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# Heat Exchangers: A Survey on Thermal Efficiency and Cost-Effective Design

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## Abstract

Heat exchangers are pivotal in optimizing thermal management across diverse industrial applications, focusing on maximizing thermal efficiency and minimizing operational costs through innovative design and material use. This survey explores the critical role of heat exchangers in sectors such as aerospace, automotive, renewable energy, and geothermal systems. It highlights advancements in computational methods, material innovations, and design strategies that enhance heat transfer efficiency. The integration of nanofluids and advanced materials, such as ionic liquids, is emphasized for their potential to improve energy conversion processes and sustainability. The survey underscores the importance of addressing fouling issues, optimizing transient response characteristics, and leveraging machine learning for predictive modeling to reduce energy consumption and operational costs. Case studies in electric vehicles and solar thermal power plants illustrate the effectiveness of heat exchangers in improving performance and safety. The study concludes that future research should focus on integrating complex fouling models, exploring topology optimization, and developing environmentally friendly heat transfer fluids to achieve greater efficiency and sustainability in thermal systems. Overall, heat exchangers remain indispensable in enhancing the efficiency and reliability of energy systems across various industrial contexts.

## 1 Introduction

### 1.1 Role of Heat Exchangers in Thermal Management

Heat exchangers are essential for managing thermal loads across various industries, ensuring efficient heat transfer and optimizing energy use. In commercial aviation, they are crucial for designing environmental control systems (ECS) that balance conflicting objectives, such as minimizing weight and entropy generation [1]. In the automotive sector, particularly for electric vehicles, heat exchangers are vital for battery thermal management, which is critical for performance and safety [2].

In renewable energy systems, heat exchangers enhance the operation of thermoelectric generators (TEGs), with material advancements being key to improving efficiency and output power [3]. They are also indispensable in fusion power plants, where effective thermal load management is necessary for converting energy from fusion reactions into usable forms [4]. In solar energy applications, heat exchangers improve operational efficiency in solar desalination systems [5].

The nuclear power industry relies on heat exchangers to address phenomena such as the boiling crisis, which can significantly impair heat transfer rates and reactor safety [6, 7]. Effective heat transfer is critical in designing primary heat exchangers for the Molten Salt Fast Reactor (MSFR) to ensure safety and efficiency [8].

In building applications, Earth-to-air heat exchangers (EAHE) are vital for energy conservation and thermal comfort, emphasizing their role in sustainable design [9]. Their significance extends to high energy density systems, such as power electronics and nuclear reactors, where boiling heat

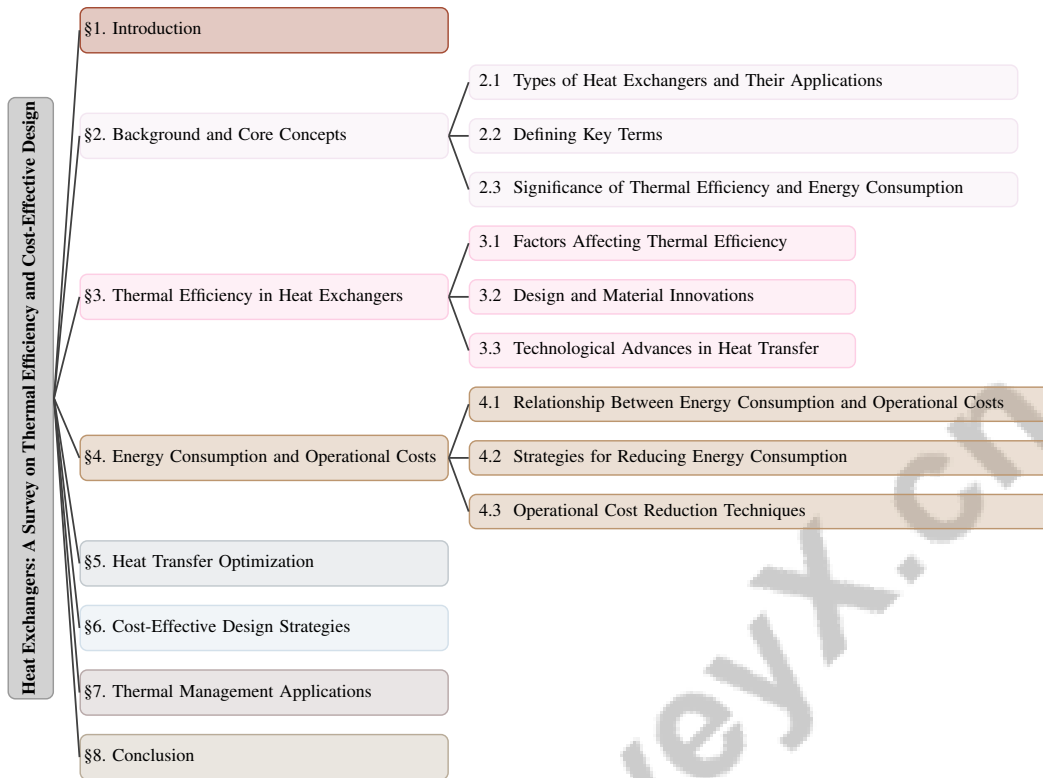


Figure 1: chapter structure

transfer is essential for effective thermal management [10]. Additionally, the thermal regulation of fiber-reinforced composites (FRC) necessitates consideration of temperature-dependent material properties in active cooling systems [11].

In the maritime industry, heat exchangers are crucial for managing thermal loads in space-constrained environments like ships [12]. The performance of cryogenic heat exchangers, particularly at liquid helium temperatures, is critical for applications requiring high effectiveness, despite existing design limitations that do not fully account for axial conduction and variable fluid properties [13]. The tube-in-tube helically coiled (TTHC) heat exchanger is preferred in specific applications, such as the helium purification system of IHEP-ADS, highlighting its importance in thermal management [14].

The emergence of ionic liquids as advanced heat transfer fluids, due to their favorable thermophysical properties, marks a significant advancement in heat exchanger technology [15]. Borehole heat exchanger arrays are also crucial for harnessing thermal energy in geothermal systems, underscoring their role in effective thermal load management [16]. Heat exchangers are thus indispensable for optimizing thermal management, enhancing the efficiency and sustainability of energy systems across diverse industrial contexts.

## 1.2 Maximizing Thermal Efficiency and Minimizing Costs

This survey aims to explore strategies that enhance the thermal efficiency of heat exchangers while simultaneously reducing operational costs, a dual objective crucial for advancing performance and sustainability across various industries. Optimizing transient response characteristics in systems like Nuclear Desalination Dual Cycle Systems (NDDDCSs) is essential for improving performance during start-up and load ramp conditions, thereby maximizing thermal efficiency [17].

In waste heat recovery, exergy analysis of CO<sub>2</sub> closed-cycle gas turbine systems reveals significant potential for improving thermal efficiency compared to traditional marine propulsion systems [18]. This underscores the importance of integrating advanced thermodynamic cycles to effectively exploit waste heat sources. The use of Particle Swarm Optimization (PSO) for determining optimal cleaning

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intervals in heat exchangers further highlights the potential for cost reduction and energy savings by maintaining system performance and minimizing energy losses [19].

Despite the benefits of open cell foams in enhancing heat transfer, their application is limited by high manufacturing costs and an incomplete understanding of transport processes within foam structures [20]. Addressing these challenges could lead to significant improvements in cost-effective heat exchanger designs. EAHEs play a pivotal role in reducing energy consumption in the building sector through passive heating and cooling systems, presenting a sustainable solution for energy-efficient building design [9].

The integration of machine learning techniques into thermal engineering offers a promising avenue for enhancing modeling accuracy and optimizing heat exchanger performance [21]. Evaluating the thermophysical properties of ionic liquid mixtures, such as [C2mim][CH3SO3], reveals their potential as efficient heat transfer fluids, providing advantages over traditional fluids [15].

The development of hybrid adaptive algorithms that adjust processing strategies based on real-time data characteristics can improve efficiency and reduce operational costs [22]. This approach aligns with the goal of leveraging technological advancements to achieve cost-effective and efficient thermal management solutions. The survey seeks to identify and evaluate innovative methodologies and technologies that contribute to maximizing thermal efficiency and minimizing costs in heat exchanger applications.

### 1.3 Structure of the Survey

This survey is designed to provide a comprehensive examination of heat exchangers, focusing on their thermal efficiency and cost-effective design. The introduction emphasizes the significance of heat exchangers in various industrial applications and their pivotal role in optimizing thermal management. Section 2 offers a background overview of different types of heat exchangers and their applications, defining key terms such as thermal efficiency, energy consumption, and operational costs, and discussing their relevance in heat exchanger applications.

Section 3 explores factors affecting thermal efficiency, including design and material innovations and technological advances in heat transfer that enhance performance. Section 4 addresses the relationship between energy consumption and operational costs, presenting strategies for reducing both in heat exchanger systems. Section 5 provides an in-depth analysis of techniques for optimizing heat transfer, focusing on computational methods—such as density-based topology optimization and level-set methods—and experimental approaches utilizing nanofluids to enhance thermophysical properties. This section also discusses the impact of design variables, flow regimes, and operating conditions on heat exchanger performance, highlighting recent advancements and methodologies aimed at maximizing heat transfer efficiency while adhering to pressure drop constraints [23, 24, 25, 26].

Section 6 discusses cost-effective design strategies, focusing on innovative design, material selection, and manufacturing processes. It examines design innovations and geometrical configurations that contribute to cost savings. Section 7 highlights the role of heat exchangers in thermal management across various industries, providing applications and case studies, particularly in renewable and geothermal energy systems, as well as in the aerospace and automotive sectors. The conclusion summarizes key findings and suggests areas for future research. The following sections are organized as shown in Figure 1.

## 2 Background and Core Concepts

### 2.1 Types of Heat Exchangers and Their Applications

Heat exchangers are pivotal in industrial applications, facilitating efficient thermal energy transfer. Their designs cater to specific needs, optimizing thermal management. Plate heat exchangers, known for compactness and efficiency, are crucial in chemical processing and food production [13]. In renewable energy, Latent Heat Thermal Energy Storage (LHTES) systems enhance solar thermal power plant efficiency [5]. Microchannel heat exchangers reduce equipment size and increase energy efficiency [27], while open cell foams promise improved heat transfer in high-energy physics [28], despite challenges in predicting their properties. Advances in superhydrophobic surfaces further enhance efficiency by mitigating the Leidenfrost effect [29].

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Cryogenic applications necessitate specialized heat exchangers for ultra-low temperatures, such as those in Joule-Thomson and Brayton cycles [30]. Metallic sinter-based designs effectively cool liquid helium [31], while cryogenic bath-type exchangers are proposed for efficient heat transfer and radon removal [32]. In geothermal systems, heat exchangers facilitate residential heating via underground thermal storage, with simulations enhancing understanding [33]. Research on inclined closed-loop buoyancy-driven exchangers and borehole heat exchangers emphasizes improved modeling and drilling accuracy [34, 16].

Incorporating polymer nanofibers into heat exchanger designs highlights the significance of molecular characteristics [35]. Deep closed-loop heat exchangers in geothermal wells are engineered for greater depths [36]. The thermodynamic efficiency of enhanced heat transfer is critical for performance optimization, as seen in studies of thermal junctions [37]. This diversity in heat exchanger types underscores their vital role across various industrial contexts.

## 2.2 Defining Key Terms

Key terms related to heat exchangers are crucial for performance analysis and optimization. Thermal efficiency measures a heat exchanger's effectiveness in heat transfer, influencing system performance [38]. Energy consumption impacts operational efficiency and costs [39], while operational costs include maintenance and energy expenses [36]. Thermal conductivity affects nanofluids' performance, highlighting the importance of temperature-dependent material properties [11]. The 'boiling crisis' in two-phase flow systems refers to a rapid temperature increase reducing heat transfer efficiency [6].

Other essential terms include pressure drop, important for understanding flow dynamics, and zeotropic mixtures used in thermal systems [40]. Entropy and exergy provide insights into thermal process efficiency [41]. Terms like density, viscosity, and thermal conductivity are vital for evaluating heat transfer performance, especially in ionic liquids [15]. Mastery of these terms facilitates the optimization of heat exchanger design and operation across applications, including aviation, energy, and thermal management in buildings. This knowledge supports innovative strategies like multi-chamber designs and machine learning-assisted modeling to enhance efficiency [21, 42].

## 2.3 Significance of Thermal Efficiency and Energy Consumption

Thermal efficiency and energy consumption are crucial in heat exchanger applications, affecting industrial processes' viability and sustainability. In cryogenic systems, optimizing thermal efficiency is essential for managing energy consumption [30]. Electric vehicles require optimal battery temperatures for energy-efficient operation [2]. Routine maintenance, such as cleaning heat exchanger networks, mitigates fouling, enhancing performance and reducing energy use [19]. Expanded microchannel heat exchangers focus on achieving high effectiveness at reduced costs [43], while advancements in aluminum heat exchangers improve thermal performance in the automotive sector [44].

Optimizing Earth-to-air heat exchangers minimizes energy loads in sustainable building design [9]. Studies on condensing flow in microtubes emphasize tailored approaches for optimizing heat transfer [45]. Challenges in thermal transport within nanocomposites, due to resistances between conductive particles and the matrix, persist [46]. Eccentric tube-in-tube helically coiled heat exchangers highlight the importance of understanding geometric factors on performance [14]. The lack of comprehensive understanding of heat transfer in stratified horizontal flows of supercritical carbon dioxide necessitates further research for universal correlations. These insights underscore the critical role of thermal efficiency and energy consumption in optimizing heat exchanger applications, driving innovation and sustainability across industrial sectors.

In recent years, the focus on enhancing thermal efficiency in heat exchangers has gained significant attention within the academic community. This emphasis is largely driven by the need to optimize energy consumption and improve overall system performance. To elucidate the complexity of factors influencing thermal efficiency, Figure 2 presents a comprehensive overview of the hierarchical structure of these factors. This figure illustrates the hierarchical structure of factors affecting thermal efficiency in heat exchangers, design and material innovations, and technological advances in heat transfer. It categorizes key aspects into design and material properties, operational challenges, innovative designs, advanced modeling techniques, and advanced techniques and materials, highlighting the relationships and contributions to overall efficiency improvements. By systematically categorizing

these elements, the figure not only provides a clear framework for understanding the multifaceted nature of thermal efficiency but also underscores the interplay between various innovations and challenges faced in the field.

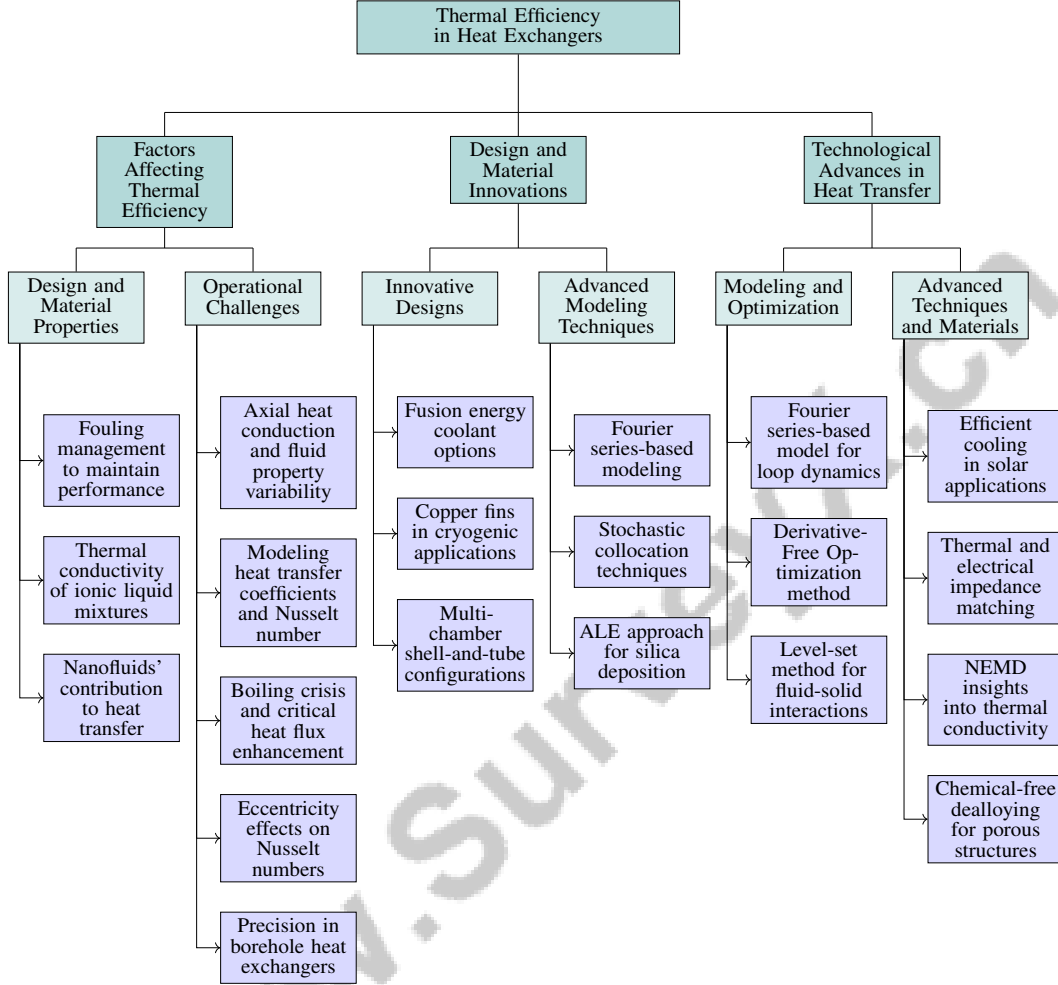


Figure 2: This figure illustrates the hierarchical structure of factors affecting thermal efficiency in heat exchangers, design and material innovations, and technological advances in heat transfer. It categorizes key aspects into design and material properties, operational challenges, innovative designs, advanced modeling techniques, and advanced techniques and materials, highlighting the relationships and contributions to overall efficiency improvements.

### 3 Thermal Efficiency in Heat Exchangers

#### 3.1 Factors Affecting Thermal Efficiency

Thermal efficiency in heat exchangers is influenced by design, material properties, and operational conditions. Colloidal silica accumulation on pipe surfaces in geothermal power stations exemplifies how fouling increases pressure loss and reduces heat transfer efficiency [47]. Thus, effective fouling management is essential for maintaining optimal performance. The thermal conductivity of materials like ionic liquid mixtures, such as [C2mim][CH<sub>3</sub>SO<sub>3</sub>], significantly impacts efficiency, with systematic measurements illustrating their potential to enhance heat transfer [15]. Nanofluids, particularly in solar applications, also contribute to improved heat transfer rates [5].

Challenges in plate-fin heat exchangers include axial heat conduction and fluid property variability at low temperatures, which impair performance and are inadequately addressed by current models [13].

Accurate modeling of heat transfer coefficients, Nusselt number, and friction factor in exchangers with twisted tape inserts is complicated by varying Reynolds numbers and twist ratios [21]. The boiling crisis, a transition from nucleate to film boiling, drastically reduces efficiency and can lead to equipment failure [7]. Enhancing critical heat flux in pool boiling remains a challenge [48].

Eccentric tube-in-tube helically coiled heat exchangers show that increased eccentricity affects Nusselt numbers, crucial for thermal efficiency [14]. Computational methods like the diffuse interface blended method enhance simulation accuracy by transitioning smoothly between solid and fluid domains [49]. Borehole heat exchangers face efficiency losses due to drilling trajectory deviations, emphasizing the need for precision [16].

Figure 3 illustrates the key factors affecting thermal efficiency in heat exchangers, categorized into design and material considerations, operational challenges, and computational methods. Each category highlights specific areas such as fouling management, axial conduction, and machine learning applications, emphasizing their impact on efficiency and performance. Addressing these factors is key to advancing thermal efficiency in industrial applications.

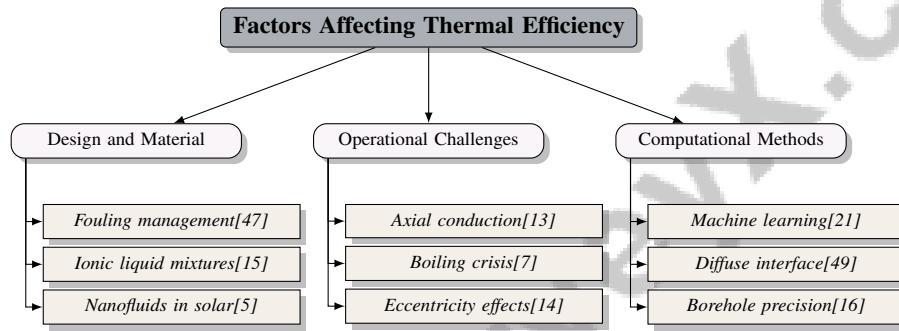


Figure 3: This figure illustrates the key factors affecting thermal efficiency in heat exchangers, categorized into design and material considerations, operational challenges, and computational methods. Each category highlights specific areas such as fouling management, axial conduction, and machine learning applications, emphasizing their impact on efficiency and performance.

### 3.2 Design and Material Innovations

Innovations in heat exchanger design and materials have led to significant improvements in thermal efficiency. In fusion energy, new coolant options and energy conversion cycles are crucial for optimizing efficiency [4]. Cryogenic applications benefit from copper fins in heat exchangers, enhancing efficiency while preventing radon emissions [32]. Material selection is critical for performance and safety in specialized applications.

Fourier series-based modeling of CNCL systems represents a major advancement, enabling accurate heat transfer predictions [34]. In geothermal applications, stochastic collocation techniques address geometric uncertainties, enhancing performance [16]. The ALE approach accurately represents silica deposition dynamics, essential for performance maintenance [47].

These innovations, including multi-chamber shell-and-tube configurations and expanded microchannel designs, enhance thermal efficiency through improved heat transfer coefficients and optimized fluid flow, while reducing production costs. Such advancements make high-performance exchangers more accessible across diverse industries, including aerospace, energy, and HVAC systems [43, 42].

### 3.3 Technological Advances in Heat Transfer

Recent technological advances have significantly enhanced heat transfer efficiency in heat exchangers. The Fourier series-based model captures coupled loop dynamics, incorporating temperature effects on fluid properties, essential for optimizing performance [50]. The Derivative-Free Optimization method effectively optimizes designs by managing complex relationships without explicit functions [51]. The level-set method enhances efficiency by accurately capturing fluid-solid interactions [26].

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In solar applications, efficient cooling of solar cells improves electrical output and utilizes thermal energy for auxiliary uses [52]. A framework considering thermal and electrical impedance matching optimizes thermoelectric systems, enhancing both thermal and electrical performance [3].

Advanced numerical methods like NEMD provide insights into thermal conductivity and interfacial properties, informing material design [46]. The MPR method refines understanding of heat transfer processes by accurately measuring intrinsic thermal conductivity [53]. Chemical-free dealloying creates porous structures without ecological drawbacks, enhancing heat transfer surfaces [54].

Plate-type heat exchangers offer higher efficiency and lower pressure drops than traditional designs [8]. The Vapor Recoil Model elucidates bubble dynamics during boiling crises, crucial for efficiency improvements [7]. Aluminum foam's enhanced surface area optimizes pool boiling heat transfer [48].

These advancements, including multi-chamber shell-and-tube exchangers and expanded microchannel designs, enhance heat transfer efficiency by integrating novel techniques and optimizing flow patterns. They address challenges across industries, offering solutions that improve heat transfer coefficients and reduce costs, leading to substantial energy savings and enhanced performance [43, 42].

## 4 Energy Consumption and Operational Costs

Analyzing energy consumption dynamics and their effects on operational costs uncovers essential elements that influence economic and functional efficiency in heat exchanger systems. The following subsections explore this relationship, focusing on strategies to optimize these parameters for improved performance and cost reduction in industrial applications.

### 4.1 Relationship Between Energy Consumption and Operational Costs

The interplay between energy consumption and operational costs is crucial for the economic and functional efficiency of heat exchanger systems. Reducing energy supply and entropy generation is vital for optimizing state transitions and stabilizing outputs, especially in port-Hamiltonian systems [41]. Enhanced thermal efficiency in transformers directly correlates with reduced energy consumption and operational costs [12]. Machine learning significantly improves predictive accuracy for heat transfer correlations, aiding in the design of energy-efficient systems [21].

To provide a comprehensive overview of the techniques and approaches that underpin this relationship, Figure 4 illustrates a hierarchical classification of various methods related to energy consumption and operational costs in heat exchanger systems. The figure categorizes these approaches into three primary groups: optimization techniques, system efficiency, and modeling approaches, each accompanied by specific examples drawn from recent research studies.

In fusion energy systems, evaluating thermal efficiency and material integrity under simulated reactor conditions highlights the impact of energy consumption on operational costs, stressing the need for efficient energy conversion [4]. Nanofluids outperform traditional methods in solar stills, illustrating the link between energy consumption improvements and reduced operational costs [5]. Incorporating wall conduction effects in CNCL system modeling significantly affects transient behavior, impacting both energy consumption and operational costs [34]. Evaluating ionic liquid mixtures like [C2mim][CH3SO3] demonstrates how physical properties influence thermal conductivity and convective heat transfer coefficients, essential for managing energy consumption [15].

Modeling complex boundary interactions without remeshing improves prediction accuracy of deposition dynamics, contributing to efficient energy use [47]. Performance stability in borehole heat exchanger arrays, despite drilling path inaccuracies, shows a nuanced relationship between drilling accuracy and operational performance, affecting energy consumption and cost efficiency [16]. Understanding and optimizing the energy consumption-operational cost relationship is vital for innovations that enhance economic viability and functional efficiency across industries like aviation, energy production, chemical processing, and HVAC systems. Key advancements include multi-chamber heat exchanger designs and machine learning for predictive modeling of heat transfer correlations, crucial for achieving improved thermal management solutions [55, 21, 42].



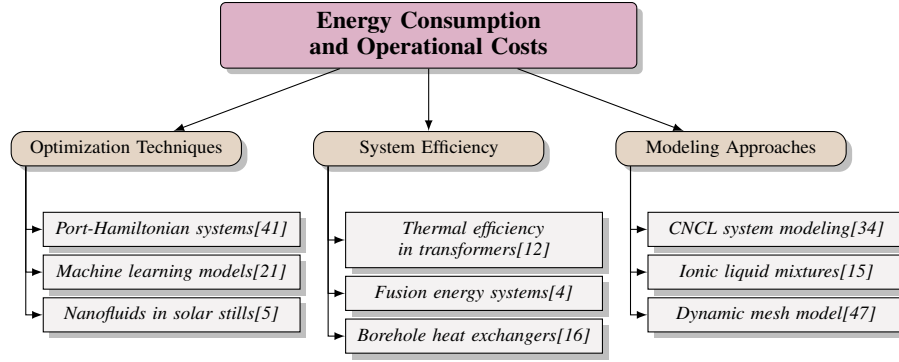


Figure 4: This figure illustrates the hierarchical classification of various techniques and approaches related to the relationship between energy consumption and operational costs in heat exchanger systems. The primary categories include optimization techniques, system efficiency, and modeling approaches, each with specific examples from recent research studies.

## 4.2 Strategies for Reducing Energy Consumption

Reducing energy consumption in heat exchangers requires advanced materials, innovative designs, and cutting-edge computational methods. Nanofluids, engineered to enhance thermal conductivity and heat transfer rates, are promising for energy reduction. The beam displacement method enables rapid and precise thermal conductivity measurements in nanofluids, crucial for optimizing their performance in heat exchanger applications [15]. Future research should focus on cost-effective synthesis methods and eco-friendly nanoparticles to further enhance nanofluid energy efficiency. Advanced computational techniques, like Derivative-Free Optimization (DFO), have optimized refrigerant circuitry designs, yielding configurations that enhance energy efficiency [21]. This method reduces computational complexity and switching overhead, making it viable for improving thermoelectric generator (TEG) modules in vehicle radiators. The CoINN method exemplifies strategies for reducing energy consumption through improved prediction accuracy and operational efficiency. In geothermal energy systems, semi- and full discretization techniques for the linear heat equation governing spatial temperature distribution are crucial for accurately modeling short-term energy dynamics. Finite difference schemes optimize energy management strategies for residential heating systems, enabling precise predictions of energy storage and retrieval capabilities, thus enhancing overall energy efficiency and operational effectiveness [56, 57, 33]. The Particle Swarm Optimization (PSO) method effectively optimizes cleaning schedules for heat exchangers, resulting in substantial cost savings and energy efficiency improvements [41]. Maintaining clean heat exchanger surfaces is crucial for minimizing energy losses due to fouling. Implementing a Luenberger observer as part of a stabilization method for parallel flow heat exchangers can also reduce operational costs through improved stability and energy efficiency. New manufacturing techniques, like 'forward conduction welding,' enable the creation of microchannels at lower costs, essential for reducing operational costs and enhancing energy efficiency [13]. Optimizing designs to balance heat transfer efficiency with pressure drop is critical for future research. The proposed WRLES method enhances understanding of the relationship between additive manufacturing (AM) surface roughness and turbulent flow dynamics, revealing how variations in roughness topography affect turbulence characteristics. This analysis establishes a high-fidelity database for evaluating novel wall models specific to AM surfaces and provides insights for optimizing cooling components in advanced engineering applications, including heat exchangers [58, 59, 60]. The 1-D semi-analytical modeling of CNCL systems facilitates easier analysis, leading to strategies for reducing energy consumption through improved design. The physical dealloying method offers ecological efficiency and simplicity, enabling the creation of porous structures on complex geometries without harmful chemicals, contributing to sustainable heat exchanger designs. Future work could explore non-ideal thermal contacts and develop materials with improved thermoelectric properties. Investigating transient dynamics of thermal regulation and integrating thermo-mechanical effects in active cooling applications are promising areas for further research [7]. Integrating advanced materials, computational methods, and optimized operational practices in heat exchanger systems holds significant potential for reducing energy consumption. Strategies like topology optimization for enhanced heat transfer efficiency, effective use of latent heat thermal energy storage (LHTES) devices, and innovative multi-chamber designs maximize heat



transfer rates while ensuring efficient operation under varying flow conditions, leading to sustainable energy management across applications, including HVAC, power generation, and industrial processes [61, 24, 42].

### 4.3 Operational Cost Reduction Techniques

Reducing operational costs in heat exchanger systems requires efficient practices and advanced optimization techniques. A notable advancement is the prediction-based approach for thermoelectric generator (TEG) reconfiguration, significantly reducing time complexity and switching overhead, achieving a 30

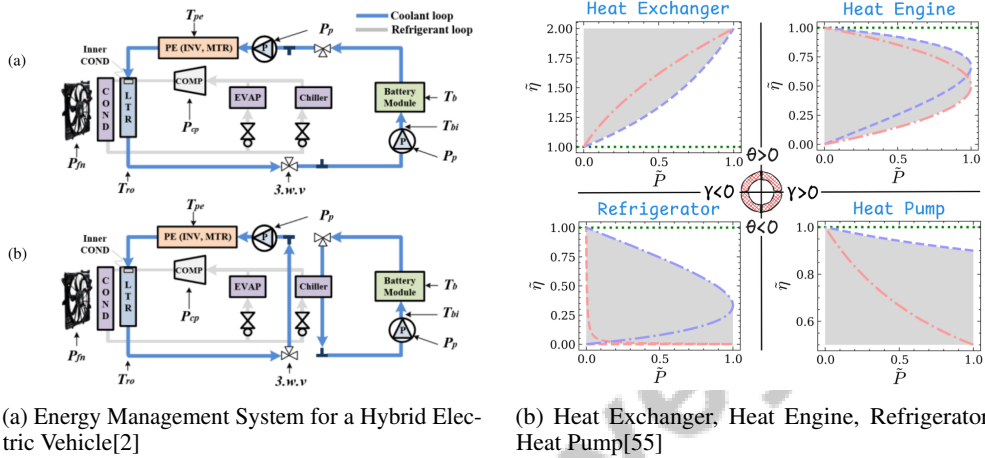


Figure 5: Examples of Operational Cost Reduction Techniques

As shown in Figure 5, the examples provided delve into energy consumption and operational costs, highlighting innovative techniques for operational cost reduction. The first part focuses on an energy management system for a hybrid electric vehicle (HEV), illustrated through a schematic diagram divided into two primary loops: the coolant and refrigerant loops. The coolant loop integrates essential components such as a condenser, evaporator, and compressor, while the refrigerant loop encompasses additional critical components. This system exemplifies strategic energy flow management within a HEV to optimize performance and reduce operational costs. The second part presents a comparative analysis of various heat transfer devices, including heat exchangers, heat engines, refrigerators, and heat pumps, distinguished by unique colored lines illustrating their efficiency as a function of pressure. This analysis provides insights into efficiency trade-offs and potential cost savings, underscoring the importance of selecting the right technology to achieve operational cost reductions in energy systems [2, 55].

## 5 Heat Transfer Optimization

### 5.1 Heat Transfer Optimization Techniques

Method Name	Optimization Techniques	Material Innovations	Application Domains
MSFC[62]	Isogeometric Analysis	Heterogeneous Materials	Heat Exchangers
NESS[5]	Computational Approaches	Nanofluids	Solar Desalination
MNRT[12]	Computational Fluid Dynamics	-	Energy Transformers
DEM-FEM[63]	Discrete Element Method	-	Heat Exchangers

Table 1: Overview of optimization techniques and material innovations applied in heat transfer systems, highlighting their application domains. The table categorizes methods such as Isogeometric Analysis and Computational Fluid Dynamics, alongside material advancements like nanofluids, illustrating their role in enhancing thermal efficiency across various sectors.

Optimizing heat transfer in exchangers demands a blend of computational methods, material innovations, and analytical techniques. This figure illustrates the primary techniques for optimizing

heat transfer, categorized into these three domains. Manipulating micro-tile geometry and material properties enhances performance metrics such as heat transfer and weight reduction [62]. Nanofluids significantly boost thermal efficiency and evaporation rates, especially in solar stills, by enhancing the thermal properties of working fluids [5]. Advanced numerical modeling and simulations are vital for optimizing cooling efficiency, as demonstrated in exhaust configuration analyses [12]. Simulating particle packing and calculating thermal conductivity based on particle interactions improve thermal conductivity in monodispersed systems, guiding material development with superior thermal characteristics [63].

These techniques collectively enhance heat transfer efficiency, driving innovations across sectors such as aviation, energy, chemical processing, and renewable energy. Multi-chamber designs in shell-and-tube exchangers improve hydraulic and thermal entrance region utilization, increasing heat transfer coefficients and capacities. Nanofluids optimize heat transfer in devices like solar collectors and refrigeration systems, addressing longstanding challenges and paving the way for advancements in thermal management technologies [25, 42].

As shown in Figure 6, diverse techniques enhance thermal system efficiency. The first example features a copper heat exchanger with high thermal conductivity, facilitating effective heat exchange through intricate tube arrangements. The second example represents heat distribution and flow dynamics via colorful circles and patterns. Lastly, the third example showcases a 3D model with hollow chambers, highlighting advanced design strategies for optimizing heat transfer through spatial configuration, applicable in fields like architecture and engineering [51, 64, 26]. Each category in the figure underscores key approaches such as micro-tile geometry, nanofluids, and advanced numerical modeling, showcasing their contributions to enhancing thermal efficiency across various applications. Additionally, Table 1 provides a comprehensive summary of the key methods and material innovations employed in optimizing heat transfer, detailing their specific techniques and application domains.

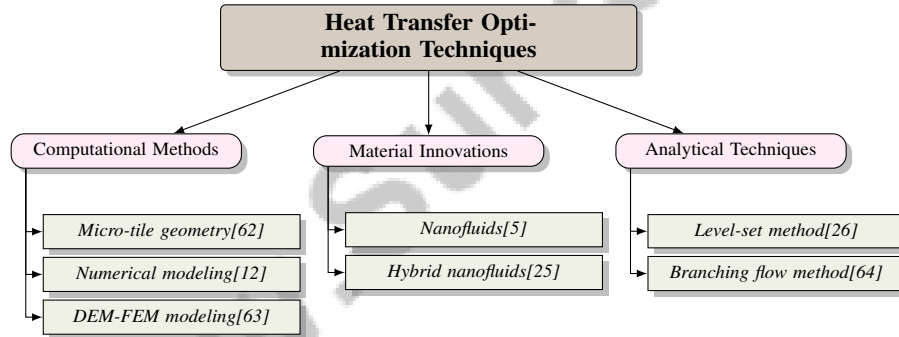


Figure 6: This figure illustrates the primary techniques for optimizing heat transfer, categorized into computational methods, material innovations, and analytical techniques. Each category highlights key approaches such as micro-tile geometry, nanofluids, and advanced numerical modeling, showcasing their contributions to enhancing thermal efficiency across various applications.

## 5.2 Computational Methods for Heat Transfer Optimization

Recent computational advancements have significantly enhanced heat transfer performance in exchangers. Sarkar et al.'s physics-informed approach predicts fine mesh data features from coarse mesh data, improving accuracy in heat transfer simulations [65]. Machine learning algorithms optimize heat transfer processes by developing predictive models that simulate thermal behavior in systems like electric vehicle thermal management and heat exchangers [27, 39, 61, 21, 2]. Advanced numerical methods, such as the level-set method, model fluid interactions and boundary conditions critical for optimizing heat transfer efficiency [21, 27].

Integrating advanced computational techniques, including topology optimization and machine learning, significantly enhances heat transfer performance. These approaches, encompassing multi-chamber designs and data-driven modeling of thermohydraulic correlations, offer effective solutions for improving efficiency across sectors like aerospace, energy, and food processing. By maximizing heat transfer rates while managing pressure drop constraints, these methodologies optimize exchanger designs and enhance practical performance [23, 24, 21, 42].

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### 5.3 Experimental Approaches and Analytical Models

Experimental methods and analytical models are crucial for optimizing heat transfer in exchangers, providing insights into thermal system dynamics. Advanced setups like the Modified Pulse Reflectometry (MPR) method measure thermal conductivity and convective heat transfer coefficients, characterizing nanofluids' thermal properties [5]. Fourier series-based models simulate transient behavior, guiding exchanger design and optimization [34]. Integrating CFD simulations with experimental data enhances model accuracy, predicting thermal performance under diverse conditions.

Numerical methods addressing wall and axial heat conduction in plate-fin exchangers tackle challenges in low-temperature applications, optimizing designs by capturing thermal and fluid dynamics interactions [13]. The diffuse interface blended method simulates multiphase flow and heat transfer without complex mesh adjustments, providing a stable framework for modeling heat exchanger dynamics [49].

Combining experimental methodologies with analytical techniques, such as machine learning and topology optimization, enriches understanding of heat transfer optimization. This approach drives innovations in exchanger technology, evidenced by improved heat transfer coefficients and optimized designs yielding performance gains of up to 113

## 6 Cost-Effective Design Strategies

### 6.1 Innovative Design and Material Use

The development of cost-effective heat exchanger solutions hinges on innovative design and material use, which enhance thermal efficiency and operational performance. Advanced computational techniques, like the integration of Discrete Element Method (DEM) and Finite Element Method (FEM), facilitate accurate modeling of thermal conductivity by accounting for realistic particle packing structures [63]. This highlights the role of computational modeling in refining design strategies for improved efficiency.

Nanofluids in heat exchangers connected to solar stills represent a significant innovation, boosting thermal conductivity and heat transfer rates, thereby enhancing efficiency in renewable energy systems [5]. Numerical modeling of plate-fin heat exchangers indicates an optimal thermal conductivity of around 3.5 W/m-K, emphasizing the importance of precise material selection for high-performance designs [13].

Future research in polymers should focus on new filler materials, optimized filler distribution, and theoretical models to predict thermal conductivity in polymer nanocomposites [35]. This underscores the importance of material innovation in thermal management solutions. Moreover, numerical models for simulating and optimizing exhaust fans and heat exchangers are crucial for effective thermal management across industries [12]. In fusion power plants, integrating materials, coolants, and energy conversion systems is vital, highlighting the significance of innovative design strategies in energy-intensive applications [4].

Rapid modeling of conjugate natural convection loop (CNCL) systems using Fourier series techniques offers a cost-effective alternative to complex 3-D simulations, facilitating efficient design and optimization of thermal systems [34]. Statistical analysis of drilling inaccuracies provides insights for geothermal system design, optimizing borehole heat exchanger arrays for efficient thermal energy extraction [16]. Innovative applications of materials and design strategies show significant potential for achieving cost-effective solutions that enhance thermal efficiency, as demonstrated by convective meta-thermal concentration in Stirling engines, improving efficiency by up to 1460% [43, 62, 38, 66].

### 6.2 Material Selection and Manufacturing Processes

Material selection and manufacturing processes critically impact the cost-effective design of heat exchangers, influencing thermal performance, durability, and economic viability. The evolution of heat exchangers is marked by material types, such as aluminum versus copper, and manufacturing techniques like brazing and multilayer materials [44]. This underscores the necessity of selecting appropriate materials and processes to optimize thermal efficiency and minimize costs.

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The choice between aluminum and copper is crucial in applications where weight and corrosion resistance are important. Aluminum's lightweight and high thermal conductivity make it suitable for automotive and aerospace applications, while copper's superior thermal and electrical conductivity is ideal for high-performance applications [44]. Advanced brazing techniques and multilayer materials enhance structural integrity and thermal performance, enabling compact and efficient designs.

Manufacturing processes significantly influence the cost-effectiveness of heat exchanger designs. Dimensions, such as approximately 2.0 m in height, 1.5 m in length, and 0.7 m in width, are dictated by application requirements, necessitating precise manufacturing techniques for optimal performance [8]. The variability of heat transfer coefficients under different conditions poses manufacturing challenges, as current studies lack a universal correlation, leading to prediction deviations [67]. Addressing these challenges requires standardized manufacturing processes accommodating diverse conditions.

Innovative manufacturing techniques, such as physical dealloying, offer ecological efficiency and simplicity, enabling the creation of porous structures on complex geometries without harmful chemicals [54]. This method applies to various thermal management equipment, representing a sustainable approach to enhancing thermal performance while minimizing environmental impact.

Strategic material selection, such as advanced polymers and aluminum alloys, alongside innovative manufacturing processes like forward conduction welding and brazing, is crucial for developing cost-effective heat exchanger designs. These designs must meet contemporary industrial applications' stringent performance and durability requirements, including resistance to thermal shocks, pressure fluctuations, and mechanical vibrations. Advancements in microchannel heat exchanger technology demonstrate potential for enhanced effectiveness and reduced production costs, underscoring the importance of integrating modern materials and techniques to optimize energy efficiency and performance [43, 44].

### 6.3 Design Innovations and Geometrical Configurations

Design innovations and geometrical configurations are key to enhancing heat exchangers' efficiency and cost-effectiveness. Advanced design strategies enable substantial improvements in thermal performance and operational efficiency. Topology optimization, which uses a single design variable to represent fluids and the solid interface, allows for complex geometrical configurations that enhance heat transfer, contributing to cost savings and improved energy efficiency [24].

Cryogenic applications require high heat transfer efficiency for necessary liquefaction rates while maintaining ultra-purity standards. Proposed cryogenic bath-type heat exchangers offer high efficiency, crucial for these applications [32]. Additionally, improvements in plate-fin heat exchanger design through considerations of axial conduction and variable properties enhance their effectiveness, ensuring more accurate designs [13].

Innovative design strategies are vital for optimizing refrigeration systems, where balancing cost and energy efficiency is essential. Current research highlights optimization gaps, indicating the need for innovative design strategies to address these challenges [30]. In geothermal applications, analytical expressions for moving infinite media have significantly improved computational efficiency for thermal modeling, facilitating effective design and optimization [56].

The application of Earth-to-air heat exchangers (EAHE) in building design emphasizes comprehensive experimental validation to address performance variability, highlighting the need for innovative configurations that adapt to different environmental conditions, enhancing energy efficiency and reducing operational costs [9].

Integrating advanced design innovations, such as multi-chamber configurations and topology optimization techniques, significantly enhances thermal performance by improving heat transfer efficiency and maximizing heat exchange between fluids. These innovations lead to substantial reductions in operational costs and promote sustainability and economic viability across various industrial applications, including aviation, energy, chemical processing, and HVAC systems. Research indicates that optimized shell-and-tube heat exchangers can achieve performance improvements of up to 113

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## 7 Thermal Management Applications

### 7.1 Applications and Case Studies

Heat exchangers are indispensable in diverse industrial sectors for effective thermal management. In aerospace, they are integral to aircraft environmental control systems, ensuring thermal stability and passenger comfort under varying conditions [1]. In the automotive industry, particularly for electric vehicles, they are crucial for battery thermal management, where supervised learning-based strategies enhance performance and safety [2]. Their role in prolonging battery life and improving vehicle efficiency is paramount.

In renewable energy systems, heat exchangers enhance thermoelectric generator efficiency by utilizing advanced materials for better waste heat conversion [3]. In nuclear power, they are vital for preventing the boiling crisis, ensuring reactor safety and reliability [6, 7].

Earth-to-air heat exchangers (EAHE) in building designs exemplify their role in energy conservation, reducing energy consumption through passive heating and cooling [9]. In maritime applications, innovations like cryogenic heat exchangers are crucial for managing thermal loads in space-constrained environments [13]. Additionally, the use of ionic liquids as heat transfer fluids offers enhanced thermophysical properties [15]. These applications underscore the multifaceted roles of heat exchangers in optimizing thermal management and contributing to environmental sustainability [24, 9, 42].

### 7.2 Heat Exchangers in Renewable and Geothermal Energy Systems

Heat exchangers enhance the efficiency of renewable and geothermal energy systems by optimizing energy conversion and thermal management. In solar thermal power plants, they facilitate energy transfer and storage, with Latent Heat Thermal Energy Storage (LHTES) systems improving energy density and efficiency [5]. In geothermal applications, borehole heat exchangers utilize underground thermal storage for sustainable heating, with numerical simulations optimizing performance [33].

In thermoelectric generators (TEGs), heat exchangers improve energy conversion efficiency by leveraging material advancements for better waste heat exploitation [3]. Deep closed-loop heat exchangers enhance geothermal heating efficiency by accessing higher temperature gradients [36].

Their integration in renewable systems is vital for improving efficiency and advancing sustainable technologies. Earth-to-air heat exchangers reduce heating and cooling loads, enhancing indoor comfort and urban environmental quality. The use of nanofluids further improves thermal performance in solar energy applications [9, 36, 25, 42, 16]. Through innovative design and material selection, heat exchangers continue to enhance energy system efficiency and reliability, contributing to sustainable solutions.

### 7.3 Thermal Management in Aerospace and Automotive Industries

In aerospace and automotive industries, heat exchangers maintain optimal thermal conditions for efficient system operation. In aerospace, they are key to environmental control systems, managing thermal loads to ensure passenger comfort and optimize conflicting objectives like weight and entropy generation [1]. Their ability to handle varying conditions is essential for aircraft performance, necessitating advanced designs.

In the automotive sector, particularly for electric vehicles, heat exchangers are crucial for battery thermal management, preventing overheating and ensuring longevity. Supervised learning-based approaches develop optimal strategies, enhancing efficiency [2]. Aluminum heat exchangers, driven by advancements in brazing and material properties, showcase efforts to improve performance and reduce energy loads [44]. Their lightweight and high conductivity make them ideal for efficiency and weight reduction.

The development of expanded microchannel heat exchangers represents a significant advancement, offering high effectiveness at reduced costs [43]. These designs optimize heat transfer while minimizing fluid volume, leading to efficient thermal management solutions.

In aerospace and automotive industries, heat exchangers are critical for optimizing thermal management, enhancing performance, and ensuring safety and reliability. Innovations in design and

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materials, such as multi-chamber configurations and architected lattice materials, significantly enhance efficiency, supporting sustainable technology evolution [43, 58, 42, 44].

## 8 Conclusion

Heat exchangers are integral to improving thermal management across numerous industries, offering significant advancements in thermal efficiency and cost reduction through innovative design, advanced materials, and computational techniques. The strategic placement and sizing of heat exchangers are crucial, with future research needed to explore both centralized and distributed configurations to optimize the balance between cost and performance. Enhancements in transformer cooling efficiency, as demonstrated by the increased use of exhaust fans, highlight the potential for significant temperature reduction within systems. In fusion power plants, innovative material use and energy conversion methods address design and operational challenges, while the application of nanofluids in solar stills suggests promising avenues for performance optimization. The development of new modeling approaches and the characterization of advanced heat transfer fluids underscore the potential for eco-friendly solutions. Continued advancements in design, material selection, and computational methods are essential for achieving greater efficiency and sustainability in thermal systems. Future research should aim to integrate complex fouling models and real-time data analytics, alongside exploring the potential of topology optimization to adapt to diverse design requirements.

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## References

- [1] Paul Feliot, Yves Le Guennec, Julien Bect, and Emmanuel Vazquez. Design of a commercial aircraft environment control system using bayesian optimization techniques, 2016.
- [2] Youngjin Kim. Supervised-learning-based optimal thermal management in an electric vehicle, 2019.
- [3] Y. Apertet, H. Ouerdane, O. Glavatskaya, C. Goupil, and Ph. Lecoœur. Optimal working conditions for thermoelectric generators with realistic thermal coupling, 2011.
- [4] M. Kovari, C. Harrington, I. Jenkins, and C. Kiely. Converting energy from fusion into useful forms, 2013.
- [5] Omid Mahian, Ali Kianifar, Saeed Zeinali Heris, Dongsheng Wen, Ahmet Z Sahin, and Somchai Wongwises. Nanofluids effects on the evaporation rate in a solar still equipped with a heat exchanger. *Nano energy*, 36:134–155, 2017.
- [6] Vadim Nikolayev and Daniel Beysens. Boiling crisis and non-equilibrium drying transition, 2016.
- [7] Vadim Nikolayev, D Beysens, Y Garrabos, C Lecoutre, and D Chatain. Bubble spreading during the boiling crisis: modelling and experimenting in microgravity, 2016.
- [8] Ugur Kose, Ufuk Koç, LATİFE ERBAY, Erdem Ogut, and Huseyin Ayhan. Heat exchanger design studies for molten salt fast reactor. *EPJ Nuclear Sciences & Technologies*, 5, 2019.
- [9] Giouli Mihalakakou, Manolis Souliotis, Maria Papadaki, George Halkos, John Paravantis, Sofoklis Makridis, and Spiros Papaefthimiou. Applications of earth-to-air heat exchangers: A holistic review, 2021.
- [10] Yang Liu, Nam Dinh, Yohei Sato, and Bojan Niceno. Data-driven modeling for boiling heat transfer: using deep neural networks and high-fidelity simulation results, 2018.
- [11] K. Adhikari, J. F. Patrick, and K. B. Nakshatrala. Effect of temperature-dependent material properties on thermal regulation in microvascular composites, 2024.
- [12] Anderson Santos Nunes, Allan Schwanz, Eduardo Postali, and Marcelo Kruger. Análise térmicafluidodinâmica de um transformador de energia a seco através da dinâmica dos fluidos computacional, 2019.
- [13] B. J. Hansen, M. J. White, and A. Klebaner. Plate fin heat exchanger model with axial conduction and variable properties, 2012.
- [14] Jianqin Zhang and Shaopeng Li. Numerical studies of an eccentric tube-in-tube helically coiled heat exchanger for ihp-ads helium purification system, 2014.
- [15] Francisco E. B. Bioucas, Carla S. G. P. Queirós, Daniel Lozano-Martín, M. S. Ferreira, Xavier Paredes, Ângela F. Santos, Fernando J. V. Santos, Manuel L. M. Lopes, Isabel M. S. Lampreia, Maria José V. Lourenço, Carlos A. Nieto de Castro, and Klemens Massonne.  $[c_2mim][ch_3so_3]$  – a suitable new heat transfer fluid? part 2: Thermophysical properties of its mixtures with water, 2024.
- [16] Philipp Steinbach, Daniel Otto Schulte, Bastian Welsch, Ingo Sass, and Jens Lang. Quantification of bore path uncertainty in borehole heat exchanger arrays, 2021.
- [17] Wian Strydom, Johannes Pretorius, and Ryno Laubscher. Start-up and transient response characteristics of natural draft direct dry cooling systems at various scales, 2023.
- [18] Vedran Mrzljak, Igor Poljak, Jasna Prpić-Oršić, and Maro Jelić. Exergy analysis of marine waste heat recovery co2 closed-cycle gas turbine system, 2020.
- [19] Totok R. Biyanto, Sumitra Wira Suganda, Matraji, Yerry Susatio, Heri Justiono, and Sarwono. Cleaning schedule optimization of heat exchanger networks using particle swarm optimization, 2015.



- 
- [20] Prashant Kumar. Investigation of kelvin-like solid foams for potential engineering applications: An attractive set of geometrical and thermo-hydraulic properties, 2014.
- [21] J. P. Panda, B. Kumar, A. K. Patil, and M. Kumar. Machine learning assisted modeling of thermohydraulic correlations for heat exchangers with twisted tape inserts, 2022.
- [22] Je-Hyeong Bahk, Thiraj D. Mohankumar, Abhishek Saini, and Sarah J. Watzman. Performance evaluation and optimization of air-to-air thermoelectric heat pump system, 2024.
- [23] Hiroki Kobayashi, Kentaro Yaji, Shintaro Yamasaki, and Kikuo Fujita. Topology design of two-fluid heat exchange, 2020.
- [24] Lukas Christan Høghøj, Daniel Ruberg Nørhave, Joe Alexandersen, Ole Sigmund, and Casper Schousboe Andreasen. Topology optimization of two fluid heat exchangers, 2020.
- [25] Eric C Okonkwo, Ifeoluwa Wole-Osho, Ismail W Almanassra, Yasser M Abdullatif, and Tareq Al-Ansari. An updated review of nanofluids in various heat transfer devices. *Journal of Thermal Analysis and Calorimetry*, 145:2817–2872, 2021.
- [26] Miguel A. Salazar de Troya, Daniel A. Tortorelli, Julian Andrej, and Victor A. Beck. Three-dimensional topology optimization of heat exchangers with the level-set method, 2021.
- [27] Tullio Traverso, Francesco Coletti, Luca Magri, Tassos G. Karayiannis, and Omar K. Matar. A machine learning approach to the prediction of heat-transfer coefficients in micro-channels, 2023.
- [28] Aitor Amatriain, Corrado Gargiulo, and Gonzalo Rubio. Numerical and experimental study of open-cell foams for the characterization of heat exchangers, 2023.
- [29] Meng Shi, Ratul Das, Sankara Arunachalam, and Himanshu Mishra. Unexpected suppression of leidenfrost phenomenon on superhydrophobic surfaces, 2021.
- [30] A. Alekseev. Basics of low-temperature refrigeration, 2015.
- [31] J. Pollanen, H. Choi, J. P. Davis, B. T. Rolfs, and W. P. Halperin. Low temperature thermal resistance for a new design of silver sinter heat exchanger, 2008.
- [32] M. Murra, D. Schulte, I. Cristescu, J. M. Disdier, C. Huhmann, D. Tatananni, and C. Weinheimer. Cryogenic bath-type heat exchangers for ultra-pure noble gas applications, 2022.
- [33] Paul Honore Takam, Ralf Wunderlich, and Olivier Menoukeu Pamen. Short-term behavior of a geothermal energy storage: Modeling and theoretical results, 2023.
- [34] Akhil Dass and Sateesh Gedupudi. Fourier series based modeling of the dynamics of inclined closed loop buoyancy driven heat exchangers with conjugate effect, 2020.
- [35] Congliang Huang, Xin Qian, and Ronggui Yang. Thermal conductivity of polymers and polymer nanocomposites, 2018.
- [36] Mark McClure. Technical barriers for deep closed-loop geothermal, 2023.
- [37] Karen Hovhannisyan and Armen E. Allahverdyan. Thermodynamics of enhanced heat transfer: a model study, 2010.
- [38] Y. Apertet, H. Ouerdane, C. Goupil, and Ph. Lecoer. Comment on "effective thermal conductivity in thermoelectric materials", 2014.
- [39] Dennis Kibalama, Yuxing Liu, Stephanie Stockar, and Marcello Canova. Model predictive control for automotive climate control systems via value function approximation, 2021.
- [40] J. A. Montanez-Barrera, J. M. Barroso-Maldonado, A. F. Bedoya-Santacruz, and Adrian Mota-Babiloni. Correlated-informed neural networks: a new machine learning framework to predict pressure drop in micro-channels, 2022.
- [41] Friedrich Philipp, Manuel Schaller, Karl Worthmann, Timm Faulwasser, and Bernhard Maschke. Optimal control of port-hamiltonian systems: energy, entropy, and exergy, 2024.

- 
- [42] Alexey Andrianov, Alexander Ustinov, and Dmitry Loginov. Improvement of heat exchanger efficiency by using hydraulic and thermal entrance regions, 2018.
- [43] David C. Denkenberger, Michael J. Brandemuehl, Joshua M. Pearce, and John Zhai. Expanded microchannel heat exchanger: design, fabrication and preliminary experimental test, 2012.
- [44] Zbigniew Mirski and Jarosław Pabian. Modern trends in production of brazed heat exchangers for automotive industry. *Welding Technology Review*, 89(8), 2017.
- [45] Abdolali K Sadaghiani. Parametric study on hydrothermal properties of condensing flow in microtube heat exchangers using numerical and experimental approaches, 2021.
- [46] Alessandro Di Pierro, Maria Mar Bernal, Diego Martinez, Bohayra Mortazavi, Guido Saracco, and Alberto Fina. Aromatic molecular junctions between graphene sheets: a molecular dynamics screening for enhanced thermal conductance, 2019.
- [47] James N. Hewett and Mathieu Sellier. Modelling ripple morphodynamics driven by colloidal deposition, 2018.
- [48] K. Mondal and A. Bhattacharya. Recent advances on pool boiling heat transfer processes, 2021.
- [49] Tanyakarn Treeratanaphitak and Nasser Mohieddin Abukhdeir. Diffuse-interface blended method for imposing physical boundaries in two-fluid flows, 2023.
- [50] Prasanth Subramaniyan, Akhil Dass, Shivangi Tiwari, and Sateesh Gedupudi. Fourier series-based modelling of the effects of thermal coupling on the transient dynamics of component loops in a coupled natural circulation loop, 2023.
- [51] Nikolaos Ploskas, Christopher Laughman, Arvind U. Raghunathan, and Nikolaos V. Sahinidis. Optimization of circuitry arrangements for heat exchangers using derivative-free optimization, 2017.
- [52] IK Karathanassis, E Papanicolaou, V Belessiotis, and GC Bergeles. Design and experimental evaluation of a parabolic-trough concentrating photovoltaic/thermal (cpvt) system with high-efficiency cooling. *Renewable Energy*, 101:467–483, 2017.
- [53] Jian Zeng, Ka Man Chung, Sarath Reddy Adapa, Tianshi Feng, and Renkun Chen. In-situ thermal transport measurement of flowing fluid using modulated photothermal radiometry, 2021.
- [54] Artem Nikulin, Yaroslav Grosu, Jean-Luc Dauvergne, Asier Ortuondo, and Elena Palomo del Barrio. Physical dealloying for two-phase heat transfer applications: pool boiling case, 2023.
- [55] Yu-Han Ma and Cong Fu. Unified approach to power-efficiency trade-off of generic thermal machines, 2024.
- [56] Philippe Pasquier and Louis Lamarche. Analytic expressions for the moving infinite line source model, 2022.
- [57] Jasleen Kaur, Ramandeep S. Johal, and Michel Feidt. Thermoelectric generator in endoreversible approximation: the effect of heat-transfer law under finite physical dimensions constraint, 2021.
- [58] M. Pelacci, A. G. Robins, and S. Szyniszewski. Drag reduction of a circular cylinder through the use of an architected lattice material, 2021.
- [59] Victor Coppo Leite and Elia Merzari. A new rans correction to account for varying viscosity effects, 2021.
- [60] Himani Garg, Lei Wang, Guillaume Sahut, and Christer Fureby. Large eddy simulations of fully-developed turbulent flows over additively manufactured rough surfaces, 2023.
- [61] Kedar Prashant Shete, S. M. de Bruyn Kops, Dragoljub, and Kosanovic. A physics-based scaling of the charging rate in latent heat thermal energy storage devices, 2020.

- 
- [62] Pablo Antolin, Annalisa Buffa, Elaine Cohen, John F. Dannenhoffer, Gershon Elber, Stefanie Elgeti, Robert Haimes, and Richard Riesenfeld. Optimizing micro-tiles in micro-structures as a design paradigm, 2019.
- [63] Jian Zeng, Ka Man Chung, Xintong Zhang, Sarath Adapa, Tianshi Feng, Yu Pei, and Renkun Chen. Thermal conductivity modeling of monodispersed microspheres using discrete element method, 2021.
- [64] Ian Tobasco. Optimal cooling of an internally heated disc, 2022.
- [65] Rajat Kumar Sarkar, Ritam Majumdar, Vishal Jadhav, Sagar Srinivas Sakhinana, and Venkataramana Runkana. Redefining super-resolution: Fine-mesh pde predictions without classical simulations, 2023.
- [66] Xinchun Zhou, Xiang Xu, Xiaoping Ouyang, and Jiping Huang. Convective meta-thermal concentration for ultrahigh efficient stirling engine with waste heat and cold utilization, 2024.
- [67] Luisa F Cabeza, Alvaro de Gracia, A Inés Fernández, and Mohammed M Farid. Supercritical co<sub>2</sub> as heat transfer fluid: A review. *Applied thermal engineering*, 125:799–810, 2017.

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