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A Review on Innovations in Heat Exchanger Technologies: From Computational Modelling to Thermal Management

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Abstract- - ***This comprehensive review spans a multitude of studies focused on advancements in heat exchanger technologies and methodologies. The researches range from Computational Thermal Fluid Dynamics (CtFD) applications in stellarator and tokamak coils to cutting-edge simulation tools for plate heat exchangers. The studies encompass a variety of methods, including experimental mock-ups, numerical simulations, analytical models, and innovative algorithms, all aiming to enhance the understanding, design, and efficiency of heat exchangers in various applications. With a primary focus on thermal dynamics, these studies provide insights into heat transfer properties, pressure drops, cooling systems, predictive modeling, and cost-effectiveness, among other pertinent topics.***

Keywords ***Heat Exchanger Technologies, Computational Thermal Fluid Dynamics, Thermal Management, Predictive Modeling, Nanofluid Applications.***

I. INTRODUCTION

In recent years, the use of Heat Exchangers (HE) has grown considerably. Originally designed for the chemical and food processing sectors in the 1930s, these devices are now found across various industries and energy sectors. Their popularity stems from their compact design, efficient heat transfer capabilities, resistance to bio-fouling, and their modularity [1]. They can be easily taken apart for cleaning or adjusted to meet different thermal requirements. A plate heat exchanger is constructed from a sequence of individual plates, which are held together between two robust end covers and secured with bolts. Depending on the intended use of the exchanger, these plates may be joined with gaskets, welded, or brazed. A typical plate design for a plate heat exchanger can be seen in Fig-1. Oftentimes, stainless steel is chosen for the plates due to its heat tolerance, durability, and resistance to corrosion [2]. Gaskets are employed to seal the plates, ensuring that the fluids flow in the correct alternate channels and avoiding any leaks. Heat exchangers are devices specifically engineered to transfer heat between different mediums. Their main functions include either heating or cooling elements, with cooling often taking precedence in many industries to safeguard equipment from excessive temperatures. These devices come in a variety of forms, each boasting its own set of benefits and limitations. Their applications span a vast array of industries, being integral components in both heating and cooling systems. Many industrial operations require specific thermal conditions for optimum performance. Consequently, maintaining these ideal temperatures is crucial. Within various industrial settings, heat exchangers play an essential role in ensuring machinery, chemicals, water, gas, and other materials remain within desired temperature ranges [3]-[5]. Additionally, they can reclaim and redirect heat or steam, which might otherwise be wasted, to be utilized elsewhere, enhancing overall efficiency.

II. LITERATURE REVIEW

In a study by Richard et al. [1], a new approach using Computational Thermal Fluid Dynamics (CtFD) was introduced for examining a meander-flow path (MF) fin-type heat exchanger (HX). This was specifically intended for HTS current leads in the LTS coils of the W7-X stellarator and the JT-60SA tokamak. Experiments on an HX mock-up were carried out at the Karlsruhe Institute of Technology, which served as a basis for verifying the accuracy of the computational model. The study began with the hydraulic assessment of the mock-up, followed by an investigation into its heat transfer properties.

In research conducted by Sterkhov et al. [2], the focus was on modernizing the existing steam-power units using a gas turbine combined cycle (CCGT) incorporating a pressurized heat recovery steam generator (PHRSG). The study reveals that such a scheme aligns with the stipulations of the energy development program. One significant advantage is the cost-saving aspect, as it allows for the retention of some equipment components. Through a heat transfer analysis, the team demonstrated the feasibility of simulating the heat exchange process using boiler design software. They found that the ideal flue gas pressure within the PHRSG is around 4–5 bar. Increasing the flue gas pressure to this range maximizes the heat transfer coefficient. Simultaneously, this pressure range is also where the most significant reduction in metal usage is observed[1].

In a study by Lin et al. [3], a unique model for predicting heat load was introduced, leveraging the hybrid spatial-temporal attention long short-term memory (STALSTM). Their findings highlight that the STALSTM model outperforms others in terms of prediction accuracy. Furthermore, the study underscores the value of integrating spatial-temporal characteristics and the attention mechanism.

Plis et al. [4] crafted a model grounded in the equations of mass and energy balances, paired with empirical ties that chart the heat transfer process and working fluid's pressure drop within the heat exchanger. They determined empirical coefficient unknowns utilizing operating data through the least-squares method. The model not only computes no measured operational parameters and energy evaluation indicators but is also flexible enough to accommodate the evolving technical conditions of the HRSG. They then juxtaposed the model's calculations with actual measurement outcomes. The precision of the model was affirmed through metrics such as the determination factor and the root mean square error.

Sauciuc et al. [5] explored the potential of phase change systems, particularly vapor chambers, to curtail the spreading resistance found in the base of heat sinks. Given that significant advancements remain elusive, there's an urgency to discern the boundaries of limitations for phase change-heat spreaders in CPU cooling, and stack up their efficacy against solid metals with high thermal conductivity. The team introduced two foundational models to clarify heat transfer constraints in phase change systems. Leveraging these models, one can estimate the comparative spreading resistance between phase change systems and solid metals.

In a study led by Khan et al. [6], a one-dimensional mathematical representation of fins encompassing convective, conductive, and radiative elements is proposed. The formulated approach employs the function-approximation prowess of Legendre polynomials integrated with artificial neural networks (ANNs), the global search optimization potential of the Whale Optimization Algorithm (WOA), and the local search precision of the Nelder-Mead algorithm. Comparing the experimental findings with contemporary techniques underscores the superiority of this method. They found that the accuracy of temperature approximation was influenced by the values of Nc, Nr, and λ. The efficacy of the LeNN-WOA-NM algorithm's solutions were further confirmed using metrics like absolute errors, MAD, TIC, and ENSE.

Sixel et al. [7] introduce an innovative application of three-dimensional printed direct winding heat exchangers (3-D-DWHX) aiming to enhance the stator's thermal management in high power density electrical machines. This 3-D-DWHX maintains direct touch with stator windings, leading to heightened continuous current densities. This translates into an elevated continuous power rating and power density. In a nonencapsulated motorette test, a polycarbonate-aluminum flake 3-D-DWHX achieved significant results. Finite element studies indicated even more promising results for encapsulated versions in terms of current density and hotspot temperatures, resulting in a commendable continuous specific power.

In research by Coble et al. [8], the focus was on analyzing the calorimetric dynamics across the intermediate heat exchanger, aiming for real-time primary flow rate inference. Applying heat balance equations to a designed forced flow loop validated the potential of this technique. Factoring in relevant time lags and heat losses, they successfully inferred the primary flow rate with admirable accuracy, as backed by the prediction variance and mean value data.

Liu et al. [9] delve into the architectural design of a cryogenic box, covering aspects such as vacuum system design, refrigerator choice, heat exchanger design, and material selection. Their calculations reveal a thermal load of 25.09 W during the typical operation of the HTS maglev vehicle, which is well within the 120 W cooling capacity of the cryogenic system functioning at 65 K. This affirms the viability of the cryogenic system, potentially serving as a blueprint for future HTS maglev vehicle projects.

Gai et al. [10] examine the integration of an oil-based shaft cooling system in a high-speed automotive traction motor. Initial analyses determine iron and air friction losses across varied speeds. To gauge the system's thermal behavior, they employ both analytical and numerical methods for steady-state and dynamic conditions. Empirical tests are executed to understand key cooling system parameters. Prototype simulations and tests indicate the shaft's rotational speed augments heat exchange efficacy within the coolant and the hollow-shaft's internal surface. Nevertheless, the influence of high rotational velocities diminishes at around 30,000 r/min due to flow saturation.

In research by Qing et al. [11], an exhaustive analytical model that factors in unique temperature-dependent properties and the effective heat transfer coefficient (EHTC) for both-side heat exchangers is formulated. This model aims to scrutinize the intrinsic and extrinsic dynamics of the TEG. Their findings pinpoint certain behaviors relating to optimal load ratio, cold-side EHTC, and hot-side EHTC. Furthermore, they shed light on the optimal dimensions and cross-sectional area ratio of TE components.

Ahmand et al. [12] introduce a pioneering neuroevolutionary algorithm that synergizes the capabilities of feed-forward artificial neural networks (ANNs) and the advanced metaheuristic, Symbiotic Organism Search (SOS) algorithm. Their analysis relies on several performance indicators, such as RMSE, AE, GD, MAD, NSE, and ENSE. The assessment, both statistical and visual, suggests their method's aptness for real-world applications. When juxtaposed with benchmark solutions, their methodology emerges as notably superior.

Pearson et al. [13] delve into a comprehensive design overview, encompassing a preliminary assessment of the tritium breeding ratio (TBR) using neutronics analysis. They also discuss the current status of research and development pertinent to SCYLLA©.

In research led by Kuppusamy et al. [14], they conduct an experimental study on the innovative Triple Fluid Heat Exchanger (TFHEX) designed for heat management in hybrid cooled servers. The TFHEX, characterized by its finned double-tubed design, employs two liquid mediums (hot and warm water) and a gaseous medium (hot air). While some disparities were noted between the experimental and analytical findings, the outcomes suggest that the TFHEX offers the adaptability to handle heat from diverse fluids in varying proportions. This makes it a promising solution for data centers operating in warmer environments.

Some authors [15]–[19] executed a detailed three-dimensional conjugate forced convection heat transfer examination on a range of shell-and-tube counter-flow microchannel heat exchangers. Through their investigations of various cross sections (including circular, square, and those with radial ribs), they determined that the circular cross section with radial ribs yielded the most consistent temperature distribution and optimal heat transfer. To achieve maximum efficiency in such heat exchangers, one should factor in these insights during a multi-objective constrained optimization process, especially when contemplating the additive manufacturing of these compact units.

Jung et al. [20] embarked on a study with the objective of elucidating the thermal and pressure drop properties of plate heat exchangers, emphasizing the importance of design factors like channel spacing. Their numerical analyses in relation to flow patterns and channel spacing revealed consistent patterns in the j factor based on the flow rate and channel space. Similarly, they noted a systematic reduction in the f factor with an increase in the mass flow rate.

Khaled et al.[21] examined the potential of using a counter flow concentric tube heat exchanger to harness heat from generator exhaust gases. This captured heat is then utilized to warm water. The most effective setup involved water circulating in the inner tube with a diameter ratio (inner to outer) of 0.75, achieving an average waste heat recovery rate of 26 kW.

Lie et al.[22] created a comprehensive experimental system to assess the heat transfer properties of a heat exchanger. This system boasts automated features, precision in measurements, user-friendly operation, and adaptability. By implementing the Wilson Method to manage experimental data and create fit curves, they derived an empirical equation. This equation closely mirrors traditional ones and proves useful in designing heat exchangers.

Authors [23]–[27] explored the properties of three different nanofluids based on CuO and TiO2, testing various volume fractions and mass flow rates. Using computational fluid dynamics (CFD), they simulated the behavior of each nanofluid at a volume fraction of 0.2%. Their simulations revealed that the CuO nanofluid outperformed the others, with a heat transfer increase of 61%, while experimental data indicated a 50% increase at a 0.05% volume fraction and 62% at a 0.2% volume fraction for CuO.

Raffaele et al. [28] introduced an innovative simulation tool crafted for precise evaluations and designs of single- and multi-passage plate heat exchangers under steady conditions. This tool, grounded in a local one-dimensional effectiveness-NTU method combined with established techniques for determining heat transfer coefficients and pressure drops, is versatile across different conditions, plate designs, and working fluids. An in-depth sensitivity assessment further highlighted the impact of chevron angles and corrugation aspect ratios, leading to the development of a performance index for plate heat exchangers that encompasses both heat duty and pressure drop.

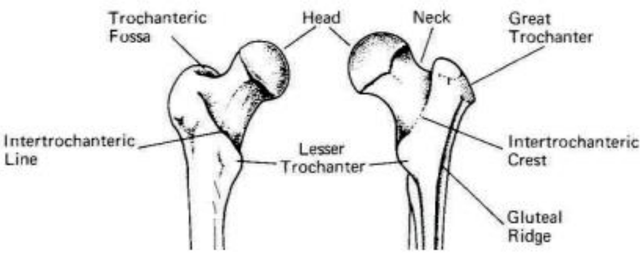

Figure 1. Structure of Femur Bone

Lower Extremity The lower extremity of the femur (or distal extremity) is larger than the upper extremity. It is somewhat cuboid in form, but its transverse diameter is greater than its anteroposterior (front to back). It consists of two oblong eminences known as the condyles. Anteriorly, the condyles are slightly prominent and are separated by a smooth shallow articular depression called the patellar surface.

III. CURRENT CHALLENGES AND FUTURE SCOPE

Accuracy in Computational Models: Computational models need to be validated with real-world experiments to ensure their accuracy, as seen in the study by Richard et al. [1]. Predicting heat load, as proposed by Lin et al. [3], remains challenging, and while the STALSTM model may be superior, it still needs to be compared against real-world data. Modernization & Cost: Upgrading existing infrastructures to modern technology, such as steam-power units to gas turbine combined cycles, as Sterkhov et al. [2] did, requires substantial investment and the retention of some equipment components. Complex Mathematical Representations: Creating a one-dimensional mathematical representation that encompasses various heat transfer elements, as Khan et al. [6] did, can be challenging and often requires advanced algorithms and computational tools. Limitations of Current Technologies: Sauciuc et al. [5] identified limitations in phase change systems for CPU cooling. The challenge lies in discerning the boundaries of these limitations. Real-time Inferences: Real-time inferences and data processing, as attempted by Coble et al. [8], present challenges in terms of accuracy and speed. Integration of New Systems: The integration of novel systems, such as the oil-ased shaft cooling system examined by Gai et al. [10], into existing machinery can be challenging, especially in determining efficiency and adaptability. Material and Design Limitations: The choice of materials, heat exchanger designs, and factors like channel spacing, as explored by various authors, remain crucial. Design optimization is required to maximize efficiency. Nanofluids: While Sa lameh et al.[19] explored the potential of nanofluids, achieving consistency between experimental data and simulations remains challenging.

Advanced Computational Models: Enhanced computational models that can more accurately predict real-world scenarios are needed. The hybrid spatial-temporal attention model by Lin et al. [3] and the equations of mass and energy balances model by Plis et al. [4] are promising candidates. Optimization of Systems: Systems like the Triple Fluid Heat Exchanger by Kuppusamy et al. [14] offer potential optimizations for better heat management. Nanofluid Research: Given the promising findings regarding CuO nanofluid by Salameh et al.[19], there's significant scope for more in-depth exploration into the properties and applications of nanofluids. Phase Change Systems: With the challenges identified by Sauciuc et al. [5], further research into the limitations and potential optimizations of phase change systems for heat dissipation is warranted. Advanced Simulation Tools: The introduction of precise evaluation tools, as Raffaele et al.[20] did, can streamline the design and efficiency assessment processes for heat exchangers. Material Research: Continued research into materials that offer superior heat transfer properties, as identified by Liu et al. [9] and Sixel et al. [7], will be essential for the advancement of heat exchanger technology. Neuroevolutionary Algorithms: The innovative algorithm by Ahmand et al. [12] shows promise, indicating a trend towards the confluence of artificial intelligence and thermal dynamics. 3D Printing: Sixel et al. [7]'s introduction of three-dimensional printed direct winding heat exchangers hints at the broader adoption of 3D printing in the creation of advanced heat exchangers.

IV. CONCLUSION

The realm of heat exchanger research has witnessed significant advancements in recent times, as showcased by the myriad of studies discussed. Innovations span from the microscopic design elements, such as fin optimization and nanofluid applications, to macroscopic system improvements, including modular designs and system integration. The integration of computational tools, whether it's CtFD, ANN, or novel algorithms, has notably improved the prediction, simulation, and optimization processes. As industries continue to demand better efficiency, cost-effectiveness, and environmental sustainability, these advancements pave the way. The need for real-world applications, experimental validations, and industry collaborations will be paramount to ensure the translation of these academic pursuits into tangible technological advancements.

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