

Advancements in Heat Exchanger Design for Improved HVAC System Efficiency

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Abstract

Due to their direct impact on usage of energy, operational effectiveness, and environmental sustainability, heat exchangers have become vital components of the air conditioning, ventilation, and heating (HVAC) systems. The growing demand for energy-efficient HVAC solutions has driven extensive research and development efforts aimed at improving heat exchanger performance. Traditional designs, such as shell-and-tube and fin-and-tube heat exchangers, have long been utilized in HVAC applications. Nevertheless, these traditional types frequently display shortcomings in terms of compactness, water drop, and heat transfer efficiencies. Recent innovations in heat exchanger technology have introduced advanced materials, optimized geometries, and novel heat transfer mechanisms, leading to significant enhancements in system performance. The adoption of microchannel heat exchangers has enabled greater heat transfer efficiency due to their increased surface area and improved fluid dynamics. Additionally, the integration of phase-change materials (PCMs) allows for effective thermal energy storage, reducing energy fluctuations and peak loads in HVAC systems. Additive manufacturing, or 3D printing, has further revolutionized heat exchanger fabrication by enabling complex, lightweight, and highly efficient designs that were previously unattainable with traditional manufacturing methods. Promising options for improving energy efficiency include hybrid heat exchangers, which integrate thermoelectric circuits or many heat transfer steps. Moreover, the rise of smart HVAC technologies has facilitated the incorporation of IoT-based monitoring systems, enabling real-time performance optimization and predictive maintenance to enhance system reliability and longevity. This review provides an in-depth analysis of these key advancements in heat exchanger design, exploring their impact on HVAC efficiency, cost reduction, and environmental sustainability. Additionally, emerging trends and future research directions are discussed, emphasizing the continued evolution of energy-efficient and eco-friendly HVAC solutions to meet global energy challenges.

Keywords: Heat exchanger technology, HVAC system efficiency, thermal energy transfer, advanced heat transfer materials, phase-change materials (PCMs), smart HVAC innovations

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Received Date: March 07, 2025

Accepted Date: March 10, 2025

Published Date: March 21, 2025

Citation: Shubham Mishra. Advancements in Heat Exchanger Design for Improved HVAC System Efficiency. Journal of Refrigeration, Air Conditioning, Heating and Ventilation. 2025; 12(1): 44–52p.

INTRODUCTION

The growing demand for energy-efficient heating, ventilation, and air conditioning (HVAC) systems has led to significant advancements in heat exchanger technology. As HVAC systems are responsible for a large portion of energy consumption in residential, commercial, and industrial buildings, improving heat exchanger efficiency is a critical factor in reducing energy use, operational costs, and environmental impact. Heat exchangers facilitate the transfer of heat between fluids, playing a vital role in regulating temperature and optimizing system performance.

Traditional heat exchangers, such as fin-and-tube and shell-and-tube designs, have been widely used due to their reliability and well-established manufacturing processes. However, these conventional designs often present limitations, including suboptimal heat transfer rates, excessive pressure drops, and large spatial requirements. The inefficiencies in these systems contribute to increased energy consumption, higher operational costs, and a greater environmental footprint. As global energy regulations become more stringent, industries are seeking alternative solutions to improve the efficiency and sustainability of HVAC systems [1].

Recent advancements in heat exchanger technology have focused on developing compact, high-performance designs that maximize heat transfer efficiency while minimizing energy losses. New materials, such as advanced metal alloys and polymer composites, have been introduced to improve thermal conductivity, corrosion resistance, and durability. Additionally, the integration of enhanced heat transfer fluids, including nanofluids and phase-change materials (PCMs), has allowed for better thermal management and reduced energy fluctuations.

Innovations in heat exchanger geometry have also played a crucial role in improving system efficiency. Microchannel heat exchangers, for example, utilize small-diameter tubes and enhanced surface structures to increase heat transfer rates while reducing overall system weight and footprint. These compact heat exchangers are particularly beneficial for applications requiring high thermal performance in limited spaces, such as automotive air conditioning and small-scale refrigeration systems [2].

Another transformative development in heat exchanger design is the use of additive manufacturing, or 3D printing, which allows for the creation of intricate geometries optimized for maximum heat transfer. Unlike traditional manufacturing methods, additive manufacturing enables the production of lightweight, customized heat exchangers with enhanced surface features that improve fluid dynamics and heat dissipation.

Additionally, hybrid heat exchangers that integrate multiple heat transfer mechanisms, such as thermoelectric elements or multi-fluid systems, have demonstrated significant potential in enhancing HVAC efficiency. These designs allow for more effective heat recovery and energy conservation, making them particularly suitable for sustainable building applications.

Beyond physical design improvements, the rise of smart HVAC technologies has introduced intelligent monitoring and control systems that enhance heat exchanger performance. The incorporation of Internet of Things (IoT) sensors enables real-time data collection, predictive maintenance, and adaptive thermal management, ensuring optimal efficiency under varying operational conditions.

FUNDAMENTAL PRINCIPLES OF HEAT EXCHANGER DESIGN

Heat exchangers are critical components in HVAC systems, responsible for transferring thermal energy between fluids to achieve heating or cooling. Their performance depends on the optimization of heat transfer mechanisms and design parameters that influence efficiency, pressure drop, and overall system performance. A well-designed heat exchanger maximizes heat transfer while minimizing energy losses and material costs. To achieve this, engineers focus on improving three fundamental heat transfer mechanisms: conduction, convection, and radiation. Additionally, performance metrics such as effectiveness, overall heat transfer coefficient, pressure drop, and compactness ratio are used to evaluate heat exchanger efficiency and suitability for specific HVAC applications [3].

Heat Transfer Mechanisms

Heat exchangers rely on three primary modes of heat transfer:

1. *Conduction*: This is the transfer of heat through a solid material without any movement of the substance itself. It follows Fourier's Law:

$$q = -kA \frac{dT}{dx}$$

Where:

- q = Heat transfer rate (W),
- k = Thermal conductivity of the material (W/m·K),
- A = Cross-sectional area (m²), and
- $\frac{dT}{dx}$ = Temperature gradient (K/m).

Metals with high thermal conductivity, such as copper and aluminium, are commonly used in heat exchangers to facilitate efficient conduction.

2. *Convection*: This mode involves heat transfer between a solid surface and a moving fluid. It follows Newton's Law of Cooling:

$$q = hA(T_s - T_f)$$

Where:

- h = Convective heat transfer coefficient (W/m²·K),
- T_s = Surface temperature (K), and
- T_f = Fluid temperature (K).

Enhancing convection can be achieved by increasing fluid velocity, improving surface roughness, or incorporating extended surfaces (fins).

3. *Radiation*: This is the transfer of heat via electromagnetic waves, occurring even in a vacuum. The Stefan-Boltzmann Law governs thermal radiation:

$$q = \sigma A \varepsilon (T^4 - T_{\infty}^4)$$

Where:

- σ = Stefan-Boltzmann constant ($5.67 \times 10^{-8} \text{ W/m}^2 \cdot \text{K}^4$),
- ε = Emissivity of the surface, and
- T and T_{∞} = Temperatures of the emitting and surrounding surfaces (K).

Performance Metrics

Heat exchangers are evaluated using various performance metrics to determine their efficiency and suitability for a given application:

- *Effectiveness (ε)*: The ratio of actual heat transfer to the maximum possible heat transfer. It is calculated as:

$$\varepsilon = \frac{Q}{Q_{\text{max}}}$$

Higher effectiveness indicates better performance in transferring heat between fluids.

- *Overall Heat Transfer Coefficient (U)*: This parameter represents the total resistance to heat transfer across multiple layers (fluid-solid-fluid) in the exchanger. It is calculated as:

$$\frac{1}{U} = \frac{1}{h_1} + \frac{x}{k} + \frac{1}{h_2}$$

Where:

- h_1 and h_2 are convective heat transfer coefficients of both fluids,
- x is the wall thickness, and
- k is the thermal conductivity of the separating material.

A higher U -value signifies a more efficient heat exchanger.

- *Pressure Drop (ΔP)*: This is the loss of pressure as the fluid flows through the heat exchanger, influenced by factors such as tube diameter, fluid velocity, and exchanger geometry. A lower pressure drop is desirable for reduced energy consumption and improved efficiency.

- *Compactness Ratio*: Defined as the ratio of heat transfer surface area to exchanger volume, compact designs with higher surface area-to-volume ratios enhance heat exchange efficiency while minimizing space requirements [4–7].

INNOVATIONS IN HEAT EXCHANGER MATERIALS

The choice of materials in heat exchanger design plays a crucial role in determining the efficiency, longevity, and sustainability of HVAC systems. Traditionally, metals such as copper and aluminium have been the preferred materials due to their high thermal conductivity and durability. However, with the increasing need for energy-efficient and cost-effective solutions, researchers and manufacturers are exploring alternative materials, including advanced metal alloys, polymers, composites, and phase-change materials (PCMs). These innovations offer enhanced thermal properties, corrosion resistance, and the potential for weight reduction, making them ideal for modern HVAC applications.

Advanced Metals and Alloys

Metals have long been the backbone of heat exchanger design due to their excellent thermal conductivity and mechanical strength. However, traditional materials such as pure copper and aluminium face challenges related to corrosion, weight, and cost. Recent advancements in metallurgy have led to the development of high-performance metal alloys that significantly enhance heat exchanger efficiency and durability.

- *Aluminium Alloys*: These alloys provide an excellent balance between thermal conductivity, corrosion resistance, and lightweight properties. They are commonly used in microchannel heat exchangers due to their ability to improve heat transfer efficiency while maintaining structural integrity.
- *Copper-Nickel Composites*: The addition of nickel to copper improves corrosion resistance, especially in marine and high-humidity environments. This makes copper-nickel alloys ideal for HVAC systems operating in coastal or industrial settings where exposure to corrosive elements is a concern.
- *Stainless Steel*: Known for its superior strength and resistance to oxidation and chemical exposure, stainless steel is a preferred material in applications requiring high durability and minimal maintenance. While it has lower thermal conductivity compared to copper and aluminium, its long-term reliability makes it suitable for demanding HVAC conditions.

These advanced metal alloys not only extend the lifespan of heat exchangers but also contribute to improved energy efficiency by reducing heat loss and optimizing heat transfer performance [8].

Polymer and Composite Heat Exchangers

The use of polymers and composite materials in heat exchanger design is gaining attention due to their lightweight nature, cost-effectiveness, and resistance to corrosion and fouling. Unlike metals, polymers do not suffer from oxidation or galvanic corrosion, making them ideal for applications exposed to aggressive chemical environments.

Key advantages of polymer and composite heat exchangers include:

- *Corrosion Resistance*: Unlike metal-based heat exchangers, polymer composites do not rust or degrade in harsh chemical environments, reducing maintenance requirements and extending operational life.
- *Lightweight Construction*: Polymers and composites weigh significantly less than metals, leading to easier handling, installation, and reduced structural support requirements.
- *Lower Manufacturing Costs*: Injection moulding and other polymer processing techniques allow for cost-effective mass production of heat exchangers, making them attractive for large-scale HVAC applications.
- *Design Flexibility*: Unlike metals, polymers can be moulded into complex shapes, enabling the development of highly efficient heat exchanger geometries with optimized heat transfer characteristics.

However, one of the challenges of polymer-based heat exchangers is their relatively lower thermal conductivity compared to metals. To address this, researchers are exploring composite materials that integrate thermally conductive fillers such as graphene, carbon nanotubes, and ceramic particles into polymer matrices to enhance their heat transfer capabilities [9].

These developments have paved the way for hybrid heat exchangers that combine the benefits of both metals and polymers, offering a balance between thermal performance and cost efficiency.

Phase-Change Materials (PCMs)

To understand the effectiveness of phase-change materials (PCMs) in heat exchanger applications, it is essential to calculate the amount of thermal energy they can store and release during phase transitions. The total thermal energy stored (Q) in a PCM consists of two components:

1. *Sensible Heat*: The energy required to raise the temperature of the material before and after phase change.
2. *Latent Heat*: The energy absorbed or released during the phase transition (melting or solidification).

The total heat stored by a PCM can be calculated using the following formula:

$$Q = mC_p\Delta T + mL$$

Where:

- Q = Total thermal energy stored (Joules or kJ),
- m = Mass of the PCM (kg),
- C_p = Specific heat capacity of the PCM (J/kg·K),
- ΔT = Temperature change before or after phase transition (K or °C), and
- L = Latent heat of fusion of the PCM (J/kg).

Example

Consider a PCM with the following properties:

- Mass (m) = 2 kg
- Specific heat capacity (C_p) = 2000 J/kg·K
- Temperature change before melting (ΔT) = 10°C
- Latent heat of fusion (L) = 150 kJ/kg

Applying the formula:

$$Q = (2 \times 2000 \times 10) + (2 \times 150000) = 40000 + 300000 \text{ J or kJ} = 340000 \text{ J or 340 kJ}$$

This means the PCM can store 340 kJ of thermal energy, which can be utilized for thermal regulation in an HVAC system, reducing energy consumption and enhancing efficiency.

By optimizing the selection of PCMs based on their thermal properties, HVAC systems can improve energy savings and maintain stable indoor temperatures more effectively.

GEOMETRIC AND STRUCTURAL ADVANCEMENTS IN HEAT EXCHANGERS

The structural design of heat exchangers plays a crucial role in determining their efficiency and thermal performance. Traditional heat exchangers often rely on relatively simple geometries, which, while effective, do not fully optimize heat transfer. Recent advancements have introduced innovative designs that maximize surface area, enhance fluid dynamics, and reduce energy losses. These improvements not only increase heat transfer efficiency but also lead to more compact and lightweight heat exchangers, making them ideal for modern HVAC applications. Key developments include microchannel heat exchangers (MCHEs), enhanced surface plate heat exchangers, and 3D-printed heat exchangers. These innovations help reduce pressure drops, enhance turbulence, and improve overall heat exchange rates, making HVAC systems more energy-efficient and environmentally friendly [10–13].

Microchannel Heat Exchangers

Microchannel heat exchangers (MCHEs) have emerged as a breakthrough technology in the HVAC industry due to their highly efficient heat transfer capabilities. Unlike conventional fin-and-tube exchangers, MCHEs use small-diameter parallel channels to facilitate rapid heat exchange between fluids. These compact designs significantly increase the heat transfer surface area while reducing the weight and size of the heat exchanger.

One of the key advantages of MCHEs is their ability to minimize refrigerant charge, which contributes to lower environmental impact and improved system efficiency. Additionally, the small channels create a more uniform distribution of the working fluid, reducing temperature gradients and enhancing overall performance.

Calculation of Heat Transfer in MCHEs

The heat transfer rate (Q) in an MCHE can be estimated using the following equation:

$$Q=UA\Delta T_{lm}$$

Where:

- Q = Heat transfer rate (W),
- U = Overall heat transfer coefficient (W/m^2K),
- A = Heat exchanger surface area (m^2), and
- ΔT_{lm} = Log mean temperature difference (K).

By increasing the surface area (A) and optimizing fluid flow through microchannels, MCHEs achieve higher efficiency compared to traditional designs, making them widely used in automotive air conditioning and residential HVAC systems.

Plate Heat Exchangers with Enhanced Surface Structures

Plate heat exchangers (PHEs) utilize stacked metal plates with thin channels to facilitate heat exchange between fluids. These exchangers are known for their compact size and high efficiency, making them suitable for various HVAC applications. Recent advancements have focused on enhancing the surface structure of these plates to improve thermal performance without causing excessive pressure drops.

Innovative surface features, such as *chevron patterns*, *dimpled surfaces*, and *vortex generators*, have been introduced to increase turbulence within the fluid channels. Enhanced turbulence promotes better mixing of the fluid layers, reducing thermal resistance and improving heat transfer efficiency [14].

One of the critical aspects of plate heat exchanger design is balancing heat transfer performance with pressure drop considerations. The pressure drop (ΔP) can be estimated using the Darcy-Weisbach equation:

$$\Delta P=fDL2\rho v^2$$

Where:

- ΔP = Pressure drop (Pa),
- f = Friction factor,
- L = Channel length (m),
- D = Hydraulic diameter of the channel (m),
- ρ = Fluid density (kg/m^3), and
- v = Fluid velocity (m/s).

By optimizing these structural features, modern plate heat exchangers achieve improved thermal performance while minimizing energy losses, making them a preferred choice for industrial and commercial HVAC systems.

3D-Printed Heat Exchangers

The emergence of additive manufacturing, commonly known as *3D printing*, has revolutionized heat exchanger design by enabling the creation of highly complex geometries that optimize heat transfer efficiency. Unlike traditional manufacturing methods, which often impose geometric limitations, 3D printing allows for the development of intricate lattice structures, porous surfaces, and variable channel shapes that maximize heat dissipation.

One of the significant advantages of 3D-printed heat exchangers is their ability to integrate multi-functional features, such as *optimized flow distribution*, *enhanced surface roughness*, and *customized cooling paths*. These features contribute to improved heat exchanger performance while reducing weight and material usage [15].

Thermal Performance Estimation in 3D-Printed Heat Exchangers

The efficiency of a 3D-printed heat exchanger can be evaluated using the Nusselt number (Nu), which represents the ratio of convective to conductive heat transfer:

$$Nu = kh/D$$

Where:

- Nu= Nusselt number (dimensionless),
- h= Convective heat transfer coefficient (W/m²K),
- D= Characteristic length (m), and
- k= Thermal conductivity of the fluid (W/mK).

By designing custom geometries that enhance convection, 3D-printed heat exchangers achieve higher Nusselt numbers, leading to better thermal performance in HVAC applications. Future advancements in additive manufacturing will continue to push the boundaries of heat exchanger efficiency, allowing for more sustainable and energy-efficient solutions in modern HVAC systems.

SMART AND ADAPTIVE HEAT EXCHANGER TECHNOLOGIES

The continuous advancement of technology has led to the development of smart and adaptive heat exchanger systems that enhance efficiency, reliability, and maintenance. Traditional heat exchangers operate without dynamic adjustments, often leading to inefficiencies due to fouling, scaling, and suboptimal performance. The integration of smart technologies, including Internet of Things (IoT) sensors, predictive analytics, and self-cleaning mechanisms, has revolutionized the way heat exchangers function in modern HVAC systems. These innovations enable real-time monitoring, data-driven decision-making, and automated cleaning processes that significantly extend equipment lifespan and reduce energy consumption. The ability to dynamically adjust performance based on real-time conditions ensures that HVAC systems operate at peak efficiency while minimizing downtime and maintenance costs. As HVAC systems become more connected and intelligent, smart heat exchangers will play a crucial role in enhancing sustainability and reducing overall energy consumption in residential, commercial, and industrial applications.

IoT-Enabled Heat Exchanger Monitoring

The integration of Internet of Things (IoT) technology in heat exchangers has transformed their operation by enabling real-time performance monitoring and predictive maintenance. IoT sensors collect and transmit data related to temperature, pressure, flow rate, and overall heat transfer efficiency. This information is analysed using machine learning algorithms and cloud-based analytics to identify inefficiencies, detect early signs of fouling or scaling, and recommend maintenance actions before performance degradation occurs.

One of the key benefits of IoT-enabled monitoring is the ability to implement predictive maintenance strategies. Instead of following a fixed maintenance schedule, HVAC systems can optimize maintenance

intervals based on actual operating conditions, reducing unnecessary service costs and preventing unexpected failures. Additionally, IoT connectivity allows remote access and automated control, enabling facility managers to adjust heat exchanger performance from anywhere.

A simple formula used to monitor heat exchanger efficiency in IoT-based systems is:

$$\eta = \frac{Q_{\text{actual}}}{Q_{\text{theoretical}}} \times 100$$

Where:

- η = Heat exchanger efficiency (%)
- Q_{actual} = Actual heat transfer rate (W), and
- $Q_{\text{theoretical}}$ = Theoretical maximum heat transfer rate (W).

By continuously analysing this efficiency metric, IoT-based systems can provide insights into heat exchanger performance and trigger alerts when efficiency drops below acceptable thresholds. This proactive approach enhances system reliability, improves energy efficiency, and reduces operational costs.

Self-Cleaning and Anti-Fouling Technologies

Fouling and scaling are major challenges in heat exchanger operation, leading to reduced heat transfer efficiency, increased energy consumption, and higher maintenance costs. Over time, deposits such as mineral scaling, biological growth, and particulate fouling accumulate on heat exchanger surfaces, creating thermal resistance that impairs performance. To combat these issues, self-cleaning and anti-fouling technologies have been developed to enhance heat exchanger longevity and maintain peak efficiency.

Self-cleaning mechanisms utilize automated cleaning cycles that dislodge and remove accumulated deposits without requiring manual intervention. This can be achieved through techniques such as ultrasonic cleaning, pulsating fluid flow, and chemical injection systems that break down fouling layers. Additionally, heat exchangers can be coated with advanced anti-fouling materials, such as hydrophobic or antimicrobial coatings, which prevent the adhesion of contaminants and biofilms.

The impact of fouling on heat exchanger performance can be quantified using the fouling factor (R_f):

$$R_f = \frac{1}{U_f} - \frac{1}{U_o}$$

Where:

- R_f = Fouling resistance ($\text{m}^2 \cdot \text{K}/\text{W}$),
- U_f = Heat transfer coefficient with fouling ($\text{W}/\text{m}^2 \cdot \text{K}$), and
- U_o = Heat transfer coefficient without fouling ($\text{W}/\text{m}^2 \cdot \text{K}$).

A higher fouling resistance (R_f) indicates significant performance degradation, prompting the need for cleaning or maintenance. By integrating self-cleaning and anti-fouling technologies, HVAC systems can minimize fouling buildup, maintain optimal heat transfer rates, and reduce energy waste, ultimately leading to improved system efficiency and cost savings.

CONCLUSION AND FUTURE DIRECTIONS

The ongoing advancements in heat exchanger design are playing a pivotal role in enhancing the efficiency of HVAC systems. As energy demands rise and environmental concerns grow, the need for highly efficient and sustainable heat exchange solutions becomes increasingly important. Traditional heat exchangers, while effective, have limitations related to energy losses, material constraints, and system reliability. Continuous research and technological innovations are addressing these challenges by introducing novel materials, improved geometries, and intelligent control mechanisms.

One of the most promising areas of future development is the application of biomimetic designs, which take inspiration from natural systems to optimize heat transfer efficiency. These designs can enhance fluid dynamics and minimize energy consumption. Additionally, artificial intelligence (AI) and machine learning (ML) are being integrated into HVAC systems to enable real-time monitoring, predictive maintenance, and automated adjustments, leading to improved performance and reduced operational costs.

Hybrid thermal management systems, which combine multiple heat transfer mechanisms such as phase-change materials and thermoelectric elements, also offer significant potential for improving heat exchanger efficiency. Future research should focus on reducing thermal resistance, minimizing pressure drops, and developing environmentally friendly refrigerants and heat transfer fluids to support global sustainability initiatives. By leveraging these advancements, HVAC systems can achieve higher efficiency, lower energy consumption, and a reduced carbon footprint.

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