Review on Design and Thermo-Hydraulic Performance Analysis of Pillow Plate Heat Exchanger

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Abstract

Pillow Plate Heat Exchangers (PPHEs) are increasingly important in many industries because of their compact design, cost-effectiveness, and structural integrity. This review paper comprehensively analyzes the design parameters and thermo-hydraulic performance of PPHEs. The design section describes the formation process, geometrical parameters, material selection, and flow configurations. The thermo-hydraulic performance analysis covers heat transfer mechanisms, pressure drop characteristics, and the influence of various design and operational parameters. Recent advancements, challenges, and future research directions in PPHE technology are also discussed. This review aims to provide a valuable resource for researchers and engineers seeking to understand and optimize PPHEs for diverse applications, and contribute to the development of more efficient and sustainable heat exchange solutions.

Keywords: Pillow-plates, Heat exchanger, Heat transfer, Thermo-hydraulic performance, Design parameters

1. Introduction

Reducing energy consumption is a key goal in advancing sustainable development within the global economy. Achieving this requires the adoption of innovative processing technologies and high-efficiency equipment. Heat exchangers play a vital role across many industries, including food and chemical processing, oil and gas, and power generation. With increasing demand for compact and efficient systems, interest in advanced heat exchanger designs has grown significantly.

Recent research emphasizes improving heat exchanger performance by optimizing design features. Enhancements such as modified channel geometries, advanced surface structures, use of novel materials, and integration of flow-disturbing components have been widely studied. For example, improving the internal structure of shell-and-tube and plate heat exchangers can lead to better heat transfer efficiency. These modifications may include helical baffles, twisted tapes in shell-side flow (as shown in reference [2]), or turbulence-promoting inserts in tubes (as described in reference [4]).

Material selection also plays a crucial role in performance and durability. Reference [1] explores the use of graphite sheets in plate heat exchangers, offering enhanced corrosion resistance and compatibility with aggressive fluids, making them suitable for harsh processing environments. Among compact heat exchangers, the Pillow-Plate Heat Exchanger (PPHE) stands out for its efficient design. PPHEs consist of two metal plates welded together and inflated to form channels. These units offer several advantages: low manufacturing cost, compactness, light weight, high pressure resistance, and flexibility in heat transfer surface design. Their structure allows for customizable flow paths and reduced pressure drops. In comparison, chevron plate heat exchangers (chevron PHEs) also feature corrugated surfaces to improve turbulence and heat transfer. However, PPHEs differ significantly in terms of plate manufacturing, channel geometry, and assembly. While both designs rely on surface undulations for efficient heat transfer, PPHEs are particularly favored in modern applications due to their adaptability and structural advantages. The ongoing development of heat exchanger geometries and materials is critical to meeting the energy efficiency needs of contemporary industry. Compact, high-performance exchangers like PPHEs are becoming increasingly relevant as industries strive to lower energy use and operating costs while maintaining process reliability.

2. Design of Pillow Plate Heat Exchanger

Pillow plate heat exchangers (PPHEs) offer enhanced efficiency and compactness. Their design involves complex geometric, material, and fluid dynamic considerations.

2.1 Formation Process

The manufacturing of PPHEs has evolved. Initially, two metal sheets were superimposed, their edges welded, and the structure inflated with hydraulic pressure to form the pillow shape. Finally, the plates were spot-welded for uniformity. The modern method involves spot-welding the plates in a specific pattern before edge welding and hydroforming, simplifying the process and enhancing structural integrity. Emerging techniques like incremental electrohydraulic forming [6], [7] may enable thinner plates and the creation of enhanced surfaces for improved heat transfer [7] [1].

2.2 Geometric Design Parameters

The geometric configuration of a PPHE is crucial in determining its thermo-hydraulic performance. Key parameters include:

- Plate thickness (δ)
- Weld-spot diameter (dws)
- Longitudinal pitch (SL)
- Transversal pitch (ST)
- Inflation height (hi)

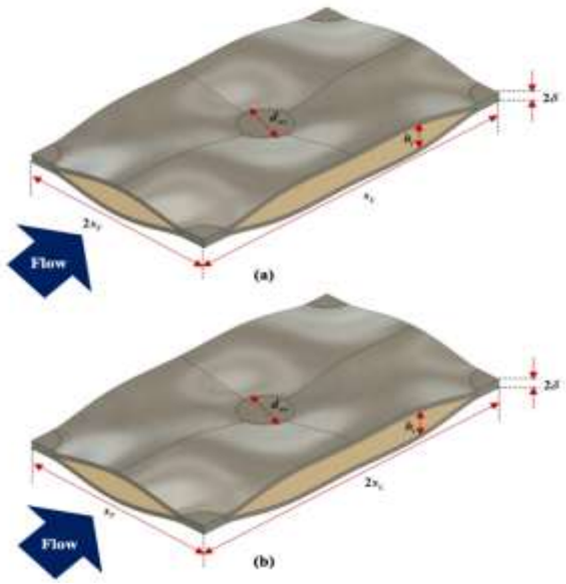

Fig. 1. Design parameters indicating the pitch definitions according to (a) older studies and (b) recent studies.

- **Longitudinal and Transverse Pitch**: The arrangement of weld spots, defined by SL and ST, dictates the flow path and turbulence within the channels. A smaller pitch generally leads to higher heat transfer coefficients but also increased pressure drop. The pitch ratio (SL/ST) is a critical parameter. When this ratio is less than 1, the configuration is considered transverse; when greater than 1, it's longitudinal [1, 3]. Variations in the pitch ratio alter flow behavior and heat transfer. For example, a more transverse configuration (smaller SL/ST) might induce more flow mixing.

- **Weld Spot Diameter**: The size of the weld spots (dws) influences flow restriction and the extent of flow mixing. Larger weld spots can create more flow disturbance, enhancing turbulence and thus heat transfer. However, they also increase flow resistance, leading to a higher pressure drop. The optimal weld spot diameter balances these two competing effects.

- **Inflation Height**: The inflation height (hi) determines the channel volume and the effective heat transfer surface area. A larger inflation height increases the surface area available for heat exchange, which directly improves heat transfer. However, it also increases the volume of the channel, which can affect fluid velocity and pressure drop. The relationship between inflation height and heat transfer is generally positive, but the pressure drop increases non-linearly with inflation height.

Table 1: Chronological summary of the literature in terms of investigated design parameters.

Year	Reference	Material	dws [mm]	ST [mm]	2SL [mm]	hi [mm]	L [mm]	W [mm]	δ [mm]	Orientation
2007	Mitrovic and Peterson [24]	SS	10	72	42	3.4	1000	300	0.8	Vertical
2014, 2015, 2017	Tran et al. [30]	AISI 321	10, 12	72, 42	42	3.4, 3, 7	1000	300	0.8, 1	Vertical
2017, 2019	Arsenyeva et al. [16]	AISI 321	NM	42	72	3.4	1000	300	0.8	NM

2.3 Channel Geometry and Flow Distribution

The unique pillow-like structure of PPHEs creates complex flow channels with varying cross-sectional areas. This geometry promotes flow mixing and disrupts boundary layer development [8], leading to enhanced heat transfer. The design must ensure uniform flow distribution [9], [10] to maximize heat exchanger effectiveness and minimize dead zones. Factors like the shape of the pillow and the arrangement of the plates influence flow distribution. CFD simulations are often used to analyse and optimize flow distribution [10], [11] within PPHE channels.

2.4 Material Selection

The choice of material for PPHEs is governed by factors such as:

- **Corrosion Resistance**: The ability of the material to withstand the corrosive effects of the fluids involved.
- **Thermal Conductivity**: The material's ability to conduct heat. Higher thermal conductivity is desirable for efficient heat transfer.
- **Mechanical Strength**: The material must be strong enough to withstand the operating pressures and temperatures.

- **Cost**: The economic aspect of the material.

Stainless steel is frequently used due to its balance of these properties. Table 1 lists some common materials and their properties. However, other materials like aluminium, titanium, and specialized alloys may be preferred for specific applications, such as those involving highly corrosive fluids or extreme temperatures [1].

Table 2: Materials for PPHEs

Material	Thermal Conductivity (W/mK)	Corrosion Resistance	Strength	Cost
Stainless Steel	15 - 20	High	High	Moderate
Aluminium	200 - 250	Moderate	Low	Low
Titanium	17	Very High	High	High
Copper	400	Moderate	Moderate	Moderate

2.5 Design Optimization

Optimizing PPHEs involves balancing heat transfer performance with pressure drop considerations. These are often competing factors; for instance, increasing turbulence enhances heat transfer but also increases pressure drop. Design optimization typically involves:

- **CFD Simulations**: Computational Fluid Dynamics simulations are used to analyze flow patterns, temperature distributions, and pressure variations within PPHEs. These simulations help visualize and quantify the effects of different design parameters.
- **Multi-objective Optimization**: Techniques like Pareto optimization can be used to find the optimal combination of design parameters that satisfy multiple objectives (e.g., maximizing heat transfer and minimizing pressure drop).
- **Parametric Studies**: Systematic variation of design parameters (SL, ST, dws, hi) to understand their individual and combined effects on performance.

2.6 Manufacturing Considerations

The manufacturing process influences achievable geometries and the cost-effectiveness of production. Modern techniques include:

- **Laser Welding**: Provides precise and strong welds, which is crucial for the structural integrity of PPHEs.
- **Hydroforming**: Uses hydraulic pressure to expand the plates into the desired pillow shape. This process allows for the creation of complex geometries.

Design for Manufacturability (DFM) principles are essential to minimize production costs and ensure product quality. Factors like weldability of the materials, ease of forming, and assembly complexity are considered.

2.7 Design Correlations and Modeling

Accurate prediction of heat transfer and pressure drop is essential for the design and analysis of PPHEs. Researchers have developed various correlations and models to estimate these performance parameters. These models often incorporate geometric parameters, fluid properties, and flow conditions. These correlations are crucial for designers to predict the performance of PPHEs under different operating conditions and to optimize the design.

3. Thermo-hydraulic Performance Analysis

3.1 Heat Transfer Characteristics

Heat transfer in PPHEs depends on flow regime, fluid properties, and pillow plate geometry. Complex flow patterns with recirculation and turbulence enhance heat transfer [2, 4].

3.2 Pressure Drop

Pressure drop is important in PPHE design, affecting pumping power. It is influenced by flow rate, fluid viscosity, and channel geometry [2, 4].

3.3 Performance Evaluation

Thermo-hydraulic performance is evaluated using parameters like the heat transfer coefficient, Nusselt number, friction factor, and thermo-hydraulic efficiency. These parameters are used to optimize PPHE design and operation [3, 4].

3.4 Governing Thermohydraulic Parameters

3.4.1 Reynolds Number (Re)

The Reynolds number defines the flow regime in PPHEs — laminar, transitional, or turbulent. For PPHEs:

$$Re = \frac{\rho U d_h}{\mu}$$

where:

- ρ = fluid density
- U = flow velocity
- d_h = hydraulic diameter
- μ = dynamic viscosity

Experimental and numerical studies show turbulent flow dominance typically beyond $Re > 2000$, with PPHEs efficiently operating across 1200–7800 Reynolds number range.

3.4.2 Prandtl Number (Pr)

The Prandtl number is a fluid property:

$$Pr = \frac{c_p \mu}{k}$$

where:

- c_p = specific heat
- k = thermal conductivity

For water and air flows inside PPHEs, typical Prandtl numbers are about 5.0 for water and 0.7 for air, influencing the thermal boundary layer thickness relative to the velocity boundary layer.

3.4.3 Nusselt Number (Nu)

The Nusselt number characterizes the convective heat transfer:

$$Nu = \frac{hd_h}{k}$$

where:

- h = convective heat transfer coefficient

Various empirical correlations were proposed:

- Inner channels (for turbulent flows):

$$Nu = 0.067Re^{0.774}Pr^{0.338}$$

- Outer channels (air side):

$$Nu = 0.027Re^{0.8}Pr^{0.3}$$

with small deviations (~10%) from experiments.

3.4.4 Friction Factor (f)

The friction factor reflects hydraulic losses:

$$f = \frac{2\Delta P d_h}{\rho L U^2}$$

where:

- ΔP = pressure drop
- L = length of flow path

Empirical correlations show:

- For inner PPHE channel:

$$f = A + \frac{B}{Re}$$

where A and B depend on geometrical parameters.

Typical deviations between experiments and models are within ±10%.

3.4.5 Heat Transfer Performance

The heat transfer rate (Q) is:

$$Q = m \cdot c_p \cdot (T_{\text{in}} - T_{\text{out}})$$

where m = mass flow rate.

Overall heat transfer coefficient U is determined using:

$$\frac{1}{U} = \frac{1}{h_1} + \frac{1}{h_2} + \frac{\delta}{\lambda} + R_f$$

- h_1, h_2 = convective coefficients on each side
- δ = wall thickness
- λ = material conductivity
- R_f = fouling resistance

Typical performance observations:

- High heat transfer rates for small hydraulic diameters (narrow channels).
- Increased turbulence from pillow deformations enhances Nu and Q.

3.5 Influence of Geometrical Parameters

Parameter	Typical Range	Effect on Performance
Longitudinal pitch $2s_L$	42–72 mm	Higher s_L reduces pressure drop.
Transverse pitch s_T	36–72 mm	Wider s_T reduces flow resistance.
Inflation height h_i	3–5.5 mm	Greater h_i increases turbulence and Nu.
Weld spot diameter d_{ws}	6–10 mm	Larger d_{ws} slightly increases ΔP.

4. Practical Experimental Setup

Experimental Configuration:

- Water (70°C) in internal channels, air (20–25°C) externally.
- Small-scale PPHE with three internal and external channels.

`**Geometrical Details**:

Plate Length (L)	1000 mm
Plate Width (ST)	300 mm
Inflation Height (hi)	3.5 mm
Spot Diameter (dws)	10 mm
Longitudinal Pitch (2sL)	72 mm
Transverse Pitch (sT)	42 mm

5. Factors Affecting Thermohydraulic Performance

Parameter	Effect
Pillow Height (hi)	Increases turbulence, improves heat transfer but raises Δp
Weld Spot Pattern	Affects flow distribution and secondary flows
Reynolds Number (Re)	Higher Re improves Nu, but increases pumping costs
Fluid Properties (Pr)	Higher Pr enhances thermal boundary layer disruption
Manufacturing Tolerances	Affect repeatability and performance

6. Applications of Pillow Plate Heat Exchangers

PPHEs are used in various industries (Table 2), including food processing, the chemical industry, HVAC, refrigeration, and energy recovery, where their efficiency and compactness are advantageous [1, 5].

Table 2: Applications of PPHEs

Industry	**Application**
Food Processing	Cooling and heating of milk, pasteurization, wine cooling, chocolate production
Chemical Industry	Heat exchange in chemical processes, cooling of corrosive fluids
HVAC	Evaporators, condensers, and gas coolers in air conditioning systems
Refrigeration	Cooling of refrigerants
Energy Recovery	Waste heat recovery, preheating of fluids

7. Challenges and Future Research Directions

Challenges include fouling and the need for better design tools. Future research should focus on robust design correlations, two-phase flow, application-specific designs, and new materials and manufacturing [1].

8. Conclusion

Pillow Plate Heat Exchangers are a promising solution for efficient heat transfer. This review has highlighted their design parameters, thermo-hydraulic performance, and potential for future development. Continued research will lead to more efficient and sustainable heat exchange solutions [12], [13].

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