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STATE-OF-THE-ART REVIEW ON THE INFLUENCE OF FIN GEOMETRY ON AIR-SIDE HEAT TRANSFER AND PRESSURE DROP IN COMPACT HEAT EXCHANGERS

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Abstract

This review comprehensively examines the influence of fin geometry on the thermo-hydraulic performance of compact heat exchangers (CHEs), emphasizing both plate-fin heat exchangers (PFHEs) and printed circuit heat exchangers (PCHEs). The study integrates findings from experimental investigations, numerical simulations, and analytical correlations to elucidate the relationship between fin configuration, heat transfer enhancement, and pressure loss. For PFHEs, louvered fins demonstrated superior heat transfer augmentation but incurred high pressure penalties, while perforated and wavy fins provided balanced performance with moderate hydraulic losses. In PCHEs, channel topology—ranging from straight and zigzag to wavy, S-shaped, and airfoil fins—significantly influenced flow distribution and overall efficiency. Straight channels offered minimal pressure drop yet limited enhancement, whereas zigzag and wavy geometries improved convective mixing and thermal uniformity. S-shaped fins effectively mitigated reverse flow and reduced pressure loss by up to fivefold, and airfoil fins achieved optimal thermal–hydraulic synergy with superior flow stability. Empirical and semi-empirical correlations for Nusselt number, friction factor, and Colburn j-factor were reviewed and compared across various Reynolds number regimes. The findings underscore that optimal fin geometry selection is critical to balancing heat transfer augmentation with hydraulic efficiency, making advanced PCHE designs—especially wavy, S-shaped, and airfoil configurations—promising candidates for supercritical CO_2 Brayton cycles, molten-salt systems, and next-generation high-efficiency energy applications.

Keywords: Louvered fin, perforated fin, wavy fin, plate-fin heat exchanger, Nusselt number, pressure drop, CFD, experimental.

Introduction

A compact heat exchanger is a piece of equipment that usually operates for efficient heat transfer from one fluid to another [1]. Generally, a compact heat exchanger has a high heat transfer area to volume ratio, large heat transfer coefficients, flow passages, small flow, and the fluid in a laminar flow as shown is Figure 1 [2]. Compact heat exchangers are capable of containing a heat transfer area of at least 400 m^2/m^3 [3]. Gas flow is usually related to undesirable heat transfer coefficients, and compact heat exchangers are employed in a case where the heat transfer is either; between two gases, or involves heat transfer between gas and liquid [2]. An example of a compact heat exchanger is a fin-tube heat exchanger, and as illustrated in Figure 2, a Plate-fin heat exchanger is an example of a Compact heat exchanger which exists in a form. Compact heat exchangers were developed to minimize the size of a heat exchanger plant relevantly. Compact heat exchangers are defined to have a high area density, which is a comparison of the area of the heat exchanger's heat transfer surface to the volume of the heat exchanger [4]. A compact heat exchanger is normally defined as compact if values are above 700 m^2/m^3 for gas to gas, or 400 m^2/m^3 for either gas to liquid or liquid to gas [3].

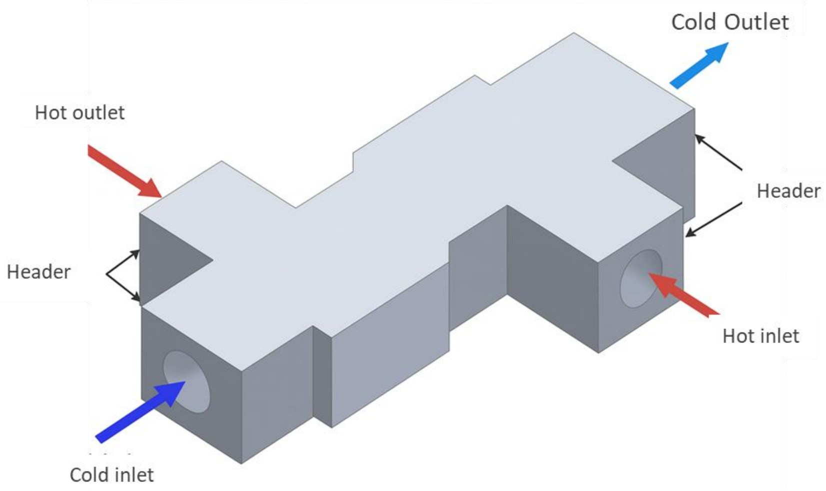

Figure 1. Diagram diagram of a compact heat exchanger [5].

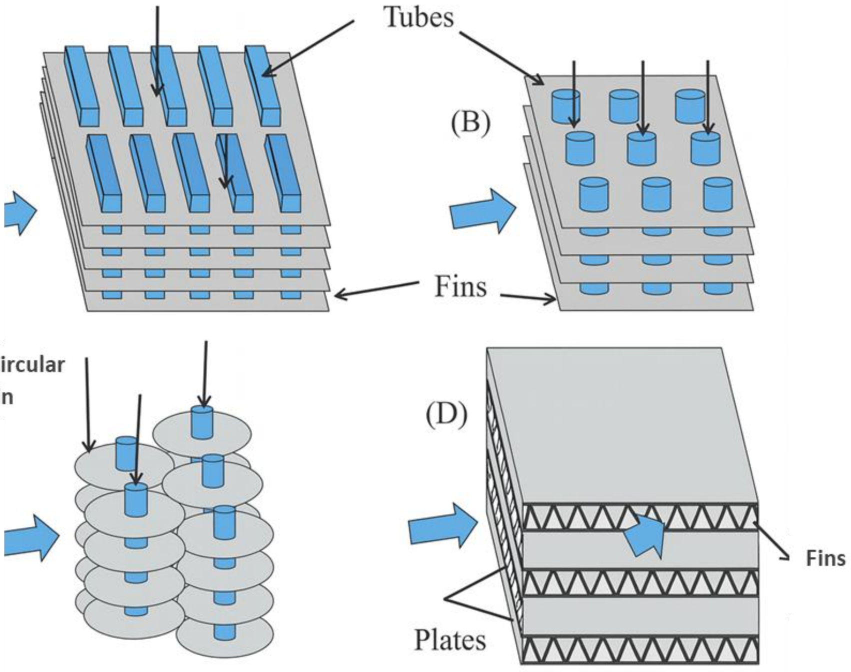

Figure 2. Compact heat exchangers: (A, B, C) fin-type heat exchanger and (D) plate-fin heat exchanger.

A heat exchanger is a mechanism wherein thermal energy is transferred from one set of Itwo or morejimmiscible fluids, commonly divided by a metallic wall, while the fluids are at different temperatures and in thermal connection [6]. A number of studies have been performed in these recent years to improve heat exchangers performance. In the industry, domestic and chemical and power engineering, a heat exchanger are used like intercooler, boiler, air cooler economizers and HVAC&R (heating ventilation-air-conditioning-and-refrigeration) also [7,8]. Various kind of heat exchangers are used in thermal plants. These include the fin-and-tube, shell and tube, double pipe heat exchangers etc [9,10]. It then follows, based on the ratio of heat transfer surface area to volume for the HEs, that they can be categorized as compact. A heat exchanger is characterized as being compact if the ratio of its heat transfer surface area to its volume per unit thermal power exceeds700 m2 /m3 for air and 300 m2 /m3 for liquid- or two-phase flows [11]. Thermal–hydraulic performance of compact fin-and-tube HEs is the primary concern in this paper. The total thermal resistance for the compact heat exchangers is the sum of three components: liquid-side convective thermal resistance, air-side convective thermal resistance, and wall (tube) conductive thermal resistance [12]. Due to the low heat transfer coefficient on the air side, most of the overall heat transfer process is controlled by the air-side thermal resistance [13]. Therefore, the former studies focused on improving the airside heat transfer by using fins to enlarge surface area and enhance air flow disturbance. Furthermore, the effect of various designs of fins on HEs performance is paid a great deal of attention because it is one of the most effective techniques for improving heat transfer rate at air side [14,15].

This review aims to provide a comprehensive and critical assessment of the influence of fin geometry and channel configuration on the thermo-hydraulic performance of compact heat exchangers (CHEs), encompassing both plate-fin (PFHE) and printed circuit heat exchangers (PCHE). The novelty of this work lies in its systematic integration of experimental findings, numerical simulations, and empirical correlations to elucidate the interdependence between geometry, flow structure, and heat transfer mechanisms across a wide range of Reynolds numbers. By classifying and comparing continuous (straight, zigzag, wavy) and discontinuous (S-shaped, airfoil) channel designs, the study highlights the fundamental trade-offs between convective enhancement and pressure loss, providing a unified framework for performance evaluation. Furthermore, this review consolidates correlations for the Nusselt number, friction factor, and Colburn j-factor to support predictive modeling and optimization. Ultimately, the research aims to identify geometrical configurations that deliver the optimal balance between thermal efficiency and hydraulic stability, thereby advancing the design of next-generation compact heat exchangers for high-performance energy systems such as supercritical CO_2 Brayton cycles and molten-salt thermal storage technologies.

Performance Optimization and Main Types of Compact Heat Exchangers

Overview of compact heat exchangers: structures, performance, and materials.

Plate-Fin Heat Exchanger (PFHE)

The plate-fin heat exchanger (PFHE) is a kind of highly efficient heat exchanger which has been widely used in the field of engineering machinery, power systems, medical units and chemical engineering due to its compact structure and excellent heat transfer performance [16]. This higher performance is achieved by combining between parallel plates -in the core - metal fins which are usually corrugated or louvered to produce a dense heat-releasing surface. Several cores are brazed together, along with headers and flanges to form a single lightweight, efficient thermal unit. The fin arrangement rules the thermo-hydraulic performance of PFHEs by disturbing boundary layer, inducing flow mixing and improving convection heat transfer [17]. Heat transfer fins are most often made of aluminum alloys that have high thermal conductivities coupled with low densities, resulting in a surface area density greater than 1000 m^2/m^3 [18]. Flat, wavy, offset strip, louvered and perforated fins are all typical fin geometries suited to distinct thermal or flow requirements. Despite their many benefits, PFHEs are prone to corrosion and fouling; these attributes constrain the application of PFHE and require the careful selection of working fluids [19].

Fin thickness is an important parameter that affects heat transfer and flow resistance field. For example, Kays [20] presented that the pressure drop increases about 25% when the fin thickness is changed from 0.006 in to 0.01 in. Patankar and Prakash [21] also numerically showed that blower fins with thicker fin stock result in higher pressure loss, while not yielding a corresponding heat transfer benefit. Cur and Sparrow [22] find that plate breaks increase the convective performance but they do this with a smaller parameteric value (up to 65%) for collinear arrangements of aligned plates, but also increasing the pressure drop. In addition, later investigations [23] verified that by increasing plate thickness a higher pressure drop would be achieved and also there are other empirical correlations for porous fins in which the permeability, porosity and modified j-factors are related to each other leading an optimized PFHE design. At low Reynolds number, were reported (Re) determines the area goodness factor wavy fins perform better than plate and louvered fin with the maximum value of area goodness factor (Re <1500) [24]. Choi et al. [25], that is, the separated PFHEs with fin heights (7.5–15 mm) have Colburn j-factors higher than continuous by about 6–12%.

Apart from experiments, numerical simulations are now contributing to a better understanding of fin geometry optimization. Elliptical tube–fin PFHEs are 1.5–4.9% more efficient in transfer rate and they have a pressure decrease of type amounts to 22–32 compared to louvered-tube solutions [13]. On the other hand wave fins usually have smaller j and f values than louvered fins under the same conditions [26]. Jeong et al. [27] proposed a modified louvered PFHE in which the crease angle can greatly affect the crease cycle and the number of louvers, thereby controlling global thermal performance. The thermal– hydraulics behaviors of PFHEs are mainly dominated by the heat transfer area, heat transfer coefficient, and the temperature difference. Within space constraints of space-frames, attention has centered on inducing optimal flow distribution and turbulence in order to enhance heat transfer. Jiao et al. [28] showed that the flow uniformity is greatly influenced by the distributor inlet angles and mass flow rate, whereas in Zhang et al. [29] alleviated two-phase maldistribution—flow and temperature non-uniformity decreased by 16.8% and 74.8%, respectively— using header redesign. Vortex generators (VGs), too, are found to be successful in flow promotion; Song et al. [30] demonstrated that small curved delta-wing VGs were more efficient at low-Re, while large circular-arc-shaped winglets became superior with higher Re.

Song and Tagawa [31] also related the transverse VG spacing to the longitudinal vortex interaction and heat transfer augmentation.

In PFHEs, horseshoe vortices developed from the flow around tube bundles locally increase heat transfer while creating wake regions of poor performance. This problem is solved by incorporating elliptical tubes and staggered arrangements, which enhance heat transfer performance as well as reduce pressure loss. Herringbone fins are even more effective to improve thermal performance compared to plain ones as they generate additional surface area and periodic flow-disruptions which weaken the boundary layer. However, more wave angles lead to a higher pumping power and pressure drop even-although they improve heat transfer. Louvered and slit fins offer better heat transfer performance compared to corrugated fin [32], however; they suffer from fouling problem and adverse pressure drop because of periodic boundary layer interruption. Hybrid fin–VG configurations, therefore, have been considered as poten-tial alternatives to optimize the trade-off between heat transfer augmentation and increase in flow pressure drop, which extend interest toward applica-tion of PFHEs for advanced thermal systems.

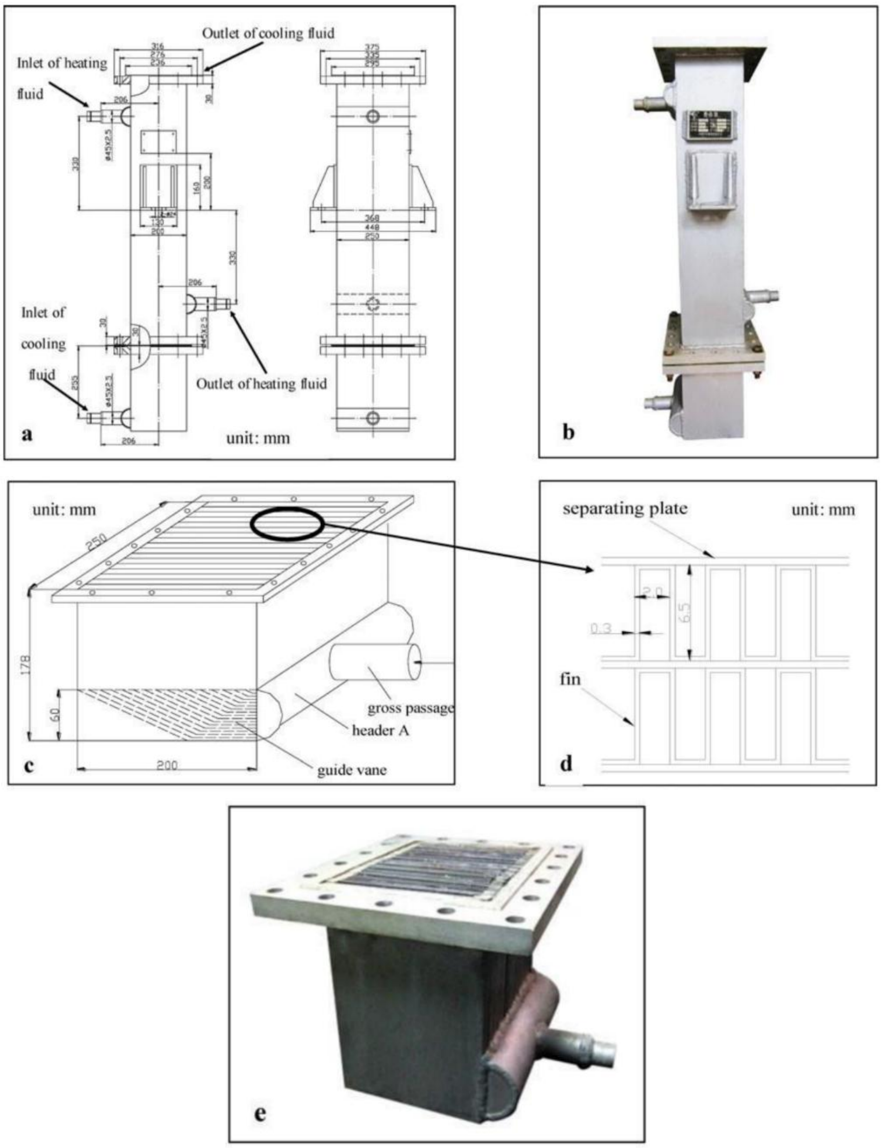

Figure 3. (**a**) Graphic diagram of a PFHE (**b**) PFHE picture (**c**) Graphic diagram of test section (**d**) The fin's geometry (**e**) Test section picture [29].

Printed Circuit Heat Exchanger (PCHE)

The manufacture of the printed circuit heat exchanger (PCHE) is a stark contrast to that for plate-fin type. In the case of PCHE, individual metal plates are micro- etched using photo-chemical techniques to produce precise flow channels and then stacked and diffusion bonded under high temperature/pressure conditions. The solid-state forming procedure avoids the melting-related defects and reduces plastic deformation during forging, which is beneficial for the formation of high-quality parts with superior structure quality and capable of resisting severe thermal–pressure conditions. According to the flow pattern, PCHEs are divided into continuous (straight, zigzag, wavy) and discontinuous channel design (S-shaped or airfoil shape), so that they are very suitable for rising supercritical CO_2 Brayton cycle.

PCHE with Straight Channels

Straight channels are the simplest configuration of PCHEs and often used as baseline cases compared to complicated geometries. They are simple in design providing pass-through transparency without tearing allowing the lowest possible pressure drop and high hydraulic performance. Nonetheless, the thermal performances of straight-channel PCHEs are very sensitive to system conditions and fluid properties in the neighborhood of pseudo-critical point because heat transfer coefficients change rapidly over this range. In experimental work, it has been shown that in the vicinity of the pseudo-critical point, heat removal is much more efficient at cooling [33]. Baek et al. [34] also noted that at low Reynolds numbers, axial conduction governs heat transfer in low-temperature regions. Building on this work, Mylavarapu et al. [35] conducted an experimental evaluation of the performance of PCHE at high temperatures and pressures based on a high temperature helium test facility, where detailed numerical correlations were given for the Colburn -factor and Nusselt number over large ranges of thermal and flow conditions. Similarly, Chu et al. [36] and Park et al. [37] investigated flowing supercritical carbon dioxide (S-CO_2) under different thermodynamic conditions and their analysis also suggests that higher pressure levels enhance the overall thermal–hydraulic performance straight-channel PCHE.

Because an experimental rig is highly expensive and complex, mathematical simulation has played a vital role in PCHE investigation with its advantage of flexibility, rapidly producing data and multivariable interactions understanding. Yoon et al. [38] proposed a computational model for the thermal design and cost analysis of cross-flow PCHEs. Xiang et al. [39] reported that for the horizontal S-CO_2 channels, local heat transfer deterioration at high heat flux is caused by a buoyancy-would induced secondary flow that re-distributes temperature and velocity fields. Zhang et al. [40] verified that local heat transfer performance at low mass flux is controlled not only by the specific heat variation but by buoyancy WARRANT NO.R1SC04070IV. To describe these results in broader terms, Kim et al. [41] reported a low-Reynolds-number ($Re < 150$) correlation (from experimental data), whereas Li et al. [42] developed a PDF-based correlation for forced convection of S-CO_2. Subsequent works [43–46] further developed these models by including the buoyancy, geometrical effect and fluid property to improve the prediction accuracy for Nusselt number and friction factor. Li et al. [47] also established a semi-empirical correlation to predict the effect of transient turbulence flow on S-CO₂ heat transfer and Chu et al. [48] and Ren et al. [49] presented corrections to consider flow maldistribution and buoyancy.

PCHEs are considered to be promising candidates for use as intermediate heat exchangers in future nuclear power reactors because they can operate with high temperature and pressure [50]. Investigating their transient characteristics is essential for safety and control of the system. Chen et al. [51] established a transient model to predict steady-state and transient thermal responses in straight-channel PCHEs, although discrepancies between numerical and experimental results were found to be due to unspecified heat losses. Marchionni et al. [52] conducted full S-CO₂ Brayton cycle model with PCHE dynamics, and pointed out that high-density variation triggers thermal expansion of gas and pressure oscillations, leading to thermal stresses harmful to component integrity.

Boundary conditions (inlet temperature and heat flux) also affect the thermal–hydraulic performance. Li et al. [42,47] found that although high heat flux substantially restricts heat transfer in heating, it has a small effect in cooling. Zhang et al. [45] found that pressure, mass flux and channel diameter have great effects on heat transfer and pressure drop in S-CO₂ flows. Meshram et al. [53] investigated turbulent-flow characteristics between straight-and zigzag channels, and Chai & Tassou [54] showed that the inlet effects induce the localized deterioration in heat transfer with stabilization along the flow passage due to three-dimensional simulation. Ma et al. [55] further developed this concept by using neural network models to forecast dynamic responses on different support conditions so that it can be easily incorporated in full-cycle simulations. Similarly, Kwon et al. [56] developed quasi-steady-state performance models of PCHE regenerators and precoolers for off-design operations to support system-level optimization of S-CO₂ Brayton cycles.

The channel structure and distribution are of great significance to the PCHE performance. Jeon et al. [57] showed that thermal effectiveness is enhanced by increasing channel size at a constant mass flow rate, while the effect of channel spacing and cross-section shape are negligible under fixed hydraulic diameter. Aneesh et al. [58] observed that staggered electrode designs with hot–cold cells provide similar performance as aligned channels, while single banking solutions are superior to double banking on both fronts. The effect of cross-sectional shape has been extensively studied: Figley et al. [59] demonstrated that semicircular channels have greater critical Reynolds numbers for transition, whereas Tu and Zeng [60] noted that although circular channels had larger convective coefficients than semicirculars, the latter provided a higher surface area and therefore a better heat transfer performance. Other works on triangular and rectangular channels [61] reported that geometry also influences flow uniformity, heat transfer coefficient and structural reliability of the thermally stressed equipment. While the spacing between channels has a small effect on heat transfer, it has an important influence on mechanical performance under pressure loading.

Gravity induced buoyancy effects are indeed inherent to the actual operation, and they need therefore to be taken into account during the simulation of PCHEs. It was further found that buoyancy contributes to the enhancement of heat transfer in the vicinity of pseudo-critical point for mixed convection S-CO₂ flow in horizontal microtubes. Xiang et al. [39] and Zhang et al. [62] found the presence of the asymmetric temperature fields and secondary flows to be essential characteristic features in buoyancy driven convection more generally, and for an increase at the top wall and decrease at the bottom. The trends are seen to be strongly anticorrelated with mass flow rate, indicating decreasing buoyancy effect in high-flux situations.

Surface cavities is another well-established method to improving heat transfer with the effect of breaking boundary layer development and generating fluid mixing. Aneesh et al. [58] showed that the addition of hemisphere pits on straight microchannels had higher improvement for heat transfer while leading to larger pressure drop. Based on these works, adding geometrical, size and distribution changes of internal TBs may optimize enhanced heat transfer by balancing with hydraulic penalty.Comparator This analysis is based on a combination of three new findings.

PCHE with Zigzag Channels

When diffusion-bonded to form a monolithic core, the straight or zigzag channels provide ease of construction by chemical etching and can be more robust structurally as compared to PCHEs with interrupted fins. Zigzag-channel PCHEs have called a significant attention in recent year because of their outstanding heat transfer performance and mechanical robustness, which are appropriate to advanced thermal systems including supercritical CO_2 (S-CO_2) Brayton cycle. Insights from these studies are integrated by combination with other experiences and experiments with similar valves under larger category of operating conditions to optimize their performance parameters in the terms of geometry, flow configuration, and operation for obtaining better energy conversion efficiency and reliability upon use at severe thermal environment. Both experimental and numerical investigations have been crucial in understanding the thermo-hydraulic performance of zigzag-channel PCHEs operating under various inlet conditions. Nikitin et al. [63], proposed in experiment on S-CO2 loop the empirical models of local heat transfer coefficient and pressure drop, which are a function of Reynolds number. Similarly, Kim et al. [64] used the KAIST helium test loop in a laminar flow regime ($350 < Re < 1200$) to develop overall friction factor and Nusselt number correlations, which were validated by 3-Dimensional CFD simulations. They further investigated it in a following work [65] with an extended range of Reynolds numbers from 2000 to 58,000 by tuning the auxiliary CFD-based correlations for both heating and cooling cases. Predictive accuracy was again enhanced by Bennett and Chen [66] included channel geometry (Ø, L) and inlet conditions (mflux,T f) in the development of correlations for zigzag doubleducts.

However, PCHEs have not been widely tested as precoolers for S-CO 2 Brayton cycles due to experimental constraints. Cheng et al. [67] performed a 100-kW experimental test and found that a higher inlet water temperature has the effect of decreasing pressure drop without however increasing heat transfer effectiveness, so as to improve overall performance is obtained at higher water Re. The complementary numerical studies by Ma et al. [68] showed that despite the flow development being unfinished at high temperatures, the fluid velocity and temperature are also stabilised after reaching the second pitch. Chen et al. [69] that due to the periodic bends in zigzag channels localized disturbances are generated in the flow, fully developed flow is not maintained and temperature distributions display wavy characteristics along channel length.

Reliable modeling in CFD simulations is critical for the accurate prediction of PCHE performance. Kim et al. [70], compared horizontal vs. vertical PCHE orientations experimentally and numerically, finding that only vertically oriented plates delivered reliable pressure drop data. Yoon et al. [71] validated the correlations for laminar-flow semicircular zigzag geometries, and Chen et al. [72] presented a simulation work of the transient thermal behavior of helium-cooled PCHEs subjected to step changes in inlet conditions, validating their model against an experiment.

Geometric optimization has been the main research area to enhance zigzag PCHEs. Lee and Kim [73] showed that the effectiveness and friction factor increase with the heat transfer area, while there exist trade-offs between configurations of maximum heat transfer at minimum pressure loss. Their follow-up work [74] showed an optimal cold channel inclination angle to be ~110° taking into account the thermal and hydraulic performance. Saeed and Kim [75] generalized the predictions over a broad Reynolds number, clearly establishing that serrated features are highly dependent on the flow regime thereby requiring separate correlations for individual Re ranges. Zhang et al. [76], found by entropy generation and field synergy analysis that large bending angle leads to a high heat transfer rate but at the cost of pressure drop, which is substantially affected with local heat transfer by reverse flow and secondary one.

Advanced modeling techniques have also been included in optimization approaches. Lee and Kim [77] used response surface approximation and genetic algorithm to optimize channel angle and aspect ratio, resulting in higher thermal performance with lower mass. Jiang et al., [78] developed high-temperature and low-temperature regenerator designs for 100-kWe S-CO_2 recompression cycles from corrosion resistant, high-strength materials, based on validated numerical–experimental hybrid models, where a maximum light weight design with a higher angle was found as the most effective one for bulk deployment. In order to alleviate the high pressure drop in zigzag channels, Lee et al. [79] suggested hybrid designs with the short inserted straight sections in between bends. Computational studies showed that pressure loss (with 0.5 mm or 1 mm straight inserts) was greatly reduced but not at the expense of heat transfer efficiency and that flow would be prevented from separating in a radial outflow condition, aside from reverse flow at turning corners. Similarly, Ma et al. [80] a two-sided etched zigzag configuration with elliptical slot was proposed where an improvement in the heat transfer with the increase of the height of the slot at the expense of pressure losses was observed.

Apart from the thermal-hydraulic optimization, evaluation methodologies and sensitivity analyses have been investigated for zigzag-channel PCHEs. Li et al. [81] proposed an operation point analysis method considering the effect of temperature and pressure loading, while Bennett and Chen [82] found bending angle, radius of curvature, channel width and mass flow rate are main sensitivity parameters for PCHE performance. Their subsequent fluid–structure interaction study [83] from finite element analysis illustrated a high degree of coupling between thermal stress and flow-induced deformation, highlighting the necessity for considering structural reliability in high-pressure settings.

PCHE with Wavy Channels

When zigzag channels are progressed to a wavy design, as in printed circuit heat exchangers (PCHEs), which have adopted channel forms featuring waves,2 pressure losses can be further improved without significant loss of heat transfer performance. Sharp flow separation at bends can be alleviated by the smooth curvature of wavy channels, which results in a smaller pressure drop than that of zigzag channels, although less favorable thermal performance is achieved. Baik et al. [84] are able to achieve a pressure drop reduction of 40–65% with smooth wavy geometries compared to traditional zigzag channels and they developed separate correlations for laminar (water side) and turbulent (CO_2 side) flow. The later work of Baik et al. [85] showed that the thermal effectiveness of wavy-channel PCHEs is ~16.4% greater than that of their straight-channel counterparts;Naceur et al. [86], optimum correlations for friction and Nusselt numbers were determined over Reynolds numbers of 350–2100 for wave angles between 5° and 15°.

Enhanced heat transfer was reported in Sung and Lee [87] for Reynolds number between 1,000 and 3,000 as a result of better temperature uniformity in the mixing region. Amplitude and period of waviness have a great effect on the performance as increasing amplitude or period lead to improved heat transfer up to a critical value, after which the better values of them depreciate the effectiveness [85]. Yang et al. periodic variations in heat transfer and friction coefficient distribution were found, [88], refined a back to back correlations with a Nusselt number prediction error within 10%. Moreover, Wang et al. [89] correlated the increase of cooling rate for sinusoidal channels to not an augmentation of surface area but to a greater local turbulent activity close to wave crests. Cui et al. [90] also proved that circular cross-section yielded the greatest thermal efficiency, while the vertical elliptical geometries minimize flow resistance and higher Prandtl number have significant convective effects near the pseudo-critical region. Aneesh et al. [91] noted that the hydraulic performance of straight channels with zigzag inserts was superior to all other configurations whilst heat transfer performance is best for wavy channels; however, it was indicated that wavy channel representing an acceptable trade-off between thermal enhancement and hydraulic efficiency for high power PCHE applications.

PCHE with S-Shaped Fin Channels

The S-shaped fin is a discontinuous flow channel design of PCHE (printed circuit heat exchangers), as a further evolution of the sinusoidal channel to prevent reverse flow and minimize low-momentum recirculation regions. Ngo et al. [92] first proposed this design and showed by combined experiments and numerical analyses that, comparing to the traditional designs, a 3.3 times of volume reduction and a remarkable pressure loss decreases (37% on CO_2 side, 10 times for water side) can be achieved for S-shape fin PCHE. Using response surface methodology and genetic algorithm, Saeed and Kim [93] optimized the fin geometry for heat transfer and pressure drop, resulting in correlations between them, with 2.4 times smaller pressure losses with respect to zigzag channels at low Reynolds. Tsuzuki et al. [94,95] optimized designs by demonstrating the best types of S-shape configurations that can lower as much five times drop pressure in a zigzag channel due to a uniform distribution velocity and absence of vortices, leading to an enhanced thermal–hydraulic performance.

PCHE with Airfoil Fin Channels

A difference shape model of airfoil fin (a special interrupted channel configuration in PCHEs) was first attempted by Kim [96]. In symmetric wing-like geometry, working fluid comes in from the leading edge and exist from the trailing edge under counterflow mode of operation to obtain higher thermal performance. Xu et al. [97] revealed that staggered airfoil-based fins contribute to the improvement of overall hydrothermal performance and flow resistance governs it among others. Furthermore, the newly presented diamond (rhombic) fin configuration h as better hydraulic performance when compared to other patterns: i.e., it could result in lower flow resistance and pressure drop, which are very important for supercritical CO2 as a working fluid.

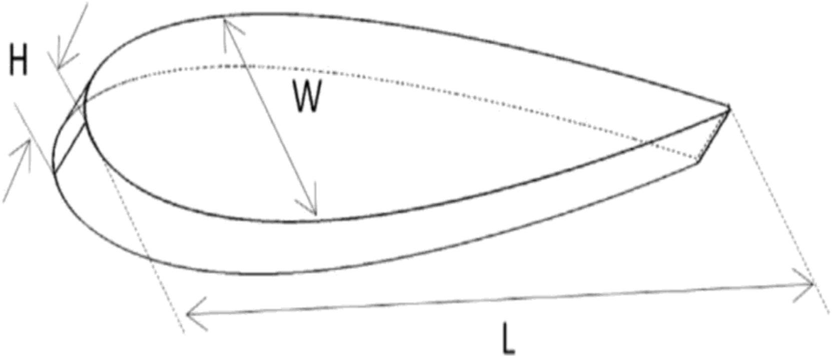

Figure 4. Diagram illustration of a symmetrical airfoil fin [97].

The geometric setting of the airfoil fins—horizontal/vertical, staggered pitch—is critical for the thermal–hydraulic efficiency of printed circuit heat exchangers (PCHEs). Kim et al. [98] showed, through computational simulations, that while staggered patterns have a negligible effect on heat transfer, it largely reduces pressure loss, and an optimal staggering ratio ($\xi_s = 2 L_s / L_h = 1$) reconciles between the two. More horizontal or vertical space provides better hydraulic performance but at the expense of heat transfer. Ma et al. [99] experimentally substantiated these observations, noting small vortices around the fin fillets which enhance heat transfer and drag. Chu et al. [100], developed relationships for the Colburn j and f factors ($8000 < Re < 100{,}000$), finding that greater windward areas and shorter fins provided better global performance.

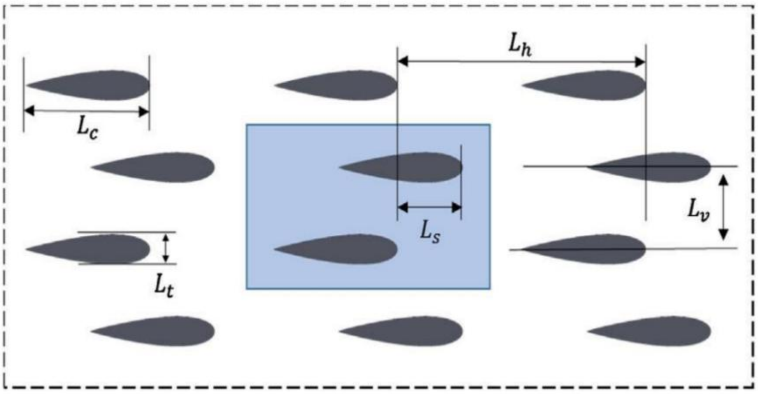

Figure 5. Geometric parameters of the fin arrangement [99].

Numerical analyses show that the NACA 0020 airfoil is found to have lower pressure drop and to possess a comparable heat transfer performance as conventional zigzag-channel PCHEs. However, with constant vertical pitch value, the increase in pressure loss is still much higher compared to that of the improvement in heat transfer [101]. Cui et al. [102] presented two altered airfoil fin geometries, one for better comprehensive performance at low Reynolds number and the other one for lower-pressure drop, and proved that staggered arrangement destroys boundary layers and promotes convective heat transfer well. Due to manufacturing difficulties, empirical studies are scarce. Pidaparti et al. [103] experimentally investigated NACA 0020 and offset-rectangular fin PCHEs at close to the critical region, suggesting empirical correlations for Nusselt numbers and friction factors.

The approach has been recently generalised to molten salt cooled PCHEs. Fu et al. [104] showed that S-CO_2–molten salt airfoil configurations in staggered formations cause less thermal and pressure fluctuations and overall loss as compared to the one in parallel layout. Wang et al. [105] and Shi et al. [106] improved heat transfer correlations for both molten-salt and synthetic-oil systems and found that the high inlet temperature can enhance the performance of molten-salt but decrease its pressure drop. Kwon et al. [107] optimized airfoil-fin allocation with a cost-based objective func- tion for the combined fabrication and operating costs. Nevertheless, it has been found from the literature review that experimental and numerical studies on airfoil-fin PCHEs are less reported, hence there is a need to continue this research for enhanced thermal–hydraulic optimization and correlation models.

Table 1. Summary of the obtained results discussedin the previous literature.

Fin/Channel Type	**Main Characteristics**	**Thermal Performance (Heat Transfer)**	**Hydraulic Performance (Pressure Drop)**	**Key Findings / Correlations**	**References**
Louvered Fins (PFHE)	Multiple inclined louvers create strong flow disturbance	Highest heat transfer enhancement	Highest pressure drop due to strong flow separation	Best suited for high-performance air-side heat exchangers despite pressure penalties	[13,20–31]
Perforated Fins (PFHE)	Include holes to promote mixing	Moderate enhancement	Moderate pressure drop	Provide a balanced performance between efficiency and resistance	[13,20–31]
Wavy Fins (PFHE)	Smooth periodic curvature; extended surface area	Moderate-to-high enhancement (Nu ↑ 25–45%)	Moderate pressure loss (f ↑ 60–90%)	Optimal when wave angle is balanced; excessive angles increase pumping power	[26,32]
Straight Channels (PCHE)	Simplest structure; minimal flow disruption	Moderate heat transfer, sensitive near pseudo-critical region	Lowest pressure drop	Empirical correlations for Nu, f, and j-factor developed; buoyancy effects significant	[33–49]
Zigzag Channels (PCHE)	Alternating angled channels creating secondary flow	High heat transfer (Nu ↑ 30–50%)	High pressure drop	Optimal angle ≈ 110°; inserting short straight sections reduces pressure loss	[63,64,73–76,65–72]
Wavy Channels (PCHE)	Smooth sinusoidal geometry derived from zigzag	16–20% higher than straight channels	40–65% lower than zigzag	Increased amplitude improves heat transfer up to critical value; excessive waviness lowers efficiency	[84–91]
S-Shaped Fins (PCHE)	Discontinuous channel eliminating reverse flow	Excellent thermal–hydraulic balance	2.4–5× lower pressure drop vs. zigzag	Optimized by wing angle and fin dimensions; uniform flow distribution achieved	[92–95]
Airfoil Fins (PCHE)	Symmetrical wing-like structure, counterflow operation	High heat transfer under staggered arrangement	Low pressure drop, best hydraulic efficiency	Staggered and diamond fins improve performance; correlations for Re = 8,000–100,000 established	[96–107]

Conclusion

This review establishes that fin geometry and channel configuration exert decisive influence on the thermal–hydraulic behavior of compact heat exchangers (CHEs). For plate-fin heat exchangers (PFHEs), louvered fins provide the strongest convective enhancement but at the cost of higher flow resistance, whereas perforated and wavy fins offer balanced performance with lower pressure penalties. In printed circuit heat exchangers (PCHEs), straight channels yield minimal pressure drop, zigzag channels deliver superior heat transfer at high hydraulic cost, and wavy configurations achieve up to 65 % pressure-loss reduction while maintaining satisfactory thermal effectiveness. S-shaped and airfoil fins further improve flow uniformity, suppress vortices, and reduce pressure losses by factors of two to five relative to traditional designs. Empirical and numerical correlations for the Nusselt number, friction factor, and Colburn j-factor were consolidated across a wide Reynolds-number range, confirming geometry-driven trade-offs between heat-transfer augmentation and pumping power. Overall, optimized wavy, S-shaped, and airfoil PCHE designs exhibit the most favorable thermal–hydraulic synergy, positioning them as promising candidates for next-generation **supercritical CO_2 Brayton** and **molten-salt energy-conversion systems** requiring high compactness, structural integrity, and operational efficiency.

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