CHEMICAL ENGINEERING TRANSACTIONS

VOL. 88, 2021

A publication of

AIDIC

The Italian Association
of Chemical Engineering
Online at www.cetjournal.it

Guest Editors: Petar S. Varbanov, Yee Van Fan, Jiří J. Klemeš

ISBN 978-88-95608-86-0; **ISSN** 2283-9216

DOI: 10.3303/CET2188144

Pillow-Plate Heat Exchangers: an Overview on Advances, Limitations and Prospects

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Pillow-plate heat exchangers (PPHEs) represent an innovative and promising alternative to conventional equipment. The waviness of the pillow-plates promotes lateral mixing and turbulence, which results in a good thermo-hydraulic performance, offering a significant energy-saving potential. Since PPHE also offer several important structural and cost related advantages over conventional heat exchangers, e.g. compact, light and pressure-resistant construction, low pressure drop on the product media side, as well as low capital and operating costs, their use in process industries is growing. However, the implementation of PPHE is still limited due to the lack of comprehensive data and publicly available proven design methods, while their range of applicability has not yet been fully determined.

The purpose of this contribution is to present the current state of the art of PPHE, with particular attention to recent advances in terms of modelling and prediction of the performance of such equipment, while highlighting the advantages in terms of sustainability and efficiency of the various applications compared to conventional solutions. In addition, the future prospects in modelling and application of these devices will also be delineated.

1. Introduction

In recent decades, increasing attention has been paid to the sustainability of products and processes, fostering possible improvements aimed at maintaining a balance between the exploitation of resources and the improvement of the quality of life of modern human society.

In this context, thermal energy recovery represents a key aspect for the sustainable design and operation of processing plants, as minimizing energy consumption translates into reduced environmental impacts and costs. Heat recovery in an industrial process takes place through the heat recovery system, a set of units i.e. heat exchangers – designed to meet the process thermal demands – where exchange of thermal energy between two or more mediums occurs. As heat exchangers are essential in the operation of many systems (Chew et al., 2015), increasing the efficiency and reliability of heat exchangers represents a crucial matter to enhance the overall systems performance and reduce anthropogenic footprint.

Heat exchangers can be divided in two main categories on the basis of their functioning: i) direct heat exchanger, where the exchanging mediums are in direct contact (e.g. cooling towers); and ii) indirect heat exchanger, where such mediums are separated by thin conducting walls to prevent mixing. Many types of technical solutions have been developed, like shell-and-tube (vertical/horizontal), plate (gasketed, welded etc.) and micro heat exchangers.

Since decades, the most spread solution in process industry is represented by shell-and-tube heat exchangers (STHE). This is because such equipment is suitable for a wide range of operating conditions thanks to their robust and flexible as well as easy to build design, which made them exchangers with well-known performances. However, they lack compactness and exhibit low heat transfer rates for a given Reynolds number, due to the presence of stagnant zones, which turn into a loss of useful exchange surface. In contrast to STHE, plate heat exchangers (PHE) are compact, lightweight, flexible in size and provide large overall heat transfer coefficients, but they suffer from generally limited operating ranges of pressures and temperatures (Shah and Sekulic, 2003) and tend to have other complications depending on the adopted technical solutions (e.g. leak tightness issues

Paper Received: 9 May 2021; Revised: 4 July 2021; Accepted: 17 September 2021
Please cite this article as: Vocciante M., Kenig E.Y., 2021, Pillow-Plate Heat Exchangers: an Overview on Advances, Limitations and Prospects, Chemical Engineering Transactions, 88, 865-870 DOI:10.3303/CET2188144

for gasketed PHE or difficulty in cleaning when welded). Nevertheless, PHEs can represent an economic method in various industries to both increase the thermal efficiency and decrease the fuel demand by waste heat recovery (Lianzheng et al., 2019), also thanks to different possible flow arrangements.

Since the first plate heat exchanger appeared in the late 20th century, many advancements and improvements have been done on PHEs design and manufacture (Ayub, 2003). However, to further increase sustainability of both process plants and equipment units, and reduce energy consumption, more efficient heat transfer systems with optimized design are needed (Hesselgreaves et al., 2016). This prompted research efforts on development of advanced geometries and enhanced surfaces for different equipment types to yield higher HE coefficients.

From the geometrical point of view, different configurations have been conceived to increase the thermal performance of PHEs. Solutions experimentally and numerically investigated included multi-layers and multi-channels with different flowing fluids (Malinowski et al., 2019) and/or resorting to mini- and micro-channels (Shyam et al., 2018). As regard surface enhancements, in addition to increase the plate efficiency by increasing turbulence, some solutions like corrugation patterns also produce a self-cleaning mechanism, which reduces fouling propensity and helps to diminish clogging problems deriving from their small flow passages. The most common surface pattern used is the chevron design (Abou Elmaaty et al., 2017).

Among the various types of compact heat exchanger with different geometrical configurations, gasketed and corrugated plate heat exchangers are known for their high thermal efficiency (Tabares et al., 2019). In this equipment, a number of gasketed plates constrained between an upper carrying bar and a lower guide bar are compressed between the fixed frame and the movable frame by using many tie bolts. Based on this, novel corrugated plate heat exchanger (CPHE) were studied both numerically and experimentally (Al Zahrani et al., 2020), also including the effect of geometrical parameters (pitch, depth, and angle of corrugation) on the thermal performance of the system (Wang et al., 2017).

Another solution is represented by welded plate heat exchanger (WPHE), a stack of corrugated plates welded to one another to create the flow passages for the exchanging fluids. Also in this case, plates are corrugated to create high turbulence and wall shear stress, thus increasing the thermal performance for the same exchange surface. WPHE construction features grant higher operating temperatures and pressures and make it suitable for multi-stream applications (Martínez-Rodríguez et al., 2020). Investigations on the use of WPHE also indicate superior overall thermal performance in terms of fouling mitigation (Tamakloe et al., 2013), making it an attractive option in heavy duty applications. The type of surface corrugation and the number of passes are critical elements to consider for the optimal design of this equipment (Arsenyeva et al., 2016).

The constant search for more efficient solutions, granting more efficient heat transfer surfaces with reduced pressure drop and low production cost, resulted in an innovative design of WPHEs, the so-called pillow-plate heat exchangers (PPHEs). They are characterized by a pillow-like surface and fully welded construction (leak tightness). This turns in a similar heat transfer performance compared to other PHE solutions, but using less material and a reduced volume. For instance, the low weight and compactness of pillow-plates make them ideal as condensers (PPC) in distillation applications, in which they can be implemented directly into the column head. In this sense, PPHEs represent a highly sustainable equipment, as they contribute to increasing energy savings while reducing the environmental impact compared to other PHEs (Arsenyeva et al., 2019a).

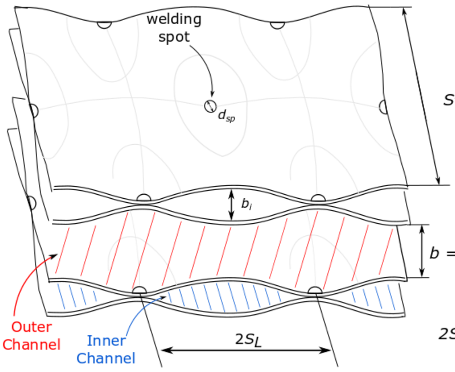
PPHEs have a great flexibility compared other types of heat exchangers. One of the key aspects induced by their particular structure is the possibility of having channels with different cross-sectional area for hot and cold fluids. However, the great variety of constructive and operational parameters that characterizes a PPHE has to be further optimized to compete and exceed the efficiency and compactness of other high efficiency PHEs. Indeed, in spite of the advantages, PPHEs market penetration is currently still slow, mainly due to the lack of comprehensive design principles and the existence of considerable uncertainties in the dimensioning of such apparatuses (Piper et al., 2015a). Yet, in recent years the situation has been progressively changing.

This review aims to gather current knowledge on these innovative heat exchangers, illustrating their structure, thermal performance and heat transfer enhancement mechanisms, as well as their advantages and limitations. Also, PPHEs recent advances and prospects for improvement will be discussed.

2. PPHE structure and geometry

A pillow-plate consists of two overlapping sheets of metal (usually stainless steel), spot-welded together with a specific pattern and seam-welded along the edges mainly by laser or TIG welding process without metal filling (Arsenyeva et al., 2019a). By means of inlet and outlet nozzles, these sheets are then expanded from the inside by hydroforming, i.e. with the aid of an incompressible medium such as water, assuming their characteristic pillow-like structure (Piper et al., 2015a).

Depending on the thickness of the sheets, this process can result in the production of "single embossed" pillow-plates (only one sheet is deformed if it is much thinner than the other), useful for making e.g. pillow-plate jacket vessels, or “double embossed” (symmetrical) pillow-plates, mainly used for the design of PPHEs, where several pillow-plate panels are adjusted together with a certain distance from each other to form a package and inserted into a housing. This arrangement determines an internal flow path IC (inner channel) between the welded sheets of the pillow-plates and an external flow path OC (outer channel) identified by the space between adjacent pillow-plates (Figure 1). As the distance between the panels can vary, the cross-sectional area of the OC can be adjusted, affecting the thermo-hydraulic performance and pressure drop of the OC.



d_{sp} = *welding spot diameter*

S_T = *transversal distance between welding spots*

b_i = *inner expansion of the pillow-plate*

b = *narrowest distance bitween pillow-plates panels*

$2S_L$ = *longitudinal distance between welding spots*

Figure 1: Sketch of a pillow-plate with characteristic geometry parameters.

Pillow-plates shell structure confers high structural strength, so that high pressures of hundreds of bars can be handled, while their wavy geometry results in valuable thermo-hydraulic properties and can be easily adapted to requirements at low cost thanks to high-grade automated manufacturing. Finally, the fully welded design guarantees hermetic seal, ensuring a high level of operational reliability, and allowing for lightweight constructions, as no supporting structures are required.

Turbulent flowing induced by the pillow-like structure not only causes top-notch efficiency for the heat transferring, but also results in a self-cleaning property and reduces fouling tendency. In addition, in contrast to IC, the OC is usually not fully welded, so these channels are cleanable, making PPHEs also suitable for dirty and highly viscous media if they are fed into the OC. This feature helped make PPHEs commonly used in chemical and oil refining industry. Other uses include top condensers in distillation columns and falling film evaporators in food industry as well as in pulp and paper industry.

As PPHEs features and extreme flexibility bring certain advantages over conventional chevron-type PHEs, investigations on heat transfer and pressure drop in PP panels with different geometries is finally intensifying in recent years. In the next section, contributions that have marked the main advances in understanding the dynamics of these devices are summarized.

3. PPHE dynamics

First experimental results regarding the single-phase flow in pillow-plate channels were by Mitrovic and Peterson (2007), whom investigated forced convection heat transfer and pressure drop for IC of an electrically heated pillow-plate and condensation of isopropanol vapor in the OC caused by means of cooling with water in the IC of a PPHE. This investigation was followed by a first numerical study on the IC flow and heat transfer (Mitrovic and Maletic, 2011). In this contribution, various welding spot pattern as well as the inflation height were analyzed, although with numerous approximations on the geometry of the pillow-plates, the flow conditions (supposed laminar) and the boundary conditions (e.g. constant wall temperature).

The complex pillow-plate geometry was accurately reconstructed for the first time in a simulation study by Piper et al. (2015a) as a result of simulating the inflation process itself by which a PP is produced. In this works, the authors also proposed correlations for the hydraulic and equivalent diameters, cross-sectional area and heat transfer coefficient for a wide range of pillow-plate panel geometries, based on relevant parameters like heat transfer surface area and channel volume for the IC and OC, as a result of an extensive study on geometric parameters (welding spot pattern, inflation height, and distance between adjacent plates).

In Piper et al. (2016a), a comprehensive CFD-based investigation of IC single-phase turbulent flow was performed for a number of geometries. Some modifications to optimize the PP panels were considered, e.g. the variation of the distances between the welding spots or the use of oval-shaped welding spots (up to 37% more efficiency). Based on these outcomes, in Piper et al. (2017) correlations for Darcy friction factor and Nusselt number in form of a power law approach were derived, allowing the calculation of pressure loss and heat transfer for a wide range of conditions. In addition, a modelling approach based on a two-zone flow pattern (recirculation zones and the meandering core flow induced by the welding spots) was developed for the IC.

Regarding the OC flow, correlations for friction factor and heat transfer coefficient based on CFD simulations made for one type of pillow-plate geometry and turbulent flow were suggested in Piper et al. (2016b). It was found that boundary layer separation occurs upstream of the welding spots, leading to large, flat-shaped recirculation zones, which strongly affect the friction factor and reduce the heat exchange efficiency. A study on the efficiency of various turbulent models was also performed for the OC flow in Vocciante et al. (2018).

A small-scale PPHE was investigated both experimentally and numerically by Arsenyeva et al. (2019a), finding semi-empirical correlations for friction factor, pressure drop, and heat transfer reliable in a wide range of flow conditions. A comparative case study on PPHEs was also conducted in Arsenyeva et al. (2019b). In this study, a first attempt to design a PPHE was proposed, based on currently available correlations for the estimation of its construction parameters to meet specific process conditions and ensure minimum costs. In addition, a comparison with a chevron-type PHE designed for the same process conditions confirmed a superior performance of the PPHE when operated with significantly different mass flow rates for IC and OC.

4. Recent developments, Limitations and Prospects

Below are some critical issues that still affect PPHEs, as well as recent research that aims to overcome these limitations.

4.1 Welding structure, crack failure and material selection

Edge welding joints are usually a common and economical design for the main structure of PPHEs. However, particular conditions can cause warping and cracking problems, leading to premature failure of welding, and consequent fluid leakage. A reason can be found in stress concentration at connection position or misalignment of plates in the installations (Deen et al., 2010). Another probable cause is a chemical attack by specific ions to which the constituent material of HE is susceptible. In the specific case of PPHEs manufacturing, AISI 316L austenitic stainless steel is widely used due to its good weldability and malleability, as well as the good corrosion resistance guaranteed by the high concentration of Ni and Cr that characterize the austenitic alloy, which, in turn, results being weak in environments with a certain amount chloride ion (Sedriks and Dudt, 2001).

Guo et al. (2021) investigated the crack failure detected at the edge joints of a corrugated 316L steel PPHE served in oil refinery after 80,000 h of functioning to figure out the root cause. Based on the detailed observation of the crack and microstructure nearby, a number of measures are suggested to minimize or solve the problem, including modification of the welding structure (without narrow gap to avoid the crevice corrosion), replacement of the materials (e.g. with duplex or ferrite stainless steel), periodic inspection and strict deionization of cooling water to avoid the influence of chloride ions.

4.2 Surface structuring

It is a known fact that the type of surfaces used in PPHEs is less effective than other corrugated surfaces such as the chevron-type. In this sense, efforts have been made to improve thermo-hydraulic performance by developing solutions to further favor the generation of local turbulence.

Djakow et al. (2017) suggested a solution based on a secondary structuring of the pillow-plate surface with dimples to be obtained by Electrohydraulic Incremental Forming (EHIF). IC numerical investigations report an increase in the heat transfer coefficient of 24 % compared to a smooth-surface pillow-plate, but no OC investigations were performed, making it impossible to determine the overall heat transfer coefficient of the "dimpled" PPHEs. As the introduced dimpled surface was expected to also have an important effect on the OC thermo-hydraulic characteristics, the CFD-based investigation was resumed and completed in Piper et al. (2019). Here, the numerical results confirm dimples secondary structuring as effective in improving mixing near the wall by regular disturbances of the turbulent boundary layer, in addition to affecting the recirculation zones, which turns to be greater in number but smaller and less energetic. This leads to an overall thermo-hydraulic efficiency increased by 11.2 % compared to conventional pillow-plates.

Structuring the PP surface by EHIF also involves an increment in the area moment of inertia of the metal sheets. This allows to manufacture pillow-plates of equal mechanical stability using thinner sheets, thus offering a high potential for weight reduction. Based on this, further improvements are expected by exploring other types of secondary structures.

4.3 Multi-stream PPHE

In the design of heat recovery networks, there is often an interest in reducing the number of HEs, either to contain capital costs or due to space constraints for the installation. In these circumstances, a possible option consists in resorting to HEs capacity of managing multiple streams. However, the conventional structure of a PPHE allows to handle only two operating fluids, one flowing in the plate and the other flowing in the gap between the plates. Different from the existing investigations, Lin et al. (2020) recently proposed a novel plate design for PPHEs which is capable of accommodating two flowing channels in each panel. In this contribution, they performed an experimental study coupling this new structure with a phase change material (PCM) filled in the gap between panels as an energy storage medium. Indeed, by providing good thermal performance, more flexibility and better adaptability for the application on the latent thermal energy storage (where a conventional PPHE cannot be used), this novel multi channels PPHE has a wide application prospect as PCM heat storage system to be implemented in real applications (i.e. solar water energy storage or waste heat recovery).

4.4 Nanofluid effects

Another approach that can play an important role in effectively enhancing the performance of thermal systems consists in using nanofluids as working fluid (Eshgarf et al., 2021). Shirzad et al. (2019) recently investigated, by numerical simulations, the behavior of a PPHE operating with several nanofluids (CuO, Al_2O_3 and TiO_2). Their results suggest that a rise in volume fraction turns in an improvement in HE performance. In particular, by varying the volume fraction from 2 to 5 %, an increase in heat transport was recorded, up to 43.3 % for Al_2O_3 nanofluid. This makes the use of nanofluids in coupling with PPHEs an option certainly worthy of further study.

4.5 Conjugate heat transfer

In numerical studies published so far, the two flow paths (IC and OC) of a PPHE have mostly been investigated as separate problems due to the complexity of the overall system. However, such approach does not allow to catch the real dynamics that are established precisely by virtue of the mutual interaction between the IC and OC flow, e.g. thermal inefficiencies caused by predominant recirculation zones, or the influence of the material used for the pillow-plate manufacturing. In Zibart and Kenig (2021) conjugate heat transfer simulations were carried out for a PPHE operated in countercurrent mode, i.e. IC and OC flows are simulated simultaneously under consideration of the thermal coupling through the sheet material. Allowing a realistic reproduction of the coupled heat transport between IC, metal sheet and OC, this represent a substantial progress against uncoupled simulations and brings numerous benefits, including the possibility of conducting a detailed analysis of the individual thermal resistances of a PPHE, that the authors exploited to create correlations for their correct calculation. Furthermore, on the basis of the obtained results, some fit functions have been proposed to correct some of the correlations currently available based on decoupled CFD simulations, such as those presented by Piper et al. (2017) for the prediction of the thermal transport coefficients and the thermal resistance of IC flow.

5. Conclusions

A brief overview of pillow-plates heat exchangers (PPHEs) was here presented, including the differences in structure compared to other HEs, their peculiar features, flow arrangement and possible applications. In addition, some limitations have been highlighted as well as some recent advances and future prospects, including different strategies to enhance the performance of the equipment.

PPHEs combine the advantages of the most commonly used conventional heat exchanger types, being as pressure and temperature resistant as shell-and-tube heat exchangers and as cost-effective and compact as plate heat exchangers. In addition, they have peculiarities that allow, for example, the heat transfer surface area to be further reduced compared to other types of PHE under the same application conditions, and this translates into further benefits in terms of process sustainability.

However, PPHE design and optimization require reliable correlations to estimate the overall heat transfer coefficient and friction factors, and the relevant information is available in the literature for a limited number of pillow-plate panels only. Thus, further investigations on PPHEs are necessary.

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