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Review Article

ENGINEERING INTERVENTIONS AND DESIGN EVOLUTION OF PLATE HEAT EXCHANGERS FOR FOOD PROCESSING

SAGARIKA N.*[1] AND MODI R.B.[2]
[1]Department of Food Process Engineering, College of Food Processing Technology & Bio-Energy, Anand Agricultural University, Anand, 388110, Gujarat, India
[2]Department of Food Processing Technology, College of Food Processing Technology & Bio-Energy, Anand Agricultural University, Anand, 388110, Gujarat, India
*Corresponding Author: Email - sagarikan@student.aau.in

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Abstract: Heat exchanger is one of the most commonly used equipment for pasteurization, sterilization, and other heating as well as cooling applications. There are many heat exchangers designs available in the market, but many factors need to be considered for selection of a heat exchanger. Among the various designs of heat exchangers, plate heat exchanger offers improved efficiencies when compared to tubular designs. The major advantage of the plate heat exchanger is that higher heat transfer rates can be obtained within small space. Also, it can operate under higher fluid pressures. Considering the importance of a heat exchanger in the food industry and to make readers aware about the stage-wise developments, the designs of the plate heat exchangers have been reviewed.

Keywords: *Heat exchanger, Gasket, Terminal, Six plate, Pressure plate, Frame plate*

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Introduction

Heat exchanger is a device used to transfer heat energy between two or more fluids at different temperatures. Transfer of heat between a solid surface and a fluid, or between solid particulates and a fluid, can be possible by using a heat exchanger. Typical applications of a heat exchanger include heating or cooling of a fluid stream, evaporation or condensation of single or multicomponent fluid streams. The main objective of a heat exchanger is to recover or reject heat, sterilize, pasteurize, fractionate, distill, concentrate, crystallize, and also control a process fluid [1,2]. Several types of heat exchangers viz. plate, tubular, scraped surface, shell and tube, tube in tube, concentric tube etc. are used in the food industry, but the most common are plate heat exchangers. They are one of the most efficient methods of heat transfer for fluid products. Well-designed plate heat exchangers can serve to meet biggest challenges like maximizing run times, promoting cleanability and keeping up with food trends [3].

Plate heat exchanger

The basic design of a plate heat exchanger (PHE) was patented over a century ago and the first commercially successful design was introduced in 1923 by the Aluminium Plant and Vessel Company i.e. APV. At the initial stages, the design of plate heat exchanger was similar to a filter press in which cast gun metal plates were enclosed in a frame. But later in 1950's the design has been modified in such a way that instead of cast gun metal plates, pressed plates were used [4, 5].

Plate-type heat exchangers comprises of thin plates which have either smooth or corrugated surfaces. Based on the leak tightness required, Plate heat exchangers (PHEs) can be classified as gasketed, welded (one or both fluid passages), or brazed. PHEs are mainly classified into frame and plate, brazed plate, and shell-and-plate heat exchangers. Among the three types of heat exchangers, Frame-and plate heat exchanger (FPHE) is most commonly used because of its ease in cleaning, simple adjustment of heat transfer area, compactness and excellent thermal-hydraulic performance. The limitation of this heat exchanger is that it cannot withstand very high temperature and pressure fluctuations [6].

Working Principle

Plate heat exchangers comprises of multiple plates installed inside a frame. In between the plates, channels are formed and the corner ports are arranged in such a way that the two media flow through alternate channels. Once fluid passes through the plates, heat exchange takes place from hotter to the colder side. In order to have effective heat transfer rate, sufficient velocity of fluid across the plates must be provided and also the pressure drops should be controlled. Though the plate heat exchangers work on the same basic principle, but they can be customized for different users and functions. Plates' arrangement into these models is different for each and every application [3].

Evolution of designs of Plate Heat Exchangers

With the updation of knowledge and experience in the operation and performance of the PHEs, various researchers have tried to improve the designs of various parts of the heat exchangers, with a view to improve the efficiency and performance aspects. The noted improvements in the designs are summarized here as below:

Novel six-port plate design of PHE

Thomson (1960) [7] designed a plate heat exchanger incorporating a novel six-port plate which permits considerable economy in design and manufacture. It comprises of cooling, heating and regenerator section interposed between the cooling section and the heating section. By employing a six-port plate such versatility in design has been achieved that three sections of a plate heat exchanger can be made to operate without use of any intermediate terminals. It is well known in this art that when a four-port plate is used, as has been customary up to this time, it is necessary to employ terminals between each section since the use of two processing fluids in one section required full use of both the top and bottom ports on a four-port plate. Therefore, to enter or exit any fluid between sections it was necessary to employ a costly terminal. When six port plate is used in a two-section heat exchanger considerable advantage is still realized.

It is possible with the six-port plate to provide a simplified piping arrangement where desired since it is possible to enter and exit a fluid on the same end of the heat exchanger.

Advances in plate heat exchanger

After the year 1960, the heat exchanger has been modified in such a way that each heat exchanging plate has one or more pressed grooves for gaskets. This arrangement helps in sealing between the two adjacent heat exchange plates. The main purpose of the glue line is to hold the gasket on the plate while operation. Johansson (1983) [8] modified the heat exchanger by fastening the gaskets on the heat exchange plates of a plate heat exchanger to overcome complication in process and also to minimize the cost of heat exchanger. In this invention, the problem of gluing is avoided by arranging the gasket's fastening points outside the sealing area by the gasket groove, at which fastening points of the gasket is fixed outside the heat exchange plate. It is also possible to fasten the gasket mechanically to the plate but the presence of joints limits the field of utilization of these heat exchangers with regard to the pressure, temperature and to certain fluids like solvents or corrosive fluids. Peze and Fechner (1987) [9] designed a plate heat exchanger with a plurality of juxtaposed metallic plates with spaces between them, each plate being joined in tight manner, by its periphery to the two adjacent plates so that every space receives a flow of a first fluid whereas the other space receives a flow of a second fluid, substantially parallel to the first. The plates are paired by straight seam welding in two opposite end parts of the plates of each pair of plates. In extension to this, Andersson *et al*., 1990 [10] developed a plate heat exchanger for viscous fluids, in which spacing has been provided for widening the inlets and outlets of the channels. Inter plate channels are formed by juxtaposing the plates to give the maximum throughput. Later on, in 1988, Pfeiffer [11] invented a heat exchanger possessing rectangular plates, those are rotated with an angle of 180° relative to one another. Here the plates have rectangular heat exchange zone in the middle and two triangular heat exchange zones adjacent to the middle zone on opposite sides. The triangular zones carryout the flow through cross section of the middle zone to the inlet and outlet opening. The triangular zones result in a high-pressure loss which leads to difficulty for exchange of pressure. Kull *et al*., 1999 [12] designed a plate heat exchanger comprises a plurality of heat exchanger plates stacked one above the other. The plates each have a peripheral edge projecting from its plate plane. The heat exchanger plates succeeding one another in each case are sealingly connected at their edges, so that flow ducts for at least two heat exchange media form between the plates. Each of these flow ducts is connected via openings in the heat exchanger plates to at least one other flow duct, so that a first heat exchange medium can flow through a first group of ducts loaded in parallel and a second heat exchange medium can flow through another group. So that a heat exchanger constructed in this way offers a satisfactory heat transmission capacity even in the case of widely varying volume flows of the media involved, the openings for the first heat exchange medium have a substantially larger cross section than the openings for the second heat exchange medium. The main problem with this is, flow channels show a relatively large volume, leading to the occurrence of Leidenfrost phenomenon which can be avoided by redesigning a plate heat exchanger by stacking pattern. Here, the plates are arranged one over the other, and between which primary sided flow channels are formed for a first heat exchanger medium to be evaporated, and secondary sided channels are formed for a second heat exchanger heat carrier medium. This arrangement results in the formation of the primary sided and secondary sided flow channels by maintaining a minimum spacing between two adjacent heat transfer plates, with meshing pattern [13]. Sometimes it is desired that part of a liquid to be heat treated is by-passed to the plate heat exchanger. In such a case a tubular connection is usually connected outside the plate heat exchanger between its inlet and its outlet. A valve being arranged to direct a larger or smaller part of the liquid arriving at the plate heat exchanger through said tubular conduit. If desired, a valve of this kind may be adapted to direct the whole of the liquid flow through either the plate heat exchanger or the conduit. This is quite expensive. In order to overcome this, Jonsson *et al*., 1999 [14] designed a by-pass passage which can be arranged in any desired part of the plate package. Preferably, the by-pass passage is formed in one of the outermost plate interspaces in the plate package, i.e. one end plate of the plate package is used to delimit the by-pass passage. A plate package end plate of this kind is often completely planar, i.e. it is not as the real heat transfer plates provided with turbulence generating corrugations or the like. Thereby, the distance between the two plates which are to delimit the by-pass passage need not be particularly large in order to give the by-pass passage a relatively large through flow capacity.

Application of PHE in Refrigeration system

Plate heat exchangers are often used as evaporators for evaporation of refrigerants circulated in refrigeration systems. But it possess a number of disadvantages like very expensive, and also the refrigerant entering the said inlet channel of the plate heat exchanger is not evenly distributed to the various evaporation flow paths between the heat transfer plates. In order to overcome the above said disadvantages, Bertilson *et al*., 1999 [15] designed a plate heat exchanger which is easy and cheap to manufacture and in which the heat transfer plates are formed such that an even distribution of a refrigerant or other liquid to be evaporated can be obtained to the various evaporation flow paths between the heat transfer plates. Here the heat transfer plates are provided with additional ports forming a distribution channel through the plate stack and that the heat transfer plates form first passages, which are distributed along the inlet channel and interconnect the latter with a distribution channel, and second passages connecting the distribution channel with the first flow paths between the heat transfer plates. The main advantage of this system is no extra components are needed for accomplishment of restriction of the refrigerant or other liquid flow into the separate flow paths forming evaporation spaces between the heat transfer plates. Also, the plate heat exchanger designed in this manner can be used not only for evaporation of refrigerants but also for evaporation of other liquids. This means that use of an expansion valve of the kind often used in a refrigeration system is not always necessary.

Efficiency of PHE

With the intention of increasing efficiency of the plate heat exchanger more effectively Blomgren (2000) [16] designed a plate heat exchanger with interspaces between plates, each plate is delivering with a press pattern which forms an angle with the mentioned main directions of flow. By this designing the second fluid meets a considerably lower flow resistance than the first fluid through the plate heat exchanger. To create the largest possible area enlargement of the plate it is recommended that pressing of the mentioned ridges and valleys to be done in the plate there by the plate may be used to a maximum for the present heat transfer. So, in order to improve the useful life of the interiors of plate heat exchangers without significantly increasing pressure loss of medium flowing through channels between heat exchanger plates, an additional plate that has guide channels with at least one inlet and one outlet, which lead from one flow channel of one medium to the other flow channel of the same medium is being provided [17]. Also, increased turbulence in the medium is possible by provision of a guide channel between the plates. Inclusion of guide channels produces very limited pressure loss. As the additional plates that include guide channels are located, the efficiency of plate heat exchanger is very high. Plate heat exchangers are usually designed with thicker end plates, which are called frame plate and pressure plate, respectively. Since the plate package in many applications should be able to resist high inner pressures, the frame plate and the pressure plate become very thick and heavy. This means that the whole plate heat exchanger becomes heavy and expensive. To avoid this problem, Gronwall (2007) [18] designed a plate heat exchanger which is light, inexpensive and easy to manufacture. This is achieved by using tie sheets and beams perpendicular to the extension plane. This makes the plate heat exchanger very light in comparison with conventional plate heat exchanger having frame and pressure plates. Sreejith *et al*., 2014 [19] designed and optimized a plate heat exchanger in which heat exchanger channels are formed between plates and the corner ports are arranged so that the two media flow through alternate channels. The corrugation of the plates provides the path between the plates, supports each plate against the adjacent one, enhances the turbulence and complete counter-current flow creates efficient heat transfer.

Table-1 *Design considerations and limitations of plate heat exchanger*

Year	Design Considerations	Limitations
1960	1. Consists of a six-port plate	1. It is a very complicated process
	2. No need to use any intermediate terminals	2. Highly expensive
	3. Possibility to enter and exit the fluid on the same side of the terminal	
1980	1. Gaskets are fastened to the heat exchanger plates	1. The presence of joints limited the field of utilization of these heat exchangers
	2. Problems of gluing are avoided entirely	
1990	1. Consists of rectangular plates which are rotated by 180°C relative to one another	1. Flow channels exhibit relatively large volume
	2. Satisfactory heat transmission capacity	2. Occurrence of Leidenfrost phenomenon
2010	1. Plate containing guide channels is being provided	1. The whole plate heat exchanger is heavy and expensive
	2. Efficient heat transfer by using corrugated plates	
2017	1. Consists of a pack of embossed plates with apertures	
	2. NBR, EPDM, Flororubber are used as sealing material	

Finally, the designed plate heat exchanger will cost approximately Rs. 4,05,000 which can replace the existing heat exchangers which costs around Rs. 5,60,000. This leads to great reduction in space and cost without affecting the heat transfer efficiency.

Effect of plate spacing in PHE design

In plate heat exchanger, plate spacing variable influences plate heat exchanger design. Plate spacing effects on channel velocity, cross sectional area, equivalent diameter and Reynolds's number at both hot and cold fluid sides [20]. Jiang *et al.*, (2013) [21] presented a plate heat exchanger with multi-objective optimized design and showed that the increment of the pressure drop through the condenser can be done by decreasing total heat transfer surface area of a condenser. Keeping this in view Nur *et al.*, 2015 [20] studied the effect of plate spacing in efficiency of plate heat exchanger and showed the rise of plate spacing result in the increase of total heat transfer area and total number of plates, at the same time rise of plate spacing also results in decrease of cold and hot fluid total pressure drop, hence the size choice of plate spacing is adjusted with the requirement of the purpose of application. Shenghan and Pega (2017) [22] observed the effect of end plates on heat transfer of plate heat exchanger and stated that end plates, instead of being treated as adiabatic, function as fins due to the contact between the corrugated surfaces of adjacent plates. The fin efficiency increases with contact area and decreases with heat transfer coefficient. The effect of end plates is quickly weakened by the increased number of plates in real applications, but it could be significant when number plates are small, as is often the case in laboratory settings for the development of heat transfer correlations.

Advanced PHE design

For designing, manufacturing, supplying and services of plate heat exchangers, HRS Process Systems Ltd has acquired exclusive rights by the way of license manufacturing agreement [23]. As per the latest design in 2017 the plate heat exchanger is as follows: The heart of a Plate Heat Exchanger is a pack of embossed plates with apertures. The plates are assembled with an angle of 180° to each other. To ensure perfect sealing, each plate is provided with a gasket. The plate with gasket pack is mounted in a rack and is compressed with help of tightening bolts between the movable plate and fixed plate. To maximize heat transfer, warm and cold media are normally fed through the plate heat exchanger in one-pass or multi-pass counter flow. To prevent mixing of two media if the gasket leaks, every gasket is installed twice in the entry and exit area and creating a safety room that is being open to the outside.

Based up on the design and the type, adhesive & non-adhesive (clip-system) gasket may be used as a sealing material. Some well-known, tried and tested materials are:

NBR (Nitrile Butadiene Rubber): For universal use like aqueous and unctuous media e.g. water/oil uses.

EPDM (Ethylene Propylene Rubber): Used for water, steam applications and for many chemical compounds which do not contain mineral oil, grease.

Fluororubber (Viton): Extremely resistant to organics solvents, sulphuric acid, vegetable oil and other chemicals at higher temperatures.

Advantages of plate heat exchangers

- Low costs for installation, investment, operation and maintenance.
- High heat transfer efficiency (K-values on average 3-5 times higher than in case of bare-tube heat exchangers).
- Availability of asymmetrical flow gap for cost effective solution.
- Application of smallest temperature differences *i.e.*, < or = 1°C
- Less space required that is up to 75 percentage.
- Since high turbulent flow behavior effective for self-cleaning.
- Possibility in increment of additional capacity by fitting extra heat transfer plates
- Leak proof by double gasket groove system for high safety with regards to media mixing.
- Easy to clean, open and operation
- Low operating weight or low liquid content

Summary and Conclusion

In this article the advances in plate heat exchanger has been described in brief. Among the heat exchangers, plate heat exchangers are most commonly used for heat transfer between two fluids at low to medium pressures. Some of the designs consists of corrugated plates on a frame which creates high turbulence and high wall shear stress, both of which leading to a high heat transfer coefficient and a high fouling resistance. But, based on the above-mentioned studies, it can be concluded that there is a potential for leakage in plate heat exchangers. Also, high pressure drops are there and these are not suitable for large fluid temperature. So, still further advancement in plate heat exchangers is required.

Application of review: Study of step by step development of plate heat exchanger by many researchers. The advantages and limitations of each design was very well summarized. By considering the above facts an effective design and development of plate heat exchanger in food processing industry can be achieved further.

Review Category: Dairy Engineering, Food Process Engineering

Abbreviations: PHE: Plate Heat Exchanger
APV: Aluminium Plant and Vessel Company
FPHE: Frame and Plate Heat Exchanger

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