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Use of high performance plate heat exchangers in chemical and process industries

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Abstract — At present, plate heat exchangers constantly open up new application fields in the chemical, process, and allied industries due to their numerous advantages. The channel flow between individual plates is characterized by high turbulence induced at low flow velocities. Heat transfer coefficients are generally higher in plate heat exchangers than in conventional shell-and-tube heat exchangers. According to the nature of the process, physical properties of the media, and allowable pressure drops, plates with a variety of patterns are available to adapt the equipment optimally to the specific process conditions. For handling aggressive media the module welded plate heat exchanger was developed. The laser welded modular design keeps the inherent advantages of plate type heat exchanger. It can be disassembled and mechanically cleaned outside the modules. The capacity can also be subsequently modified by changing the number of plates, or the plate patterns can be altered as it can be with the gasketed units. Typical applications of module welded plate heat exchangers in the chemical industry are acid coolers, thermal oil coolers, or condensers for hydrocarbon mixtures. © 1999 Éditions scientifiques et médicales Elsevier SAS

heat transfer / pressure drop / plate heat exchanger / module welded plates / laser welding / cleaning

Nomenclature

A	installed heat transfer surface	m^2
CR	chloroprene	
EPDM	ethylene–propylene terpolymer	
EPDM/PTFE	EPDM with PTFE coverage	
FPM	fluorinated rubber	
HNBR	hydrogenated NBR	
IIR	butyl rubber	
M	module welded design	
NBR	nitrile–butadiene rubber	
(P)	plate gasket	
p	design pressure	bar
PTFE	polytetrafluoroethylene	
(R)	ring gasket	
T	maximum operating temperature	°C
TL	plate heat exchanger type	

1. INTRODUCTION

Energy costs are rising, fueled on the one hand by increased global consumption and by stringent environmental protection legislation, and safety regulations in industrialized nations on the other. A high primary energy consumption is typical of the chemical and process industries. Each production is tied up with requirements for profitability and process efficiency. The optimum utilization of heat, in particular, is decisive for the overall efficiency of any production process. Additionally, energy recovery saves on primary energy and is a important contribution for environmental protection due to reduced emissions. One of the main strategies for energy saving, creation of closed production cycles, and manufacturing of environmentally friendly products is the reusing of heat already generated in the process as efficiently and economically as possible. The most common energy recovery technique is to utilize the heat from a higher temperature process stream to heat a colder stream by suitable heat transfer equipment. In production processes there will be normally a large number of hot and cold streams and there will be an optimum arrangement of the streams and equipment for energy recovery

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that can be found by utilization of thermal integration analysis [1].

Thermal reuse requires efficient and economically designed heat exchangers. In the chemical, process, and allied industries heat exchangers are an essential part of various technologies. The choice of the most suitable heat exchanger type is a vital problem of basic engineering, and an indispensable condition to minimize the total plant costs including capital, maintenance, and operating costs. Currently the most common used type of heat transfer equipment is the conventional shell-and-tube heat exchanger well known for many decades. The optimum design of this has been published by Reppich et al. [2]. This paper will address issues pertaining to the design, construction, thermal and hydraulic properties, operation, and industrial application of plate heat exchangers.

There is a broad range of different heat exchanger types available. In accordance with the current market analysis [3], in 1996 the total market for heat exchangers in Europe amounted to USD 3.61 billion. The European market will increase probably to USD 4.43 billion by 2003. The plate type heat exchanger has, according to market analysts, a market share of 13.1 %. This corresponds to the second position after the conventional shell-and-tube heat exchanger that holds 39.9 %. Over the last decade, market demand for plate heat exchangers has increased considerably. These increased customer demands are primarily due to significant benefits that the equipment offers compared with other heat exchanger types, and even to economic factors such as capital, operating and maintenance costs.

In the past, plate heat transfer systems were used extensively in the food and beverage industries, as they can be readily taken apart for periodical inspection and cleaning. Due to their features and advantages plate heat exchangers in the last years constantly open up new application fields in the chemical, process, and allied industries. Plate heat exchangers have increasingly proven useful in a wide range of industrial applications, i.e. for single phase heat transfer processes as heater or cooler as well as for condensation and evaporation. Wherever possible, a plate heat exchanger will be usually an economic solution to fulfill the required heat transfer process, subject to safety and reliability considerations.

The main features and advantages of plate type heat exchangers are:

– low space requirement due to compact size, low weight;

– low filling contents, subsequently a faster start up/shut down and control of equipment are permitted;

– high overall heat transfer coefficient due to intensive turbulence induced by the corrugated plate surface;

– high shearing forces and turbulences are the basis for low fouling tendency;

– the utilizing of low temperature differences between the both fluids is possible;

– the flexibility on account of modular design, i.e. practicable adjustment to changed process requirements by changing of the number of plates, or varying of plate patterns;

– easy maintenance and dismantling for inspection or cleaning, e.g. mechanical or chemical cleaning, back flushing, cleaning in place.

2. PRINCIPAL TYPES OF PLATE HEAT EXCHANGERS

Various equipment suppliers offer different principal types of plate heat exchangers for use in the chemical industry. Plate heat exchangers can be fabricated in gasketed, welded, or module welded design characterized by the model in which the flow channels for the two heat exchanging media are sealed. According to the type of heat exchanger the individual plates are sealed relative to each other by gaskets placed in circumferential grooves or by welding. Further, often in refrigeration systems and district heating systems brazed plate heat exchangers are applied which are not considered in this paper.

2.1. Gasketed plate heat exchangers

Plate heat exchangers comprise a plurality of corrugated heat exchanger plates having thicknesses normally between 0.5 and 0.8 mm. The plate pack is mounted between a fixed and a moveable pressure plate, positioned by an upper and a lower carrying bar, and compressed by several tightening bolts to a specified dimension given on the name plate, *figure 1*. On the fixed and moveable carbon or stainless steel pressure plates there are connections for inlet and outlet of both fluids. Corner ports in the plates form, for both mediums, a distributor channel to direct the flow from plate to plate, and a collector channel. The arrangement of the plate pack creates two interleaved channel systems enabling the two fluids to flow past and between each other without physical contact. The fluids can pass the heat exchanger either in cocurrent

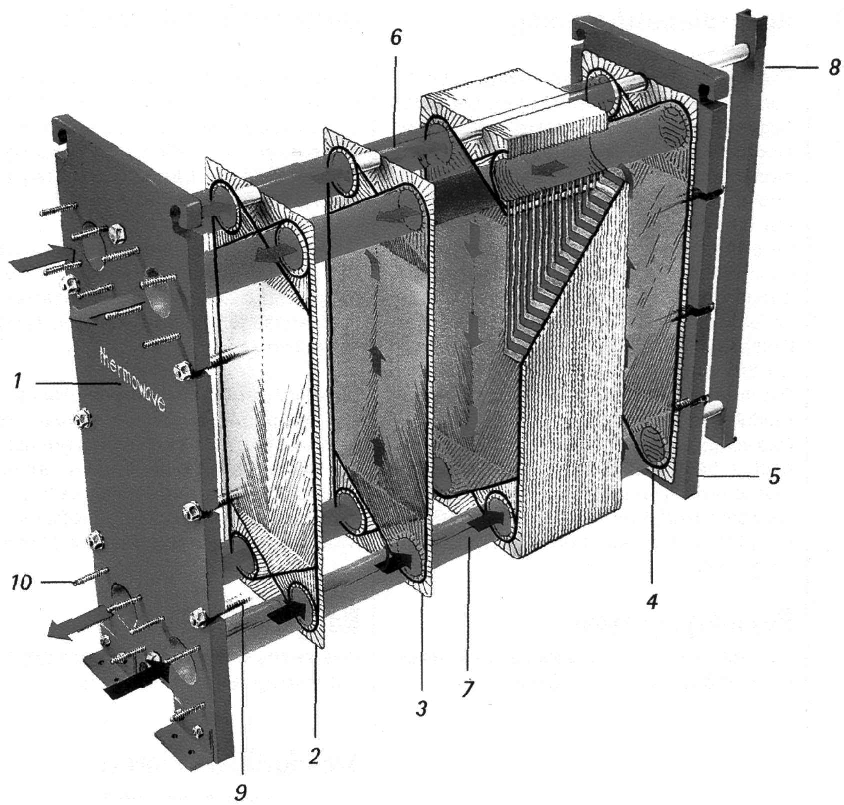

Figure 1. Typical gasketed plate heat exchanger (Thermowave GmbH).

or counter-current flow. Plate heat exchangers can be designed for single-pass or multi-pass arrangement. By installing baffle plates without ports in the plate pack either one or both fluids can be conducted several times through the channels and thus participate longer in the heat transfer process. This way there can be realized an economic design even with small temperature differences between the two fluids, or if the flow rates or the viscosities of the two fluids are very different.

Gasketed plate packs can be dismantled. After opening all flow spaces are directly accessible for inspection and cleaning purposes. If required, plates or gaskets can be replaced. Depending on the operating conditions, medium and temperature resistant gaskets, either glued or fastened without adhesive, seal the plates round their edges. In general, today, the adhesive-free gasket fastening is preferred. Adhesive-free sealing:

– provides the option of using high-quality elastomeric materials which are difficult to glue;

– simplifies the replacing of used or damaged gaskets, if necessary;

– saves maintenance costs and assembly time.

On the other hand, the use of glued gaskets is recommended if during the operation intensive pressure variations are expected, or mechanical cleaning with high pressure cleaners or brushes is required.

Usually, the gasketed design is simpler to manufacture. This plate heat exchanger type is however limited in its maximum operating temperature by the heat resistance of the gasket material to about 170 °C. The maximum operating pressure is limited to about 25 barg. From the commercial point of view, gasketed design offers the best price–performance ratio of all plate exchanger types.

2.2. Welded plate heat exchangers

In order to extend the range of use of plate heat exchange apparatus, welded constructions were developed.

Welded plate heat exchangers use plates similar to those in the gasketed plate exchangers mentioned above, but the plate edges are sealed by welded joints. This allows us to increase the temperature rating from −50 °C up to 350 °C and operating pressures from full vacuum to 40 bar. Welded exchangers retain the compact size and high heat transfer coefficient whilst giving security against leakage. An obvious disadvantage is that this heat exchanger type cannot be dismantled for mechanical cleaning. Therefore, their use in the chemical industry is restricted to applications where fouling does not occur. Further, if a welded plate heat exchanger fails, repair is difficult or even impossible.

A combination of gasketed and welded plate construction developed in the last years is also used. An overview of module welded plate heat exchangers is presented below including their construction, design, operation, and industrial applications.

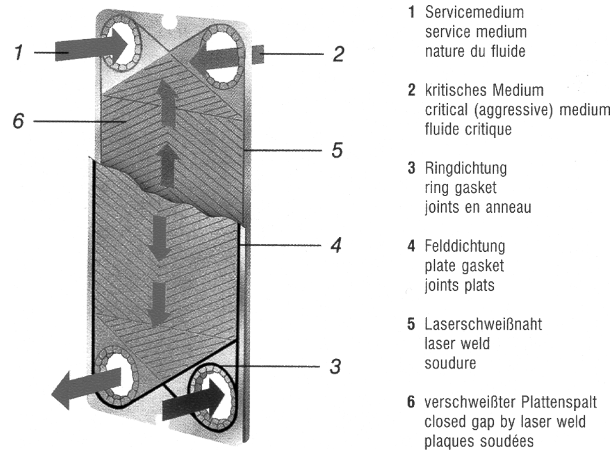

Figure 2. Construction of a welded module (Thermowave GmbH).

2.3. Module welded plate heat exchangers

Because of the limited resistance of elastomeric materials to temperature and chemicals, no satisfactory solution could be offered in the past using gasketed plate heat exchangers under difficult operating conditions, or in aggressive or otherwise hazardous environments. In practice, selection of gasket material becomes more limited at high operating temperatures and high pressures particularly in aggressive liquids or gases.

With the development of the new generation of module welded plate heat exchangers environmental and safety considerations can be taken into account during the design of the equipment. The driving force in the development was the extension of applicability of dismantable plate heat exchangers. The innovative module welded design can be used in the chemical and pharmaceutical industry, in food processing industry, for heat recovery systems, and for refrigeration applications [4].

In order to build a sealed flow channel for the aggressive, or the gasket attacking fluid, two embossed heat exchanger plates made of weldable materials are joined together by means of the laser beam welding technique (*figure 2*). In the laser beam welding process the extremely high beam energy of the laser is utilized to melt the material. The computer-controlled precision welding process guarantees a constant welding quality without needing any filler materials. The contactless energy transfer in a defined inert atmosphere enables high speeds with the highest weld quality being achieved. During welding the heat-affected zone of welded joints is very small. This results in low thermal stresses and little structural changes in the welding region. Furthermore, a perfect shielding of the welding zone can be attained. This is required for processing materials reacting with atmospheric gases like titanium.

The module welded design is characterized by a reduction of 90 % of the gasket length necessary for the aggressive medium. As shown in *figure 2* for this medium, no plate gaskets, also referred to as field gaskets, are required. Therefore the risk of leakage will be decreased considerably. Only two remaining ring gaskets come in contact with the aggressive medium. They are located in the port holes from one module to the next and create the distributor and collector channel. These specially designed gaskets are made from highly resistant materials such as fluorocarbon rubbers, or other rubber polymers covered with fluoropolymers (PTFE or Hostaflon® TFM PTFE).

The flow of the service medium outside the modules is confined by peripheral elastomeric gaskets. An intermixing of the two fluids is prevented by a double weld and a double ring gasket in the port holes. Ring gaskets are provided with leakage grooves. If a leakage occurs, the leak will be external and can be easily detected.

By means of laser welded modular design the advantages of the plate type heat exchanger are retained. Unlike the welded construction, the module welded heat exchanger can be disassembled and mechanically cleaned outside the modules. By either enlarging or reducing the number of modules, or changing flow patterns, heat trans-

TABLE I
Elastomeric gasket materials, operating temperatures, and typical fields of application.

Gasket material	Temperature range	Applications
Nitrile–butadiene rubber (NBR, LT-NBR, HNBR)	from −40 to 150 °C	water, fluids on mineral oil basis, animal and vegetable oils and fats, aliphatic hydrocarbons, silicone oils
Ethylene–propylene terpolymer (EPDM, EPDM-NT, EPDM-HT)	from −20 to 170 °C	water, saturated steam, alcohols, ketones, organic and anorganic acids and bases, solvents
Chloroprene rubber (CR)	from −30 to 80 °C	ammonia, freons, carbon dioxide, silicone oils, bleaching agents, chlorine, ozone
Butyl rubber (IIR)	from −20 to 120 °C	refrigerants (R22, R134a)
Fluorinated rubber (FPM)	from 0 to 160 °C	mineral oils and fats, chlorinated and aromatic hydrocarbons, petrol, acids, bases

fer and pressure drop can be precisely adjusted to the individual needs, as it can be with gasketed units.

The module welded type can be used for operating temperatures from −40 °C up to 170 °C, depending on the temperature resistance of ring gaskets, and operating pressures from full vacuum to 25 barg. This design is not susceptible to thermal stresses. Compared to welded units the module welded version is considerably more cost beneficial.

3. GASKET MATERIALS

Gasketed and module welded plate heat exchangers commonly employ elastomeric sealing gaskets of a complex shape manufactured by means of special moulds. *Table I* summarizes various elastomeric gasket materials, their fields of application, and temperature limits. Typical materials are nitrile–butadiene rubber, ethylene–propylene terpolymer, chloroprene rubber, butyl rubber, and fluorinated rubber. There are normally different grades of each rubber polymer with different additives affecting the chemical resistance and mechanical properties.

Elastomeric materials coming in contact with process liquids or gases can be attacked by these depending on the nature of the media, operating temperature, pressure and time of exposure. There are two basic types of effects of media on elastomeric gaskets. Physical penetration and absorption of an agent cause swelling of the gasket sometimes combined with extraction of soluble materials from the rubber. Chemical attacks, e.g., oxidation, results in degradation of the physical properties. The expected gasket life time varies based on many factors including resistance of gasket material to chemicals, mechanical properties, and resistance to aging. Selection of gasket material is based on years of practical experience of both heat exchanger and rubber manufacturer.

In the chemical industry high demands are asked of the equipment availability. Gaskets are often subject to violently aggressive environments. Frequently, fluorocarbon elastomers (FPM) are used as the gasket material featuring high temperature and chemical resistance, long life, good mechanical properties, and sufficient resistance to ageing. They have good resistance to oils, acids and many hydrocarbons that act as solvents for other rubber materials.

Various process solutions are attacking any rubber material so highly that standard gasketed heat exchanger constructions are normally unable to operate for a reasonable time. The module welded design is usually preferred for fluids which are aggressive, toxic, inflammable, environmentally harmful, and/or for critical operating conditions because of the drastic reduction of the gasket length required. Gaskets with fluoropolymer covering (PTFE or Hostaflon® TFM PTFE), comprising a core of elastomeric material (e.g., NBR or EPDM) have been developed for applications requiring an universal chemical resistance to the medium being passed through the heat exchanger.

4. SELECTION OF PLATE MATERIAL

The selection of the plate material with a sufficient chemical resistance depends on many parameters. Among these are the chemical composition of the media, metal wall temperature, and operating conditions. Some media cause corrosion attacks of dissimilar nature and appearance, and there are several forms of localized corrosion that can occur on heat exchanger plates. If an unsuitable plate material is used, corrosion can lead under certain circumstances to rapid failure of the plates.

4.1. Corrosion mechanisms on heat exchanger plates

In practice, the most common types of localized corrosion observed on plate heat exchangers are pitting, crevice corrosion, and stress corrosion cracking.

Pitting is characterized by attacks at small discrete areas at a high propagation rate, thereby causing corrosion failure in a short time. Pitting corrosion is mainly caused by the impact of halide ions present in aqueous solutions and most cooling waters that are concentrated particularly in gaps. Halide ions facilitate a local break-down of the passive layer of the metal surface which results in circular penetration.

Crevice corrosion occurs under the same conditions as pitting in aqueous solutions. In narrow crevices the influence of capillary forces is significant and in plate heat exchangers it is practically impossible to avoid the penetration of liquids into a crevice, i.e. areas under gaskets.

Furthermore, residual stresses from the cold forming process of plates can cause stress corrosion. Stress corrosion cracking is caused by the combined effect of tensile stress and corrosive environment. Like pitting and crevice corrosion, stress corrosion is most frequently caused by aqueous solutions containing halides.

4.2. Plate materials

There are three groups of plate materials most frequently used in chemical and allied industries: low and high alloyed austenitic stainless steels, nickel based alloys, and titanium. The most economical plate material that satisfies process and mechanical requirements, and that has a sufficient resistance to the mentioned corrosion mechanisms over the working life of the plate heat exchanger should be selected. All of the above mentioned material groups are weldable by means of laser beam welding and can be therefore used for the module welded design.

Low alloyed stainless steel 1.4301 (ASTM 304) has a very limited applicability to handle solutions with low halide ions contents in non-oxidizing environments, e.g., closed cooling water or glycol loops. Due to the molybdenum content, the grades 1.4401 (ASTM 316) and 1.4571 (ASTM 316Ti) are suitable for solutions containing halide ions depending on the operating temperature, e.g., cooling tower water. In most chemical process applications, if cooling water obtained from rivers is used, plate materials 1.4539 (ASTM N08904) and Avesta 254 SMO® (ASTM S31254) have been successful in order to prevent corrosion over a wide temperature range. The common feature of these both high alloyed austenitic grades is the use of chromium and molybdenum as the important alloying elements, and the addition of copper. The grade Avesta 254 SMO® has in addition a high content of nitrogen to improve mechanical properties. The high levels of molybdenum in particular endow 1.4539 and Avesta 254 SMO® with good resistance to pitting and crevice corrosion. Furthermore, due to their relatively high nickel contents in combination with the high levels of chromium and molybdenum 1.4539 and Avesta 254 SMO® show a good resistance to stress corrosion cracking.

Nickel based alloys provide resistance to general corrosion, pitting, crevice corrosion, and stress corrosion cracking in a broad range of severe environments. The high nickel and molybdenum contents provide good corrosion resistance in reducing environments while chromium imparts resistance to oxidizing media. Alloys C-276, C-4 and C-22 have exceptional resistance to many of the most severe media encountered in chemical processing. Included are many solvents and acid solutions such as warm sulfuric acid at temperatures below the boiling point.

For use in strongly halide containing environments such as seawater, brackish water, or brines the use of titanium is required.

5. HEAT TRANSFER AND PRESSURE DROP

In plate heat exchangers the channel flow between the individual chevron patterned plates is characterized by a high degree of turbulence, achieved even at low flow velocities, and at Reynolds numbers as low as 10, which makes plate heat exchangers very suitable for handling high viscous fluids. The transition from laminar to turbulent flow will normally occur at Reynolds numbers of 100 to 300 depending on the plate pattern used. In contrast, the flow in smooth tubes will only be turbulent with certainty for Reynolds numbers greater than 10^4 [5].

The overall heat transfer coefficient in plate heat exchangers is often much higher than those obtained for conventional shell-and-tube exchangers, e.g., for liquids the overall heat transfer coefficient will be typically three to four times higher. The higher efficiency means that the heat transfer surface can be smaller than in tubular type exchangers, yet still able to perform the same duties. Furthermore, the mean temperature difference will generally be higher in a plate heat exchanger than in shell-and-tube exchanger, as the flow arrangement gives a close approach to pure counter-current flow.

Since heat transfer and the pressure drop are closely related, the economic design of heat exchanger equipment should involve the determination of the optimum pressure drops [6]. Plate heat exchangers can be used for moderate operating pressures if relatively high pressure drops are allowed. Flow rates and, particularly, operating pressures of both hot and cold fluid should be similar. If there are substantial differences of operating pressures between the two fluids the rapid rise in pressure drop on the side with the lower operating pressure is to be considered.

Plate patterns

Having decided that a plate heat exchanger is a possibility for a particular service, there are several factors to be considered in the choice of suitable plate patterns. There are available plates with different sizes and a wide variety of patterns. The selection of pattern type depends on:

- process conditions;
- nature and pollution of the fluids used;
- state and physical properties of fluids;
- the allowable pressure drops.

Consequently, each pattern has been developed to create turbulent flow across the entire heat transfer surface of the plate. Even flow distribution combined with turbulence generated inside the channels between the plates eliminates dead spots and maldistribution. The characteristics of plate structures are determined by the stamping depth, the wave length, and the stamping angle. According to the stamping depth, plate patterns can be divided into:

- thin layer structures with corrugation depth of 2 to 2.5 mm;
- thick layer structures with corrugation depth of 3.5 to 4 mm.

Thin layer plates were developed especially for applications in the chemical industry. This high-performance pattern ensures overall heat transfer coefficients up to 5000 $W \cdot m^{-2} \cdot K^{-1}$, assuming clean conditions on both sides with reasonable pressure drops. Therefore, size and cost reduction of a plate heat exchanger is possible. This kind of pattern, allowing an high thermal efficiency, is characterized by a low corrugation depth and a corrugation angle of 60°. Plates with such a thermodynamically hard pattern are mainly used for single phase heat transfer processes and homogeneous liquids, or to make use of small mean temperature differences between the hot and cold medium.

For condensing and evaporating processes, on the other hand, the choice of gentle patterns is recommended. These patterns have higher corrugation depth and corrugation angles of 30° or 60° to support both the removal of the condensate, and the leaving of vapor and inert gases if present. This plate type is also designed for high viscosity applications, for viscous liquids (e.g., polymers), and for shear-sensitive fluids, as well as for large volume flow rates at low pressure drops, and for fluids with a high solid content.

In certain applications, plates with different patterns can be combined in the same plate pack, or two plates of varying patterns can be fitted together by laser welding. The combination of thin layer and thick layer structures will have a positive effect on heat transfer, e.g., for two phase flow, or while handling of media having very different volume flow rates or viscosities. This hybrid arrangement is also for utilizing the allowable pressure drops on both sides. Moreover, a different numbers of passes can be installed in order to utilize the given allowable pressure drops.

In view of the number of different plate types available by plate exchanger manufacturers it is difficult to give general correlations for heat transfer and pressure drop estimation. The heat transfer coefficient and the pressure drop for the surface of corrugated plates can be predicted approximately using the correlations of Martin [7]. Usually, plate heat exchangers will be designed by the manufacturers by means of computer programs based on many years of research, and on extensive tests to evaluate heat transfer coefficients and pressure drop for single phase and two phase flow [4]. By selecting a suitable plate pattern, the equipment can be optimally adapted to the specific operating conditions.

6. FOULING AND MAINTENANCE

In practice, scale or deposits on heat exchange surfaces cause a decrease in thermal performance during operation due to reduced overall heat transfer coefficient. Subsequently, there is to be noted a rapid rise in pres-

TABLE II
Applications of plate heat exchangers in the chemical and process industries (Thermowave GmbH).

TL	*A*	Material	M	Medium 1	Medium 2	Gasket 1 (P)	Gasket 1 (R)	Gasket 2 (P/R)	*p*	*T*
650	66.0	1.4301	M	Ammonia	Ethylene Glycol	weld	CR	CR	16	−30/50
90	2.1	1.4401	M	Butadiene	Cooling Water	weld	EPDM/PTFE	EPDM	6	−20/50
150	1.8	1.4401		Crude Fatty Acid	Saturated Steam	HNBR	HNBR	EPDM	6	−10/140
150	5.1	1.4401	M	Acetone/Butanol	Anticora	weld	EPDM/PTFE	EPDM	10	−10/60
400	14.8	1.4541		Ammonia Solution 25 %	Cooling Water	EPDM	EPDM	EPDM	16	−10/60
150	7.4	1.4571		Methanol 40 %	Toluene/Hexane/MeOH	EPDM	EPDM	EPDM	6	−20/170
250	5.4	1.4539		Organic Solution	Cooling Water	FPM	NBR	NBR	6	−10/80
250	7.0	1.4539	M	Epichlorohydrin	Cooling Water	weld	EPDM/PTFE	EPDM	6	−10/150
500	158.9	1.4539		Process Water	Waste Water	EPDM	EPDM	EPDM	7	−10/70
90	0.6	Avesta 254 SMO	M	Toluene	Cooling Water	weld	EPDM/PTFE	EPDM	6	−10/100
500	19.2	Avesta 254 SMO	M	Stripping Gas	Condensate	weld	FPM	EPDM	6	−10/90
500	46.6	Avesta 254 SMO	M	Marlotherm	Cooling Water	weld	FPM	NBR	6	−10/100
250	8.1	Hastelloy C-276	M	Sulphuric Acid	Cooling Water	weld	FPM	NBR	6	−10/120
500	28.8	Hastelloy C-276	M	p-Xylene	Saturated Steam	weld	FPM	EPDM	16	−10/170
250	11.9	Titanium		Sodium Hydroxide	Cooling Water	EPDM	EPDM	EPDM	10	−10/120
500	117.6	Titanium		Ethylene Glycol 30 %	Cooling Water	NBR	NBR	NBR	10	−10/100

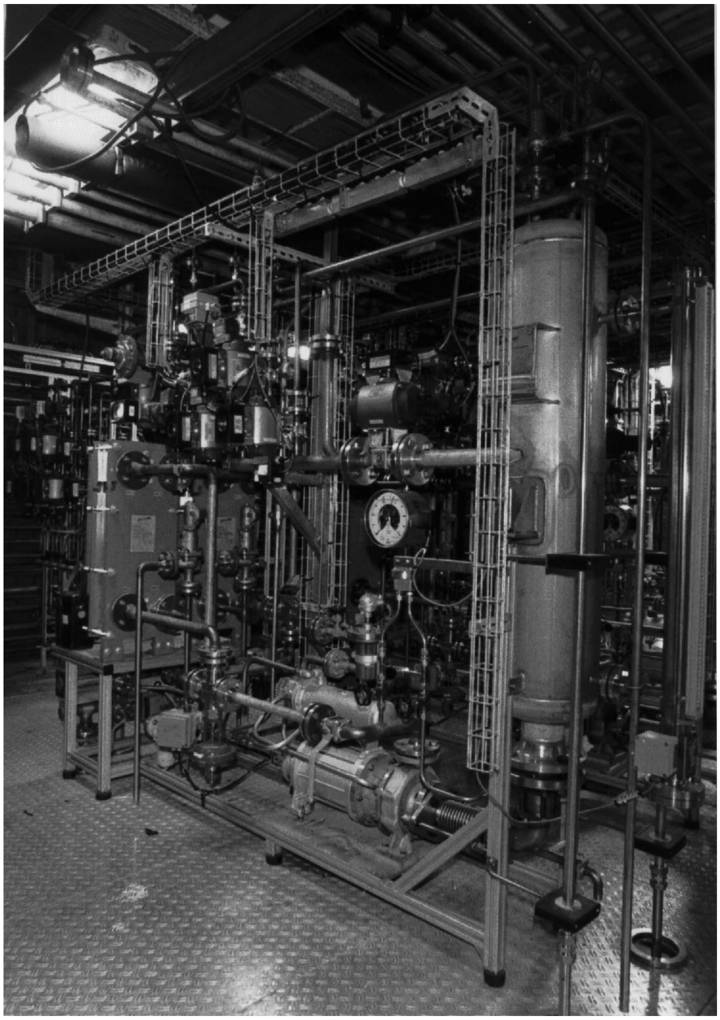

Figure 3. Module welded plate heat exchangers in the chemical industry (by courtesy of BASF).

sure drops, and therefore higher maintenance costs due to higher pump energy.

Depending on the installed plate pattern the fluids tend more or less to the formation of fouling layers on the plate surface. Some factors affecting the rate of scale or deposit build-up are:

– operating conditions;
– fluid type;
– nature and concentration of pollutants;
– channel flow velocities;
– plate surface finish;
– metal wall temperatures;
– wall shear forces on the plates.

Due to the turbulent flow created by the corrugated plate surface the plate heat exchanger tends to have a lower scale and deposit build-up compared with other exchanger types. However, if highly polluted fluids participate in the heat exchange process, fouling can not be avoided. Relatively high wall shear stresses on the heat transfer surface will provide a self-cleaning action that will limit fouling. Therefore, in many cases, an equilibrium is established between formation and removal of scale or deposits. An important design parameter for minimizing fouling effects is the minimum channel flow velocity, e.g., for low viscous liquids 0.1 $m \cdot s^{-1}$.

In order to reach again the nominal capacity and to remove deposits, the unit must be cleaned. Depending on the accessibility of the heat transfer surfaces, cleaning can be done periodically either mechanically or by forced circulating and flushing media known as 'cleaning in place' processes. Depending on type of fouling and pollutants, or the user's requirement for product quality, the cleaning intervals can vary from several times a week to once every few years. If module welded plate heat exchangers are used and one of the fluids is likely to cause heavy fouling it should, where possible, be located outside the modules to the gasketed channel to gain an easier access. Proper maintenance and adequate cooling water treatment should reduce the risk of fouling. If necessary, strainers properly sized and located, should be provided at the installation to protect the plate channels from particles and fibers.

Fouling resistances are incorporated into thermal design as a means of compensating for the performance reduction during operation which is inherent with fouling effects. In the choice of fouling resistances, care has to be taken that these cannot be assumed to have the same values as those used in the tubular heat exchanger design. Otherwise, the much higher heat transfer coefficient in plate heat exchangers results in an excessive overdesign, and the recommended flow velocities necessary to avoid fouling effects cannot be achieved [8]. A properly thermal and hydraulic design decreases fouling effects on heat transfer, and results in lower maintenance costs.

7. APPLICATIONS IN CHEMICAL INDUSTRY

In various branches of the chemical and process industries a large number of both gasketed and module welded plate heat exchangers has been successfully used.

Table II shows several installations of plate heat exchangers in chemical and allied processes including the heat transfer surface, the fluids, plate and gasket materials, design pressures, and maximum operating temperatures. For each application, the plate material was selected subject to the nature of media and operating conditions, considering the mentioned specific constructional features of plate heat exchangers.

Typical applications of module welded plate heat exchangers in the chemical industry are coolers of acetic acid, sulphuric acid, and organic solutions, thermal oil coolers (*figure 3*).

In chemical industry, plate heat exchangers were also used for the cooling of polymers with viscosities up to 10^4 cP. For these applications gentle plate patterns are used, and a combination was attained of both heat transfer and intensive mixing. Further applications include condensers of steam, ammonia, or hydrocarbon mixtures arranged as head condenser of distillation columns. It is anticipated that future developments in module welded plate technology will yield additional benefits for the chemical industry.

8. SUMMARY AND CONCLUSIONS

Owing to its benefits the plate heat exchanger has gained more and more acceptance as compared to alternative exchanger types in many industrial applications over the last few years. For handling of liquids it has become an indispensable plant component. Due to continuous improved design methods based on extensive testing the use was extended step by step to condensing and evaporating duties, or to special applications, e.g., cooling of polymers. By means of a wide range of available plate patterns the equipment can be optimized according to the operating conditions, or adapted to changed process parameters later. In the chemical and process industries besides the gasketed plate type the module welded type in particular has proved a success. On condition that both gasket and plate materials are properly selected, plate heat exchangers can be used in aggressive environments as well.

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