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Heat Transfer Performance in Double Pipe Heat Exchangers: A Comprehensive Review

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ABSTRACT

This review paper provides a comprehensive analysis of the heat transfer performance of Double Pipe Heat Exchangers, a crucial component in thermal engineering applications. The focus of this review is on the construction, working principles, and enhancement techniques of DPHEs, with a particular emphasis on the factors influencing their thermal performance. Key findings highlight the significant impact of flow arrangement, fluid properties, and geometric modifications on heat transfer efficiency. The enhancements such as twisted tape inserts, hybrid nanofluids, and finned tubes have been shown to substantially improve performance, although they introduce trade-offs in pressure drop and maintenance. The review also identifies current challenges, including material compatibility, fouling, and the need for energy-efficient solutions in industrial settings. Furthermore, future research directions are explored, particularly in the areas of smart monitoring, eco-friendly fluids, and multi-objective optimization. This paper suggested with recommendations for further investigations into innovative materials, manufacturing techniques, and the integration of digital technologies for real-time performance optimization.

1. INTRODUCTION

Heat exchangers are critical components in thermal engineering systems, where the efficient transfer of thermal energy between two or more fluids is essential. They are widely utilized in a variety of industries including power generation, chemical processing, refrigeration, air conditioning, and automotive sectors [1]-[2]. Their primary purpose is to optimize energy usage, improve system efficiency, and contribute to the overall sustainability of industrial operations.

There are several types of heat exchangers, classified based on their flow arrangement, design, and application [3]. Common configurations include shell-and-tube [4], plate, finned tube, spiral, and double pipe heat exchangers (DPHEs) [5]. Among these, the double pipe heat exchanger stands out for its simplicity, ease of maintenance, and cost-effectiveness. In a DPHE, one fluid flows through the inner pipe while another fluid flows through the annular space between the inner and outer pipes. This configuration supports both co-current and counter-current flow, with counter-current generally offering higher heat transfer efficiency [6].

DPHEs are especially suitable for applications where heat transfer requirements are moderate, and space or cost constraints limit the use of more complex exchangers. They are commonly used in chemical processing units, oil refineries, food and beverage industries, and HVAC (Heating, Ventilation, and Air Conditioning) systems [7]. Their modular nature also makes them an ideal choice for educational and experimental purposes.

The primary objective of this review paper is to present a comprehensive analysis of the heat transfer performance in double pipe heat exchangers. The paper explores the fundamental principles, key parameters influencing thermal performance, enhancement techniques, and a critical evaluation of recent experimental and numerical studies. Furthermore, this review aims to identify current challenges, highlight advancements, and suggest future directions for improving the efficiency and reliability of DPHE systems in various thermal engineering applications.

2. FUNDAMENTALS OF DOUBLE PIPE HEAT EXCHANGER

A DPHE is among the simplest types of heat exchangers, characterized by its straightforward construction and effective thermal performance for small to medium heat duty applications. The basic structure consists of two concentric pipes: the inner pipe carries one fluid, while the annular space between the inner and outer pipes carries the second fluid. This design allows direct thermal interaction between the hot and cold fluids across the wall of the inner pipe [8].

A. Construction and Working Principle

The DPHE comprises an inner tube and an outer tube arranged coaxially. The hot or cold fluid flows through the inner tube, and the other fluid flows through the annular gap. Heat transfer occurs across the wall separating the two fluids. The exchanger is usually constructed in a modular or U-tube layout to increase heat transfer area and compactness. Materials used in construction vary based on application and fluid properties, ranging from metals like copper and stainless steel to polymers for corrosive environments [8].

B. Flow Arrangements: Parallel vs. Counter Flow

There are two primary flow configurations in a DPHE:

Parallel Flow: In this arrangement, both fluids enter the exchanger from the same end and flow in the same direction. While this setup is easier to construct, it generally results in lower thermal efficiency because the temperature gradient between the fluids decreases along the length of the exchanger.

Counter Flow: Here, the fluids enter from opposite ends and move in opposite directions. This arrangement maintains a higher average temperature difference across the length of the exchanger, leading to better heat transfer efficiency. Most industrial applications prefer counter-flow configurations due to their superior performance.

C. Governing Equations for Heat Transfer

The basic equation governing heat transfer in a DPHE is derived from the concept of conductive-convective heat exchange:

$$Q = U \cdot A \cdot \Delta T_{lm} \tag{1}$$

Where, Q = rate of heat transfer (W), U = overall heat transfer coefficient $(W/m^2 \cdot K)$, A = effective heat transfer area (m^2), ΔT_{lm} = log mean temperature difference (K), given by:

$$\Delta T_{lm} = \frac{(T_{h,i} - T_{c,i}) - (T_{h,o} - T_{c,o})}{\ln\left(\frac{(T_{h,i} - T_{c,i})}{(T_{h,o} - T_{c,o})}\right)} \tag{2}$$

Where subscripts h and c denote hot and cold fluid respectively, and i and o indicate inlet and outlet temperatures.

D. Performance Metrics

Several key parameters are used to evaluate the thermal performance of a DPHE:

Heat Transfer Coefficient (U): A measure of the exchanger's ability to transfer heat across the pipe wall, accounting for convection, conduction, and fouling effects.

Number of Transfer Units (NTU): Defined as:

$$NTU = \frac{U \cdot A}{C_{min}} \tag{3}$$

Where, C_{min} is the minimum heat capacity rate among the two fluids. NTU helps in analyzing heat exchanger performance independent of fluid inlet temperatures.

Effectiveness (ε): Ratio of actual heat transfer to the maximum possible heat transfer. For a counter-flow exchanger:

$$\varepsilon = \frac{1 - e^{-NTU(1-C_r)}}{1 - C_r e^{-NTU(1-C_r)}} \tag{4}$$

Where, $Cr = \frac{C_{min}}{C_{max}}$ is the capacity rate ratio.

These metrics form the basis for evaluating and comparing various heat exchanger designs and configurations, especially under different enhancement techniques and operating conditions.

3. Parameters Affecting Heat Transfer Performance in Double Pipe Heat Exchangers

The thermal performance of a DPHE is influenced by several interacting parameters. These include the flow configuration, fluid properties, geometry of the exchanger, flow regime, and material considerations. A thorough understanding of these parameters is essential for optimizing design and improving the efficiency of heat transfer in DPHE systems.

A. Flow Configuration: Co-current vs. Counter-current

The flow arrangement plays a critical role in determining the overall heat transfer rate. In co-current flow (parallel flow), both hot and cold fluids move in the same direction. Although this design is straightforward, the temperature difference between the fluids decreases rapidly along the length of the exchanger, limiting the heat transfer [9].

In contrast, counter-current flow enables the fluids to move in opposite directions. This maintains a higher temperature gradient throughout the exchanger, resulting in more effective heat transfer. Counter-current flow is generally preferred in industrial applications due to its superior thermal performance and higher effectiveness.

B. Fluid Properties

The thermophysical properties of the working fluids greatly affect the heat transfer capability:

Viscosity (μ): Higher viscosity increases resistance to flow, reducing the convective heat transfer coefficient. Lower viscosity fluids typically enhance turbulence and improve heat transfer.

Density (ρ): Affects the Reynolds number and hence the flow regime. Higher density fluids can increase the momentum of flow and promote turbulence.

Thermal Conductivity (k): Fluids with higher thermal conductivity facilitate better heat conduction across the boundary layer, enhancing the overall heat transfer rate.

Specific Heat (cp): Influences the fluid's capacity to absorb or release heat. A higher specific heat improves the energy transfer per unit mass.

C. Pipe Geometry and Surface Area

The geometry of the inner and outer pipes determines the available heat transfer surface and flow characteristics:

Inner diameter and length: Smaller diameters can promote turbulence, while longer pipes provide more area for heat transfer.

Wall thickness: Affects thermal resistance. Thinner walls usually reduce resistance, provided structural strength is maintained.

Surface enhancements: Use of fins, grooves, or inserts on the pipe surface can increase the surface area and induce turbulence, thereby enhancing convective heat transfer.

D. Temperature Difference, Reynolds Number, and Nusselt Number

Temperature Difference (ΔT): The driving force for heat transfer. A higher temperature difference between fluids increases the rate of heat exchange.

Reynolds Number (Re): Determines whether the flow is laminar or turbulent:

$$Re = \frac{\rho u D}{\mu} \tag{5}$$

Where, u is fluid velocity, D is the hydraulic diameter. Turbulent flow ($Re > 4000$) generally enhances convective heat transfer but also increases pressure drop.

Nusselt Number (Nu): Indicates the enhancement of heat transfer through convection over conduction:

$$Nu = \frac{hD}{k} \tag{6}$$

Where h is the convective heat transfer coefficient. Empirical correlations relate Nu to Re and Prandtl number (Pr) for different flow regimes.

E. Fouling Factors and Material Selection

Fouling: The accumulation of unwanted materials (scale, biofilms) on heat transfer surfaces degrades performance by adding thermal resistance and reducing flow area [10]. Regular cleaning and the use of fouling-resistant materials or coatings can mitigate this issue.

Material Selection: The thermal conductivity of pipe materials directly affects heat transfer efficiency. Metals like copper and aluminum offer high thermal conductivity, whereas stainless steel is chosen for its corrosion resistance despite lower conductivity [11]. The choice also depends on compatibility with the working fluids and cost considerations.

4. Enhancement Techniques for Heat Transfer in Double Pipe Heat Exchangers

Improving the heat transfer performance of DPHE is a key objective in thermal engineering, especially when dealing with energy efficiency and compact system design. Over the years, various enhancement techniques have been developed to intensify heat transfer without significantly increasing pressure drop or system complexity [12]. These techniques can be broadly categorized into active and passive methods, with some hybrid techniques combining both.

A. Use of Inserts

One of the most widely adopted passive enhancement methods involves using internal inserts to disturb the boundary layer, promote turbulence, and enhance mixing.

Twisted Tapes: Helically twisted metal strips inserted into the flow channel induce swirling flow, disrupting the thermal boundary layer and increasing convective heat transfer. Studies have shown that twisted tapes significantly improve the Nusselt number but may increase pressure drop [13].

Wire Coils: Helical wire coils placed inside the inner tube create secondary flow patterns, promoting fluid mixing and enhancing heat transfer. They are particularly effective in laminar and transitional flow regimes.

Ribs and Baffles: Internal ribs or baffles increase the surface area and flow turbulence, especially beneficial in long tubular exchangers. However, careful design is needed to avoid excessive pressure losses.

B. Nanofluids and Hybrid Nanofluids

The use of nanofluids, which are suspensions of nanoparticles such as Al_2O_3, CuO, TiO_2 in base fluids like water, oil, or ethylene glycol, has emerged as a promising strategy to enhance thermal conductivity and convective heat transfer [14].

Nanofluids: Improve thermal properties, increase heat transfer coefficient, and reduce the thermal boundary layer thickness. Their performance depends on nanoparticle type, size, concentration, and dispersion stability [15].

Hybrid Nanofluids: These are combinations of two or more types of nanoparticles are $Al_2O_3 - Cu, TiO_2 - SiO_2$ in a base fluid, offering improved thermal and rheological properties. Hybrid nanofluids often outperform single-component nanofluids in terms of heat transfer efficiency [16].

C. Corrugated and Finned Tubes

Modifying the surface geometry of the tubes is another effective passive method to improve heat exchanger performance.

Corrugated Tubes: Introducing periodic surface deformations such as corrugations or spiral indentations on the inner tube enhances turbulence and disrupts the thermal boundary layer, leading to improved heat transfer rates.

Finned Tubes: Extended surfaces in the form of external or internal fins significantly increase the effective heat transfer area, especially useful in air-cooled or low-conductivity fluid systems.

These modifications can be tailored based on flow conditions and required thermal duty.

D. Active and Passive Enhancement Methods

Passive Techniques: Do not require external energy input. Examples include twisted tapes, surface roughness, extended surfaces (fins), nanofluids, and inserts [17]. These are more widely adopted due to their simplicity and cost-effectiveness.

Active Techniques: Require external power sources to stimulate flow and heat transfer, such as vibrating the tube walls, using electrostatic fields, or rotating components [18]. Although effective, these methods are complex and less commonly used in DPHEs.

Hybrid Techniques: Combine active and passive methods (nanofluids in a vibrated tube) to maximize thermal performance, though they also demand careful design to balance benefits and operational cost.

5. NUMERICAL AND EXPERIMENTAL STUDIES ON HEAT TRANSFER IN DOUBLE PIPE HEAT EXCHANGERS

The advancement of both computational and experimental techniques has significantly contributed to the understanding and optimization of heat transfer in DPHE. Numerical simulations, especially using Computational Fluid Dynamics (CFD), have become vital tools to visualize flow patterns, predict thermal behavior, and evaluate enhancement techniques before practical implementation [19]. Complementing this, experimental studies provide real-world validation and insights into operational performance under various conditions.

A. Overview of CFD Simulations and Their Findings

CFD has emerged as a powerful method for analyzing heat transfer in DPHEs. Using governing equations of fluid dynamics and heat transfer—such as the Navier-Stokes and energy equations—CFD provides detailed insights into flow behavior, temperature distribution, and pressure drop.

Key findings from CFD studies include:

Effectiveness of Inserts: Simulations involving twisted tape inserts or wire coils have shown considerable enhancement in the Nusselt number due to increased turbulence and secondary flow generation. However, this comes with a trade-off in pressure drop.

Nanofluids: CFD models incorporating nanofluids (Al_2O_3-water or CuO-water) reveal substantial improvement in convective heat transfer coefficients, particularly in turbulent flow regimes [12]. Hybrid nanofluids demonstrate even better performance.

Geometry Optimization: Parametric studies using CFD have been conducted to optimize the inner and outer diameters, length-to-diameter ratio, and the use of corrugated or finned surfaces. Such simulations aid in maximizing thermal performance while minimizing material cost and pressure loss.

Flow Configuration Impact: CFD studies validate that counter-flow arrangements consistently outperform co-current configurations in terms of heat transfer efficiency and outlet temperature difference.

B. Review of Major Experimental Results from Literature

Numerous experimental investigations have been conducted to verify numerical predictions and understand real-world behavior under various operating conditions:

Inserts and Surface Modifications: Experiments using twisted tapes and wire coil inserts have confirmed a 25–80% increase in heat transfer rates compared to plain tubes, depending on the Reynolds number and insert design [20].

Nanofluids and Hybrid Nanofluids: Laboratory studies have demonstrated that the use of nanofluids can enhance the heat transfer coefficient by up to 30–50% over base fluids. For example, Al_2O_3-water nanofluids showed optimal results at 0.1–0.3% volume concentration [21]. However, higher concentrations may increase viscosity and pumping power requirements.

Finned and Corrugated Tubes: Experiments show that finned tubes provide up to 40% improvement in heat transfer with only moderate increases in pressure drop. Corrugated tube designs also show similar enhancements by inducing flow disturbances [22].

Material and Fouling: Experimental data emphasize the importance of material selection. Stainless steel and copper are widely tested, with copper offering superior heat transfer but lower fouling resistance. Anti-fouling coatings are under investigation to reduce long-term degradation [23].

C. Performance Comparison Using Various Enhancement Techniques

Table 1 provides a comparative summary of various enhancement techniques based on experimental and numerical studies:

Technique	Heat Transfer Enhancement	Pressure Drop	Common Study Method
Twisted tape inserts	High (30–60%)	Moderate to High	CFD & Experimental
Wire coil inserts	Moderate to High	Moderate	CFD & Experimental
Nanofluids	Moderate (20–50%)	Low to Moderate	CFD & Experimental
Hybrid nanofluids	High (up to 60%)	Moderate	CFD
Corrugated tubes	Moderate	Moderate	Experimental
Finned tubes	High (30–40%)	Low to Moderate	Experimental

6. Applications and Case Studies in Industry

`DPHE have wide-ranging applications across various industrial sectors due to their simple design, ease of maintenance, and versatility in handling different fluids and operating conditions. This section highlights key industrial applications of DPHEs and presents selected case studies demonstrating their performance and adaptability in real-world scenarios.

A. Industrial Applications of DPHEs

Chemical and Process Industries: DPHEs are extensively used in chemical industries for heating and cooling of process fluids. Their ability to operate under high pressures and temperatures makes them suitable for corrosive and reactive environments. Common applications include:

- Pre-heating of reactants
- Cooling of exothermic reaction products
- Solvent recovery systems

HVAC (Heating, Ventilation, and Air Conditioning): In HVAC systems, DPHEs serve in heat recovery loops, water heating, and cooling circuits. They are particularly useful for:

- Domestic and industrial hot water systems
- Chilled water circuits in air conditioning units
- Heat pumps and geothermal systems

Power Generation Plants: In power plants, DPHEs are used in auxiliary systems such as lube oil cooling, pre-heating feedwater, and cooling condenser effluent. Their compact size and effectiveness in handling high-temperature fluids make them ideal for:

- Gas turbine intercoolers
- Boiler feedwater heaters
- Waste heat recovery units

Food and Beverage Industry: DPHEs are utilized in thermal processing, pasteurization, and CIP (Clean-In-Place) systems. Their hygienic design options make them suitable for:

- Heating of dairy products
- Cooling of beverages
- Sterilization processes

Pharmaceutical and Biotech Sectors: Due to their precise temperature control and ability to handle viscous or sensitive fluids, DPHEs are used for:

- Cooling of fermentation products
- Heating of batch reactors
- Controlled crystallization processes

B. Selected Case Studies

Case Study 1: Heat Recovery in a Petrochemical Plant

A petrochemical facility employed DPHEs to recover heat from hot effluents to preheat incoming process water. By using finned inner tubes and twisted tape inserts, the plant improved energy efficiency by 28% and reduced fuel consumption for boilers, leading to significant operational cost savings.

Case Study 2: Nanofluid Application in a Cooling System

An experimental setup in an academic-industry partnership tested $Al_2O_3 - water$ nanofluids in a DPHE used for a high-performance computing center's liquid cooling system. The study showed a 32% enhancement in heat transfer rate, maintaining stable operation with only a 10% increase in pumping power.

Case Study 3: Food Industry Pasteurization Line

A food processing company integrated a corrugated tube DPHE into its pasteurization line for milk processing. The modified design enabled rapid heating with a minimal footprint, increasing throughput by 15% and reducing heat exchanger fouling, thereby decreasing maintenance frequency.

Case Study 4: Solar Thermal Integration in Rural HVAC System

A renewable energy project deployed DPHEs to transfer thermal energy from solar collectors to a water heating system in rural households. Using passive enhancements like twisted tapes, the system achieved higher efficiency even during low solar radiation periods, ensuring reliable hot water supply.

C. Benefits Realized in Industrial Applications

Improved energy efficiency and reduced fuel consumption

- Enhanced heat transfer performance with compact designs

- Lower maintenance and operating costs
- Flexibility in handling varied fluids and flow conditions
- Adaptability to different heat source integrations (solar, waste heat)

7. Future Trends and Research Directions

As the demand for energy-efficient and compact thermal systems continues to rise across industries, research on Double Pipe Heat Exchangers (DPHEs) is evolving rapidly. Future advancements are expected to focus on improving thermal performance, reducing environmental impact, and integrating intelligent systems for real-time optimization and control. This section outlines emerging trends and key areas for future research.

A. Advanced Working Fluids

Nanofluids and Hybrid Nanofluids: The use of nanofluids has already demonstrated promising heat transfer improvements. Future research is moving toward:

- Stability enhancement techniques to prevent nanoparticle agglomeration.
- Hybrid nanofluids ($Al_2O_3 - Cu, TiO_2 - CuO$) that combine benefits of multiple nanoparticles.
- Studies on eco-friendly and bio-based nanofluids for sustainable thermal applications.

Phase Change Materials (PCMs): Incorporating PCMs in DPHE systems could enable thermal energy storage, especially for intermittent sources like solar energy.

B. Geometrical and Material Innovations

Additive Manufacturing (3D Printing): The use of 3D printing for fabricating complex internal geometries, such as lattice structures or customized inserts, is an emerging area that allows:

- Tailored flow paths
- Localized heat transfer enhancement
- Reduced material waste

Smart Materials and Coatings: Future DPHEs may employ smart materials with self-cleaning or anti-fouling properties, as well as coatings that adjust thermal conductivity dynamically based on operating conditions.

C. Digitalization and Smart Monitoring

Integration of IoT and AI: The combination of IoT-enabled sensors and AI algorithms could facilitate:

- Real-time monitoring of temperature, pressure, and flow rates
- Predictive maintenance to minimize downtime
- Adaptive control systems for optimized heat transfer under varying loads

Digital Twins: Creating digital twins of DPHE systems allows for simulation-driven operation and fault detection, thereby improving reliability and performance prediction accuracy.

D. Sustainable and Green Engineering Approaches

Energy Recovery Systems: Future DPHE applications will emphasize maximizing heat recovery in waste heat streams from industrial processes, minimizing energy loss.

Low-GWP Refrigerants and Fluids: With environmental regulations tightening, the use of refrigerants and fluids with low Global Warming Potential (GWP) will be a crucial focus.

Lifecycle and Environmental Impact Assessment: Assessing the environmental footprint of DPHEs over their lifecycle—from material selection to end-of-life recycling—will become a standard research criterion.

E. Optimization and Multi-Objective Design

Multi-Objective Optimization Techniques: Researchers are increasingly adopting multi-objective algorithms such as genetic algorithms, particle swarm optimization to simultaneously optimize:

- Heat transfer performance
- Pressure drops
- Cost and material usage

CFD-ML Integration: Combining Computational Fluid Dynamics (CFD) with Machine Learning (ML) models is a growing trend to accelerate simulations and predict performance across a wide range of conditions without repeated physical testing.

Challenges and Limitations

While DPHE offer simplicity and versatility in many thermal systems, they are not without inherent challenges. These limitations can influence performance, maintenance costs, and long-term reliability, especially when advanced enhancement techniques or unconventional fluids are used. Understanding these challenges is critical for optimizing design and operation.

A. Trade-offs Between Pressure Drop and Heat Transfer Enhancement

One of the most significant design challenges in enhancing DPHE performance is managing the balance between increased heat transfer and the associated pressure drop:

- Inserts and surface modifications (twisted tapes, wire coils, fins) increase turbulence and improve heat transfer but also lead to higher pressure losses.
- Elevated pressure drops require more pumping power, increasing operational energy costs and reducing system efficiency.
- Optimizing enhancement geometry and fluid flow rates becomes essential to achieving the best trade-off between thermal performance and hydraulic efficiency.

B. Maintenance and Fouling Issues

Fouling is a common issue in heat exchangers, leading to decreased heat transfer rates and increased pressure drop over time:

- Deposition of salts, biological matter, or particulates on the heat transfer surface reduces thermal conductivity.
- Enhanced surfaces or small flow passages (such as in corrugated or finned tubes) are more susceptible to clogging and are harder to clean.
- Regular maintenance and chemical cleaning are often required, which can disrupt operations and add to lifecycle costs.

C. Material Compatibility and Cost

The selection of materials for DPHE construction must consider fluid compatibility, thermal performance, and budget constraints:

- Corrosive fluids may require special alloys like stainless steel or titanium, which significantly increase the initial cost.
- Nanofluids and hybrid working fluids may react with traditional metals, leading to corrosion, erosion, or degradation of material over time.
- Thermal expansion mismatches between inner and outer pipes can lead to stress and failure, especially under cyclic heating conditions.

D. Size and Space Constraints

Though compact, DPHEs are not always ideal for large-scale applications due to limited surface area for heat transfer. Scaling up often requires:

- Multiple units in parallel or series, which complicates system design.
- More floor space and connections, leading to increased installation and maintenance complexity.

E. Limited Versatility in Complex Systems

DPHEs may not be the optimal choice in systems with:

- Multi-stream heat exchange requirements
- Phase change operations such as condensation and evaporation
- Highly variable flow conditions

In such cases, shell-and-tube or plate heat exchangers may offer better performance and flexibility.

Conclusion

The DPHE remain a fundamental and widely used component in thermal engineering due to their simplicity, flexibility, and cost-effectiveness. This review has comprehensively covered the key aspects of DPHEs, including their construction, operating principles, performance parameters, influencing factors, enhancement strategies, and applications across various industries. The analysis reveals that heat transfer performance in DPHEs is significantly influenced by factors such as flow arrangement like counter-flow outperforming parallel flow, fluid properties, geometry, and surface modifications. Enhancement techniques like twisted tape inserts, corrugated tubes, and the use of nanofluids or hybrid nanofluids have been shown to substantially improve heat transfer effectiveness. Among these, hybrid nanofluids and passive enhancement methods stand out as promising, offering substantial gains in thermal performance with moderate complexity.

Furthermore, numerical simulations using CFD and experimental studies consistently validate the effectiveness of these enhancements and provide valuable insights into optimizing design configurations. Industrial case studies underline the versatility of DPHEs in diverse sectors including chemical processing, HVAC systems, and power generation.

However, challenges such as the trade-off between heat transfer and pressure drop, maintenance concerns, and material compatibility must be addressed to maximize system reliability and efficiency. Advanced manufacturing techniques such as 3D printing, the integration of smart sensors and AI-driven monitoring, and the development of environmentally friendly working fluids represent the next frontier for research.

Conflict Of Interest

The authors declare that they have no conflict of interest.

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