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Review Article

Recent and Emerging Trends in Plate Heat Exchangers Performance Enhancement: A Review

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Abstract

Increasing the demand for greater efficiency and sustainability in corrugated plate heat exchangers has driven comprehensive research to address the drawbacks of conventional designs. This review summarizes the latest developments in enhancing plate heat exchanger performance, with a focus on plate surface geometry and working-fluid effects. The most important geometric details for thermo-hydraulic properties, such as chevron angle, corrugation pattern, plate spacing, and corrugation depth and pitch, are systematically examined with respect to their thermo-hydraulic effects. The review also covers surface coatings, including potential contributions to fouling mitigation and pressure drop reduction, as well as persistent issues related to durability, health, and environmental impact, along with their associated costs. The review also discusses the application of nanofluids as working fluids, explaining that while they can improve heat transfer, they also entail drawbacks such as increased viscosity, pressure drop, and unknown long-term effects on plate integrity. In addition to designs and material strategies, the review focuses on how they incorporate sustainable and renewable energies into plate heat exchangers to reduce dependence on fossil fuels and their negative impact on the environment, as well as reducing operational costs. Also, cutting-edge data-driven techniques, including machine learning, deep learning, and artificial intelligence, are presented as promising extensions to other CFD techniques to develop and enhance predictive models while reducing computational costs and time. Finally, several research gaps are identified, including insufficient attention to unsteady and oscillatory flow conditions, highlighting areas that require further investigation.

Keywords: *Plate heat exchanger; heat transfer; nanofluid; thermal-hydraulic; artificial intelligence; artificial intelligence.*

1. Introduction

Heat exchangers are critical to a wide range of systems, including power plants, process industry, heat recovery systems, etc. In order to achieve high performance of systems, it is crucial to continuously improve heat exchanger design, reliability, and maintainability. Heat exchangers exist in diverse types that can be categorized by construction, including, but not limited to, shell-and-tube, plate-and-frame and finned-tube. There are multiple heat exchanger arrangements present, among which Plate Heat Exchangers (PHEs), as shown in Figure 1, composed of the brazed, welded and gasketed ones, have attracted a great deal of attention because of the excellent thermal response, small design and flexible construction, as well as quick repair facility. These benefits justify the appeal of PHEs for application in the power generation, chemical and petrochemical industries, refrigeration and air conditioning, food processing, renewable energy systems and waste heat recovery. Driven by the urgent need for a higher heat-transfer surface-to-volume ratio in the pasteurization industry, Richard Seligman invented the PHE in 1923 [1]. These units were first introduced by APV UK Ltd. for pasteurization processes. A typical PHE consists of a stack of thin, corrugated plates arranged to form narrow flow channels between adjacent plates. The corrugation patterns, often arranged in a chevron configuration, play a crucial role in enhancing heat transfer by inducing strong flow mixing, secondary flows, and turbulence at relatively low Reynolds numbers [2]. As a result, PHEs can achieve high heat-transfer coefficients while maintaining a relatively small heat-transfer surface area compared with conventional shell-and-tube heat exchangers [3]. Additionally, the modular nature of PHEs enables easy capacity adjustment by adding or removing plates, offering operational flexibility that is highly valued in modern thermal systems.

Commercial demand for heat exchangers has increased substantially in the past decades. In 2024, the global market size was USD 23.0 billion, and sales are anticipated to grow to USD 32.3 billion by 2029 [4]. The global PHEs market size is estimated to be in 2025 at USD 6.55 billion, and on the rise to USD 10.21 billion by 2033 [5] with a CAGR of 5.7% during the forecast period (2025-2033). Such growth is facilitated by increasing investments in energy-efficient technologies, a growing investment in HVAC and refrigeration infrastructure, increased activity in petrochemical and chemical processing, and regulatory pressure to reduce energy consumption and greenhouse gas emissions. PHEs, although reliable, often operate far from

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their theoretical performance limits due to laminar flow, boundary-layer development, and limited fluid mixing, all of which reduce heat-transfer rates. Researchers have aimed to enhance both thermal and hydraulic performance to meet overall performance requirements, reduce operating expenses, and significantly decrease atmospheric pollutant emissions.

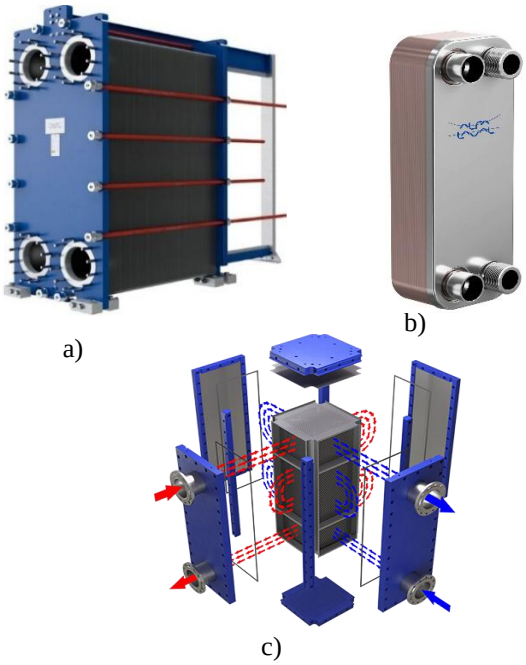


Figure 1. PHEs types, (a) Gasket PHE, (b) Brazed PHE, and (c) Welded PHE (courtesy of Alfa Laval Company).

Most PHE enhancement techniques are summarized in Figure 2. The chevron angle (β) is widely recognized as one of the most influential geometric parameters [6–10], which affects both thermal and hydraulic performance. García-Castillo et al. [6] investigated the effects of β and its economic viability. They found that the β increases the Nusselt number (Nu) but also increases the pressure drop.

Additionally, they reported a significant 95% reduction in heat transfer area compared to shell-and-tube heat exchangers. Zhu [9] numerically explored a wide range of β and Reynolds numbers (Re) on PHEs, which are 18° - 72° and $10 \leq Re \leq 6000$. The findings indicated that, at low Re, increasing β significantly enhances heat transfer, but at high Re, the enhancement becomes relatively modest.

Many studies have confirmed that the β exhibits a positive correlation with thermal performance and a negative correlation with hydraulic performance [8,11,12]. Furthermore, β can also affect the regularity of flow distribution; the greater β, the less maldistribution [11]. M. M et al. [13] reviewed the concept of irregular distribution flow and summarized various techniques proposed to mitigate this issue. Moreover, heat exchange fluids are not limited to water; nanofluids have been widely studied for their potential to enhance heat transfer, although often at the expense of increased pressure drop. Behrozifard et al. [14] investigated the effects of GO and Al_2O_3/water nanofluids in corrugated PHEs. At a volume concentration of 0.03%, GO and Al_2O_3/water hybrid nanofluids enhanced thermal efficiency by up to 37% and 21%, respectively, compared to water. Wciślik and Taler [15] numerically investigated TiO_2 + SiO_2 / DI + EG hybrid nanofluids that absorb solar energy and exchange heat with household water. They concluded that at 1.5% vol., the economic and energetic performance is 13–26% more efficient than that of water. Elias et al. [16] experimentally investigated the impact of a water-based Al_2O_3 nanofluid on heat transfer in PHEs with different chevron angles. The nanofluid concentration examined from 0 to 0.5% vol., and the study tested β of 30° and 60°. At the last-mentioned angle, they observed that increasing both Re and nanofluid concentration improved heat transfer and reduced pressure drop relative to the base working fluid. It should be noted that the use of nanofluids increases viscosity, thereby requiring higher pumping power and increasing operational costs and associated emissions [17].

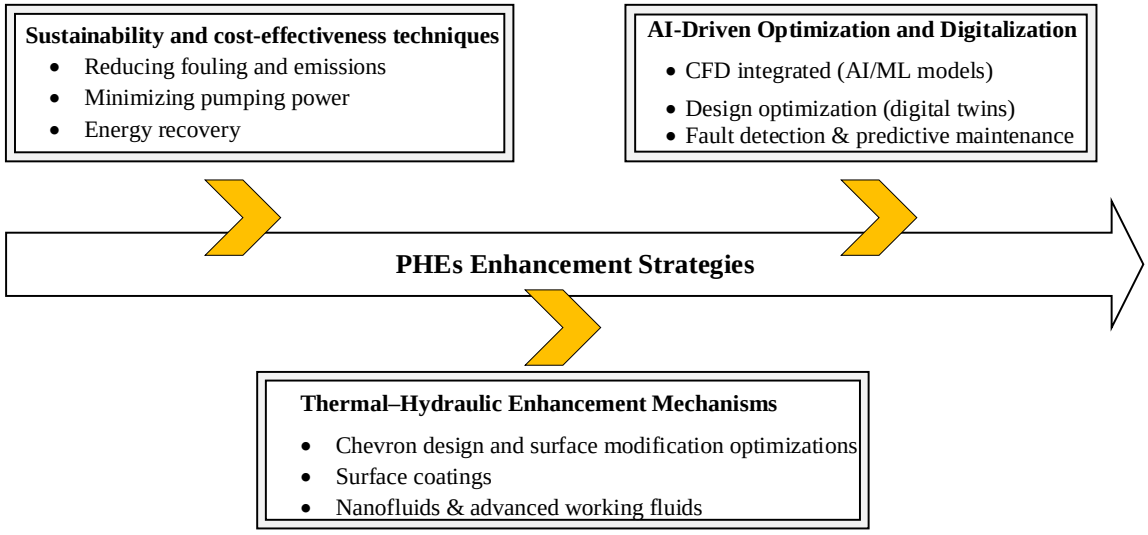


Figure 2. The existing predominant techniques adopted to enhance thermal performance.

In addition to fluid-induced hydraulic drawbacks, PHEs are significantly affected by surface-related phenomena that further degrade thermal–hydraulic performance. Fouling is a critical factor in PHEs' operation, as it forms a thin deposit layer that acts as a thermal resistance, increases surface roughness, and reduces the effective cross-sectional flow area. For example, in a milk-processing plant, the fouling thickness can reach 0.028 mm within the first hour of operation [18]. There are two active methods for removing fouling: chemical cleaning and mechanical cleaning,

commonly referred to as cleaning-in-place (CIP). The first method can be utilized for all PHE types, whereas mechanical cleaning is limited to gasketed plate heat exchangers (GPHEs). The latter method is widely used in sensitive industries, such as food and beverage processing. Berce et al. [19] investigated corrugated PHEs to demonstrate the effects of fouling on heat transfer performance. Infrared thermography was used to observe the fouling caused by calcium carbonate crystallization, including its location and size. During variable durations without contact, this methodology produced temperature contours before and after fouling. They found that at low velocity, fouling led to poor flow distribution, particularly on the hot outlet side, reducing effectiveness by 17%. The same technique was used before by Freund and Kabelac [20] to estimate local heat transfer coefficients in PHEs. Applying special coatings on the plate surface has been shown to mitigate fouling [21]. Liu et al. [22] evaluated the ability of Ni-P-PTFE and Ni-P-TiO_2 coatings to minimize foulant adhesion and maximize PHE efficiency. The surface can be roughened using a nanoscale machine to increase the coating's adhesion [22]. Kukulka and Leising [23] experimentally evaluate the cost and effectiveness of some coatings. Throughout history, given the difficulty of experimental work, an alternative approach was developed: the numerical approach, or computational fluid dynamics (CFD). This approach is characterized by rapid completion using finite difference or finite volume methods, implemented across various models. However, it does not provide an exact solution, as it often requires validation. Since CFD requires a model (solver), numerous models have been developed, especially for fouling studies. Indumathy et al. [18] developed and validated a 1D model used to predict when fouling becomes a significant issue for scheduling cleanup appointments. The fouling deposition and cleaning process reduces product profitability by about 80% [24]. A 2D model developed by Sharma and Macchietto [25] integrates mechanisms of fouling and cleaning, enabling faster and more accurate simulations. Another CFD model was developed to simulate fouling caused by phosphate-calcium nanoparticles on PHEs [26]. The developed model can be used for many fluids [27]. Despite agreement among most researchers on various enhancement strategies, a persistent research gap persists for each method, confirming the need for further in-depth research.

This review aims to provide a comprehensive assessment of recent advancements in corrugated plate heat exchangers (PHEs), with a particular focus on the improvement of thermo-hydraulic heat transfer techniques and emerging optimization strategies. Although the literature surrounding PHEs is comprehensive, with the aim of maintaining depth, clarity, and relevance, this review is restricted to a well-chosen and representative subset of studies. The criteria for selection were developed based on several key considerations, including:

- Direct relevance to corrugated PHEs.
- Explicit investigation of thermo-hydraulic performance, including heat transfer enhancement and pressure drop characteristics.
- Studies addressing key geometric parameters (e.g., chevron angle, corrugation depth and pitch, surface modifications, and coatings).
- Advanced working fluids, including nanofluids.
- Recent developments in sustainability, renewable energy integration, and AI-oriented prediction/optimization methods.

2. Plate Heat Exchanger Structure

Determination of structural and geometric properties of PHEs is essential to accurately identify their thermo–hydraulic response and to achieve the optimum structure and operative performance. Unlike conventional heat exchangers, which generally have simple flow paths, the PHEs are characterized by complex, corrugated channels, where the flow behavior is strongly dictated by the geometry of the channels.

2.1 Plate Stack Arrangement

The plates are assembled either with a rubber gasket between them and tightened with bolts or by precision welding, or brazing their edges, depending on the required pressure, temperature, and maintenance considerations. The most common types are gasketed PHEs (GPHEs) and brazed PHEs (BPHEs), which withstand pressures from vacuum to 25 and 130 bar, respectively [28,29]. GPHEs can be disassembled for cleaning and maintenance as shown in Figure 3 [30], making them particularly suitable for hygienic applications such as dairy processing and beverage pasteurization [31]. In contrast, BPHEs are permanently sealed and are typically employed in applications with low fouling risk, such as chemical processing, HVAC, and refrigeration systems [32–34]. The intersecting corrugation contact points between adjacent plates provide mechanical strength to withstand high pressures, while the induced turbulence enhances heat transfer at the expense of increased pressure drop.

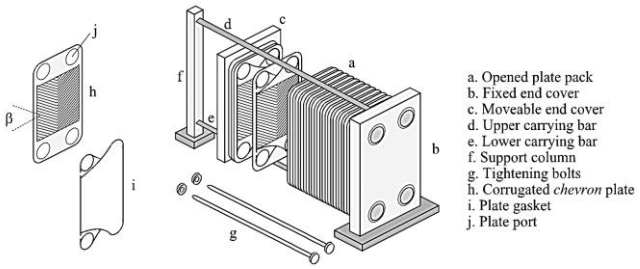


Figure 3. The assembly and components of the GPHE [30].

2.2 Plate Material

The plates are made of different metals. Stainless steel is the most widely used steel as a plate material because of its high mechanical flexibility, corrosion resistance, and ease of cleaning. Nevertheless, it can also yield poor thermal performance or be inefficient in costs, especially in cases where high thermal conductivity is desired or material and fabrication costs may be low. To that end, alternative materials have been researched to bridge these limitations. For instance, polypropylene–graphite composites [35] and copper plates [36] have been studied on the basis of their favorable economic or thermal characteristics. D.H. Nguyen et al. [37] studied the thermal–hydraulic behavior of PHEs formed of nickel, copper, and silver, indicating the strong impact of material choice on heat transfer and pressure drop characteristics. Jamzad et al. [38] proposed a new PHE based on flexible graphite (density 2.1 $g \cdot cm^{-3}$), which exhibits a higher thermal conductivity (300–600 $W \cdot m^{-1} \cdot K^{-1}$) than those of aluminum, copper, and stainless steel and thus provides

more economical manufacturing processes. Although the graphite PHE achieved a heat transfer rate similar to that of a stainless-steel PHE, the pressure drop was 26% higher, which appeared due to the smaller inter-plate spacing (0.5 mm for graphite compared with 1.8 mm for stainless steel under the presence of the same design).

2.3 Plate Geometry

The geometrical parameters of the chevron plate in a CPHE are shown in Figure 4 [39]. The thermal–hydraulic performance of PHEs is strongly governed by the geometry of the plate surface and channel configuration. The corrugated (chevron) plate surface enhances heat transfer by increasing the effective heat transfer area and by inducing eddies within the flow channels, which intensify fluid mixing and disrupt thermal boundary layers [40,41]. The resulting secondary flows significantly increase convective heat transfer coefficients; the term "secondary flows" refers to the flow structures induced by the corrugated geometry. Even at low Re, the wavy channel configuration creates flow separation and recirculation zones [42,43]. Sarraf et al. [10] analyzed the flow structure using streamlines, as illustrated in Figure 5. At very low Re, the flow develops a relatively stable helical pattern. This helical motion generates secondary flow structures and contributes to the mixing of fluids near the wall, leading to partial disruption of the boundary layer. But the overall mixing is still moderate because there are minimal inertial effects at low R

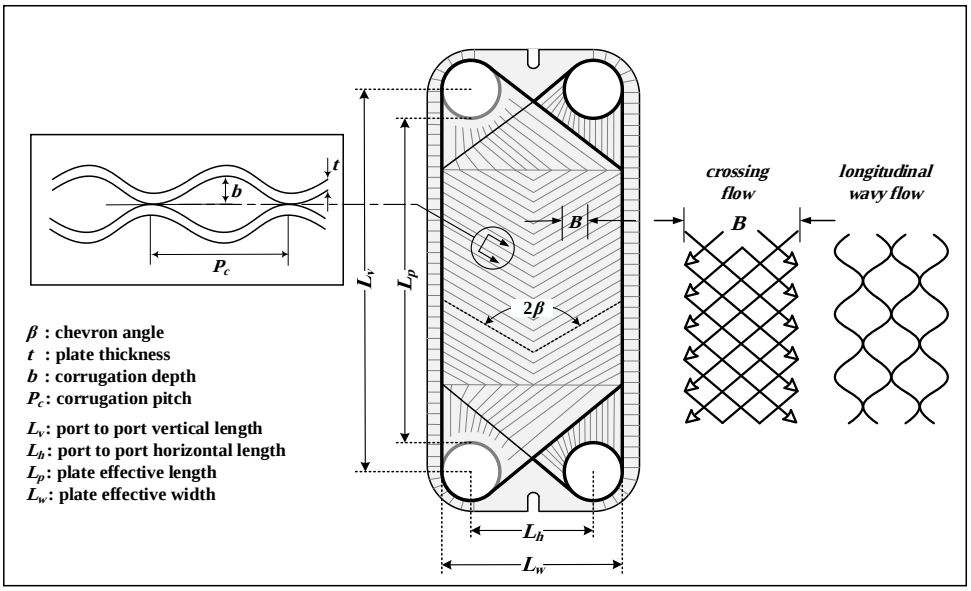


Figure 4. Geometric specifications of a chevron-shaped thermal plate [39].

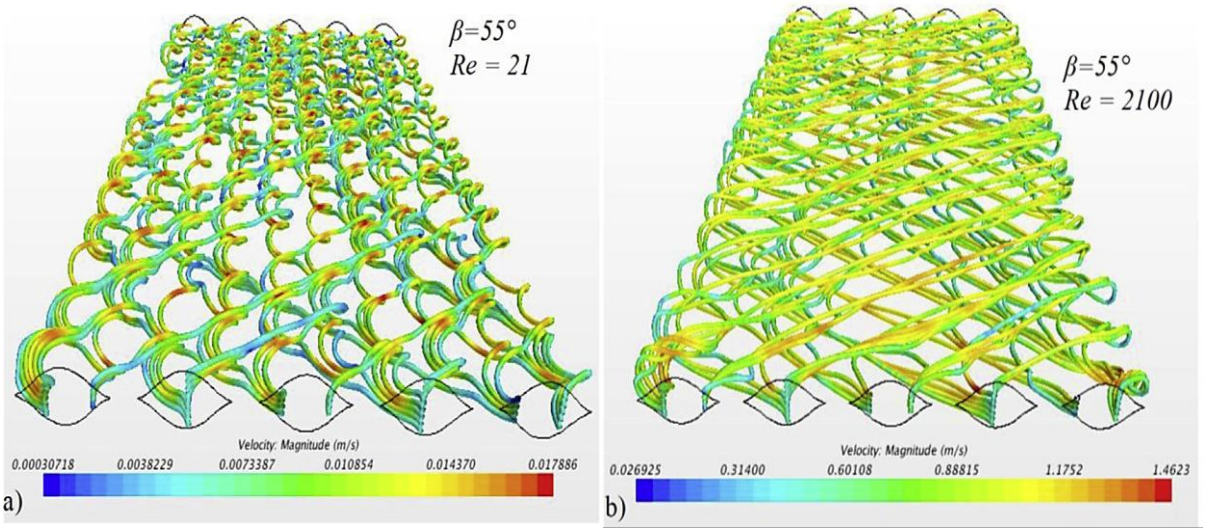


Figure 5. Flow streamlines contours depicting (a) a helical flow pattern at Re = 21 and (b) a cross-flow structure at Re = 2100 [10].

With an increase of Re, the flow structure is more complex, the cross-flow interaction is strong and the vortex formation is marked. These vortices facilitate frequent flow separations and reattachments, leading to considerably more disruptive boundary layer formation and hence higher heat transfer. Meanwhile, these mechanisms cause additional momentum loss in the form of flow resistance, recirculation zones, and frictional effects. This accounts for the comparably large friction factor at low Re, e.g., $f \approx 18$ at Re = 21, where the helical flow structure increases the effective flow path and wall interaction. Consequently, the observed thermo-hydraulic behavior is a direct result of the interplay of enhanced mixing mechanisms and the corresponding pressure loss penalties.

2.3.1. Chevron Angle

Of the geometric parameters, the chevron angle (β), that is the angle between the corrugation ridges and the main flow direction, is one of the most influential [49–51]. Commercial PHEs typically use a β between 30° and 65°. Lower angles (30°-40°) produce a lower pressure drop and weaker mixing, and larger angles (60°-65°) produce stronger turbulence and higher heat transfer coefficients to the detriment of higher pressure loss [9]. As such, intermediate angles of 45°–60° are frequently used in industry to give a better trade off [30]. This trade-off demonstrates that even when optimization of heat transfer is achieved in principle, optimizing for system efficiency does not guarantee that system performance becomes optimal. Configurations that could provide great thermal improvement are, in many cases, less effective based on hydraulic penalties. So, a balanced assessment is needed which takes the heat transfer and the pressure drop into account together. Which is why combined performance criteria, e.g., Performance Evaluation Criterion (PEC) or JF factor, are widely applied, as these provide a real-world representation of the efficiency of the overall system.

2.3.2. Corrugation Pitch and Depth

Although several studies have proposed alternative corrugation patterns for PHEs, such as triangular [27,47], trapezoidal, or mixed geometries [48], sinusoidal (wavy) corrugation remains the most widely adopted surface pattern in commercial and industrial PHEs. The corrugation pitch (P_c), which is the distance between two peaks in the corrugation, is an important geometric parameter that controls how often the flow is disturbed and the boundary layer is interrupted in PHEs [49]. A smaller corrugation pitch indicates a greater flow diversion per unit length. This enhances the secondary flows and mixing process, increasing Nu [50]. But decreasing the pitch also increases the frictional resistance because flow is sped up and decelerated more often, resulting in a larger pressure drop [51]. Recent experimental and numerical studies suggest an optimal pitch range has been established where heat transfer enhancement exceeds the hydraulic penalty [52–55]. Furthermore, the depth (or amplitude) of the corrugation (b), defined as the vertical distance between the crest and trough, directly affects the strength of the cross-stream velocity components and the formation of turbulence and vortices in the channel [56]. A higher depth of the corrugation increases flow turbulence (even at Re ~ 400) and increases the wall shear stress [27]. This accelerates convective heat transfer and may even delay development of fouling. On the other hand, high corrugation depth can cause considerable pressure loss and flow path maldistribution, particularly at low Re [13]. The depth of the corrugation is found to influence the pressure drop more than the pitch based on CFD studies. This emphasizes the importance of thermo-hydraulic optimization [46, 55, 56]. Accordingly, most modern commercial PHE designs employ a corrugation pitch of 6-12 mm and corrugation depths of 1-4 mm, which depend on application and the permissible pressure drop.

2.3.3. Hydraulic Diameter

The hydraulic diameter (D_h) is an important geometric property to describe the flow and heat transfer in the narrow, non-circular channels of plate heat exchangers. In general, it is defined as $D_h = 4A_c/P_w$, where A_c is the area of the channel's cross-section, and P_w is the wetted perimeter. In PHEs, the hydraulic diameter is typically very small – about 2 to 6 mm. It is easy for flow to become turbulent and hence the heat transfer coefficient increases at lower Re. However, a smaller D_h results in heightened wall shear stress and frictional losses, leading to a larger pressure drop with a higher need for pumping power. In recent experimental and CFD works, alterations of plate spacing, corrugation depth, and corrugation geometry have been suggested to influence the hydraulic diameter, which significantly affects both Nu and the friction factor (f). This makes D_h a key factor in optimizing and predicting PHE performance [59–63].

Hydraulic diameter (D_h) in many PHE configurations can be expressed as:

$$D_h = \frac{2b}{\phi} \tag{1}$$

where, (ϕ) represents a dimensionless parameter, typically referred to as the surface enlargement factor (also defined as the developed area divided by the projected area), which is frequently employed to characterize the steepness of the corrugation, and it is given by Eq. (2) [41].

$$\begin{aligned}\phi &= \frac{1}{P_c/2}\int_0^{P_c/2}\sqrt{1+\left[\frac{d}{dy}\left(f\,(y)\right)\right]^2}\,dy \\ &\approx \frac{1}{6}\left(1+\sqrt{1+\left(\frac{\pi b}{P_c}\right)^2}+4\sqrt{1+\frac{1}{2}\left(\frac{\pi b}{P_c}\right)^2}\right)\end{aligned} \tag{2}$$

2.4. Fundamental Equations and Performance Indicators for PHEs

The main governing relations and performance metrics generally used in evaluating PHE performance in the literature are described in this section. The goal is not to introduce definitions, but to establish a consistent set of thermo-hydraulic parameters that are repeatedly used across experimental and numerical studies. Having these metrics presented in the same form not only allows for easier comparison of the reported results, but it also helps identify how geometric modifications, working fluids, and operating conditions influence overall PHE performance.

2.4.1. Flow characterization and Reynolds Number

The Reynolds number (Re) is used to characterize the flow regime and plays a key role in determining thermo-hydraulic behavior in plate heat exchangers. In PHEs, however, flow transition does not follow classical behavior due to the presence of corrugated and chevron-type surfaces, which promote earlier transition at significantly lower Re values [64–67]. The following relation calculates the Re in PHEs:

$$\mathrm{Re} = \frac{\dot{m}D_h}{A_c\mu} \tag{3}$$

These surface features induce strong secondary flows, flow separation, and vortex formation, leading to enhanced mixing and destabilization of the laminar regime. As a result, the critical Reynolds number ($\mathrm{Re_{cr}}$) in PHEs is strongly dependent on geometric parameters such as chevron angle (β), corrugation depth and pitch, and hydraulic diameter [68,69]. Figure 6 illustrates the different flow regimes and their corresponding Re ranges in PHEs. Based on this

behavior, Zhu and Haglind [70] proposed a geometry-dependent correlation for predicting the Re_{cr}, expressed as:

$$\mathrm{Re}_{cr} = \exp\left[\frac{5.62 - 1.13(\sin\beta)^{2.5}}{0.83 + 0.43(\sin\beta)^{5}}\right] \tag{4}$$

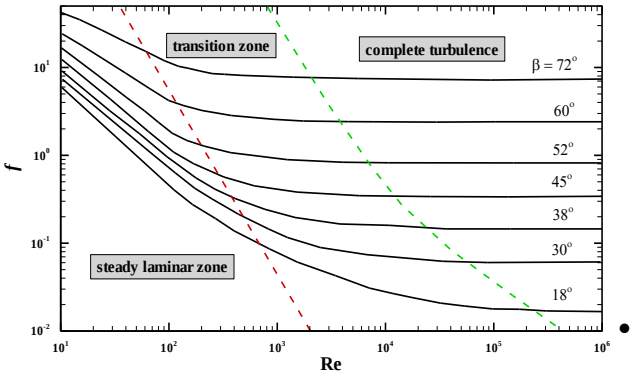


Figure 6. f-Re diagram for cross-corrugated PHEs at different β [70].

2.4.2 Heat Transfer Rate and Energy Balance

The heat transfer performance of PHEs is evaluated based on an energy balance between the hot and cold streams. To reduce experimental uncertainty, the effective heat transfer rate is commonly taken as the average of the values calculated from both sides [12].

The heat transfer rates on the hot and cold sides are expressed as [71]:

$$Q_h = \left(\dot{m} c_p (T_i - T_o)\right)_h \tag{5}$$

$$Q_c = \left(\dot{m} c_p (T_i - T_o)\right)_c \tag{6}$$

Accordingly, the average heat transfer rate is given by:

$$Q_{avg} = \frac{Q_h + Q_c}{2} \tag{7}$$

The overall heat transfer coefficient (U) is then determined using the LMTD method:

$$U = \frac{Q_{avg}}{A \Delta T_{LMTD}} = \left[\frac{1}{h_h} + R_{f,h} + \frac{t}{k_{wall}} + R_{f,c} + \frac{1}{h_c}\right]^{-1} \tag{8}$$

where U accounts for the combined effects of convection, wall conduction, and fouling resistance. The LMTD is expressed as [71]:

$$\Delta T_{LMTD} = \frac{\left[(T_{h,i} - T_{c,o}) - (T_{h,o} - T_{c,i})\right]}{\ln\left[(T_{h,i} - T_{c,o}) / (T_{h,o} - T_{c,i})\right]} \tag{9}$$

2.4.3. Heat Transfer and Hydraulic Performance Parameters in PHEs

Nusselt Number

Nusselt number (Nu) is a dimensionless parameter used to quantify the convective heat transfer performance of PHEs. It represents the ratio of convective to conductive heat transfer resistances across the fluid boundary layer and is defined as:

$$Nu = \frac{hD_h}{k} \tag{10}$$

In PHEs, the Nusselt number is strongly influenced by the Reynolds and Prandtl numbers, as well as geometric parameters such as the corrugation angle, pitch, and depth. Due to the complex corrugated geometry, empirical correlations are commonly employed and are generally expressed in the form:

$$Nu = a\,\mathrm{Re}^{m}\,\mathrm{Pr}^{b}\left(\mu/\mu_w\right)^{0.14} \tag{11}$$

where a, b, and m are geometry-dependent constants determined experimentally or numerically (see Table 1 for more PHE Nu empirical correlations).

Colburn and Fanning Factors

The Colburn heat transfer factor (j-factor) is widely used to evaluate and compare the thermal efficiency of compact heat exchangers, including PHEs, while accounting for flow conditions. It is defined as [54]:

$$j = \frac{Nu}{\mathrm{Re}\,\mathrm{Pr}^{1/3}} \tag{12}$$

The friction factor is a dimensionless parameter that characterizes the hydraulic resistance and pressure losses within the flow channels of a plate heat exchanger. It is commonly defined as [60]:

$$f = \frac{\Delta p}{(L/D_h)(\frac{1}{2}\rho u^2)} \tag{13}$$

Another frequently reported form relates the friction factor directly to Reynolds number through empirical correlations:

$$f = c\,\mathrm{Re}^{-n} \tag{14}$$

where c and n are geometry-dependent constants, such expressions are particularly useful for incorporating friction losses into system-level models and optimization frameworks for PHEs, (see Table 1 for more collected f correlations).

Thermo-Hydraulic Performance Criterion (JF factor)

To assess the overall efficiency of enhancement techniques in PHEs, the combined JF performance factor is often employed. This criterion simultaneously accounts for heat transfer enhancement and pressure drop penalty and is expressed as [72]:

$$JF = \frac{(j/j_{ref})}{(f/f_{ref})^{1/3}} \tag{15}$$

where the subscript *ref* denotes values for a reference configuration (e.g., smooth or flat plate).

3. Thermal–Hydraulic Enhancement Mechanisms

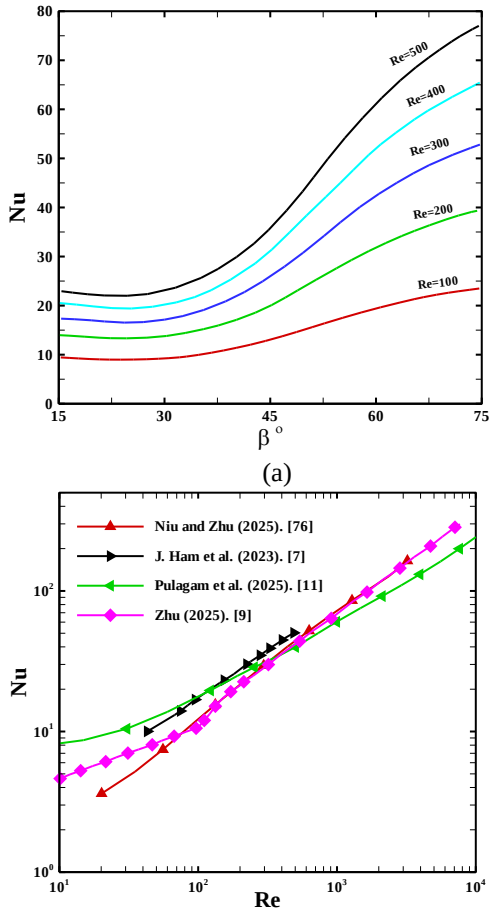
Plate heat exchangers typically have four ports for working fluids, with two as inlets and the other two as outlets, allowing for various flow arrangements. Depending

on the application, PHEs have been investigated under various operating conditions, including single-phase [59], two-phase [43], and three-phase [78] flows. In addition to flow configuration and phase response, several studies have been done to enhance the thermal–hydraulic performances of PHEs using various enhancement techniques. Given their importance, this section discusses three primary enhancement groups that are commonly described in the literature. The first group involves surface modifications, such as changes in corrugation geometry, aimed at intensifying turbulence and heat transfer. The second group focuses on surface coatings, which are employed to improve thermal performance and mitigate fouling while maintaining acceptable pressure drop levels. The last group concerns the use of nanofluids as working fluids, which have demonstrated potential to enhance thermal conductivity and convective heat transfer. Collectively, these groups represent the dominant research directions in recent PHE studies and serve as the foundation for ongoing thermal–hydraulic optimization efforts.

3.1. Chevron Design and Surface Modification Optimizations

The chevron angle (β) is one of the most relevant geometric parameters associated with heat transfer and pressure drop in PHEs. Modifying β greatly affects the effective heat transfer area and flow structure of the channels and thus overall thermal performance, as proven by several studies [6,80]. By increasing β, the flow is subjected to stronger redirection, leading to more intense vortical structures and secondary flows. These processes enhance the fluid mixing and constantly disturb the thermal boundary layer, hence increasing heat transfer coefficients.

As illustrated in Figure 7, As flow builds momentum, its effects become more pronounced, empowering these mechanisms to work more efficiently. However, these enhancements in heat transfer do not come without a cost. The same flow disturbances that promote the mixing increase the flow resistance, and a significant increase in the pressure drop occurs. This situation is a reflection of an intrinsic thermo-hydraulic trade-off, in which improved thermal performance comes at a cost of higher pumping power. Zhu [9] reported that higher β significantly enhances heat transfer at low Reynolds numbers, while simultaneously inducing a pronounced increase in pressure drop. Consequently, large β is generally recommended for applications operating under low Reynolds number conditions where enhanced heat transfer is prioritized. Although the relationship between β and thermal enhancement is usually positive, Nilpueng et al. [8] showed that this trend may reverse in the presence of surface roughness, as roughened surfaces can increase flow resistance disproportionately relative to the heat transfer gains. Furthermore, excessive surface roughness may promote fouling deposition, which can deteriorate long-term thermal performance and increase maintenance requirements. Figure 8 shows the effect of the chevron angle (β) on the Nusselt number in PHEs. Higher β values tended to induce higher Nu values, particularly at high Re. This trend results from the greater redirection caused by the larger β. Fluid enters the corrugated channels in more marked zigzag paths as it leaves the distribution zone. This more pronounced redirection increases secondary flow pathways and induces vortex formation in the grooves. Hence, the boundary layer is continuously disturbed, promoting better mixing between the core flow and the near-wall area. The effect is stronger at higher Re; the inertial forces enhance these mechanisms, leading to an enhanced improvement of heat transfer. Sadeghianjahromi et al. [45] experimentally studied this phenomenon according to BPHEs with 4 chevron configurations (L, M, H, LH) corresponding to β of 35°, 50°, 65° and a mixed condition of 35°/65°, respectively.



(b)Figure 7. Different and recent studies on (a) Nu and (b) f, at β = 60° at wide range of Re.

Their results confirmed that β significantly influences thermal performance, with the H-type configuration having the highest Nu while the L-type having the lowest. Other than single-phase flow, the relationship between β and working fluid properties has also been investigated using nanofluids.

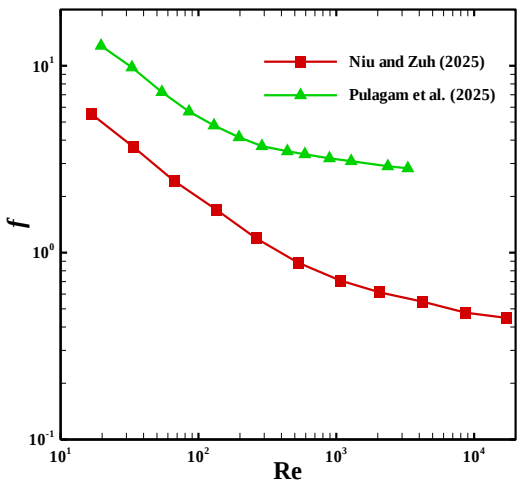


Figure 8. Impact of β on Nu at various Re [7].

Table 1. Overview of recent experimental (E) and numerical (N) investigations on corrugated PHEs.

Authors and year	Topic	Working fluid	Parameters range	Focus	Cost Effective	Correlations
Nilpueng et al. (2018) [8]	E	Water	Re: 1200 – 3500 Pr: 5.39 – 5.65 ε: 0.95 μm – 2.75 μm	chevron angle (β) and surface roughness (ε)	Boost overall performance	$Nu = 0.343\,\mathrm{Re}^{0.604}\,\mathrm{Pr}^{0.33}(\varepsilon/D_h)^{0.133}(\beta/30)^{-1.327}$ $f = 1.98\,\mathrm{Re}^{-0.237}(\varepsilon/D_h)^{0.168}(\beta/30)^{-0.903}$
Al-Zahrani et al. (2020&2021) [72], [65]	N	Water	Re: 500 – 2000	Modify geometry, boost overall performance	Reduce maldistribution	For modified: $Nu = 0.096\,\mathrm{Re}^{0.8273}\,\mathrm{Pr}^{1/3}(\mu/\mu_w)^{0.14}$ & $f = 12.52\,\mathrm{Re}^{-0.094}$; $\beta = 60^o$ $Nu = 0.1134\,\mathrm{Re}^{0.7721}\,\mathrm{Pr}^{1/3}(\mu/\mu_w)^{0.14}$ & $f = 12.48\,\mathrm{Re}^{-0.184}$; $\beta = 30^o$ For unmodified: $Nu = 0.2354\,\mathrm{Re}^{0.6415}\,\mathrm{Pr}^{1/3}(\mu/\mu_w)^{0.14}$ & $f = 5.47\,\mathrm{Re}^{-0.2934}$; $\beta = 60^o$ $Nu = 0.2332\,\mathrm{Re}^{0.6175}\,\mathrm{Pr}^{1/3}(\mu/\mu_w)^{0.14}$ & $f = 5.47\,\mathrm{Re}^{-0.2934}$; $\beta = 30^o$
Liu et al. (2021) [22]	E	Water	Re: 0 – 1000 Pr: 3.54 – 4.31	Enhance surface: coating	Reduce fouling	For coated $Nu = 0.333\,\mathrm{Re}^{0.502}\,\mathrm{Pr}^{0.4(0.3)}(\mu_f/\mu_w)^{0.14}$ & $f = 52.374\,\mathrm{Re}^{-0.216}$ For uncoated $Nu = 0.231\,\mathrm{Re}^{0.583}\,\mathrm{Pr}^{0.4(0.3)}(\mu_f/\mu_w)^{0.14}$ & $f = 33.735\,\mathrm{Re}^{-0.125}$ $0.84 < \mu_f/\mu_w < 1.19$
Adeghianjahromi et al. (2022) [45]	E & N	Water	Re: 50 – 10 000 $35° \le \beta \le 65°$	β	Optimized chevron selection	$Nu = 0.0037\beta^{1.247}\,\mathrm{Re}^{0.9164\beta^{-0.068}}\,\mathrm{Pr}^{0.3}(\mu/\mu_w)^{0.14}$; $\mathrm{Re} < 1000$ $Nu = [0.00004\beta^{1.5107}\,\mathrm{Re} + 5.5607\beta^{0.5281}]\mathrm{Pr}^{0.3}(\mu/\mu_w)^{0.14}$; $\mathrm{Re} > 1000$; $f = C\,\mathrm{Re}^m(\mu/\mu_w)^{0.14}$ $\mathrm{Re} < 1000$; $C = 0.0062\beta^2 - 0.4784\beta + 19.834$ & $m = 0.000015\beta^2 + 0.0083\beta - 0.93$ $\mathrm{Re} > 1000$; $C = 0.00405\beta^2 - 0.333\beta + 7.6$ & $m = -0.00019\beta^2 + 0.0239\beta - 0.816$
Jafari et al. (2023) [12]	E & N	Water	Re: 50 – 10 000	Effect of brazing joints	Design optimization guidance	$Nu = \begin{cases} 0.0818\,\mathrm{Re}^{1.0154}\,\mathrm{Pr}^{0.4}(\mu/\mu_w)^{0.14} & \mathrm{Re} < 300 \\ 1.3204\,\mathrm{Re}^{0.5388}\,\mathrm{Pr}^{0.4}(\mu/\mu_w)^{0.14} & \mathrm{Re} > 300 \end{cases}$ $f = \begin{cases} 15.252\,\mathrm{Re}^{-0.384}(\mu/\mu_w)^{0.14} & \mathrm{Re} < 300 \\ 3.6509\,\mathrm{Re}^{-0.144}(\mu/\mu_w)^{0.14} & \mathrm{Re} > 300 \end{cases}$
Ham et al. (2023) [7]	E	$LiBr–H_2O$	Weak solution Re : 127.3–286.3 Strong solution Re: 49.8–574.2	β	Design optimization guidance	$Nu = \left(0.358 - 0.001267\beta + 0.1778\times10^{-4}\beta^2\right)\mathrm{Re}^{0.6355-0.1106\sin(0.1991\pi\beta/45)}\,\mathrm{Pr}^{1/3}$
García-Castillo et al. (2024) [6]	N	Water	Re: 44 – 49 000 Pr: 2-20 $30° \le \beta \le 80°$	Reduced surface area	95% reducing surface area, and 55% saving cost.	$f = \left[\left(a_L\,\mathrm{Re}^{b_L}\right)^{15} + \left(a_R\,\mathrm{Re}^{b_R}\right)^{15}\right]^{1/15}$ $j = \left[\left(c_L\,\mathrm{Re}^{d_L}\right)^{15} + \left(c_R\,\mathrm{Re}^{d_R}\right)^{15}\right]^{1/15}$ a_L, a_R, c_L, and c_R function of β
Mi et al. (2024) [49]	N	Ethylene glycol-water solution (6.5 wt%)/wat	Re_M: 50 – 1130	Ice slurry behavior	Geometric parameter effects	$Nu = 0.301(\mathrm{Re}_M\,\mathrm{Pr}_{is})^{1.22}\left(\frac{H}{D}\right)^{1.01}\left(\frac{P}{D}\right)^{-1.201}$ $f = 35.038\,\mathrm{Re}_M^{-1.304}\left(\frac{H}{D}\right)^{-1.046}\left(\frac{P}{D}\right)^{1.499}$
F. J. dos Santos et al. (2024) [73]	E	Water	Re: 260 – 3080	β	Reduce maldistribution effects	$f = A\mathrm{Re}^B$ A and B are constant depending on β
X. Zhu (2025) [9]	N	Water	Re: 10 – 6 000	β	Optimized chevron selection	$Nu_l = 2.56\cos\beta^{1.23}\,\mathrm{Re}^{(1-0.9\sqrt{\cos\beta})}\,\mathrm{Pr}^{1/3}$ $Nu_t = \left(\frac{0.578}{\sqrt{\cos\beta}} - 0.561\right)\mathrm{Re}^{(0.6+0.22\cos\beta)}\,\mathrm{Pr}^{1/3}$ $18° \le \beta \le 72°$
Kong et al. (2025) [74]	N	Water	Re: 4 765.49 – 7 963.21	Flow–Boiling Mechanism	Design optimization guidance	$h = 6.56\times10^{-4}\left(\frac{\mathrm{Re}_g}{\mathrm{Re}_l}\right)^{-4.296}(Bo)^{-0.04}(X_{tt})^{0.745}\frac{k_l}{D_h}$ Re: 4765.49 - 7963.21; $\mathrm{Re}_g/\mathrm{Re}_l$: 0.042 - 0.044 Bo: 0 - 0.067; X_{tt}: 0.094 - 0.176

L. Zhu et al. (2025) [75]	E & N	Helium	Re: 500-6000	Investigate the superfluid helium cryogenic system	Design optimization guidance	$j=\begin{cases}0.67\,\mathrm{Re}^{-0.486} & 500\le \mathrm{Re}<1500\\ 0.206\,\mathrm{Re}^{-0.322} & 1500\le \mathrm{Re}<6000\end{cases}$ $f=\begin{cases}1.614\,\mathrm{Re}^{-0.257} & 500\le \mathrm{Re}<1500\\ 0.43\,\mathrm{Re}^{-0.073} & 1500\le \mathrm{Re}<6000\end{cases}$
Niu & Zhu (2025) [76]	N	Water	Re: 10 – 10000 β: 18° – 72° ϕ: 1.0467 – 1.3072	Model development	Rapid performance prediction by machine learning	$Nu=\begin{cases}4.36e^{\sin\beta\left(37.071-13.764\phi-28.319\phi^{-1}\right)}\mathrm{Re}^{(0.836\sin\beta)/\phi} & \mathrm{Re}<\mathrm{Re}_c\\ 0.023e^{\sin\beta\left(28.928-9.757\phi-18.24\phi^{-1}\right)}\mathrm{Re}^{0.8} & \mathrm{Re}>\mathrm{Re}_c\end{cases}$ $f=\begin{cases}62.3e^{\sin\beta\left(1.548(\sin\beta)^{2.62}-0.602\phi^{-1}\right)}\mathrm{Re}^{(0.295\sin\beta)/\phi-1} & \mathrm{Re}<\mathrm{Re}_c\\ 0.3164e^{\sin\beta\left(32.64(\sin\beta)^{0.06}-9.814\phi-19.764\phi^{-1}\right)}\mathrm{Re}^{0.045\phi\sin\beta-\frac{1}{4}} & \mathrm{Re}>\mathrm{Re}_c\end{cases}$
Zeinali Heris et al. (2025) [77]	E	Graphene - COOH/water and tio_2/water nanofluid	Re: 120 – 300	Thermal performance of nanofluids	Comparison study	$Nu=0.0494\,\mathrm{Re}^{0.878}\,\mathrm{Pr}^{0.33}$

Here, the effect of β on heat transfer is studied for MWCNT/distilled-water nanofluid and was reported as an enhancement of 13.64% and 17.27% for β of 30° and 60°, respectively [79]. Simultaneously, advanced surface modifications for further thermal improvement have been studied in recent works. As depicted in Figure 9 [80–83], several novel plate geometries have been proposed, including double-corrugated plates (as shown in Figure 10) in which a secondary corrugation is superimposed onto the primary corrugation. This configuration, as depicted in Figure 9 (a), was shown to increase thermal efficiency by up to 50% while reducing the pressure drop by about 30% [80]. Additionally, Al Zahrani et al. [65] introduced a modified plate design incorporating a central separator to alter the flow path within the channel, resulting in approximately 75% increases in the Nusselt number and 42% increases in effectiveness. The same authors further investigated flow maldistribution behavior under identical operating conditions [72], highlighting the importance of flow uniformity in enhanced PHE designs. A summary of the most common and modern PHE configurations is provided in Table 2.

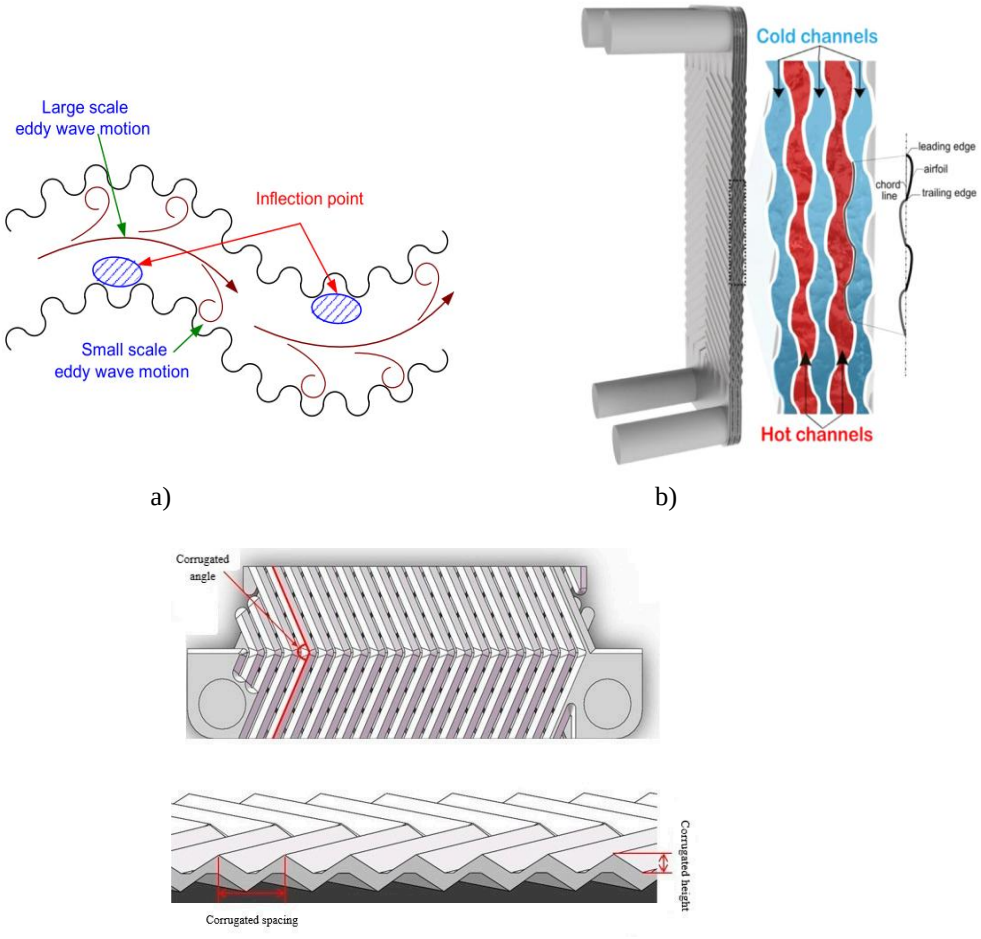
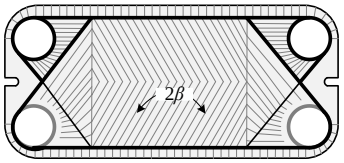
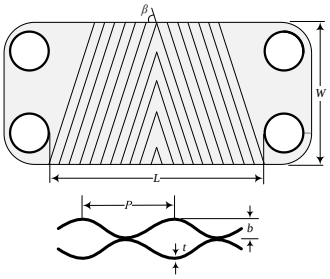
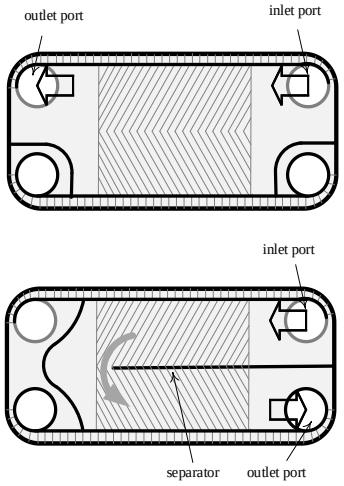
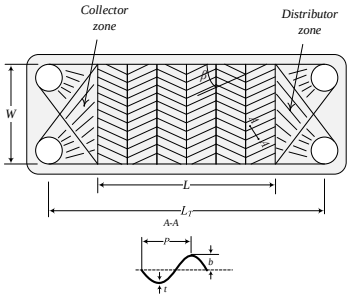
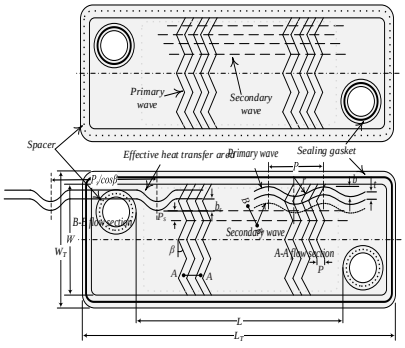
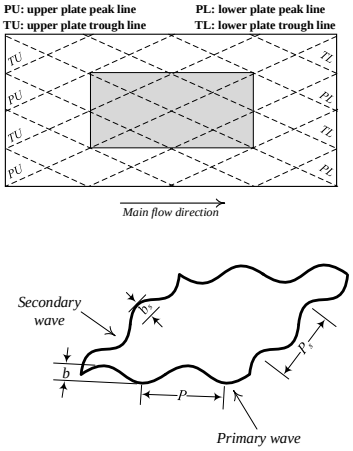


Figure 9. Various corrugated configurations proposed (a) double-wave plates [80], (b) Airfoil corrugated PHE [83], and (c) Trapezoidal PHE [82].

Table 2. Frequently configurations used of PHEs.

Ref.	Configurations	Dimensions	Ref.	Configurations	Dimensions
[29]		*N/A*	[7]		*W: 110* *L: 219* *t: 0.3* *b: 2* *P: 6.5* *β: 30°; 60°* *N: 10* D_{port}*: 23*
[65]		*β*:30°/30°; 60°/60°	[84]		*L: 720* *W: 486* *t: 0.6* *b: 1.6* *P: 12* *β: 40°* D_{port}*: 155*
[80]		W : 124 L : 267 W_T : 162 L_T : 430 P : 11 P_s: 11 b : 3.2 b_s : 0.9 β : 30° r : 2	[81]		*N/A*

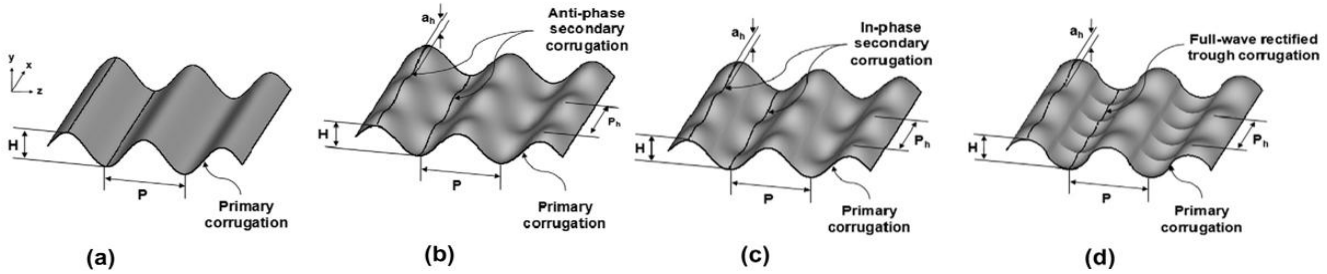


Figure 10. Configurations of four different primary surfaces with (a) conventional sinusoidal corrugation, (b) anti-phase secondary corrugation, (c) in-phase secondary corrugation and (d) full-wave rectified trough corrugation [81].

In this context, there is a gap in the literature regarding the possible modification of the plate surface, as the overall performance of double- and multi-corrugated surfaces has not been detailed. Additionally, the investigations focused on the pattern shown in Figure 4 , whereas other patterns shown in Table 2 were not thoroughly examined. Furthermore, the available publications on the effect of surface roughness on changes in β are relatively few, which calls for detailed investigations.

3.2. Surface Coatings

Many challenges arise during the operation of PHEs, including fouling, corrosion, and scaling, all of which can progressively degrade thermal–hydraulic performance and increase fouling resistance and operational costs. Consequently, surface coatings and surface modification techniques have attracted increasing research attention as promising strategies to mitigate fouling and improve long-term performance in demanding thermal environments [23,85,86]. Figure 11 shows the effect of fouling on a coated and an uncoated plate surface.



Figure 11. Fouling effect on a coated and an uncoated plate surface [21].

Urbina et al. [87] provided a comprehensive review of advanced materials and coating strategies designed for harsh operating conditions, highlighting their potential to enhance durability and fouling resistance. Several experimental studies have demonstrated that appropriately selected coatings can effectively reduce fouling formation and facilitate cleaning, as confirmed through on-site industrial case studies [21]. Kananeh et al. [85] demonstrated that applying nanocomposite antifouling coatings to GPHEs in milk processing significantly reduced fouling deposition and decreased cleaning-in-place time by 70–80% compared to uncoated stainless steel plates. However, coating application often introduces additional thermal resistance and alters surface characteristics, leading to trade-offs between fouling mitigation and thermal performance. For example, Liu et al. [22] evaluated the fouling resistance of Ni–P–PTFE and Ni–P–TiO_2 coatings and reported a significant reduction in fouling propensity; nevertheless, this improvement was accompanied by a decrease in hea t transfer performance of approximately 17.6% and an increase in pressure drop of about 15.8%. As illustrated in Figure 12, surface coatings modify friction factor and Nusselt number through both surface roughness change and add further conductive resistance. Smooth coatings reduce wall friction and pressure losses, whilst added thermal resistance typically affects convective heat transfer. In certain circumstances, as in the case of inadequate coating adhesion, a surface roughening process is required prior to the adhesion of the coating to guarantee the mechanical stability. Ahn et al. [46] used nano-electrochemical etching for plate surface modification and superhydrophobic coatings made of polymethyl methacrylate and hexagonal boron nitride to finish the process. They reported that their results showed enhanced fouling resistance and heat transfer performance, but with a higher pressure drop than on unmodified plates. Recently, Ho Nguyn et al. [88] investigated the influence of optimized surface roughness on the overall performance of PHEs using electrochemical etching combined with a multi-objective genetic algorithm. Their findings confirmed that an optimal roughness level exists at which the competing effects of heat transfer enhancement and pressure drop can be effectively balanced, underscoring the importance of integrated surface design strategies for advanced PHE applications. Coating application in PHEs can be economically restrictive in certain applications; therefore, several coating options have been investigated, with attention to both performance and cost-effectiveness. For instance, four coating techniques were evaluated for their thermal–hydraulic performance and coating cost per unit length, and special electroplating was identified as the most favorable option when balancing performance gains with economic feasibility [89]. Despite these benefits and drawbacks, field-scale data remain scarce. In particular, the influence of plate flexure and contact points on coating durability has not been quantitatively assessed. Moreover, robust correlations between coating adhesion strength and resistance to various fouling mechanisms remain limited.

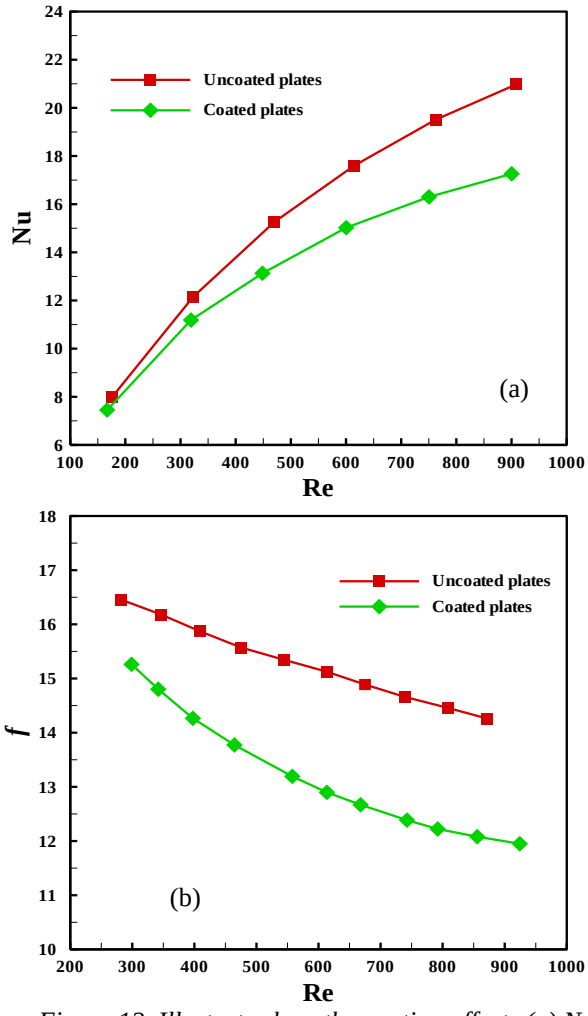


Figure 12. Illustrates how the coating affects (a) Nu and (b) f [22].

Systematic studies addressing coating degradation under prolonged operation, exposure to different working fluids, and repeated cleaning-in-place (CIP) cycles are lacking. In addition, comprehensive assessments of the health,

environmental, and economic impacts associated with coating manufacturing processes and their application in beverage manufacturing, pasteurization, and other processes have not yet been conducted. The assessments encompass the evaluation of the coatings' impact on the products, especially food products, prior to and following heat exchange operations, to verify that the coating does not compromise product safety and ensure consumer health. Also, only a limited number of predictive models currently exist that couple surface roughness evolution with contaminant deposition and fouling growth behavior.

3.3. Nanofluids and Advanced Working Fluids

The term "nanofluid" was introduced in 1995, intending to establish suspensions of nanoscale solid particles in conventional heat transfer fluids to improve the effective thermal conductivity of the working fluid [90]. The thermal conductivity of nanofluid (k_{nf}) is given by the following correlation proposed by Maxwell [91]:

$$k_{nf} = \left[\frac{k_p + 2k + 2(k_p - k)\varphi}{k_p + 2k - (k_p - k)\varphi} \right] k \tag{16}$$

Where, k_p, k, and φ are nanoparticles thermal conductivity, base fluid thermal conductivity, and particle volume fraction (%), respectively. Also, the nanofluid density (ρ_{nf}) given by Pak and Cho correlation as [92]:

$$\rho_{nf} = (1-\varphi)\rho + \varphi\rho_p \tag{17}$$

Where, ρ_p and ρ refer to nanoparticles and base fluid densities, respectively.

Additionally, the following formula used to determine the nanofluid absolute viscosity (μ_{nf}) [92]:

$$\mu_{nf} = (1+2.5\varphi)\mu \tag{18}$$

At its core, it is based on the idea of dispersing nanoparticles at low volume fractions within base fluids like water, ethylene glycol, or their mixtures, which, in principle, improve the thermal properties of materials at relatively small sizes without the sedimentation issues associated with larger particles. Nanofluids are commonly applied in PHEs where their higher fluid thermal conductivity and better microscale mixing can increase convective heat transfer performance. Figure 13 compares the effect of two nanofluids on Nu in a PHE, with respect to water. However, the development of nanoparticles necessarily changes some other thermophysical characteristics, particularly viscosity, which may lead to increased pumping power demands that offset some of the heat transfer improvements, depending on the operating conditions [93]. For instance, ZrO_2-based nanofluids were examined in a PHE employed in a low-enthalpy geothermal plant using a propylene glycol–water mixture (10:90 vol.%). Under laminar flow conditions, the nanofluid achieved a 123% increase in heat transfer compared with 8.8% for the base fluid alone [94]. In addition, the interaction of nanofluids with geometric characteristics have made increasing observations in recent research. In studies in Al_2O_3 nanofluids, it was shown that chevron angle changes have an effect on the performance of nanofluids which is similar to single phase base fluids; higher β leads to the tendency to improve heat transfer at the expense of pressure drop [16]. These results were then confirmed by Valizadeh Ardalan et al. [95], which confirms geometric effects are dominant even when nanofluids are included.

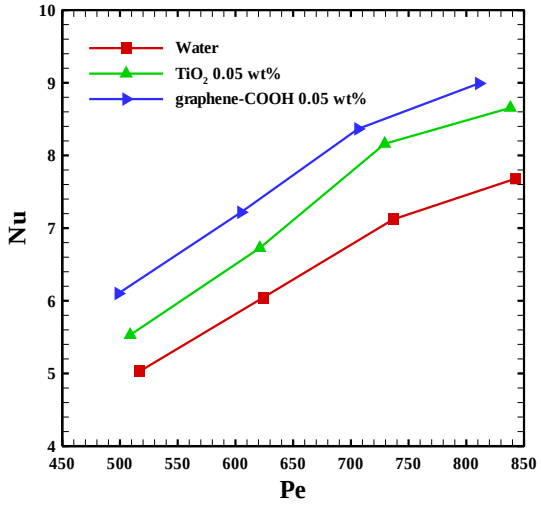


Figure 13. The influence of two nanofluids on Nu at various Peclet numbers (Pe) in PHE [77].

More recently, Behrozifard et al. [14] studied graphene oxide (GO)/water and Al_2O_3/water nanofluids incorporated into PHEs at low mass fractions 0.01–0.03% using an experimentally feasible approach. At the highest concentration studied, GO and Al_2O_3 nanofluids were 37% and 21% thermal efficient agents respectively, relative to the base medium. The combined GO and Al_2O_3 nanofluid demonstrated an intermediate enhancement of 26%, which reflects that hybrid formulations could compromise the benefits of the performance and material cost. In another work, Zeinali Heris et al. [77] compared graphene-COOH/water and TiO_2/water nanofluids and observed that the thermal performance for the graphene-based suspension improved by 27.8% compared with 15.6%. The pressure-drop penalty for graphene-COOH/water nanofluids was minimal (approximately 3.8%), whereas the net performance gain for COOH/water nanofluids was about 24.7% at a Reynolds number of 135. These results demonstrate that carefully selected nanofluids can achieve significant thermal efficiency with reasonable hydraulic penalties. However, regarding the applicability of nanofluids, the main issue is the increased pressure drop associated with the enhanced viscosity [15]. This trade off is most crucial in small systems, such as micro-PHEs. To be relevant here, Dossumbekov et al. [96] used sensitivity-based methods to assess hybrid TiO_2-ZnO nanofluids in micro-scale PHEs and demonstrated improved prediction of heat transfer performance. In industrial applications, Fe_3O_4 and SiO_2/water nanofluids have also been tested in PHEs for vegetable oil processing. By optimizing the chevron angle and using aluminum alloy plates, the thermal efficiency increased by approximately 2.6% [97]. In several experimental reports, the heat transfer enhancement occurred 10–40% and the corresponding pressure drop penalty rose by 5–30% and it depend on nanoparticle type, concentration, and flow conditions. Therefore, the overall effectiveness of nanofluids in PHE applications should not be evaluated based solely on heat transfer enhancement, but rather through a combined thermo-hydraulic performance criterion that balances the

gain in heat transfer with the associated hydraulic cost. However, the long-term impact of nanofluids on plate material degradation, corrosion behavior, and service lifetime has not been well studied, despite advanced design. In the literature, only limited attention has been paid to nanoparticle-induced corrosion or material-compatibility issues in metallic PHE plates, underscoring a critical gap that warrants systematic investigation.

4. Sustainability Considerations and AI-Driven Approaches in PHEs

The PHEs are important, regardless of the many ways they can be used. For heating, they need pumps, compressors, and heaters, which require energy, typically sourced from burning fossil fuels. Fossil fuels burn and release gases, especially CO_2. This gas is harmful to the environment because it worsens air quality, increases pollution, and raises the risk of global warming. We have not observed any clear interest in this area in previous publications, even though thermal and hydraulic optimization in PHEs has become more common. The transition to environmentally friendly, sustainable energy in PHEs is a fundamental objective that deserves significant attention. It helps reduce both emissions and wasted energy. Alongside this, the 20th – century breakthrough in high-speed digital computers had a massive impact on how CFD is applied to simulate thermal performance optimization and other design considerations. Problems that once took years to solve using traditional methods more than 60 years ago, can now be solved at low cost within hours, or even just minutes, of computer time. The increasing complexity and applicability of CFD require significant computational resources to operate computers. In recent years, Artificial Intelligence (AI) has advanced significantly, ushering in a new era of technological revolution. This global technology can greatly help our field by saving computational time and effort through predictive processes. Notably, heat exchangers as a whole can have a significant impact on life. In this section, we have combined AI/ML with sustainability and cost-effectiveness to reduce time, effort, and emissions, as these areas share a common future direction.

4.1 Integration of Sustainable and Renewable Energy Sources in PHEs Systems

The average atmospheric CO_2 level was 428.62 ppm in January 2026, compared with 426.65 ppm in January 2025 [98]. It continues to rise daily and monthly, contributing to increased greenhouse gas emissions. Hansen et al. [99] introduced a statistical study on the effects of greenhouse gas emissions on the atmosphere. The global mean temperature was rising by about 0.18 °C per decade over the previous 30 years. By 2009, the global temperature had already increased by about 0.75 °C relative to 1880–1920 (preindustrial), indicating that rising greenhouse gas levels are causing global warming. It was necessary to focus intensively on directing sustainable, clean energy rather than on burning fossil fuels. Performance enhancement refers to improvements at the PHEs component level, specifically focusing on increasing the thermo-hydraulic efficiency of the heat exchanger itself. This includes augmenting heat transfer rates (e.g., higher Nu), improving fluid mixing, and optimizing flow structures, often accompanied by a trade-off with increased pressure drop and pumping power. On the other hand, system-level sustainability integration is more than the individual component level, it is the way that the heat exchanger operates within a broader energy system. This encompasses its incorporation into renewable energy sources (solar thermal systems, for instance), its contribution to reducing overall energy consumption and environmental impact, and its long-term operational efficiency. More precisely, performance enhancement targets the heat exchanger, and sustainability integration aims to make the whole system more energy-efficient, environmentally friendly, and economically viable. The two concepts are related (device and system), but the former works at the device level, and the latter at the system level.

Furthermore, as PHEs are widely used in thermal management and heat recovery applications, their coupling with renewable energy sources, particularly solar thermal technologies, can significantly enhance energy sustainability, improve environmental performance, and reduce operational costs. Within this field, the integration of renewable energy technologies with PHEs can support sustainability objectives. Established photovoltaic or wind energy systems can supply the electrical power required to operate PHE components such as pumps and compressors, while solar thermal collectors can be used to heat the working fluids in applications such as HVAC systems and pasteurization processes. Various types of solar thermal collectors are capable of providing the temperature levels required for a wide range of thermal applications [100].

4.2 Hybrid CFD-Based Modeling Approaches

Artificial intelligence (AI) has rapidly spread to all fields and industries in our current era. A comprehensive review of the potential of AI in fluid dynamics and heat transfer is presented by Cremades et al. [101] and Nems et al. [102]. Some researchers have already begun to employ AI as an assistant in their applications and studies [103, 104]. While traditional methods are based on physical and mathematical equations, the solutions to these equations may vary. AI, however, is the complete opposite. It is primarily based on the data it was trained on, so the accuracy of its predictions depends on the amount of data it has. Mathematical formulations serve as tools for interpreting physical phenomena; however, the validity of any model ultimately depends on its ability to represent real-world behavior with sufficient accuracy.

For a long time, data has often been associated with experiments; it is also beneficial to combine AI with experimentation. Compared to conventional tools, machine learning (ML) and AI algorithms frequently lack guarantees of performance, robustness, generalization, and convergence. Therefore, AI offers new ways to approach CFD. Instead of discretizing PDEs, we can obtain continuous solutions using automatic differentiation. This is an entirely different approach to CFD [105]. Even today, it is still used for simpler cases. But there are certainly future trends in this regard, as many simulation and analysis software packages have begun to incorporate AI as a feature and have accelerated, for example, Ansys SIMAI [106]. However, this typically means that once the network is trained on a given situation, it can be sampled at any time or place. It means that the solution we have is a continuous function rather than a discrete function on a grid.

Regarding data, it can be obtained from numerical simulation (CFD) results, laboratory experiments, or published literature (numerical or empirical correlations). In engineering applications, particularly PHEs, CFD data is the most common source due to its ability to generate a large

number of parametric studies. The data should cover a wide range of influential parameters, such as Re, β, b, and etc., and be sufficient (more than 300 states) because the accuracy of the results is directly proportional to the amount of input data. The data should also be uniformly distributed and unbiased. Before inputting the data into the model, outliers should be removed, its physical consistency validated, and it should be normalized. The data is then divided into 70% for training, 15% for validation, and 15% for testing [105]. The test data should be invisible to the model during training. After these processes, the behavior of the input-output relationship will be understood. This relationship can then be used in various processes, such as real-time prediction of Nu and friction factor and optimization analysis (e.g., chevron angle, groove arrangements, and inter-plate spacing), assessing the impact of new working fluids, including nanofluids, and supporting digital twin and predictive monitoring systems. The advanced methods, such as Physics-Informed Neural Networks (PINNs) [107,108], or Model Order Reduction (MOR) [109], can be integrated to increase accuracy and reliability. Figure 14 illustrates how to construct the PINNs framework to solve the Navier-Stokes equations [108,110], where the inputs are the four variables (x, y, z, t) and the outputs are the velocity components and pressure. As we noted earlier, prediction performance relies significantly on the training data. This integration of CFD and AI demonstrates a strategic path to achieving substantial improvements in the thermal and hydraulic efficiency of PHE systems while reducing time and computational costs. As of yet we have not utilized AI to identify the most suitable nanofluid for a particular application. However, Yicong et al. [28] combined artificial neural networks (ANNs) and multi-objective genetic algorithms (MOGAs) in BPHEs to predict optimum geometry parameters from multiple options. Aradag et al. [111] developed ANN models based on experimental results. Their results showed that ANNs outperformed empirical correlations with 16% errors compared to 40% for the latter. As such, this result best correlates with experimental data. The Nusselt number of nanoparticles dispersed in water were calculated using three different machine learning algorithm: ANNs, XGBoost, and RF [112].

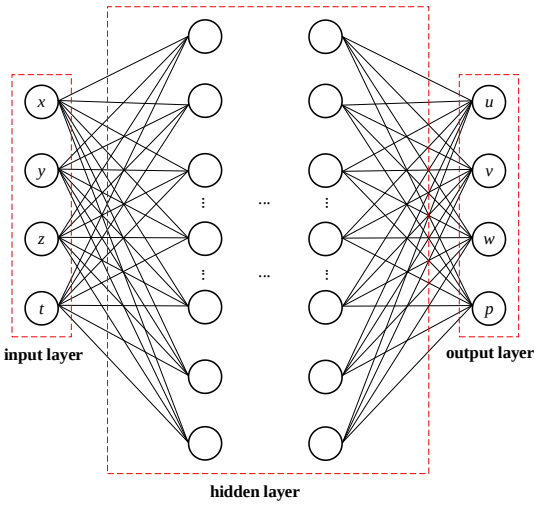


Figure 14. Framework of a Physics-Informed Neural Network (PINN) used to predict solutions of the Navier–Stokes equations.

Figure 15 compares the Nu based on the CFD simulations and the ANN model [112], showing good agreement between the two approaches. The correlation coefficient obtained for the ANN model is approximately 0.868, indicating an acceptable level of predictive capability, but generally, the accuracy could be raised to levels above 0.90. A larger and more diverse training dataset can further enhance the model's generalization performance. In general, expanding the dataset significantly improves the predictive accuracy of data-driven models. It is also worth noting that ML and DL algorithms used for predicting heat transfer coefficients in heat exchangers are significantly faster than conventional CFD simulations while maintaining reasonable predictive accuracy [112,113].

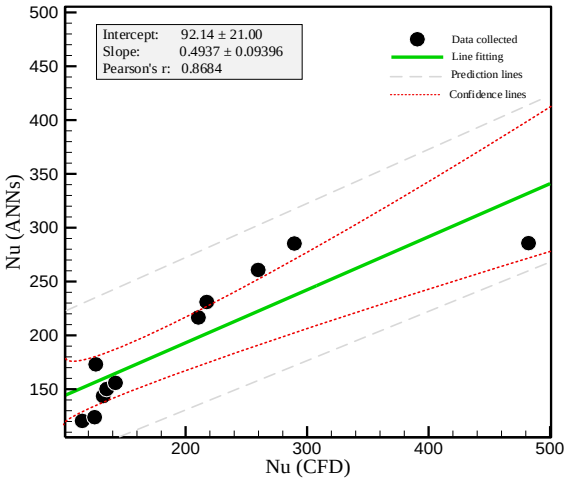


Figure 15. Comparison of Nu values estimated from CFD and ANNs algorithm [114].

Hou et al. [114] utilized Long Short-Term Memory (LSTM) and Multi-Layer Perceptron (MLP) models to monitor the health status of PHEs by predicting fouling-related performance degradation. They developed a modified model that combined both models to achieve high-precision forecasting of exit temperature and fouling thermal resistance. To achieve results within a confidence level, despite the many challenges, integrating CFD and AI produces more accurate results than either alone [115].

5. Enhancing Thermal Performance Through Unsteady Flow

Unsteady flow is characterized by temporal variations in velocity, pressure, and temperature at a given spatial location, which may arise from pulsating inlet conditions or oscillatory boundary inputs. Changeable flow may effectively enhance heat transfer by raising the convective heat transfer coefficient in boundary layers by turbulence and mixing [116,117]. Early studies also indicated that oscillatory and reversed flows can actively affect convective transfer in terms of the reversal mechanisms of the flow changing the thermal energy transport based on the amplitude and frequency of oscillation [118,120]. Wang et al. [120] experimented with heat transfer improvement in a corrugated PHE with water operated under pulsating flow conditions (Re = 1000–3000). In the case of mechanical pulsation generator of 0.45–2.25 Hz in the study the heat transfer coefficient has increased significantly, which attained the maximum with the frequency of 1.8 Hz, which leads to the generation of vortex streets that thin the thermal boundary layer. Mullisen and Loehrke [121] also experimentally explored flow mechanisms in air-cooled, interrupted-plate cores for Re ranging from 10^2 to 10^4 using

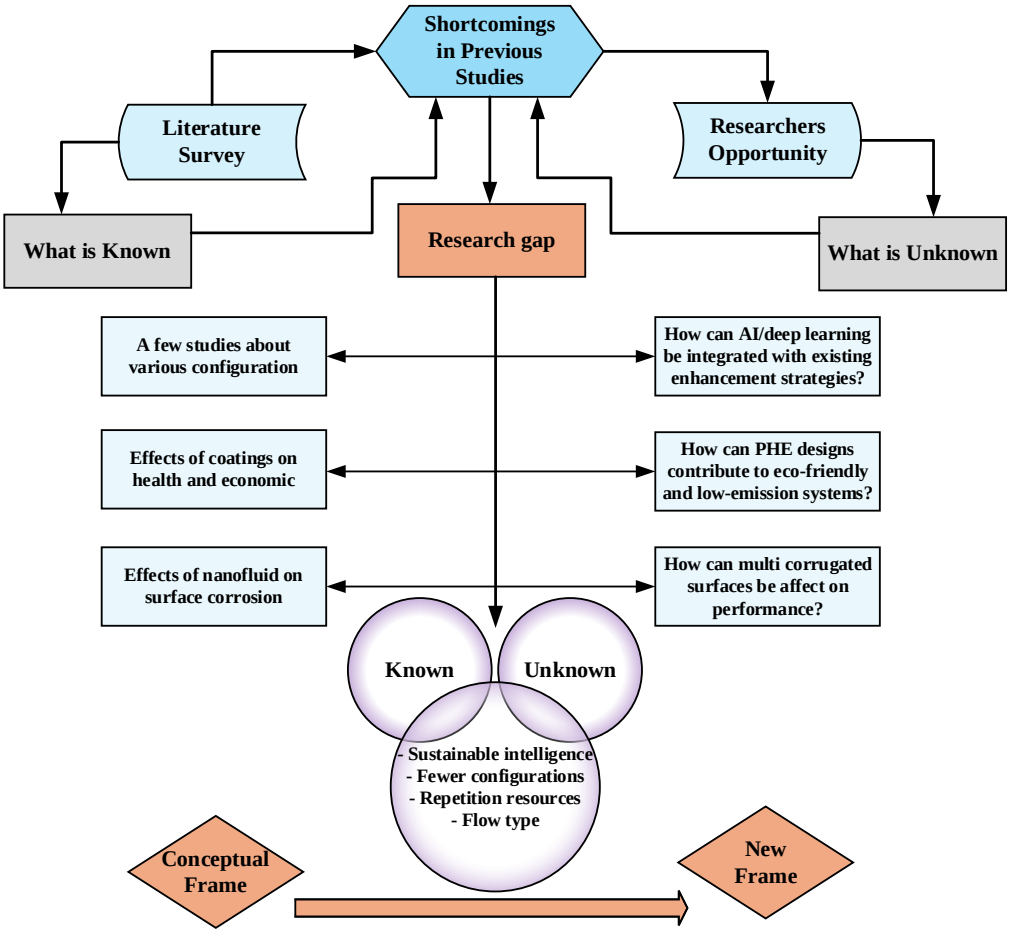


Figure 16. Conceptual flowchart highlighting the areas requiring further research in PHEs.

Schlieren visualization and transient heating. They found that inducing periodic unsteadiness by synchronized vortex shedding increases average heat transfer coefficients more than 100% in relation to continuous surfaces. This suggests that wake unsteadiness induced by surface disturbances is a significant contributor to PHE performance, indicating that corrugated designs are able to exploit unsteady mixing in the same way. The results show that active flow pulsation can reduce clogging problems in PHEs, indicating that similar unsteady control mechanisms can markedly improve the efficiency of corrugated plate channels. Physically, unsteady flow can be considered to result in additional enhancement of heat transfer in PHEs beyond steady-state conditions. Corrugated plates generate high turbulence under steady flow, but additional oscillations can induce mixing further, by periodically disrupting boundary layers and creating secondary flow structures. However, these potential benefits are likely accompanied by increased pressure drop, higher pumping power requirements, and potentially greater fouling risks. In practical PHE applications, steady flow conditions are generally preferred to ensure stable and predictable performance. However, unsteady flow may arise, for example, as a result of pump fluctuations, varying process demands, or pulsating feed streams, which would have time effects on local turbulence in the channels [122]. Several experiments have reported beneficial effects on axial thermal transport and viscous dissipation in terms of oscillatory flow, such as Jalil [119,123]. However, these results are not yet sufficiently validated for PHE geometries and should be considered as indicative rather than conclusive. Likewise, in the last few years mathematical treatments of oscillatory heat transfer have been introduced [122,124], but they have yet to be tested with the consideration of PHE systems. Accordingly, unsteady flow should currently be regarded as a prospective research direction rather than an established enhancement technique for PHEs. Future work is needed to experimentally and numerically assess its thermo-hydraulic performance, quantify the trade-off between heat transfer enhancement and pressure drop, and determine its feasibility for real-world applications. Particular attention should be given to its relevance in systems involving reciprocating or oscillatory operations, such as Stirling-cycle-based applications [125]. The limited number of PHE-specific studies in this area highlights a clear research gap and underscores the need for systematic investigation of pulsed and oscillatory flow effects in plate heat exchanger configurations.

6. Research Gap and Future Directions

The studies reported in the review demonstrate the significant differences in reported enhancement levels. This is due to differences in geometric aspects such as corrugation patterns, chevron angle, plate material, thickness, and operating conditions, including boundary conditions and Re range. These differences have a direct impact on heat transfer mechanisms and performance improvements reported. At lower Re, for instance, enhancement is frequently related to boundary layer disruption and the generation of secondary flows. At greater Re, on the other hand, turbulence intensification becomes the dominant mechanism. Those differences in the underlying physics make it difficult to compare studies directly. Furthermore, the discrepancies in reported results are primarily due to the inconsistency in evaluation criteria. Although Nu is often used as an

indication of the heat transfer performance, the j-factor, or other metrics such as PEC and JF are also used, which consider both thermal and hydraulic performance. Therefore, making meaningful comparisons requires having some standard, or at least a clear reference, for evaluation. Notwithstanding these efforts, several knowledge gaps are still found in the available literature especially when data are fragmented and specific influencing factors are not fully considered. Our study therefore aims to identify these gaps, as well as to indicate parameters that have been ignored and that may influence performance evaluation. Accordingly, Figure 16 summarizes the principal deficiencies in prior research and proposes directions for future work, providing a structured framework that supports more comprehensive and reliable investigations.

7. Conclusion

Priority was given to peer-reviewed journal articles, in particular those with experimental, numerical, or validated analytical results published in the last decade, in this review. Studies lacking careful methodological description, outdated configurations, or marginal relevance to modern PHE design were excluded. Instead of a broad, shallow coverage across all the PHE literature, this targeted approach allows for a critical and structured treatment of the most salient research directions. Based on the prior analysis, the main aspects of this review and important contributions are captured and possible topics to be investigated in future work are indicated.

- Future research should go beyond typical V-type chevron configurations and investigate fully different cavity types, such as W-shaped, or other complex design specified in Table 2, double and multi-corrugated surface designs, to better exploit their potential for thermo-hydraulic enhancement.
- There is a considerable long-term data gap pertaining to the durability, maintenance and the overall operational expenses of sophisticated surface coatings. Additionally, their possible health and environmental implications must be critically evaluated before widespread adoption.
- Although nanofluids show promise for enhancing thermal performance, the long-term stability of metal plates in contact with these fluids has not been fully explored. In particular, issues related to corrosion and material degradation remain critical concerns that require detailed experimental and numerical investigation.
- The global shift to sustainable energy systems is critical to reduce carbon emissions and mitigate climate change. Within this context, the integration of renewable energy sources with PHE systems represents a promising research avenue that warrants further exploration.
- From a thermo-hydraulic optimization standpoint, using AI and machine learning in combination with traditional models provides a great approach for rapid and accurate performance prediction with a low computational cost.
- Most research studies consider steady operating conditions, not yet so, unsteady conditions exist comparatively unmeasured. Such conditions should be studied in order to know better flow behavior, heat transfer mechanism and possible performance enhancement in PHE.

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Conflict of Interest

Authors approve that to the best of their knowledge, there is not any conflict of interest or common interest with an institution/organization or a person that may affect the review process of the paper.

Credit Author Statement

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Nomenclature

$\dot{m}$	Fluid mass flow rate [kg.s^{-1}]
c_p	Specific heat capacity [J.kg^{-1}.K^{-1}]
b	Corrugation depth [mm]
D_h	Hydraulic diameter [mm]
D_{port}	Port diameter [mm]
f	Fanning friction factor [-]
h	Heat transfer coefficient [W.m^{-2}.K^{-1}]
j	Colburn j – factor [-]
JF	JF – factor [-]
L	Effective plate length [mm]
Nu	Nusselt number [-]
P	Corrugation pitch [mm]
P_c	Corrugation pitch [mm]
Pe	Peclet number [-]
Pr	Prandtl number [-]
Re	Reynolds number [-]
Re_c	Critical Reynolds number [-]
t	Plate thickness [mm]
u	Fluid velocity [m.s^{-1}]
U	Overall coefficient of performance [W m^{-2} K^{-1}]
W	Effective plate width [mm]
W_T	Total plate width [mm]
Δp	Channel frictional pressure drop [kPa]

Greek symbols

β	Chevron angle [°]
ρ	Working fluid density [kg.m^{-3}]
φ	Nanoparticles volume fraction [%]
μ	Dynamics fluid viscosity [Pa.s]

Abbreviations

PHE	Plate heat exchanger
CFD	Computational fluid dynamics
CIP	Cleaning in place
BPHE	Brazed plate exchanger
GPHE	Gasket plate heat exchanger
DL	Deep learning
HVAC	Heating, ventilation, and air conditioning
AI	Artificial intelligence
ML	Machine learning
PINNs	Physical-informed neural networks
RF	Random forest
XGBoost	eXtreme Gradient Boosting
ANNs	Artificial neural networks
MOGA	Multi-objective genetic algorithm
MOR	Model order reduction

ppm	Parts per million

Subscripts

i	Inlet
o	Outlet
h	Hot
c	Cold
avg	Average
ref	Reference
nf	Nanofluid
p	Particles

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