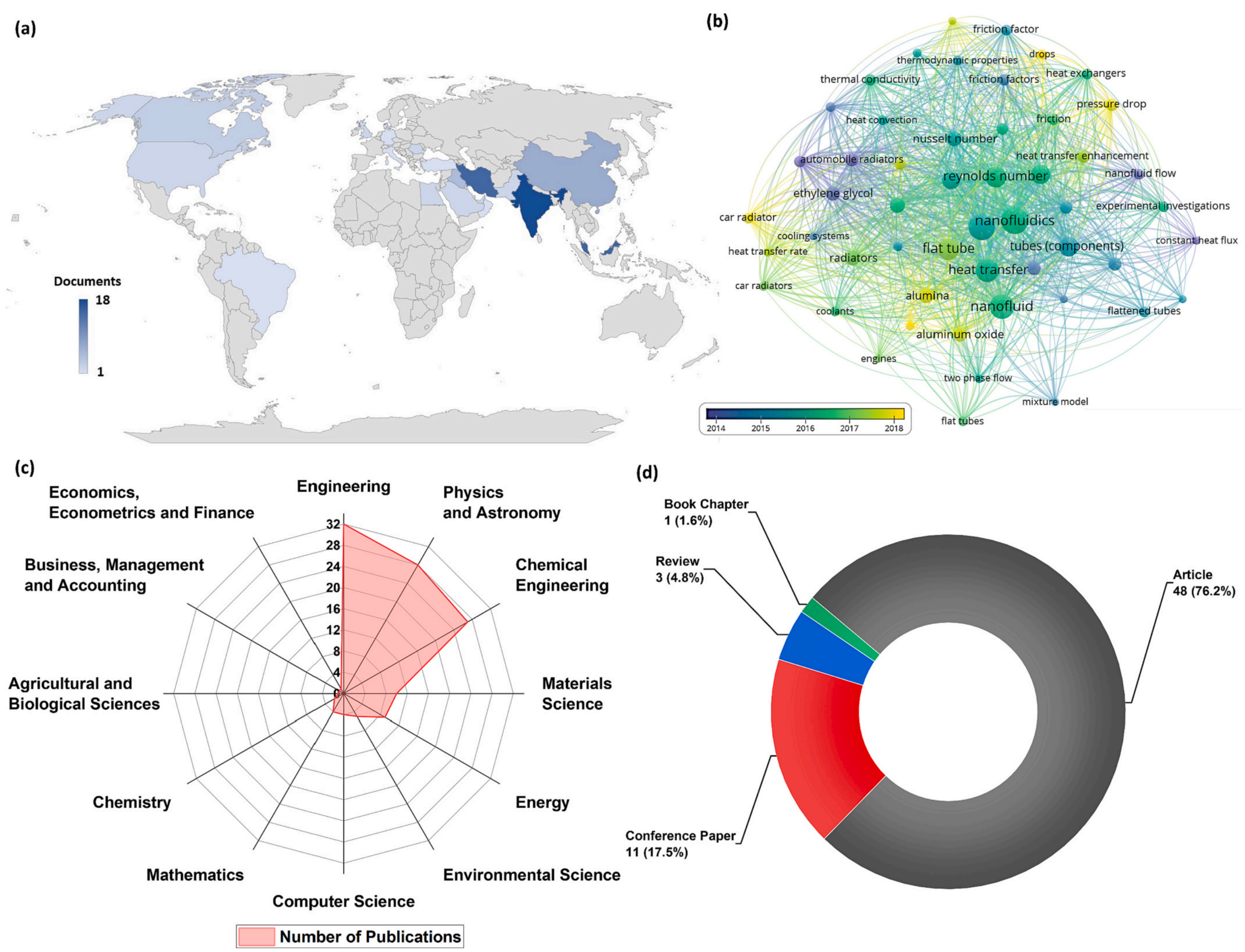

Fig. 25. Studies published on nanofluid utilization in flat tube heat exchangers (a) country wise, (b) keyword network visualization, (c) subject/areas, and (d) document type.

fluids containing ethylene glycol/water. Measuring the density of nanofluids poses challenges due to the influence of nanoparticles on the fluid's viscosity, which can hinder the accuracy of traditional measurement methods like hydrometers and pycnometers that rely on viscosity, while also affecting surface tension and other physical properties. Additionally, precise control of temperature and pressure is crucial when measuring nanofluid density, considering their potential influence, while the accuracy of density models could also be influenced by nanoparticle size, shape, concentration, base fluid type, and temperature. Nevertheless, to undertake a thorough examination and analysis of the most recent discoveries and progressions in the field, offering valuable perspectives on the influence of diverse factors on the density of nanofluids, the authors seek to bring the readers' attention to the recent review studies that specifically concentrate on the density of nanofluids [95–97].

4.2.4. Heat capacity

The specific heat (C_p) is also a significant property that greatly influences the heat transfer rate of nanofluids. The heat capacity of a nanofluid can be determined through calorimetry techniques, such as differential scanning calorimetry (DSC), by measuring the heat required to increase the nanofluid's temperature by a specific amount. Two specific heat models have been used most commonly in studies to determine the C_p of nanofluids. The first model, proposed by Pak and Cho [90], is based on the volume concentration of nanoparticles, developed considering the formula for liquid-particle mixtures, Eq. (5). The second model, presented by Xuan and Roetzel [4], incorporates a heat equilibrium mechanism developed sometime after the first one, represented with Eq. (6). The widely used model of Xuan and Roetzel [4] considers both the heat capacity of individual particles and the heat capacity of particles in the fluid and has been found to be generally accurate for a wide range of nanofluids. Zhou and Ni [98] examined the specific heat of alumina-aqua nanofluid as a function of particle volume concentration using a DSC. Their experimental findings demonstrated a satisfactory agreement with the predicted values obtained from the Xuan model. However, like other models, these models have their limitations and may not consistently deliver precise predictions for all nanofluids. It is crucial to diligently validate the model using experimental data to ensure accuracy and to recognize any potential limitations or uncertainties that may arise. The interaction between nanoparticles and the base fluid plays a crucial role in determining the impact of nanoparticles on the heat capacity of nanofluids, as strong attraction results in effective dispersion and a larger influence, while nanoparticle aggregation or settling leads to a diminished effect on heat capacity.

$$C_{p,nf} = \varphi_{np} C_{p,np} + (1 - \varphi_{np}) C_{p,bf} \tag{5}$$

$$C_{p,nf} = \left(\frac{\varphi_{np}\rho_{np}C_{p,np} + (1 - \varphi_{np})\rho_{bf}C_{p,bf}}{\rho_{nf}} \right) \tag{6}$$

As anticipated the factors, such as the base fluid, the type and size of the nanoparticles, morphology, and concentration of the nanoparticles have a notable effect on the heat capacity of nanofluid. The impact of nanoscale particles on the heat capacity of nanofluids remains inconclusive, with some studies indicating enhancement, reduction, or no change, posing challenges in accurately predicting and designing systems utilizing these fluids. The study conducted by Yarmand et al. [99] on ethylene glycol based activated carbon-graphene nanofluid observed an enhancement in heat capacity with temperature and particle concentration. Robertis et al. [100] employed the modulated temperature differential scanning calorimetry (MTDSC) technique to determine the specific heat of nanofluids. The obtained results demonstrated a strong agreement between the measured specific heat values and the tabulated values of the individual components of the nanofluid (copper and ethylene glycol). Interestingly, the inclusion of copper nanoparticles in the base fluid was found to influence the crystallization and melting processes, resulting in a reduction of the specific heat values of the nanofluids across the entire temperature range investigated. However, the collaborative efforts of different researchers in publishing review studies on the specific heat of nanofluids provide valuable resources for readers seeking a thorough understanding of this particular property [101–104].

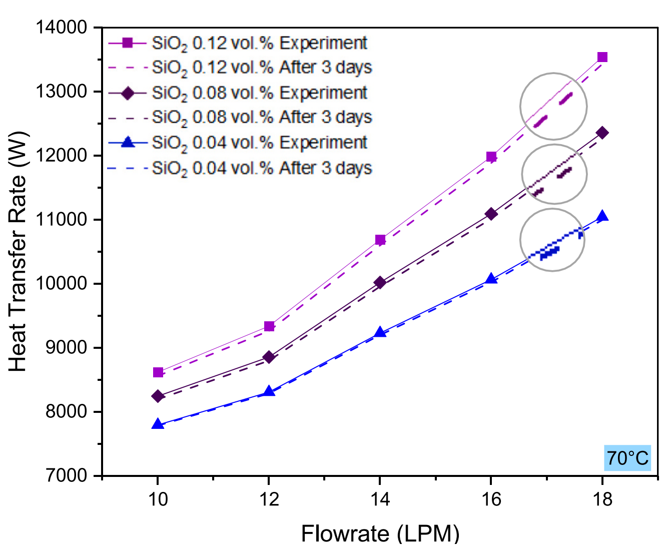

Fig. 26. Heat transfer rate repeatability assessments three days after the initial testing [106].

5. Promise of nanofluids in heat exchanger

Owing to the vast thermal transportation potential of nanofluids, they have been tested for several potential applications. Researchers have extensively explored their potential in renewable energy applications and heat exchangers. In the quest for optimal performance, nanofluids have been tested in different types of heat exchanger tubes. These include flat tube heat exchangers, plate-type heat exchangers, annular tube heat exchangers, and various other configurations. These diverse configurations have been investigated to harness the enhanced heat transfer properties offered by nanofluids.

5.1. Heat exchangers and heat exchangers' tubes

Heat exchangers exhibit a broad spectrum of classifications, primarily categorized by the direction of working fluids and the mechanism governing heat transfer. In terms of fluid direction, heat exchangers are grouped into parallel flow, where fluids move in the same direction; counterflow, featuring opposite fluid movement; and cross-flow configurations. Each design offers distinct advantages depending on the thermal system's requirements. Simultaneously, heat exchangers are classified based on their heat transfer mechanism, with regenerative models storing and recovering heat, recuperative units transferring heat directly between fluids, and evaporative systems utilizing phase change for heat transfer. This dual classification provides a comprehensive understanding of heat exchanger diversity.

Beyond fluid direction and heat transfer mechanisms, heat exchangers can be further differentiated into finned and un-finned types, showcasing the impact of fin structures on heat transfer efficiency. Specific functions also give rise to distinct heat exchanger categories, such as condensers, evaporators, and boilers, each serving unique roles within thermal systems. Flow patterns introduce the distinction between single-pass and multi-pass heat exchangers, while structural designs include variations like shell and tube configurations. This multifaceted classification system enables engineers to select the most fitting heat

Table 1
Major findings of some of the recent studies on nanofluid testing in flat tube heat exchangers.

Reference	Study type	Nanoparticles	Particle Size	Basefluid	Concentration Tested	Tube Geometry	Tube material / Roughness	Major Findings
Vajjha et al. [109]	Numerical	Al_2O_3 CuO	44 nm –	Ethylene glycol and water mixture	0-10 vol% Al_2O_3, 0-6 vol% CuO	Automotive radiator flat tube	–	At a Reynolds number of 2000 and with a 10 vol% concentration of Al2O3 nanoparticles, there was a notable 94% improvement in heat transfer rate compared to the base fluid. Furthermore, a 6 vol% CuO nanofluid composition exhibited an 89% increase in heat transfer rate when compared to the base fluid.
Elsebay et al. [110]	Numerical	Al_2O_3 and CuO	–	Water	1%, 3%, 5%, and 7 vol%	Flat tube (height 3 mm, width 9 mm, length 345 mm)	–	The heat transfer coefficient experienced notable improvement, reaching 45% for Al_2O_3 nanofluid and 38% for CuO nanofluid. It was revealed that utilizing Al_2O_3 nanofluid can reduce radiator tube length by up to 11.7% and CuO nanofluid can reduce tube length by up to 9.8%.
Yahya and Saghir [111]	Numerical	Al_2O_3	–	Water	1%, 2 vol%	Flat tube with aspect ratios from 0.15 to 1	Copper	Flat tube with aspect ratio of 0.15 showed the best heat transfer enhancement compared to circular tube. Addition of porous insert further improved heat transfer. Nanofluids with 1% and 2% Al_2O_3 by volume enhanced heat transfer by about 5% and 12% respectively compared to basefluid.
Erdogan et al. [112]	Experimental	Al_2O_3	13 nm (average)	Ethylene glycol: Water (50:50)	0.5 vol%	Automobile radiator with louvred fins; hydraulic diameter 1.923 mm	Aluminum	The utilization of a 0.5% concentration of Al_2O_3 nanofluid resulted in a maximum 9.5% increase in heat transfer compared to the base fluid. The nanofluid demonstrated an improvement in effectiveness by up to 10.4%, and the performance index saw an increase of up to 19.4%. Moreover, there was a 9.7% rise in entropy generation change on the coolant side with nanofluid, whereas it decreased on the air side. Notably, irreversibility was reduced by up to 68% when using nanofluid compared to the base fluid.
Ahmed et al. [113]	Experimental	TiO_2	Average size of 44 nm, ranging from 30 to 60 nm	Deionized water	0.1%, 0.2%, 0.3 vol%	Flat Tube (18 × 19.6 × 295 mm); Hydraulic diameter 3.35 mm	Aluminum	The friction factor diminishes with rising Reynolds number and volume concentration, while the effectiveness of the radiator is heightened by 47% with 0.2% TiO_2 nanofluid compared to concentrations of 0.1%, 0.3%, and pure water.
Sundari et al. [114]	Experimental	Al_2O_3	$<$40 nm	Glycerin-based commercial engine coolant (G13)	0.1%, 0.2%, 0.3 vol%	Flat Tube	–	A 54.56% improvement in heat transfer is noted with a 0.3% volume concentration under constant heat flux. Additionally, an effectiveness of 0.9 is attained with a 0.3% concentration at Reynolds number (*Re*) of 1500. The heat transfer coefficient rises with escalating Reynolds number and nanoparticle concentration, showcasing the potential of glycerin-based nanofluid to enhance automobile radiator performance.
Said et al. [115]	Experimental	Al_2O_3 TiO_2	10 nm 5 nm	Ethylene glycol: Water (50:50)	0.05% and 0.3 vol%	Flat Tube – Toyota Corolla 2006 model radiator with tube width 35 mm, tube height 1 mm, 36 tubes	Aluminum	Al_2O_3 at a 0.3 vol% concentration achieves a maximum heat transfer enhancement of 24.21%, while the friction factor decreases with higher volume fractions. Notably, alumina-based nanofluids demonstrate superior performance compared to titanium-based nanofluids.
Bejjam et al. [116]	Numerical	Al_2O_3	–	Ethylene glycol: Water (50:50)	0.05%, 0.1%, 0.2 vol%	Flat Tube – Tube length 31.5 cm, thickness 0.5 cm, height 3 cm, width 20 cm	Aluminum	At a fixed flow rate, coolant outlet temperature decreases with increasing particle concentration. In comparison to pure water, a nanofluid-based radiator exhibits a 10.64% increase in Nusselt

(*continued on next page*)

Table 1 (*continued*)

Reference	Study type	Nanoparticles	Particle Size	Basefluid	Concentration Tested	Tube Geometry	Tube material / Roughness	Major Findings
								number and a 3.82% increase in the heat transfer coefficient
Jadar et al. [117]	Experimental	*f*-MWCNT	Outer diameter - 20 nm, Inner diameter - 16 nm, Length - 20 µm	Deionized water	0.1 wt%	Flat Tube	Aluminum	A remarkable heat transfer enhancement of up to 45% was noticed with f-MWCNT nanofluid in comparison to deionized water. Furthermore, the radiator outlet temperature is consistently lower for the nanofluid than for water across all flow rates
Selvam et al. [118]	Experimental	Graphene nanoplatelets	Thickness - 5–10 nm, Diameter - 15 µm	Ethylene glycol: Water (30:70)	0.1–0.5 vol%	Flat Tube	Aluminum	A maximum thermal conductivity enhancement of 29% was achieved with a 0.5 vol% loading of GnP. Additionally, a 51% improvement in convective heat transfer coefficient (CHTC) was observed with 0.5 vol% GnP at a 45 °C inlet temperature. The CHTC increased with nanoplatelet loading, inlet temperature, and mass flow rate, while pressure drop increased with nanoplatelets loading but decreased at higher inlet temperatures.
Goudarzi and Jamali [119]	Experimental	Al_2O_3	40 nm	Ethylene glycol	0.08%, 0.5%, 1 vol%	Flat Tube (tube dimensions 24 × 1.5 mm) – coil wire inserts	Aluminum tube and copper coil	The concurrent utilization of coils and a 0.08% nanofluid resulted in a 5% higher enhancement compared to the use of coils alone. The Nusselt number exhibited an increase with rising Al_2O_3 concentration and cooling fan speed, the presence of nanoparticles led to a higher friction factor for nanofluids compared to the base fluid.
Rai et al. [120]	Experimental	MgO	–	Ethylene glycol: Water (60:40)	0.1–0.2 vol%	Flat Tube	Aluminum	The percentage increase in heat transfer rate within the tested concentration range ranged from 5.59% to 29.83%. The heat transfer rate demonstrated an upward trend with increasing mass flow rate of the nanofluid, reaching a maximum of 1035.04 J/s at an inlet temperature of 55 °C and a nanoparticle concentration of 0.2%.
Li et al. [121]	Experimental	SiC MWCNT	40 nm 20 nm	Ethylene glycol	0.04–0.4 vol%	Flat Tube (hydraulic diameter 3.63 mm)	Aluminum	A substantial enhancement in thermal conductivity, reaching up to 32.01%, was observed with a 0.4 vol% SiC-MWCNTs nanofluid. These nanofluids exhibited Newtonian behaviour, with viscosity increasing with nanoparticle loading but decreasing with temperature; furthermore, the convective heat transfer coefficient was 26% higher for the 0.4 vol% nanofluid compared to pure ethylene glycol.
Choi et al. [122]	Experimental / Theoretical	Al_2O_3	40-50 nm	Ethylene glycol: Water (1:1)	1.43 vol%	Round Tube hydraulic diameter 3 mm)	Stainless Steel	The radiator's heat transfer rate demonstrated improvements of up to 6.9% experimentally and 5.6% theoretically when utilizing nanofluid under a fixed Reynolds number. Remarkably, the nanofluid exhibited long-term suspension stability, persisting for over 7 months.
Soylu et al. [123]	Experimental / Theoretical	TiO_2 doped with Ag and Cu	~10 nm	Ethylene glycol: Water (50:50)	0.3–2 vol%	Flat Tube (thickness: 0.0002 m; length: 0.380 m; width: 0.018 m)	Aluminum	The highest observed increase in the overall heat transfer coefficient was 11.094%, achieved with 0.3% Ag-doped TiO_2 at a 2% concentration. The heat transfer performance exhibited a positive correlation with the level of Ag doping and concentration, while Cu doping did not enhance heat transfer properties compared to pure TiO_2.
Safikhani et al. [124]	Numerical	Al_2O_3/water	20–100 nm	Water	0–5 vol%	Flat Tube (same perimeter but different internal height 2 mm to 10 mm)	–	CFD data and GMDH neural networks were employed to model the heat transfer coefficient and pressure drop, and multi-objective optimization

(*continued on next page*)

Table 1 (*continued*)

Reference	Study type	Nanoparticles	Particle Size	Basefluid	Concentration Tested	Tube Geometry	Tube material / Roughness	Major Findings
								was conducted using the NSGA-II genetic algorithm. The utilization of nanofluid resulted in a reported increase in heat transfer.
Safikhani et al. [125]	Numerical	Al_2O_3/water	40 nm	Water	0–3 vol%	Flat tubes fitted with twisted tapes	–	Greater heat transfer enhancement was observed with the use of twisted tapes compared to both nanofluids and flat tubes. The simultaneous utilization of nanofluids, flat tubes, and twisted tapes resulted in an average heat transfer increase of 50%.
Ramalingam et al. [126]	Experimental	Al_2O_3 doped with un-milled silicon carbide (SiC_{UM}), and milled silicon carbide (SiC_M)	SiC_{UM} - 110 nm, SiC_M - 24 nm	Ethylene glycol: Water (60:40, 50:50, 60:40)	0.4% and 0.8 vol %	Flat Tube	galvanized metallic, copper. aluminum	A maximum enhancement of 28.34% in overall thermal performance was achieved with the utilization of 0.8% Al_2O_3/SiC_M. The improvement in heat transfer was attributed to the milling process, which reduced the size of SiC nanoparticles, with the nanofluid exhibiting the highest thermal conductivity at 0.8% Al_2O_3/SiC_M; however, higher heat loss was observed for the milled nanofluid due to changes in nanoparticle morphology.
Guo et al. [127]	Experimental	Al_2O_3	~10 nm	Deionized water	0.1%, 0.2%, 0.5 vol%	Multichannel-flat aluminum tube	Aluminum	At constant Reynolds number, heat transfer coefficient increased with nanoparticle volume concentration. In the entrance region, nanofluids showed 10-20% higher heat transfer than predictions. At Re = 1731, 0.5% Al_2O_3 nanofluid had 11.1% higher heat transfer coefficient at entrance. Pressure drop and friction factor increased slightly (4.4% for 0.5% Al_2O_3) with nanoparticle addition.
Sharma et al. [128]	Numerical	CuO	20 nm	Water	0–0.5 vol%	Flat Tube	–	The heat transfer coefficient demonstrated an increase with both nanoparticle concentration and temperature, reaching a 14% improvement over the base fluid at 0.5% volumetric concentration and 50 °C. On the other hand, pressure drop exhibited a significant increase with nanoparticle concentration, being 34.78% higher, while the friction factor increased with nanoparticle concentration but decreased with increasing Reynolds number and temperature.
Alirezaie et al. [129]	Experimental / analysis study	MWCNT/water Ag/water MgO/water DWCNT/water	–	Water	0–1 vol%	heat exchanger analysis	–	The MWCNT-water nanofluid exhibited the highest thermal conductivity enhancement, but its efficiency, as per the Mouromtseff criterion, was <1, suggesting increased energy consumption. The MgO-water nanofluid, on the other hand, demonstrated the best price-performance ratio, achieving a maximum efficiency of 15% and the highest efficiency-price index, as revealed by economic analysis, indicating potential justification for use in high-tech devices like electronics cooling, while most applications may not justify the high cost of nanofluids.
Sun and Liu [130]	Experimental	CuO; Al_2O_3	40 nm	Deionized water	0.1–0.5 wt%	CPU liquid cooling radiator	–	Cu-water nanofluids outperformed Al_2O_3-water nanofluids in terms of cooling performance, exhibiting a 1.1-2 times enhancement in heat transfer coefficient compared to water, while Al2O3-water nanofluids showed a 1.1-1.6 times

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Table 1 (*continued*)

Reference	Study type	Nanoparticles	Particle Size	Basefluid	Concentration Tested	Tube Geometry	Tube material / Roughness	Major Findings
								improvement. Despite an increase in friction factor with nanoparticle concentration, the thermal performance coefficient analysis indicated that the heat transfer enhancement was more significant than the increase in friction factor for both nanofluids within the specified Reynolds number range.
Oliveira et al. [131]	Experimental	MWCNT	–	Distilled water	0.05–0.16 wt%	Flat Tube (Tube dimensions width 13 mm; height 3 mm)	Aluminum	Contrarily, the results were not in favour of nanofluids, as the heat transfer rate exhibited a 3-17% reduction compared to distilled water across all test conditions. Furthermore, the reduction in heat transfer rate became more pronounced with increasing nanoparticle concentration, although the effect was less notable at higher temperatures
Abdolbaqi et al. [132]	Experimental	TiO_2	50 nm	BioGlycol and Water (20:80)	0.5–2 vol%	Flat tube with an inner hydraulic diameter of 12.5 mm and length of 1500 mm	Aluminum	The Nusselt number exhibited a 28.2% increase for nanofluids at a 1 vol% concentration compared to the base fluid. However, at concentrations above 1 vol% and a temperature of 30 °C, the Nusselt number decreased, becoming 3% lower than the base fluid at 2 vol%. The friction factor was 6.1% and 14.3% higher than the base fluid at 1 vol% and 2 vol% concentrations, respectively.
Kumar et al. [133]	Numerical	CuO Al_2O_3 ZnO	60 nm 20 nm 35 nm	Ethylene glycol: Water (60:40)	0.05–5 vol%	Automotive radiator with 17 parallel tubes of 15 mm radius and 54 louvred fins attached to tubes	Steel	The heat transfer coefficient exhibited an asymptotic increase with nanoparticle concentration, reaching up to 102.4% enhancement for CuO at 5% concentration. Both the heat transfer coefficient and Nusselt number displayed a linear increase with Reynolds number, correlations developed for Nusselt number and heat transfer coefficient predictions showed average deviations of 8.0% and 6.9%, respectively.
Zhao et al. [134]	Numerical	Al_2O_3	20-100 nm	Water	1–6 vol%	Flat tube with height of 0.006 m, width of 0.01228 m, length of 0.5 m, and hydraulic diameter of 0.0084 m	–	Increases in both heat transfer coefficient and pressure drop were observed with higher nanoparticle concentration and smaller nanoparticle sizes, with more pronounced enhancements at lower Reynolds numbers and higher temperatures. While tube flattening significantly improved heat transfer and pressure drop, nanoparticle concentration had a limited effect on the relative performance between flat and circular tubes, resulting in a maximum heat transfer coefficient ratio of 1.236 and a maximum pressure drop ratio of 1.918 at 6 vol% and a particle size of 40 nm.
Kaska et al. [135]	Numerical (CFD)	Hybrid of AlN/Al_2O_3	30 nm	Water	1–4 vol%	Flat tube with hydraulic diameter of 19 mm and length of 2 m	–	An increase in both heat transfer coefficient and pressure drop was observed with higher nanoparticle concentration. Notably, a significant heat transfer enhancement of 28-50% was achieved for concentrations ranging from 1 to 3 vol%, and while thermal efficiency was substantial within this range, it decreased above 3 vol%.
Subhedar et al. [136]	Experimental	Al_2O_3	20 nm	Ethylene glycol: Water (50:50)	0.2–0.8 vol%	Flat tube with tube width of 1.60 cm and tube height 0.18 cm	–	A 30% increase in heat transfer was observed when utilizing 0.2 vol% alumina nanofluid in comparison to the base fluid. A new Nusselt number correlation was established for nanofluid under laminar flow,

(*continued on next page*)

Table 1 (*continued*)

Reference	Study type	Nanoparticles	Particle Size	Basefluid	Concentration Tested	Tube Geometry	Tube material / Roughness	Major Findings
								demonstrating a ± 25% deviation, and the use of 0.2 vol% nanofluid enabled a remarkable 41.157% reduction in radiator frontal area while maintaining the same level of heat transfer.
Hussein et al. [137]	Numerical	TiO_2	< 100 nm	Water	1–4 vol%	Flat tube with a length of 500 mm and hydraulic diameter of 4.5 mm	–	The Nusselt number demonstrated an increase with both nanoparticle concentration and Reynolds number, reaching a maximum value that was 18% higher than pure water at a 4% concentration. Interestingly, the inlet temperature had an insignificant effect on the friction factor but led to an increase in the Nusselt number.
Zhang et al. [138]	Experimental	TiO_2	10 nm, 30 nm, 50 nm	Water	0.005–1 vol%	Flat tube with a hydraulic diameter of 1.65 mm	Aluminum	Nanofluids exhibited a slightly earlier laminar-turbulent transition compared to water. Notably, the Nusselt number increased by up to 61% for a 0.01% nanofluid with 10 nm particles at a Reynolds number of 6100, and at a given particle size, nanofluids showed an optimal volume concentration for heat transfer enhancement, while the Nusselt number decreased with increasing particle size at a given concentration.
Elsaid [139]	Experimental	Co_3O_4 Al_2O_3	Al_2O_3 - 11-25 nm, Co_3O_4 - 8-21 nm	Water: Ethylene glycol (0:100), (10:90), and (20:80)	0.02–0.2 vol%	Flat tube with a width 12.6 mm and height of 2.7 mm	Aluminum / Roughness 0.0015 mm	Comparatively, cobalt oxide nanofluid exhibited superior heat transfer performance in comparison to alumina nanofluid. The addition of ethylene glycol resulted in a decrease in heat transfer performance when compared to using pure water, and the performance index was notably higher at lower nanoparticle concentrations and Reynolds numbers.
Vajjha et al. [140]	Numerical	Al_2O_3 CuO	45 nm 29 nm	Ethylene glycol: Water (60:40)	0–6 vol%	Flat tube	–	A 1% Al_2O_3 nanofluid demonstrated a significant heat transfer enhancement of 13.2% compared to the base fluid. New correlations for Nusselt number and friction factor were developed specifically for nanofluids, and based on equal pumping power, 1-3% Al_2O_3 and 1-2% CuO nanofluids exhibited superior performance compared to the base fluid.
Huminic and Huminic [141]	Numerical	MWCNT + Fe_3O_4, Nanodiamond (ND) + Fe_3O_4	–	Water	0–0.3 vol%	Flat tube with 2.56 mm height, 16.1544 mm width, 500 mm length	–	Both MWCNT-Fe_3O_4 and ND-Fe_3O_4 hybrid nanofluids exhibited improved heat transfer performance when compared to the base fluid (water). The reduction of entropy generation was observed with increasing nanoparticle concentration and inlet temperature, and the maximum heat transfer enhancement of 21.395% was achieved with 0.3% MWCNT-Fe_3O_4 hybrid nanofluids.
Ali et al. [142]	Experimental	MgO	20 nm	Water	0.06%, 0.09%, and 0.12 vol%	Flat tube with hydraulic diameter 2.410574 mm	Aluminum	A notable heat transfer enhancement of up to 31% was achieved with a 0.12% MgO nanofluid compared to the base fluid (water). The heat transfer enhancement was more pronounced at lower flow rates, while the inlet temperature had a minor effect on the observed improvements.
Neves et al. [143]	Numerical	Al_2O_3 and TiO_2	30 nm mean diameter	Water	1–10 vol%	Flat tube with a hydraulic diameter of 4.68	–	Both heat transfer coefficient and heat flux exhibit an increase with rising Reynolds number and nanoparticle concentration, leading to elevated Nusselt number and wall shear stress. The heat transfer enhancement rises with nanoparticle concentration, there is a slight decrease observed with increasing Reynolds number.

exchanger type, considering the nuanced requirements of diverse thermal applications.

A variety of heat exchanger tube shapes are employed in practical applications, with the U-shape being the predominant and widely adopted configuration. Nevertheless, there is a significant surge in research efforts dedicated to the design and testing of innovative tube shapes. This heightened focus on exploration and experimentation stems from the crucial role these tubes play in facilitating the heat transfer process between the hot fluid and the coolant. Researchers are actively engaged in seeking novel configurations to enhance heat exchange efficiency and address specific challenges associated with diverse thermal systems [105]. Within a thermal system, the pivotal factors governing the selection process are the type and sizing of the heat exchanger. However, among these, the tubes through which the fluids traverse in the heat exchanger emerge as elements of critical significance. Fig. 22 outlines the key factors that underscore the importance of heat exchanger tube selection. These factors encompass the properties of the flowing fluid, the specific type and size of the heat exchanger, the material constituting the tubes, the geometric configuration of the tubes, manufacturing costs, and the inherent design simplicity.

The geometric shape of heat exchanger tubes assumes paramount importance, exerting a profound influence on the design and manufacturing processes, as well as the overall cost considerations. The intricate interplay of these factors underscores the need for a thoughtful and comprehensive approach when evaluating and selecting heat exchanger tubes. It is through such a holistic perspective that thermal systems can be optimized for efficiency, cost-effectiveness, and seamless integration within diverse applications. Several common geometries of heat exchanger tubes are actively employed in contemporary applications, such as flat tubes with attached louvered fins [106], spiral tubes, U-shape tubes, etc. The visual representation of the most widely used heat exchanger tubes can be observed in Fig. 23. This assortment of tube configurations reflects the ongoing advancements and options available in heat exchanger design, enabling engineers to tailor thermal solutions to diverse applications.

Due to their unique characteristics and promising thermal capabilities in heat exchanger applications, nanofluids have undergone extensive testing, encompassing both numerical simulations and experimental studies. Positive findings have been reported, prompting further research endeavours aimed at identifying optimal design and operational parameters. Numerous research groups and laboratories are actively engaged in projects related to nanofluids, indicative of the sustained interest and commitment to unlocking the full potential of these materials in the realm of heat exchange.

5.1.1. Flattened tube heat exchangers

Flattened tubes have become a predominant choice in the design of radiator heat exchangers, showcasing their versatility and efficiency in thermal management systems. These tubes, characterized by their flattened cross-sectional profile, offer distinct advantages in terms of heat transfer capabilities. To further enhance their performance, helical or louvred fins are commonly attached to these flattened tubes, creating a symbiotic relationship that significantly augments heat exchange efficiency. The flattened tube design in radiator heat exchangers provides a practical solution for optimizing space and ensuring effective thermal dissipation. This flattened geometry allows for a more compact arrangement, making it particularly suitable for applications with space constraints, such as automotive and HVAC systems. Additionally, the flattened shape promotes laminar flow characteristics, contributing to improved heat transfer rates.

Flat tube heat exchangers have gained considerable attention in recent years over the past two decades. According to data compiled from the Scopus database, the number of studies on flat tube heat exchangers and those specifically focused on using nanofluids as a working fluid has shown a fluctuating trend, Fig. 24.

The introduction of nanofluids in flat tube heat exchangers started to gain attention around 2004, with the first recorded study [107]. Subsequent years witnessed a gradual rise in the number of studies, reaching a peak in 2019 with 72 studies on flat tube heat exchangers while 7 specifically on nanofluids. However, in recent years, there seems to be a declining trend in the number of studies. In 2021, the number dropped to 55 studies on flat tube heat exchangers, and in 2022, it further decreased to 52 studies.

The observed decline in the number of studies on flat tube heat exchangers, especially in recent years, may indeed be attributed to a shift in research focus towards investigating new and unique tube shapes. As the field of heat exchanger technology advances, researchers continually seek innovative approaches and configurations to enhance heat transfer efficiency, fluid dynamics, and overall performance. The exploration of new tube shapes represents a natural progression in research, as investigators aim to overcome limitations, improve existing designs, and discover novel solutions. These efforts may include exploring unconventional geometries, intricate arrangements, or alternative materials to achieve better heat exchange characteristics.

The shift in research interest from flat tube heat exchangers to other configurations could be driven by several factors:

- ***Maturation of Flat Tube Technology***: Flat tube heat exchanger technology may have reached a certain level of maturity, where the incremental improvements become more challenging to achieve, prompting researchers to explore alternative avenues.
- ***Emerging Technologies***: Advances in manufacturing capabilities and computational tools may enable researchers to explore and analyze complex geometries more effectively, encouraging the investigation of new tube shapes.
- ***Diversification of Applications***: As heat exchanger technology expands into various industries and applications, researchers may be drawn to explore designs tailored to specific needs, leading to a divergence from traditional flat tube configurations.
- ***Interdisciplinary Collaboration***: Collaborations across disciplines, such as materials science, fluid dynamics, and thermodynamics, may drive researchers to consider novel shapes and materials that were not previously explored in the context of heat exchangers.

While the decline in studies on flat tube heat exchangers may be evident, it is important to recognize that this trend reflects the dynamic nature of scientific inquiry. The ongoing interest in investigating new tube shapes underscores the adaptability and responsiveness of the research community to emerging challenges and opportunities in the field of heat exchanger technology.

The Scopus dataset also reveals the global distribution of research studies focused on the application of nanofluids in flat tube heat exchangers, as shown in Fig. 25(a). India leads the field with 18 published studies, indicative of a robust research landscape and a significant commitment to advancing heat transfer technologies. Following closely, Iran and Malaysia contribute substantially with 15 studies each, highlighting a noteworthy interest in exploring nanofluid applications in flat tube heat exchangers. China, though presenting a lower count at 7 studies, still demonstrates a considerable interest in the intersection of nanofluids and heat exchanger technologies, aligning with broader initiatives in energy efficiency. Other countries, including Iraq, Canada, Egypt, Pakistan, Romania, Saudi Arabia, the United Arab Emirates, the United Kingdom, United States, etc., have two or fewer studies each, collectively contributing to the global exploration of nanofluid applications in this field. The distribution of studies across these countries highlights the global nature of research in this field, with different nations contributing to the advancement of knowledge in the application of nanofluids in flat tube heat exchangers. Overall, the dataset reflects a concerted global effort to leverage nanofluid technologies for enhanced heat exchange in flat tube configurations.

Research on flat tube heat exchangers spans multiple subject areas, underscoring the interdisciplinary nature of this field, Fig. 25(c). The majority of studies, totalling 32, are situated within the realm of Engineering, reflecting a primary focus on the design, analysis, and application of flat tube heat exchangers. Physics and Astronomy contribute substantially with 28 studies, delving into the fundamental principles and physical phenomena governing heat transfer processes. Chemical engineering, with 27 studies, emphasizes the chemical aspects, materials, and fluid dynamics involved in these heat exchangers. Materials science, represented by 10 studies, centres on the composition and optimization of materials for enhanced heat exchange efficiency. The Energy category encompasses 9 studies, offering a broader perspective on the role of flat tube heat exchangers in energy-related applications, including efficiency and sustainability considerations. Environmental Science, with 5 studies, explores the ecological impact and sustainability of these systems. Additionally, computer science suggests a technological aspect, mathematics contributes to quantitative analysis and modelling, chemistry explores chemical properties, while agricultural and biological sciences hint at potential applications in controlled environments. Moreover, the inclusion of single studies in business, management, and accounting, as well as economics, econometrics, and finance, suggests an exploration of economic and managerial aspects in the context of flat tube heat exchangers. This diverse distribution underscores the broad relevance and applicability of flat tube heat exchanger research across scientific and engineering disciplines.

Fig. 25(b) illustrates the interrelation of keywords extracted from a collection of articles in the Scopus database focusing on the utilization of nanofluids in flat tubes. The graph visually represents the frequency of each keyword's occurrence and their co-occurrence with other keywords. In the graph, nodes denote individual keywords, while edges represent the instances of co-occurrence. Node size corresponds to the frequency of each keyword, and node colour indicates the publication year of the associated study. The keywords "heat transfer," "nanofluid," and "flat tube" emerge as the most frequently co-occurring terms in the graph, aligning with the primary themes of the articles in the dataset. Additionally, other keywords such as "friction factor," "pressure drop," "heat exchanger," "Reynolds number," and "Nusselt number" exhibit notable co-occurrence, suggesting their significance and relevance within the discussed studies. The graph highlights additional frequently co-occurring keywords such as "nanofluid flow," "friction factor," and "pressure drop." This observation implies that within the context of flat tubes, the use of nanofluids may contribute to an increase in both friction factor and pressure drop. Fig. 25(d) shows the distribution of document types published on the discussed topic.

In flattened tube heat exchangers, the added louvred fins provide a high heat transfer surface which keeps the walls at relatively low temperatures. At the boundary layer, the temperature gradient induces the thermophoretic phenomenon of nanoparticles in which the particles move from the high-temperature region towards the low-temperature region. The thermophoretic phenomenon intensifies the heat transfer rate in louvred fin flattened tube heat exchangers. Moreover, flattened geometry itself offers a higher surface area for the convection heat transfer. Thermophoresis keeps the particles in motion and lowers the risk of clustering due to the continuous movement. Because of the higher temperature carried by the nanoparticles, particle Brownian motion also gets increased which eventually leads to a higher thermal transport rate. Higher particle motion leads to higher intermolecular interaction at greater speeds thus the risk of agglomeration of nanoparticles is reduced. The study conducted by Shah et al. [106] showed a minimal difference in the observed heat transfer rate during the repeatability tests conducted after 3 days (Fig. 26). In a study, Abbas et al. [108] examined the efficacy of innovative Fe_2O_3-TiO_2/water hybrid nanofluids in flat tubes equipped with louvred fins. The findings indicated a notable enhancement in the Nusselt number within the flat tubes, registering a 20.03% increase compared to the base fluid. The experimentation involved testing nanofluids at concentrations ranging from 0.005 to 0.009 vol%, with an inlet temperature spanning 48-56 °C, and a flow rate of 11-15 LPM.

Flattened tubes are mainly used for vehicle radiators and therefore hold critical significance as the engine's safety and performance efficiency is quite dependent on the heat removal efficiency of the cooling system. Therefore, nanofluids are considered and tested as potential coolants for future automotive engines (including Electric Vehicles i.e., EVs). These advancements offer opportunities to optimize cooling systems, improve engine efficiency, and meet the increasing demand for effective thermal management, particularly in the context of electric vehicles.

Table 1 summarizes the key findings from recent studies published between 2016 and 2022, highlighting the promising potential of nanofluids as effective coolants in flat tube heat exchangers. A thorough examination of the table indicates that the performance of nanofluids in flat tubes is intricately linked to various factors, including fluid temperature, flow rate, nanoparticle concentration in the base fluid, and the size and shape of the nanoparticles. Notably, an increase in Reynolds number is commonly associated with an enhancement in the thermal performance of the system. Higher flow rates contribute to improved heat exchange due to increased turbulence. Temperature elevation boosts the heat transfer rate by intensifying the Brownian motion of nanoparticles. However, it is crucial to note that higher temperatures can lead to surface deterioration of the channels or tubes.

Moreover, the concentration of nanoparticles plays a critical role, with an observed performance increase up to a certain limit. Beyond this threshold, the performance tends to decline, attributed to nanoparticle agglomeration and, in some cases, channel clogging. While the majority of studies report positive impacts of nanofluid utilization in heat exchangers, conflicting results emerge in some instances. Consequently, further research is imperative to establish a comprehensive understanding of the performance dynamics of nanofluids in heat exchange applications.

The evolution of flattened tube heat exchangers has marked a significant chapter in thermal management systems, especially in applications with space constraints like automotive and HVAC systems. Researchers are currently exploring novel tube shapes, spurred by factors including the advancement of flat tube technology, emerging manufacturing capabilities, diverse applications, and collaborative efforts across disciplines. Despite a decrease in recent studies on flat tube heat exchangers, this shift in focus does not diminish the continued importance of flattened tubes in thermal management innovations. These tubes remain integral to addressing challenges posed by spatial constraints in various applications.

5.1.2. *Circular tubes*

The studies on circular tubes are quite interesting as a variety of novelties have been introduced with the circular tubes i.e., the insertion of twisted tapes (Fig. 27) and longitudinal inserts to induce turbulence which leads to increased convective heat transfer. Moreover, the annular configuration is widely tested as well. Using the nanofluid as a cooling fluid intensifies the heat transfer.

Heris et al. [144] examined the heat transfer performance of nanofluids in a circular tube through experiments. They tested alumina nanoparticle-based nanofluid to examine the effect of Peclet number, Reynold's number, and nanoparticle concentration on the Nusselt number. They reported that the Peclet number and concentration increase result in enhanced heat transfer parameters such as the rate of heat transfer and the coefficient of heat transfer. They credited the improvement in heat transfer parameters to increased interparticle interaction and structural fluctuation along with increased thermal conductivity. At optimal conditions, an increment of 41% in HTC was observed compared to the base fluid (water). Fotukian and Esfahani [145] ran a series of experimental studies to evaluate the performance of γ-Al_2O_3/water nanofluid in a circular tube and reported 48 % enhancement in heat transfer coefficient (at 0.054 vol% and 10,000 *Re*). Interestingly, in the turbulent regime, the influence of concentration increase had little effect on the heat transfer. An increase in Reynold's number decreased the relative heat transfer enhancement percentage (between the nanofluid and the water). Wall temperature was observed to be much lower in the case of nanofluid as compared to the water (due to the thermophoretic effect). Ryzhkov et al. [146] analyzed the effect of thermophoretic mobility on the near-wall region of a circular tube. They observed that in the laminar range, due to the mobility induced by the thermophoretic effect, nanoparticle concentration near the wall is smaller and the velocity of flow near the boundary layer is higher as well. However, the effect of nanoparticle concentration tends to fade at higher inlet velocity due to the dominance of the turbulent effect. Mwesigye and Huan [147] conducted a thermodynamic analysis of a circular tube with Al_2O_3/water nanofluid flowing through it. The analysis showed that at a higher Reynold's number, the effect of nanoparticles in the base fluid becomes less significant in terms of thermodynamic parameters. At higher Reynold's number, the optimum cross-sectional area of the tube is high whereas at high. Moreover, past a certain range of Reynold's number, the presence of nanoparticles in the base fluid produces no impact in terms of reduction in entropy generation. Ho et al. [148] conducted a numerical analysis to analyze the effect of temperature on the performance of nanofluids in the circular tube. They observed that the temperature has a strong impact on the performance parameters. Moreover, the pumping power enhancement or the pressure drop tends to decrease at the higher temperature of the nanofluid. Ho et al. [149] conducted an experimental evaluation of Eicosane-based nanofluid in a circular tube and examined the effect of particle concentration on the surface temperature of a circular tube. An increase in nanoparticle concentration resulted in increased heat removal from the tube wall due to a higher number of thermal acquisition particles. However, a mammoth pressure drop is observed due to the increased viscosity of the flow.

Ho et al. [151] performed experimental and as well as numerical analysis of alumina-based nanofluids in a circular tube and found that the wall temperature was much lower in the case of nanofluids as compared to the base fluid. Nanoparticle insertion increased the Nusselt number as well as the pressure drop across the tube. To accurately simulate the flow of nanofluids through the tubes, it is necessary to take into account the variation of thermophysical properties of nanofluids against the temperature change. Nanoparticle concentration enhancement increases the frequency of particle interaction and therefore the resistance coefficient and the drag force are increased whereby the fluid viscosity is increased. The thermophoretic effect increases the accumulation of nanoparticles at the center of the tube which intensifies the interparticle interaction hence the viscosity is further increased resulting in higher pressure drop and pumping power.

The circular tube performance is evaluated by passing a fluid through a tube of some axial length with a circular cross-section and the tube is heated by the heaters from the outside surface. Temperature, velocity, and pressure at the inlet and outlet are monitored to derive the values of performance assessment parameters. There is a very large number of published studies on nanofluid-based circular tubes. However, the turbulence is reported to induce greater heat transfer augmentation as compared to the nanoparticle concentration. Therefore, turbulator elements such as twisted tapes and longitudinal inserts are introduced inside the circular pipes to achieve higher heat transfer performance. Zheng et al. [150] inserted dimpled twisted tape in the circular tube which resulted in increased swirl velocity and turbulent mixing which results in disturbance in the flow structure. The dimpled side yielded a 25.53% greater HTC as compared to the protrusion side of the twisted tape. Moreover, dimpled tape outperformed simple tape inserts. Furthermore, a 58.96% higher convective heat transfer coefficient for nanofluid (Al_2O_3/Water) was recorded as compared to the base fluid. Sundar and Sharma [152] inserted longitudinal tube inserts in the circular tube and found that the topmost augmentation in heat transfer coefficient in the simple tube was 55.73% for nanofluid (Al_2O_3/Water) as compared to the nanofluid in the simple tube due to the enhanced turbulence in the flow. Moreover, the topmost enhancement in HTC for nanofluid flowing twisted tape inserted circular tube as compared to the water flowing in the simple circular tube was reported to be 80.19% at 0.5 vol% and 22,000 Reynold's number. Performance of nanofluids in circular tubes as reported by various studies has been summarized in Table 2.

Sundar and Sharma [153] reported that for nanofluid the enhancement in heat transfer coefficient for nanofluid as compared to water is 30.3% and 42.17% in simple tube and tube with twisted inserts respectively due to the synergistic effect of turbulence and the nanoparticles. Ahmed et al. [154] evaluated the performance of alumina-water nanofluid in helical tape-inserted circular tubes and reported a maximum of 31%, and 31.29% enhancement in Nusselt number, and heat transfer rate respectively as compared to water. They reported that the twist ratio is a critical factor since the induced turbulence and the particle interaction with the tape impact the flow structure and heat distribution in the tube. A higher twist ratio reduced heat transfer performance was reported (Fig. 28). No considerable effect of twist ratio on the friction factor for the nanofluids has been reported in the literature.

The exploration of circular tube heat exchangers, particularly with the incorporation of innovative elements such as twisted tapes, longitudinal inserts, and nanofluids, has yielded significant advancements in heat transfer performance. The studies highlighted in this review underscore the intricate interplay of parameters like Peclet number, Reynold's number, and nanoparticle concentration, showcasing their collective impact on the Nusselt number and heat transfer coefficients. Noteworthy findings include the substantial heat transfer enhancements observed with nanofluids, attributed to increased interparticle interactions, structural fluctuations, and elevated thermal conductivity. The intricate balance between nanoparticle concentration and flow dynamics, as demonstrated by varying Reynolds numbers, emphasizes the nuanced nature of heat transfer augmentation. Recent studies, including those employing dimpled twisted tapes and helical tape inserts, showcase the potential for further improvements in heat transfer performance through enhanced turbulence. As we move forward, it is imperative to focus on refining the understanding of the complex interplay between turbulence and nanoparticle concentration, optimizing geometrical parameters like twist ratios, and exploring advanced materials for turbulator elements. Future directions should also delve into the practical implications of these findings in real-world applications, ensuring the scalability and economic viability of these heat exchanger designs. The dynamic synergy between experimentation and numerical analyses will be instrumental in unlocking the full potential of circular tube heat exchangers, paving the way for more efficient and sustainable thermal management systems in diverse industrial contexts.

5.1.3. Horizontal spiral tube heat exchangers

This section presents insight into nanofluid performance in horizontal spiral tubes for heat exchanger applications (Fig. 29). Thermal performance for nanofluids has been tested in horizontal spiral tubes in terms of percentage enhancement in heat transfer rate, convective HTC, and Nusselt number as compared to the base fluid. Even though the nanofluids outperform the base fluid in terms of thermal parameters nevertheless, the otherwise effect on flow parameters has been reported i.e., the percentage of pressure drop for nanofluids is reported to be higher as compared to the base fluids.

The influence of curvature, nanofluid concentration, and temperature of hot water on heat transfer rate, Nusselt number, and pressure are mostly analyzed in such studies. Naphon [160] experimentally investigated the heat transfer characteristics and pressure drop of titania nanofluids flowing in horizontal spirally coiled tubes. The effects of curvature ratio, hot water temperature, and nanofluid concentration were considered. The findings revealed that the Nusselt number for nanofluids was 21-34% higher compared to water, indicating enhanced heat transfer. However, the friction factor exhibited only a slight increase with nanofluids compared to water. It was found that heat transfer enhancement increased with decreasing curvature ratio and

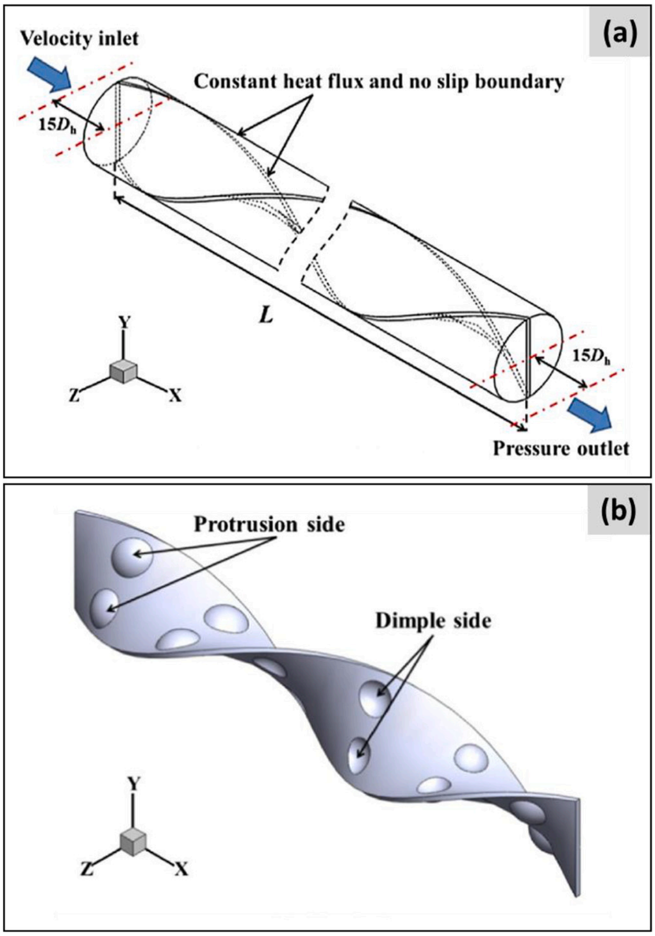

Fig. 27. (a) Circular tube with twisted tape inserts, (b) and twisted tape with protrudes [150].

increasing nanofluid concentration. The induced secondary flow caused by the centrifugal force significantly improved nanoparticle mixing. Naphon and Wiriyasart [161] appraised the heat transfer performance of nanofluid (TiO_2/Water) in a spirally coiled tube and employed flow pulsation and magnetic field. Pulsation and magnetic force induced disruption/mixing of flow structure (turbulence) which resulted in pronounced heat transfer augmentation. Structural fluctuations in the flow prompted by pulsative pumping and magnetic force intensify the Brownian motion (agitated particle migration) which leads to an increased thermal transport rate near the boundary layer (reducing the thickness of the boundary layer) of the bounding walls. The synergistic effect of using nanofluid, magnetic effects, flow pulsation, and tube curvature enhanced the Nusselt number by 18.3 %. Nevertheless, magnetic effects also prompt enhancement in friction factor. In another study Naphon et al. [162] applied artificial neural network (ANN) models to analyze and predict the pulsating heat transfer coefficient and friction factor of TiO_2/water nanofluids flowing in a spirally coiled tube under the influence of magnetic fields. Four different ANN training algorithms were tested, with the Levenberg-Marquardt Backpropagation (LMB) algorithm providing the best prediction performance based on minimum mean square error (MSE) and maximum correlation coefficient (R). Using the optimal LMB-trained ANN model with 4 hidden layer neurons, the majority of predicted Nusselt numbers and friction factors were within 2.5% and 5% of experimental values, respectively. This demonstrated the capability of the optimized ANN approach to accurately represent the thermal performance characteristics of the nanofluid-filled spirally coiled heat transfer system with applied magnetic fields. The well-trained ANN model can be applied to simulate and predict heat transfer in such complex systems without needing additional experiments.

Considering the reported literature, heat transfer enhancement can be increased by multiple times using combined techniques like tube geometry, tube inserts (turbulators), sinusoidal peristaltic pumping (flow pulsation), magnetic effects, nanofluids, etc. Some of the techniques bring forth the challenge of increased frictional loss (pressure drop and pumping power). However, the structural fluctuation of flow induced by pulsative and magnetic effects leads to increased particle migration (velocity) thereby reducing the probability of agglomeration/clustering of particles. Furthermore, the integration of nanofluids and intricate geometries, such as fractal-inspired designs or dynamically adaptable surfaces, has opened new frontiers for thermal performance enhancement. Cutting-edge research is delving into the utilization of smart materials with tunable thermal conductivity, leveraging the principles of metamaterials to achieve unprecedented control overheat transfer processes. The convergence of machine learning algorithms, specifically deep learning techniques, is revolutionizing the predictive modelling of complex heat exchanger systems, offering not only accurate simulations but also insights into optimizing parameters beyond conventional methodologies. Furthermore, the exploration of exotic heat transfer fluids, such as supercritical fluids or phase-change materials with tailored properties, is pushing the boundaries of what is achievable in terms of heat transfer efficiency and thermal energy storage.

5.1.4. Helical tube heat exchangers

Recent advancements in helical tube heat exchangers (HTHEs) underscore a multifaceted approach to improving thermal performance. The helical arrangement of the tubes induces secondary flows that promote mixing and turbulence, leading to increased heat transfer rates. Additionally, the compact design of HTHEs allows for more efficient use of space, making them attractive for applications with limited space constraints. Researchers have expanded beyond traditional tube designs, exploring innovative geometries such as conical-shaped helical tubes. These configurations exhibit promising enhancements in heat transfer capabilities, offering potential breakthroughs for efficient thermal management across various industrial applications. Concurrently, the integration of nanofluids in helical tube systems has garnered attention, demonstrating the ability of nanoparticles to boost heat transfer rates and overall efficiency. The synergy of these advancements positions helical tube heat exchangers at the forefront of research for optimizing heat exchange processes. In parallel, the materials used in helical tubes have undergone significant improvements. Advanced alloys with heightened thermal conductivity and corrosion resistance are now integral to design considerations, ensuring durability and longevity, particularly in demanding industrial environments [163–165]. A research effort led by Maziasz et al. [166] at Oak Ridge National Laboratory focused on improving the high temperature performance of compact heat exchangers, specifically for recuperators used in microturbines. Standard 347 stainless steel has been commonly used for recuperators but suffers degradation above 650 °C due to moisture-accelerated oxidation and excessive creep. The study explored alloys, including HR120, alloy 625, and a novel AL20-25 + Nb stainless alloy. These alternative alloys exhibit superior resistance to oxidation and creep when compared to the commonly used 347 stainless steel, presenting promising prospects for elevating the efficiency and durability of recuperators in high-temperature applications. Alloys, such as nickel-based superalloys and titanium alloys, offer excellent corrosion resistance, high temperature stability, and strength, making them suitable for demanding applications in extreme environments [167]. Additionally, high-temperature polymers such as polyphenylene sulfide (PPS) and polyetheretherketone (PEEK) are gaining popularity due to their lightweight nature, excellent corrosion resistance, and capacity to withstand elevated temperatures, making them valuable in electronics and aerospace [168]. Thermochromic materials, exhibiting colour

Table 2
Nanofluid performance in circular tubes – a brief summary.

Reference	Study type	Nanoparticles	Particle Size	Basefluid	Concentration Tested	Tube Geometry	Tube material / Roughness	Major Findings
Heris et al. [144]	Experimental	Al_2O_3	20 nm	Water	0.2–2.5 vol%	Circular Tube	Copper	41 % enhancement in heat transfer coefficient occurred at optimal operating conditions. The heat transfer coefficient of nanofluids rises with both Peclet number and nanoparticle concentration, surpassing predictions from single-phase heat transfer correlations based on nanofluid properties. This discrepancy suggests that mechanisms beyond enhanced thermal conductivity, such as nanoparticle dispersion, chaotic movement, Brownian motion, and particle migration, play significant roles in augmenting heat transfer by altering flow structures and temperature gradients at the wall.
Fotukian and Esfahani [145]	Experimental	γ-Al_2O_3	20 nm	Water	0.03–0.135 vol %	Circular tube with 5 mm inner diameter	Copper	As the Reynolds number increased, the degree of heat transfer enhancement diminished. Additionally, the nanofluid exhibited significantly higher pressure drop compared to pure water, while experimental findings aligned well with both Maiga et al. [156] correlation for nanofluid heat transfer and Buongiorno's model [157] under the assumption of a laminar sublayer thickness of 5.
Ryzkhov et al. [146]	Numerical	Al_2O_3	46 nm	Water	0–0.05 vol%	Circular Tube with a radius of 0.001 m	–	The reduction in viscosity near the wall increased fluid velocity in this region, leading to a flattened velocity profile near the tube axis to maintain a constant mass flow rate. At higher inlet flow velocity, the impact of nanoparticle concentration enhancement tends to fade.
Mwesigye and Huan [147]	Numerical	Al_2O_3	28 nm	Water	0–6 vol%	Circular tube with cross section area ranging from 0.0000025 m^2 to 0.05 m^2	–	There was an optimal tube cross-sectional area and Reynolds number at which entropy generation was minimized, and these optimal values increased with an increasing Reynolds number and tube cross-sectional area. The Bejan number, signifying the dominant irreversibility, decreased with a decreasing tube cross-sectional area and increasing Reynolds number. Additionally, a threshold Reynolds number existed beyond which the use of nanofluids increased entropy generation compared to the base fluid, making their thermodynamic use undesirable.
Ho et al. [148]	Numerical	Al_2O_3	36 nm	Water	0–9 vol%	Circular Tube	–	At the higher temperature of the nanofluid, the temperature, depending on thermophysical characteristics, improved, and the pressure drop decreased. The local thermal performance of the nanofluid was also enhanced.
Ho et al. [149]	Experimental	Eicosane (a phase change material)	57–138 nm	Water	1–10 wt%	Circular tube with 3.4 mm inner diameter and 4.0 mm outer diameter	Copper	Compared to pure water, phase change nanofluids effectively suppressed tube wall temperature when flow rate and heat flux were in an appropriate range, with the effect increasing at higher nano-PCM particle concentrations. In the initial entrance region, the nanofluid was less effective than pure water due to inlet subcooling; however, beyond this region, the nanofluid became increasingly effective in suppressing wall temperature through latent heat absorption from nano-PCM particle melting. Despite the benefits, there was a substantial penalty in pressure drop when using nanofluids, particularly at higher particle concentrations,

(*continued on next page*)

Table 2 (*continued*)

Reference	Study type	Nanoparticles	Particle Size	Basefluid	Concentration Tested	Tube Geometry	Tube material / Roughness	Major Findings
								highlighting the need for efforts to reduce viscosity and enhance thermal conductivity to mitigate this drawback.
Zheng et al. [150]	Numerical	Al_2O_3	30–50 nm	Water	0–4 vol%	Circular Tube with dimpled twisted insert	–	Using dimpled twisted tapes significantly enhances heat transfer compared to smooth twisted tapes, with the dimple side showing better performance than the protrusion side. The dimples disturb the flow and increase turbulence. Nanofluid outperformed the base fluid by 58.96 % in terms of convection heat transfer coefficient.
Ho et al. [151]	Numerical / Experimental	Al_2O_3	22.2–47.7 nm	Water	1–10 vol%	Circular Tube with an inner diameter of 3.4 mm and wall thickness 0.3 mm	–	Experimental and numerical analyses were performed. Considering the effect of temperature on the thermophysical properties of nanofluids yielded accurate simulation results. Wall temperature was decreased and Nusselt number and pressure drop were increased due to the nanofluids as compared to the base fluid i.e., water.
Sundar and Sharma [152]	Experimental	Al_2O_3	–	Water	0–0.5 vol%	Circular Tube with Longitudinal Insert	Copper	Heat transfer coefficients increased with nanofluid volume concentration and decreased with the aspect ratio of longitudinal strip inserts. The maximum enhancement of the Nusselt number, achieved with a 0.5% volume fraction of alumina nanofluid, ranged from 17.36% (at $Re = 3000$) to 30.30% (at $Re = 22{,}000$) compared to water, while friction factors were higher with strip inserts than in a plain tube for both water and nanofluids.
Sundar and Sharma [153]	Experimental	Al_2O_3	47 nm	Distilled water	0.02–0.5 vol%	Circular Tube with Twisted Tape Insert	Copper	The enhancement in heat transfer coefficient for nanofluid as compared to water is 30.3 % and 42.17 % in simple tubes and tubes with twisted inserts respectively. Friction factor with 0.5% nanofluid and the twist ratio of 5 was 1.096-1.2657 times higher than water in plain tube
Pathipakka and Sivashanmugam [155]	Numerical (CFD)	Al_2O_3-Water	30 nm	Water	0.5–1.5 vol%	Circular Tube with Helical Insert	Mild Steel	Heat transfer increased with Reynolds number and decreased with twist ratio, reaching its maximum enhancement at twist ratio 2.93. The Nusselt number increased with nanoparticle concentration, showing a maximum enhancement of 31% for a 1.5% volume fraction at the highest Reynolds number, and the Nusselt number enhancement ranged from 5% to 31% for various helical inserts and nanoparticle concentrations tested, with simulated values closely matching literature data for plain and helical insert tubes within a ± 10% discrepancy.
Ahmed et al. [154]	Experimental	Al_2O_3 TiO_2 ZnO	23 nm 27 nm 17 nm	Distilled water	0.025–0.1 wt%	Circular Tube with 10 mm internal diameter and 1.2 m length	Stainless Steel	In comparison to simple nanofluids, the ternary nanofluids exhibited enhanced stability and dispersion. The thermal conductivity saw an improvement up to 1.14 W/m.K at 45 °C for 0.1 wt% nanofluids, leading to a maximum heat transfer coefficient of 3200 W/m2K achieved with 0.1 wt% nanofluids at the highest Reynolds number, representing a substantial 79% increase over the base fluid. The varied particle sizes and shapes contributed to the enhanced thermal performance observed in the ternary nanofluids.
Mei et al. [158]	Experimental	Fe_3O_4	20 nm	Water	1–5 wt%	Circular Tube with length of 1.2 m and outer diameter of 10 mm	Copper	Improved thermal performance parameters were reported for nanofluids, however, the magnetic induction reduced the heat transfer performance. 22 % increase in Nusselt number was observed at 5 wt% of nanoparticles. Additionally, the effects of the magnetic field were more significant at higher Reynolds numbers in the turbulent flow regime.
Ponnada et al. [159]	Experimental	SiC	27 nm, 39 nm, and 62 nm	Distilled water	0.04–0.1 wt%	Circular Tube with an inner diameter of 28.6 mm	Copper	The topmost enhancement in Nusselt number was reported as 36.74 % and the friction factor increased by 13.5 %. Developed correlations for Nusselt number and friction factor as a function of particle size and concentration.

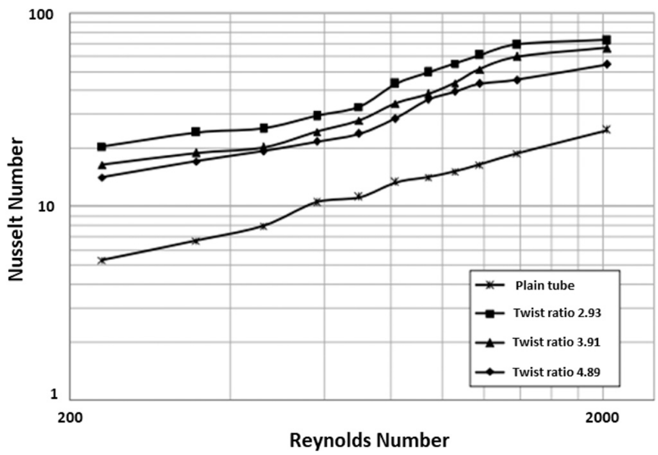

Fig. 28. Effect of twist ratio on the Nusselt number [155].

changes with temperature variations, show promise for intelligent heat exchanger design, providing visual indicators of temperature distribution for improved system monitoring. Furthermore, conductive polymers like polypyrrole (PPy) and polyaniline (PANI) offer opportunities for flexible and lightweight heat exchangers, particularly in wearable applications and electronic devices, revolutionizing heat management [169].

Computational Fluid Dynamics (CFD) modelling has become a cornerstone in this research, providing valuable insights into fluid dynamics and heat transfer characteristics within helical tubes. This computational approach aids in optimizing designs and predicting performance under varying conditions, contributing to informed decision-making in the design process. Bahremand et al. [170] conducted a comprehensive study on turbulent convection flow of nanofluids in helical tubes, employing both numerical simulations and experimental analysis. Their findings revealed an increase in heat transfer and a simultaneous rise in pressure drop within helical tubes when nanofluids were utilized as the working fluid. Rasheed et al. [171] conducted an experimental and numerical study investigating heat transfer enhancement in a shell and helical microtube heat exchanger using different nanofluids. Three helical microtube shapes (circle, oval, elliptical) were tested at various Reynolds numbers from 200 to 1800 using water initially. Results showed the circular helical microtube achieved the highest heat transfer augmentation and thermal performance compared to oval and elliptical designs due to the superior mixing from secondary flows. The circular helical microtube was further tested with alumina and zinc oxide nanofluids at 1-2% volume fractions. Heat transfer was found to increase with higher nanoparticle concentrations as well as Reynolds number for both nanofluids. Alumina nanofluid provided better thermal performance compared to zinc oxide nanofluid overall. It was also revealed that smaller nanoparticle size resulted in improved heat transfer owing to enhanced thermal conductivity and Brownian motion effects, however, a noticeable increase in friction factors was also observed.

In a similar vein, Kumar et al. [172] performed a CFD analysis focusing on the thermal and fluidic characteristics of MWCNT/water nanofluid in a heat exchanger with helical coil tubes (Fig. 30). The investigation covered the laminar regime within a Dean number range of 1300-2200, maintaining nanoparticle concentrations at 0.2, 0.4, and

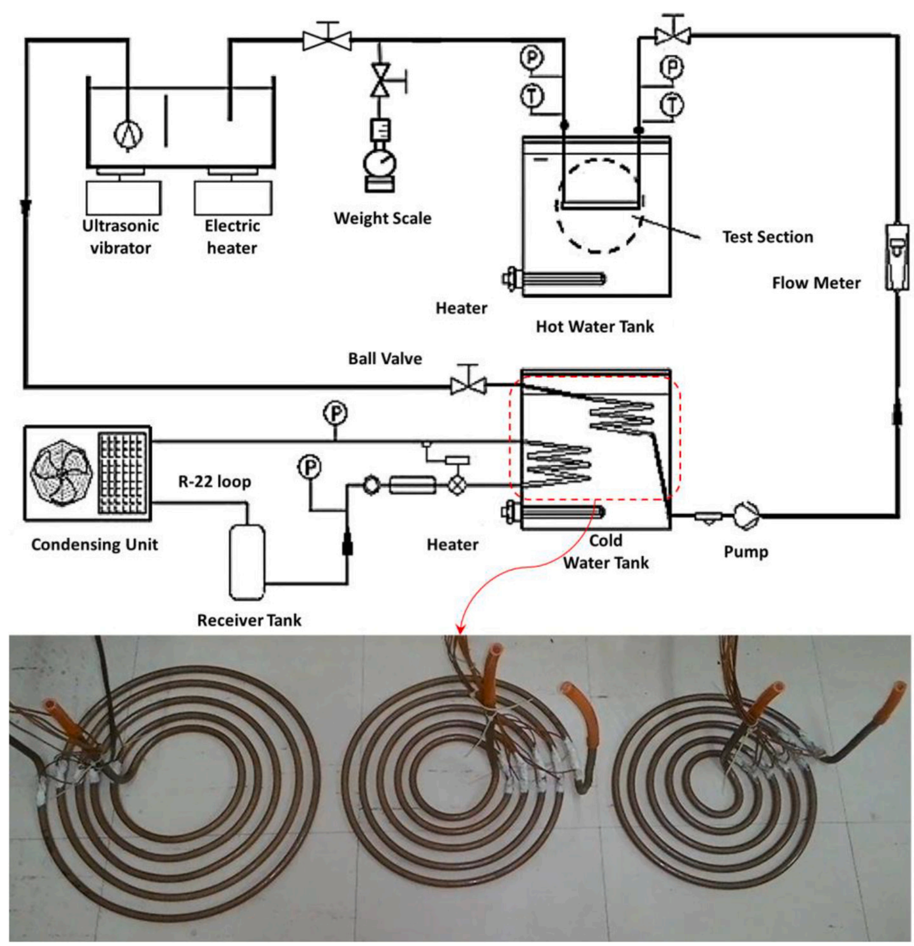

Fig. 29. Horizontal spiral tube experimental test setup [160].

0.6 vol%. Results indicated a notable 30% improvement in the Nusselt number for the 0.6 vol% nanofluid at a Dean number of 1400. Additionally, at a Dean's number of 2200, the pressure drop increased by up to 11% compared to the base fluid. Kurnia et al. [173] numerically investigated laminar heat transfer and entropy generation in helical coils and straight tubes with circular, elliptical, and square cross-sections. They found that helical coils offered higher heat transfer rates but also required more pumping power compared to straight tubes. Among helical coils, circular tube generated the lowest entropy while square tube provided the maximum heat transfer. The results provide insights into selecting optimal geometries and operating parameters for designing efficient heat exchangers based on requirements. Helical coils are suitable for high heat duty applications where pumping power is not a constraint. Straight circular tubes are preferred in mass production systems where parasitic pumping loads need to be minimized. Radkar et al. [174] conducted a comprehensive investigation to assess the thermal capabilities of ZnO/water nanofluids in helical tubes of heat exchangers. The nanofluids were prepared by dispersing the ZnO nanoparticles in water using a hydrodynamic cavitation technique. This allowed the creation of stable nanofluids with minimal agglomeration of the nanoparticles. Thermal conductivity measurements showed up to 136% enhancement for a 0.5 vol% ZnO nanofluid at 50 °C. A maximum 18.6% Nusselt number improvement was observed with 0.25 vol% ZnO nanofluid. This illustrates substantial intensification of convective heat transfer by the combination of helical geometry and studied nanofluid.

Singh et al. [176] examined water, surfactant-water solution, and carbon nanotube (CNT) nanofluid in a helical coil heat exchanger. The hydrodynamic study revealed that the friction factor decreased with increasing Reynolds number for all fluids, with CNT nanofluid exhibiting higher values. While the surfactant solution showed no heat transfer enhancement over water, the CNT nanofluid demonstrated a 62.62% increase in the overall heat transfer coefficient at a Reynolds number of 5000, suggesting its potential to replace conventional base fluids for improved heat transfer performance. Kulkarni et al. [177] investigated the heat transfer and flow characteristics of a helical coil heat exchanger using silver nanoparticles synthesized from neem leaves dispersed in water. They prepared silver nanoparticles using a green method with neem leaf extract and mixed them with deionized water to make the nanofluid with volume concentrations ranging from 0.01% to 0.05%. Experiments were conducted by passing the nanofluid through the tube side of the heat exchanger at a constant Reynolds number, while hot water was passed through the shell side at varied flow rates (Fig. 31). It was found that the presence of silver nanoparticles significantly enhanced the convective heat transfer coefficient - by up to 32% compared to water. The heat transfer enhancement increased with nanoparticle concentration and was mainly attributed to the swirling flow caused by the coil geometry, thinning of thermal boundary layer, and the Brownian motion of nanoparticles. The pressure drop was not significantly impacted by the addition of nanoparticles. Analysis of thermal performance factor revealed that a nanoparticle concentration of 0.05% volume was optimum. Thus, the green-synthesized silver nanofluid shows promise for improving heat transfer in helical coil heat exchangers without much pumping power penalty.

Niwalkar et al. [178] conducted a series of experiments on a shell and helically coiled tube heat exchanger using SiO2/water nanofluids with varying volume concentrations. They observed a notable 28.71% increase in heat transfer coefficient at 0.25% volume concentration compared to water, attributed to enhanced thermal conductivity and changes in flow and thermal fields. However, the study noted a trade-off, as the friction factor and pressure drop significantly increased by 52.61% and 62.60% respectively at the same volume concentration, indicating heightened pumping power requirements for improved heat transfer performance. Bhanvase et al. [179] explored the enhancement of convective heat transfer in a vertical helical coiled heat exchanger using water-based polyaniline (PANI) nanofluids. PANI nanofibers were synthesized through ultrasound-assisted emulsion polymerization and dispersed in distilled water at concentrations ranging from 0.1% to 0.5% volume. The study revealed a substantial 70% increase in the heat transfer coefficient at 0.5% volume concentration compared to distilled water. Bahiraei et al. [180] investigated the hydrothermal characteristics of water-Al_2O_3 nanofluid flow in a shell and tube heat exchanger equipped with helical baffles. It was found that increasing the nanoparticle concentration and baffle overlapping, as well as decreasing the helix angle, led to increases in both the heat transfer coefficient and pressure drop. The heat transfer coefficient showed a 14% increase when the concentration rose from 1% to 5% across different baffles overlapping conditions. The study observed a more pronounced impact of varying baffle overlapping on pressure drop at smaller helix angles.

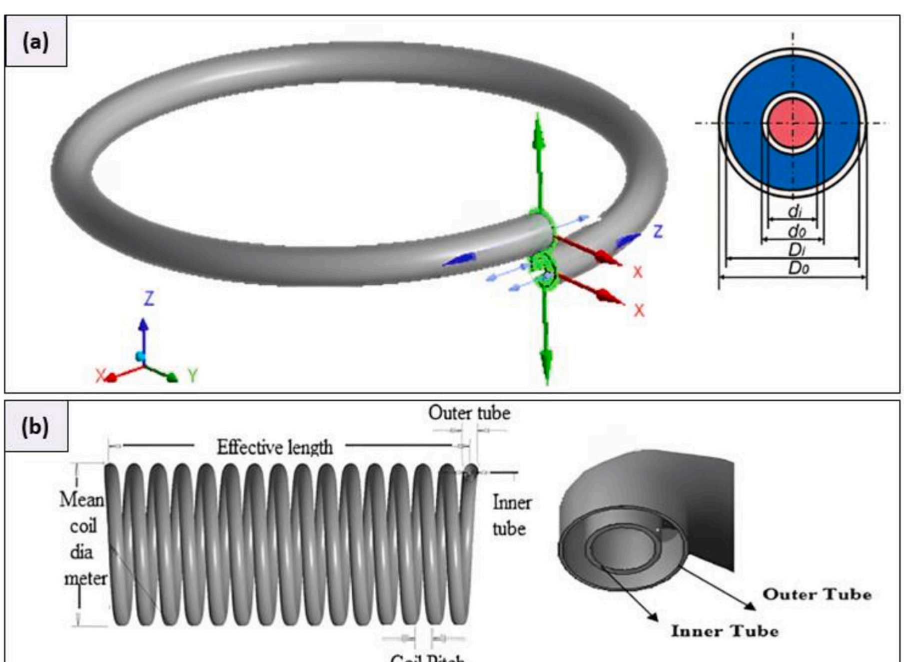

Fig. 30. Geometry design of double pipe helical tube (a) single section and [175] (b) full tube [172].

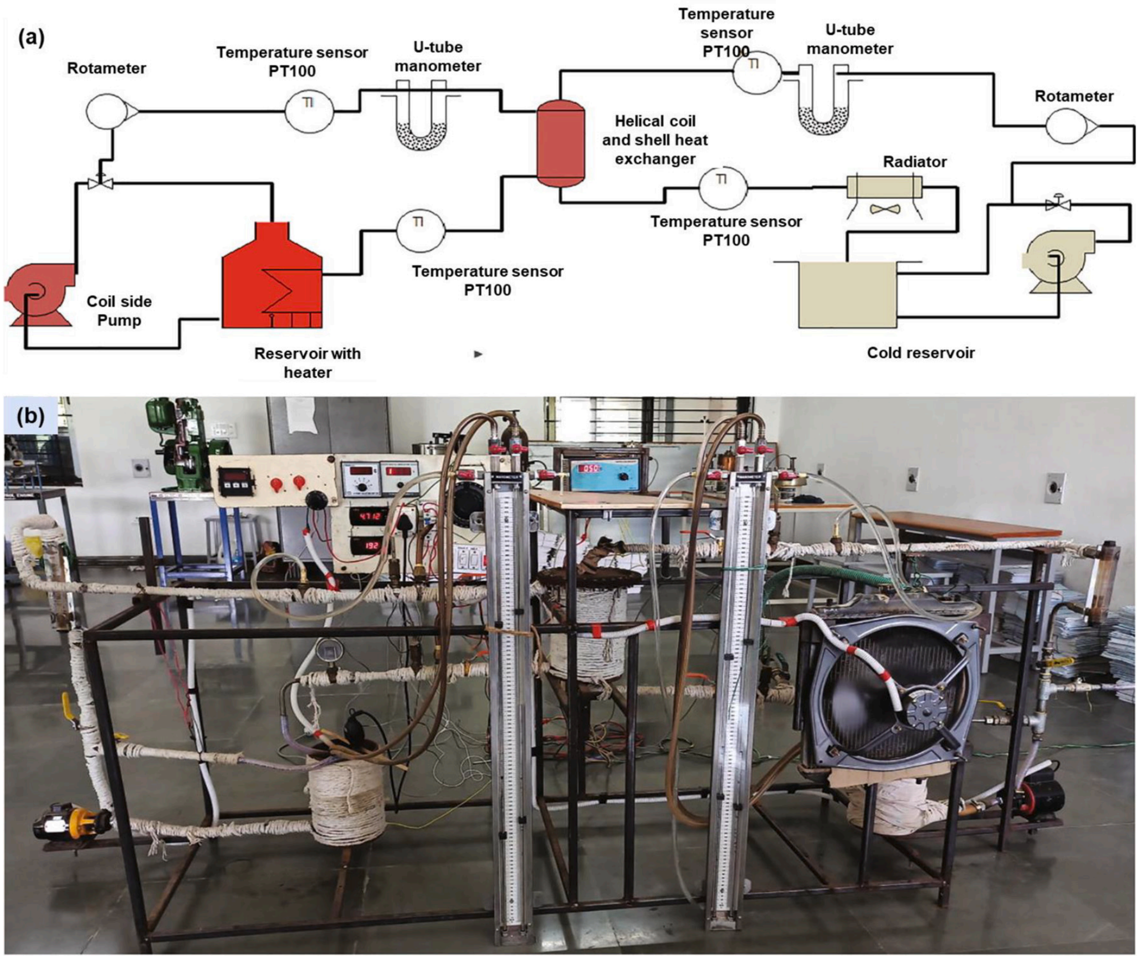

Fig. 31. Test section arrangement for helical tube heat exchanger using nanofluid (a) schematic representation, and (b) experimentation setup [177].

Specifically, at helix angles of 30 and 50°, an increase in overlapping from 0 to 0.6 resulted in reported enhancements of 105% and 38.6%, respectively. Additionally, optimal design considerations recommend smaller helix angles when aiming for a balance between high heat transfer and minimal pressure drop, while larger baffle overlapping values should be reserved for instances where augmenting heat transfer outweighs the importance of reducing pressure drop.

Narrein and Mohammed [181] explored the impact of alumina, silica, copper oxide, and zinc oxide-based nanofluids in a helical tube heat exchanger. It was found that CuO, Al_2O_3, and ZnO nanoparticle-based nanofluids demonstrated superior heat transfer enhancement compared to water, while SiO_2 nanofluid performed less favourably under specific flow conditions. Results also indicated a decline in convective heat transfer beyond 2% nanoparticle concentration due to increased pressure drop, with water-based nanofluids demonstrating the most significant thermal improvement. Guo et al. [182] performed a numerical investigation to assess the impact of flow pulsation on the thermal performance of Al_2O_3/water nanofluid in a heat exchanger with a helically coiled tube. A 1.14 times higher convective heat transfer coefficient value was recorded for 1.5 vol% nanofluids as compared to the base fluid. An increase in pulsation frequency increased the heat transfer coefficient ratio and pressure drop ratio up to a certain value and then they started to drop as shown in Fig. 32. Details of major findings of some other studies on the performance of nanofluids in helical tube heat exchangers are reported in Table 3.

Helically coiled tube heat exchangers offer the opportunity for high heat transfer due to special geometry. Quite limited types of nanofluids have been tested for application in helical tube heat exchangers [183]. Moreover, there are very few studies on double tube helical coiled heat exchangers due to design and manufacturing complexity. The pressure drop of fluid is very high in helical tube heat exchangers which makes the effectiveness of nanofluids quite trivial. The orientation of the helical tube has also been reported to have a strong Nanofluid influence on the performance of the fluid flowing inside the tube. Maghrabie et al. [184] appraised the Nanofluid influence of changing orientation on the thermal performance of the fluid through the helically coiled tube. They reported that transitioning the helical coil from a horizontal to a vertical orientation resulted in an 11% increase in the Nusselt number for water. However, for Al_2O_3/water nanofluid and SiO_2/water nanofluid with a nanoparticle concentration of 0.1 vol%, orientation led to an 8.3% and 7.5% enhancement in the Nusselt number, respectively. Moreover, the performance of nanofluids in terms of heat transfer has been reported to be far better in helical tubes as compared to straight tubes [185,186]. However, the increase in coil diameter reduces the pressure drop [187]. Helical tubes have also been tested in coned shapes for heat transfer applications (Fig. 33) [188].

The comprehensive exploration of existing literature has brought to light a pivotal aspect in the realm of heat exchanger optimization: the shape of the heat exchanger tubes exerts a pronounced influence on the performance of nanofluids within the system. However, a noticeable gap in research pertains to the scarcity of studies investigating nanofluid behaviour within heat exchanger tubes characterized by variable curvatures, especially in helical configurations. This gap presents an untapped frontier, offering opportunities to elucidate the intricate dynamics of nanofluid flow and heat transfer in complex geometries. The positive impact of nanofluid presence accentuates the importance of

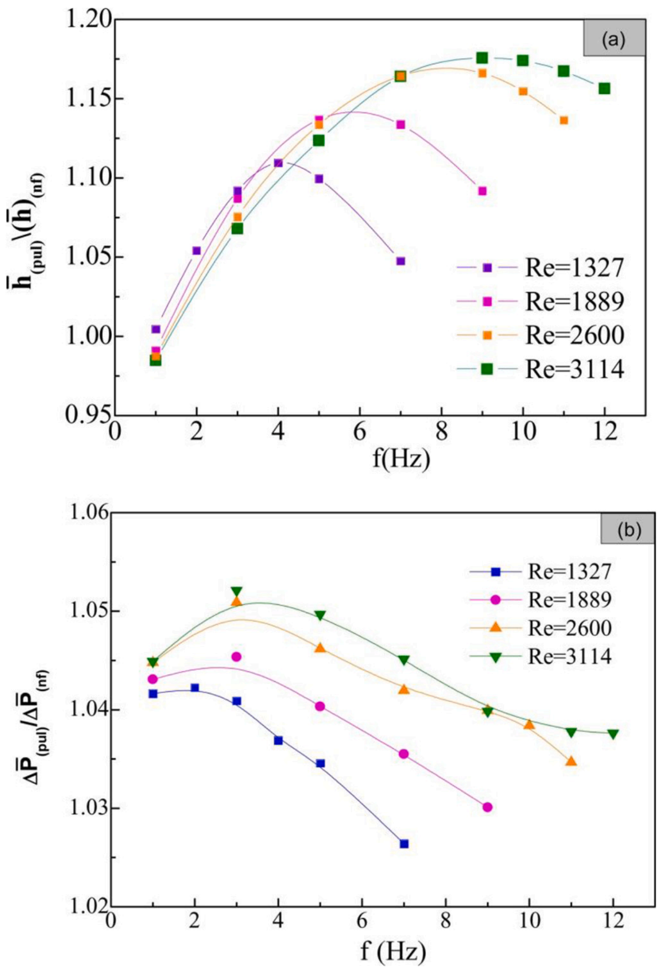

Fig. 32. Effect of pulsation frequency on (a) heat transfer coefficient ratio, and (b) pressure drop ratio [182].

extending investigations to diverse tube shapes, particularly those with variable curvatures, promising not only a fundamental understanding of nanofluid behaviour but also novel insights for optimizing heat transfer efficiency in unconventional heat exchanger designs. New forming and bending methods allow the production of helical coils with improved precision and the ability to tailor geometries. This includes finely tuning helix angles and tube shapes.

Moving forward, rigorous mechanistic modelling incorporating Brownian motion, thermophoresis, clustering and near wall effects promises to further advance the field. Most importantly, in situ transient performance data across duty cycles and thermal ageing studies in industrial environments would enable reliable helical tube heat exchanger implementation. Step-change heat transfer coefficient and associated pumping power tradeoffs must continue to be investigated for various helix angles and curvature ratios. There is also considerable interest in functionalized nanoparticles to achieve heat transfer augmentation through both latent heat effects and localized temperature-dependent aggregation-disaggregation action.

6. Advanced tube concepts

A variety of novel heat transfer intensification ideas has been proposed in recent literature. The following concepts have been reported to considerably augment the rate of heat transfer.

1. Internally and externally engrooved tubes (Fig. 34).
2. Corrugated tubes (Fig. 35).
3. Insertion of perforated conical rings (Fig. 36).
4. Insertion of conical wires.
5. Longitudinal tube inserts.
6. Insertion of twisted/helical screw tapes.
7. Tubes with external fins i.e., pin fins, louvered fins, helical fins, etc.
8. Tubes featuring surface improvements or treatments.

Biswakarma et al. [193] numerically appraised the performance of Al_2O_3/Water nanofluid in an internally v-grooved tube and obtained an increment of 13.8 % in heat transfer coefficient and 14.5 % in pressure drop. Internal grooves help to reduce the wall temperature and have a much higher Nusselt number value as compared to the plain tubes. Pourrajab et al. [194] reported an increase of 18.47 % in Nusselt number for SiO_2-Cu/Water hybrid nanofluid in an internally engrooved tube as compared to the base fluid. Kristiawan et al. [195] tested the micro-fin structure for a tube with TiO_2/Water nanofluid flowing through it and observed a hike of 80 % in pressure drop as compared to the plain tube at 0.3 vol% of nanoparticles. Therefore, heat transfer enhancement is not the only consequence of engrooving the tubes, the presence of grooves increases the frictional factor, and thereby the pressure drops, and pumping power is increased. Safarzadeh et al. [196] performed a similar analysis for helical tubes with micro-fins and reported an enhancement in hat transfer performance.

Darzi et al. [197] used externally corrugated tubes with SiO_2/Water nanofluid and observed that the heat transfer performance could be improved by increasing the corrugation height and reducing the pitch. Darzi et al. [198] reported a 330 % increase in heat transfer for Al_2O_3/Water nanofluid flowing through a corrugated tube as compared to the base fluid. Darzi et al. [199] in a similar study reported a 320 % increase in heat transfer for alumina base nanofluid in a helically corrugated tube. Nakchi and Esfahani [200] appraised the performance of Cu/Water nanofluid in a tube with perforated conical tube inserts and observed a 278.2 % increase in heat transfer as compared to the plain tube.

Kumar et al. [201] appraised the effect of longitudinal tube insert in a tube and used Fe_3O_4/Water nanofluid as a heat transfer media. They observed that increasing the aspect ratio of longitudinal tube inserts decreases the heat transfer rate. At 0.6 vol% of the nanoparticle, the Nusselt number increased by 14.7 % as compared to water and the enhancement approached 41.26 % when the longitudinal tube insert of 1 aspect ratio was introduced. However, the frictional factor also gets increased due to the tube inserts. The increase in friction factor for nanofluid as compared to the water was reported as 9.2 % which further jumped to 26.7 %. Taking into consideration the reported literature, novel ideas of heat transfer augmentation like the insertion of twisted tapes and the internal or external grooves (fins) produce anomalous results however, these additions also lead to increased pressure drop which needs to be addressed.

Tubes with surface improvements or treatments in the context of heat exchangers involve modifications to the tube surfaces to enhance heat transfer efficiency. By incorporating surface improvements and treatments, tubes can be transformed into versatile components with enhanced functionality, leading to improved efficiency, performance, and even novel applications. In this regard, surface tension and wettability are critical factors in the performance of heat exchangers. They influence how fluids interact with the surfaces of heat exchange components, impacting heat transfer efficiency, flow characteristics, and the prevention of issues such as fouling [202]. Lower surface tension is the sought-after quality, as it facilitates superior spreading and wetting of the fluid on the heat exchange surface. High surface tension promotes bubble nucleation and growth, leading to enhanced nucleate boiling heat transfer. However, excessive surface tension can also hinder bubble detachment and cause overheating at contact points, reducing overall performance. Additionally, surface tension affects droplet entrainment in two-phase flows, influencing pressure drop and flow distribution within the exchanger. The impact of wettability on heat exchangers is

Table 3
Summary of recent studies on the application of nanofluid in helical tube heat exchangers.

Reference	Study type	Nanoparticles	Particle Size	Basefluid	Concentration Tested	Tube Geometry	Tube material / Roughness	Major Findings
Bahremand et al. [170]	Experimental / Numerical	Ag	10; 30; 50 nm	Water	0.03 vol%	Helically coiled tube	Copper	The two-phase approach demonstrated significantly more accurate predictions of heat transfer behaviour compared to the single-phase approach. Heat transfer enhancement increased with coils having a greater curvature ratio, and a decrease in nanoparticle diameter further heightened the heat transfer enhancement. Interestingly, the base fluid in a helical pipe exhibited more effective heat transfer enhancement than the nanofluid in straight tubes.
Kumar et al. [172]	Numerical (CFD)	MWCNT's	–	Water	0.2%, 0.4%, 0.6 vol%	Double helically coiled tube	Copper	The heat transfer coefficient demonstrated an increase with both rising nanoparticle concentration and Dean number. At a Dean number of 2000, the Nusselt number was 20%, 24%, and 30% higher for concentrations of 0.2%, 0.4%, and 0.6%, respectively, compared to water, while pressure drop increased by 4%, 6%, and 10% for the corresponding concentrations. Additionally, correlations were developed to predict the ratios of heat transfer and pressure drop for the nanofluid compared to water.
Huminic and Huminic [175]	Numerical	TiO_2 CuO	24 nm	Water	0.5–3 vol%	Counterflow double pipe helical tube	Copper / Hydraulically smooth	At a 2% CuO concentration and with equal mass flow rates, the heat transfer rate was 14% higher compared to pure water. The water temperature increased with increasing nanoparticle concentration, attributed to enhanced heat absorption in the nanofluid. Additionally, correlations were developed to predict properties of nanofluids, such as thermal conductivity and viscosity.
Radkar et al. [174]	Experimental	ZnO	9–15 nm	Water	0.05–0.25 vol%	Helically coiled copper tube	Copper	A notable 18.6% increase in Nusselt number was achieved with 0.25 vol% ZnO nanoparticles, and the heat transfer coefficient demonstrated an increase with rising nanoparticle concentration and Reynolds number. Possible reasons for the heat transfer enhancement were identified, including improved dispersion, turbulence, and thermal conductivity, among other factors.
Singh et al. [176]	Experimental	MWCNT's	ID: 5–15 nm, OD: 50–80 nm, Length: 10–20 mm	Water	0.05 wt%	Helically coiled tube	–	The surfactant-water solution exhibited no difference in viscosity compared to water but displayed a slight increase in density. Additionally, the friction factor increased with Reynolds number for water, surfactant solution, and CNT nanofluid, and there was a

(continued on next page)

Table 3 (*continued*)

Reference	Study type	Nanoparticles	Particle Size	Basefluid	Concentration Tested	Tube Geometry	Tube material / Roughness	Major Findings
								substantial 62.62% enhancement in the overall heat transfer coefficient of the CNT nanofluid compared to water at Reynolds number 5000, attributed to the higher thermal conductivity and chaotic motion of CNT nanoparticles.
Kulkarni et al. [177]	Experimental	Ag	< 30 nm	Deionized water	0.01–0.05 vol%	Helically coiled tube	Copper	A notable 32% enhancement in the heat transfer coefficient was observed with the nanofluid compared to the base fluid. The Nusselt number exhibited an increase with both nanoparticle concentration and Dean number, while there was no significant rise in pressure drop with the nanofluid. The thermal performance factor slightly decreased with an increase in nanoparticle concentration.
Niwalkar et al. [178]	Experimental	SiO_2	17 nm	Water	0.05–0.25 vol%	Shell and helically coiled tube	Copper	The nanofluid demonstrated a substantial 28.71% increase in heat transfer coefficient compared to water. However, it also exhibited higher friction factor (52.61%) and pressure drop (62.60%). Correlations were developed to predict the thermo-physical properties of nanofluids.
Bhanvase et al. [179]	Experimental	Polyaniline (PANI) nanofibers	~100 nm	Distilled water	0.1–0.5 vol%	Vertical helical coiled tube	Copper	The heat transfer coefficient in nanofluid increases with a rise in PANI nanofiber concentration, showing a notable 69.62% enhancement for the 0.5 vol% nanofluid. Additionally, there is an increase in the heat transfer coefficient with the rise in Reynolds number, and this enhancement is particularly significant compared to a straight tube, attributed to the secondary flow generation due to the helical coil geometry.
Bahiraei et al. [180]	Numerical	Al_2O_3	–	Water	1–5 vol%	Helically coiled tube	Stainless Steel	The impact of changing baffle overlapping is more pronounced on the heat transfer coefficient and pressure drop at smaller helix angles. A neural network model has been developed, demonstrating high accuracy in predicting both heat transfer coefficient and pressure drop, with the recommendation of using small helix angles when both high heat transfer and low pressure drop are crucial.
Narrein and Mohammed [181]	Numerical	Al_2O_3, SiO_2, CuO, and ZnO	25–80 nm	Water, ethylene glycol, engine oil	0–4 vol%	Helically coiled tube	–	The enhancement of heat transfer initially increases with increasing nanoparticle concentration but declines after reaching 2%, attributed to increased viscosity and density. Additionally, smaller nanoparticle sizes contribute to higher pressure drop due to increased viscosity. The co-rotation of the tube is found to

(*continued on next page*)

Table 3 (*continued*)

Reference	Study type	Nanoparticles	Particle Size	Basefluid	Concentration Tested	Tube Geometry	Tube material / Roughness	Major Findings
								enhance heat transfer more compared to stationery and counter-rotation cases.
Maghrabie et al. [184]	Experimental	Al_2O_3; SiO_2	50 nm	Water	0.1–0.3 vol%	Helically coiled tube	Copper	The alteration of the inclination angle from 0° (horizontal) to 90° (vertical) resulted in an up to 11% enhancement in the Nusselt number, accompanied by a reduction in pressure drop by 11.8%. Additionally, in a vertical orientation at Reynolds number 6000, the Al_2O_3 nanofluid demonstrated a higher heat transfer enhancement compared to SiO_2 nanofluid, achieving a 35.7% improvement in heat transfer coefficient and a 35.5% improvement in effectiveness with 0.1 vol% compared to the base fluid.
Guo et al. [182]	Numerical	Al_2O_3	–	Water	0.5–1.5 vol%	Helically coiled tube	–	The convective heat transfer coefficient value was recorded as 1.14 times higher for 1.5 vol % nanofluids compared to the base fluid. Pulsation induces secondary flows and vortex formation, improving fluid mixing and heat transfer, and the mechanism behind heat transfer enhancement is associated with these secondary flows and thinner thermal boundary layers.
Hashemi and Behabadi [186]	Experimental	CuO	50 nm	Base oil (SN-500)	0.5%, 1%, and 2 wt%	Straight tube and helical tube with 14.37 mm inner diameter	Copper	The use of a helical tube, as opposed to a straight tube, significantly enhanced heat transfer rates. In helical tubes, nanofluids exhibited better heat transfer performance compared to straight tubes, with a maximum enhancement of 30.4%, while the enhancement was 18.7% for straight tubes with 2% nanofluid. Employing a helical tube was found to be more effective for enhancing heat transfer than using nanofluids instead of the base fluid.
Behabadi et al. [185]	Experimental	MWCNTs	–	Heat transfer oil	0.1%, 0.2%, and 0.4 wt%	Straight and helically coiled tubes	Copper	Reducing the coil diameter and increasing the pitch/ diameter ratio enhanced heat transfer in helical coils. Helical coils exhibited significantly higher heat transfer compared to straight tubes, and the combination of nanofluids and helical coils demonstrated the most substantial heat transfer enhancement, reaching up to 10 times higher than the base fluid in a straight tube.
Mohammed and Narrein [189]	Numerical	CuO	25 nm	Water	4 vol%	Helical coil tube	–	Smaller helix radius led to an increased heat transfer rate and Nusselt number, facilitated by enhanced secondary flow. Increasing the inner tube diameter also enhanced heat transfer, and the counter-flow configuration outperformed the parallel flow arrangement.

(continued on next page)

Table 3 (*continued*)

Reference	Study type	Nanoparticles	Particle Size	Basefluid	Concentration Tested	Tube Geometry	Tube material / Roughness	Major Findings
Huminic and Huminic [190]	Numerical	CuO; TiO_2	24 nm	Water	0.5–2 vol%	Tube-in-tube helical coil	Copper	The effectiveness of the heat exchanger was significantly improved by utilizing nanofluids, reaching up to 91% enhancement with 2% CuO nanoparticles. Entropy generation attributable to heat transfer effects decreased as nanoparticle concentration increased, and the addition of nanoparticles led to an overall reduction in entropy generation.
Mirfendereski et al. [191]	Experimental / Numerical	Ag	10 nm	Water	0.03 vol%	Helically coiled tubes with different curvature ratios	–	In coils with higher curvature ratios, the enhancement in heat transfer and the increase in pressure drop are more pronounced when using nanofluids compared to the base fluid. The local Nusselt number exhibits oscillations along the tube length in the entrance region before becoming fully developed. The use of nanofluid increases the fully developed heat transfer coefficient by approximately 3.5-3.8% compared to water, and the curvature ratio has a more significant impact on temperature and velocity fields than torsion ratio or Reynolds number.
Heyhat et al. [188]	Experimental	SiO_2	12 nm	Water	0.1% and 0.3 vol%	Coned helical tube	Copper	The heat transfer rate and pressure drop exhibit an increase with rising nanoparticle concentration. A lower cone angle yields higher heat transfer enhancement (up to 26%) and greater pressure drop increase (up to 117%) compared to a helical coil. While increasing the coil pitch enhances the heat transfer rate, the effect is less pronounced than that of the cone angle. The performance evaluation criterion (PEC) indicates that the combined use of nanofluids and conical coils effectively improves heat transfer.
Rasheed et al. [192]	Experimental / Numerical	Al_2O_3; ZnO	25; 50; 75 nm	Water	1.0%, 1.5%, and 2.0 vol%	Helical coil tube	Copper	The utilization of helical microtubes proved to be a significant enhancement in heat transfer compared to straight tubes, with the circle cross-section demonstrating the best performance. Specifically, at a 2% volume fraction and Reynolds number of 1800, alumina nanofluid in the circle helical microtube exhibited the highest thermal performance factor of 3.1. Additionally, particle size was identified as a factor influencing thermal performance, with smaller 25 nm particles exhibiting superior heat transfer enhancement and thermal performance compared to larger 50 nm and 75 nm particles.

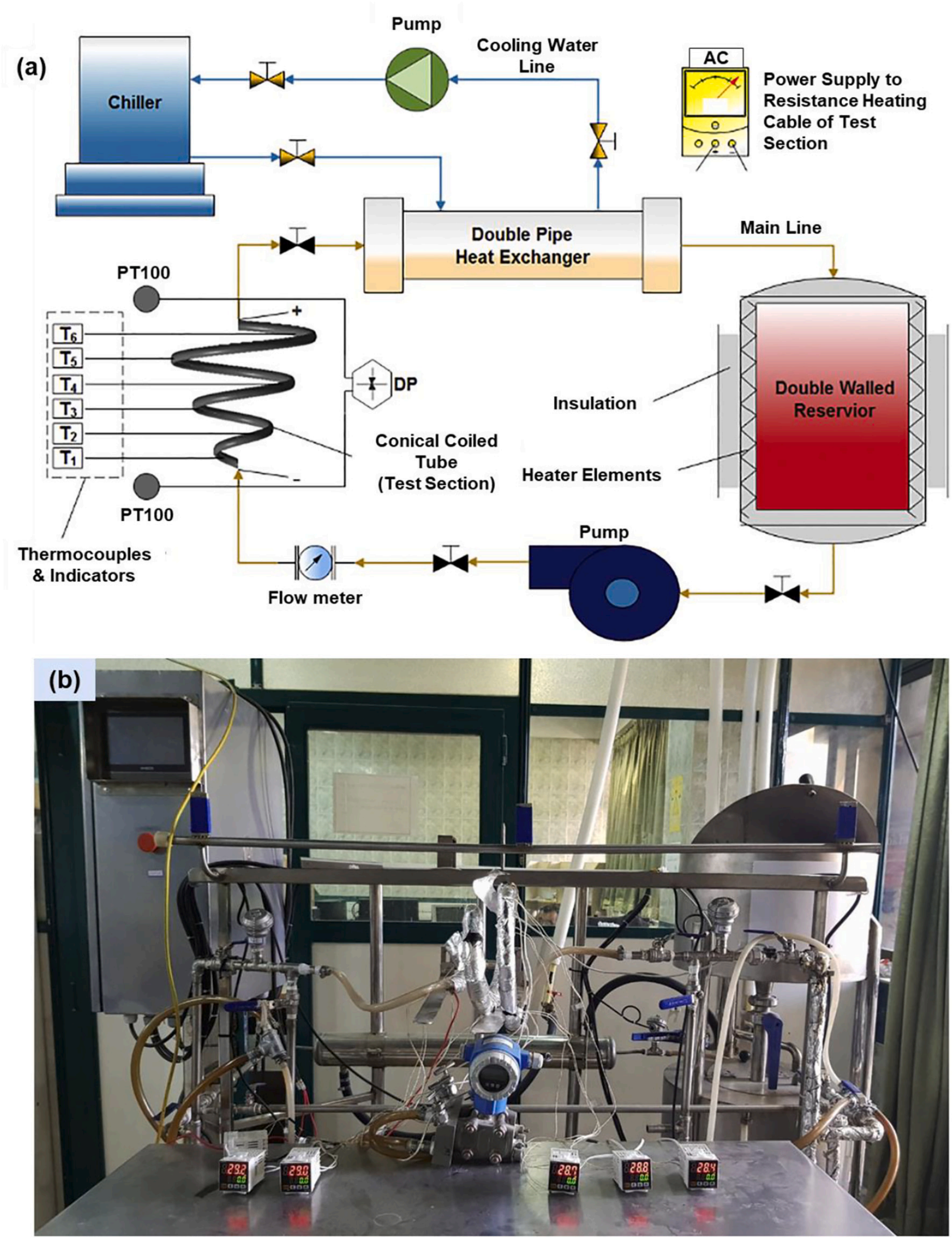

Fig. 33. Conical helical tubes experimental test section (a) schematic diagram, (b) actual setup [188].

profound. It is the difference between a fluid forming a thin, continuous film over the heat exchange surfaces or leaving behind dry spots that hinder the very essence of heat transfer. The advantages of high wettability extend beyond mere adherence, encompassing reduced resistance to fluid flow and an enhanced ability to prevent the formation of detrimental dry areas, ultimately resulting in an improved overall heat exchanger performance [203].

Hydrophilic coatings amplify wettability, while hydrophobic counterparts may be strategically employed to repel certain fluids, tailoring the heat exchanger to the specific demands of its application [204,205].

Ji et al. [206] conducted an investigation to examine the impact of a nanoscale polymer coating on nucleate pool boiling heat transfer using the refrigerant R134a. The study focused on both enhanced and smooth tube surfaces, with a 10 nm thick Parylene coating applied through plasma-enhanced chemical vapour deposition (PECVD). The study was carried out at refrigerant saturation temperatures of 6 °C, 10 °C, and 16 °C, with heat fluxes ranging from 15 to 150 kW/m^2. In the case of the smooth tube, the coating led to a reduction in surface roughness, but it adversely affected pool boiling heat transfer performance compared to the uncoated tube. The researchers attributed this outcome to the

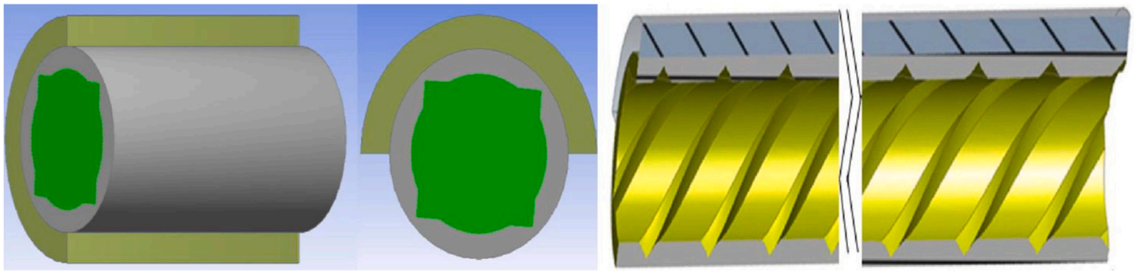

Fig. 34. Internally helically v-grooved tube [193].

Fig. 35. Helically corrugated tubes [197].

coating covering stable nucleation sites, prolonging bubble coalescence time, and introducing a minor thermal resistance. Conversely, on the saw-teeth tube, the coating resulted in a notable improvement in boiling heat transfer, 1.1 to 1.3 times greater than the uncoated surface. This enhancement was likely due to the coating activating additional nano-scale nucleation sites on the intricate geometry, thereby accelerating bubble detachment from the fins. Additionally, for the reentrant cavity tube, the coating exhibited minimal impact at low heat fluxes but contributed to a 20% increase in heat transfer at fluxes exceeding 60 kW/m^2.

In the quest to enhance heat transfer efficiency, engineers and researchers have explored inventive solutions, leading to a notable breakthrough in the form of Enhanced Thermal Conductivity Coatings (ETCCs). These coatings aim to boost the thermal conductivity of surfaces, presenting a substantial advancement in optimizing heat transfer across diverse industrial applications. The formulation of these coatings often involves advanced materials like metal oxides, ceramics, or other nanocomposites known for their exceptional thermal conductivity. When applied to surfaces of heat exchangers or other components within a thermal system, these coatings hold the promise of significantly elevating overall heat transfer performance. Researchers delve into the intricacies of these coatings, experimenting with different compositions and structures to maximize their thermal conductivity-enhancing properties [207–209].

The exploration of novel heat transfer intensification techniques presents a promising avenue for enhancing the efficiency and performance of heat exchangers. From geometric modifications like internal grooves and twisted inserts to surface treatments like hydrophilic coatings and ETCCs, each approach presents unique advantages and limitations. Choosing the optimal strategy requires careful consideration of the desired heat transfer enhancement, pressure drop constraints, and specific operating conditions. As research and development continue to advance, the future of heat transfer promises even more efficient and tailored solutions, paving the way for enhanced performance and optimized systems in a wide range of industries.

7. Conclusion

The use of nanofluids is a promising aspect of heat transfer enhancement in heat exchangers. However, taking into consideration the reviewed literature, the role of heat exchanger tube geometry/configuration has also been found to have critical implications. This study has reviewed the use of nanofluids in flat tubes, circular tubes, helical tubes, spiral tubes, and advanced insertions and grooves (fins). Up to a 330 % increase in heat transfer can be achieved by coupling the nanofluids with corrugated tubes. The research also presents a comprehensive bibliometric analysis that not only helps in evaluating and recognizing the contributions made by researchers but also provides valuable insights for policymakers and industry stakeholders. Notably, there is a growing trend of cross-disciplinary collaboration among material scientists, fluid dynamics experts, and heat transfer engineers. This

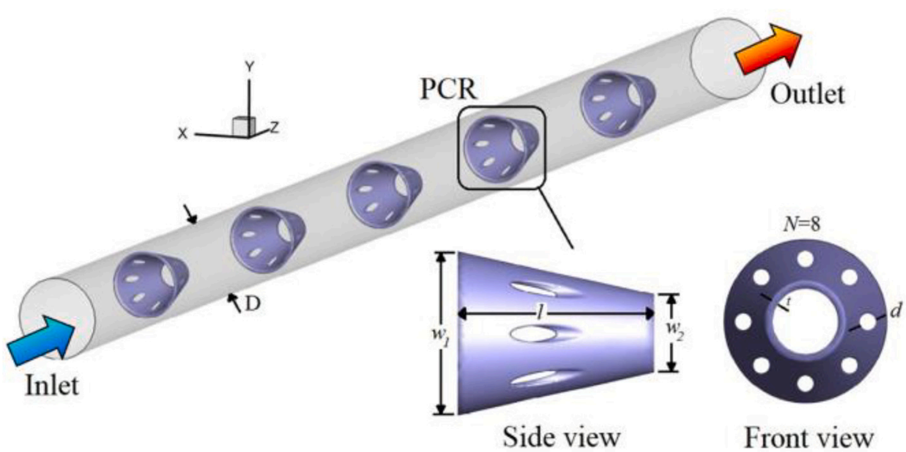

Fig. 36. Perforated conical rings [200].

convergence of expertise accelerates innovation by combining insights from diverse fields to address complex challenges in nanofluid-based heat exchangers. The study reveals the following noteworthy points or findings.

- Recent advancements in nanofluid synthesis techniques have led to more uniform dispersion of nanoparticles within the fluid medium, improving their thermal, electrical, and mechanical properties. This enhanced dispersion allows for better heat transfer, efficient energy transport, and increased stability, leading to improved performance in applications like thermal management and energy conversion. The precise control of particle size, shape, and surface chemistry can overcome traditional challenges and expand the potential applications of nanofluids.
- A new class of nanofluids named hybrid nanofluids has been developed that demonstrated improved heat transfer capabilities, as well as longer-lasting stability. The problems of stability, cost, and achieving greater control over the thermal and rheological properties urge investigators to move towards hybrid nanofluids.
- The new surfactants and stabilizers can improve the stability of nanofluids, preventing the nanoparticles from settling or aggregating. Researchers have made notable strides in comprehending the mechanisms that contribute to the enhanced characteristics of nanofluids. Through their diligent efforts, a deeper comprehension of the underlying mechanics has been achieved, shedding light on the factors responsible for the improved performance of nanofluids.
- One of the challenges in using nanofluids in heat exchangers is the tendency of nanoparticles to sediment or agglomerate over time, which can negatively impact their performance. Additionally, the stability of the nanofluid suspension can be affected by various factors such as particle leading, size, density, morphology, pH, temperature, and shear forces, which can also affect the heat transfer performance of the nanofluid.
- There are concerns about the potential for nanofluids to cause corrosion in heat exchangers. Studies have found that some nanofluids can be corrosive, while others have little or no effect on corrosion.
- It is important to note that while nanofluids can improve the performance of heat exchangers in some cases, they may not always be the best choice. Particles suspended fluids have a somewhat high production cost due to specialized equipment, precise manufacturing conditions, and expensive raw materials. Careful consideration of the cost-benefit trade-off is crucial before implementing nanofluids in a particular application to ensure their improved properties justify the higher expenses.
- In novel tube geometries/configurations, nanofluids manifest an increased pressure drop which requires to be addressed for the successful operation of nanofluids in advanced tubes with fins and inserts (internal inserts like helical tape, twisters, etc.).
- Apart from tube geometry/configuration and insertions, structural fluctuation-inducing mechanisms like flow pulsation and magnetic force can also be helpful to further improve the heat transfer performance. However, these methods result in friction factor enhancement as well.
- Scaling up the production and application of nanofluids from laboratory-scale to industrial-scale poses challenges. Researchers are actively working on overcoming issues related to scalability, ensuring consistent performance, and addressing economic feasibility for large-scale industrial applications.
- Comprehensive life cycle analyses are being conducted to assess the overall environmental impact of nanofluid-based heat exchangers. This includes evaluating the entire life cycle from raw material extraction to manufacturing, usage, and disposal, providing a more holistic perspective on their sustainability.

Despite these challenges, the potential for energy savings with the use of nanofluids in heat exchangers makes them an area of active research. Further development and optimization of nanofluid formulations and heat exchanger designs may lead to more widespread adoption of this technology in the future. While the future of heat exchangers is marked by innovation and advancements in various areas. Smart manufacturing principles and Industry 4.0 technologies are being integrated into the production processes of nanofluids and heat exchangers. This includes the use of sensors, automation, and data analytics to optimize manufacturing efficiency, quality control, and performance monitoring. The continuous evolution of heat exchanger technology involves the integration of cutting-edge materials such as graphene, graphene oxide, carbon nanotubes, metal matrix composites, ceramics (e.g., silicon carbide and alumina), titanium and titanium alloys, superalloys, shape memory alloys, advanced polymers (e.g., PEEK and polyimides), as well as hybrid and nanostructured materials. This diverse array of materials collectively enhances efficiency, durability, and overall performance in heat exchangers. In parallel, ongoing research is focused on exploring unconventional geometries to further improve performance, and the integration of smart technologies is underway to achieve adaptive and efficient heat exchanger operation. These collective developments have the potential to revolutionize heat exchanger systems, ushering in higher efficiency, reduced energy consumption, and greater support for sustainable practices across various industries.

CRediT authorship contribution statement

Hamza Babar: Conceptualization, Data curation, Formal analysis, Writing – original draft, Writing – review & editing. **Hongwei Wu:** Funding acquisition, Supervision, Writing – review & editing. **Wenbin Zhang:** Supervision, Writing – review & editing. **Tayyab Raza Shah:** Writing – original draft, Writing – review & editing. **Daniel McCluskey:** Supervision, Writing – review & editing. **Chao Zhou:** Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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