Fundamentals of Industrial Heat Exchangers

Selection, Design, Construction, and Operation

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Dr. M Moghimi Ardekani, BSc, MSc, PhD, CEng, MIMechE, FHEA, is an associate professor at Clean Energy Technologies, Staffordshire University, United Kingdom. He has more than 10 years of industrial and academic experience and has published more than 70 papers in top peer-reviewed journals and prestigious conference proceedings, 2 books, and 2 book chapters. His publications have been well received in the engineering community. He was awarded the International Green Talent Award 2015 by the German Ministry of Research and Education and was rated as a Young Promising Researcher by the National Research Foundation.

James Mahootchi, MIEAust CPEng NER APEC Engineer IntPE(Aust), is a senior project engineer and a consultant. He is a chartered professional engineer of Engineers Australia in Mechanical Engineering and Pressure Equipment Design Verification. Having many years of experience in oil, gas, petrochemical, and aviation industries, he has performed mechanical design of numerous pressure vessels, heat exchangers, etc. His main focus regarding heat exchangers includes mechanical design of shell-and-tube heat exchangers. He has also (co)authored a book titled *Pressure vessel Design, Guides, and Procedures*. As his latest work, he has been part of the design team of Western Sydney International Airport.

Josua Meyer is a professor at Stellenbosch University. His research has a broad focus on thermal sciences, but with a narrower focus on heat exchangers. His heat exchanger work focuses on fundamental work in internal forced convection, transitional flow regime, nanofluids, boiling, and condensation. On an applications level his work focuses on thermal, solar, wind, and nuclear energy. He has received 11 different teaching awards from 3 different universities. He has won more than 43 research awards including 33 awards for best article of the year or best conference paper. He is a “highly cited researcher” and is among the top 2% scientists in the world. He is on the editorial board of 13 journals and is the editor of 7 journals in his field of research. He has (co)authored more than 800 articles, conference papers, book chapters, and patents and has (co) supervised more than 150 research masters and PhD students.

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Preface

Heat exchangers are one of the most widely used pieces of equipment in various industries. It is because of this wide application that many studies have been done in this field. The heat exchanger industry is still progressing and transforming. Many large companies and researchers around the world are engaged in research and study about them, the results of which have been published in various books and articles. However, the distinction between industrial and academic perspectives in publications related to heat exchangers can be considered as one of the weaknesses of these sources. This distinction has been fuelled by the development of software related to exchangers that can be applied in both thermal design and mechanical design, and the ease of working with it. This has taken place in such a way that some engineers in the exchanger industry, with little knowledge of the design assumptions and governing relationships of heat exchangers, have entered this field relying only on the relevant software. This sometimes leads to wrong designs being made and incorrect results being obtained. On the other hand, the efforts of academic experts who ignore the industrial points and manufacturing limitations of heat exchangers will not be beneficial. For example, in academic sources, there may be no difference between a tube and a pipe, while it is clear that, in industry, these are two completely different categories. The variety of exchangers, together with their wide range and different practical applications, are among the other challenges in this field. It is rare to find a book that deals with the various aspects of heat exchangers, such as thermal design, mechanical design, material selection, corrosion in exchangers, method of cleaning, method of selecting an exchanger, and many other factors.

The aforementioned aspects prompted the authors to write a book that, while introducing the different types of heat exchangers from various perspectives, also meets the needs of both industrial and academic specialists. In preparing the book, the authors have tried to cover the various aspects of heat exchangers as widely as possible in such a way that the reader does not need to refer to different sources to a great extent. Obviously, it is not possible to write a book in the field of heat exchangers that can cover the basic needs of both industry and academia. Therefore, it seemed necessary to use the experiences of well-known companies as well as large manufacturers. Fortunately, some of these companies supported the writing of this book and provided the authors with their experiences, documents, and images.

This book is prepared in three independent parts. Part I introduces common industrial exchangers. The authors have tried to make the concept more understandable by using different images. All the general issues related to each exchanger, including the materials, fabrication methods, cleaning methods, and strengths and weaknesses of each exchanger, are stated separately. The audience of this section is broader than students and engineers who only need general information about each exchanger.

Part II is dedicated to thermal design of shell-and-tube heat exchangers. It starts with basic information about heat transfer related to exchangers. The book only deals with the design of shell-and-tube heat exchangers because exchangers of this type are considered the most widely used exchangers. Of course, only methods that are easy enough for manual calculation are presented. It is obvious that knowing these methods helps one use the software correctly. In thermal design, the requirements of the standards have been met to prepare the reader for industrial and practical design. Thermal design software is also introduced in this part, and an attempt has been made to improve the reader's skill in using the software correctly by comparing the results of the software to manual methods. Part II concludes with some educational tips in the form of questions.

Part III is dedicated to the mechanical design of shell-and-tube exchangers based on the ASME code. Although it targets an audience different from the previous one, the authors found it necessary to consider this aspect as well in order to prepare a comprehensive book about heat exchangers. It is clear that this part can also be used in the design of pressure vessels. While Part III attempts to cover all the design requirements of a shell-and-tube exchanger based on the ASME code and the TEMA standard, due to the complexity of these codes, the reader has to refer to the main text of the standard in specific designs.

The book concludes with some auxiliary material, such as corrosion and sedimentation issues as well as tables that are necessary to design and select materials. In all the parts, the objective of the authors is for the reader to achieve a complete understanding of the field. This has been done by using fabrication drawings, 3D computer images, and industrial pictures. However, like other texts, this book is not without its flaws and problems. Therefore, all experts and professors in the field are requested to help the authors by providing their constructive comments so that any identified flaws can be corrected in the subsequent edition of the book. Therefore, the authors are grateful to receive any comments, suggestions or questions about the book via hossain.nemati@iau.ac.ir.

The authors would like to express their deepest gratitude to Mr. Ali Saraei, Mr. Reza Izadi and also Mr. Alireza Shekoohi for their constant support. Also we are grateful to the companies and manufacturers whose names appear below for their support in compiling this comprehensive publication.

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Part I

Heat exchangers and their classifications

Heat exchangers, also known as exchangers, are equipment used to transfer heat from one medium to another, which could either be fluid or solid. Exchangers are often named in terms of their structures, for example, shell-and-tube heat exchangers or plate-and-frame heat exchangers; sometimes exchangers are named according to the role they play, e.g. condensers, which are used to condense fluids, or boilers, which are used to generate saturated fluids. In addition, exchangers can also be named in terms of the working fluid, e.g. air-cooled and water-cooled heat exchangers. Regardless of exchangers' names, their influential role in industries and heat recovery is undeniable. Each exchanger has a special and unique structure, depending on the working fluid and the specific role it plays. In the following section, the most regular types of heat exchangers are introduced.

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Chapter 1

Heat exchanger classifications

1.1 Introduction

Heat exchangers can be classified according to various attributes:

- Heat transfer method (direct or indirect contact)
- Functionality (regenerator or recuperator)
- Fluid flow direction
- Surface compactness
- Structure

Exchangers can be categorised according to numerous other attributes as well. However, for the sake of brevity and clarity, only the above attributes are considered. In the following section, each of these attributes is briefly discussed, because they will be used in the following chapters.

1.2 Classification of heat exchangers according to the heat transfer method

Regardless of whether the fluid inside an exchanger is single phase or two phase, or whether heat transfer in a condenser or boiler takes place with a phase change, heat transfer can be carried out through direct or indirect contact between two fluids. In direct contact, two fluids are in contact directly with each other. For instance, the mixing of two fluids with different temperatures to reach an average temperature is an example of direct contact heat transfer. Another example is the cooling of air in evaporative coolers, where heat is directly transferred from air to water, which causes the water droplets to undergo a phase change from liquid to vapour. There are many such examples in industry, which will not be discussed further.

In indirect contact exchangers, the two fluids are separated by a wall, which prevents the mixing of fluids. All exchangers discussed in the following chapters fall into this category.

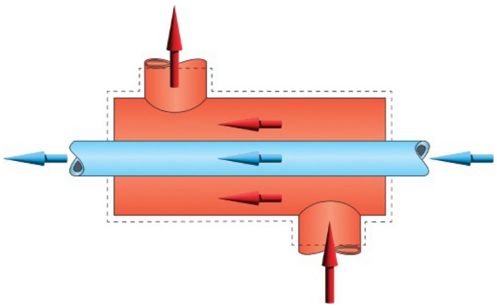
1.3 Classification of heat exchangers according to the functionality

From another viewpoint, exchangers can be classified as regenerators and recuperators. This classification might not seem accurate at first glance since almost all exchangers can act as regenerators for heat recovery in power plant cycles. However, a regenerator in this context refers to an exchanger with intermittent heat transfer instead of continuous heat transfer. For example, in one stage, the thermal energy of hot fluid is stored inside matrices or packed beds, and in the next stage, the stored heat is transferred to the cold fluid by passing it through these matrices or beds. Regardless of the variety of regenerators, there is always a possibility of fluid leakage in these exchangers. In contrast to regenerators, in recuperators, heat transfer takes place continuously. The current book only focuses on recuperator heat exchangers. Therefore, all exchangers discussed in the next chapters fall under recuperator categories.

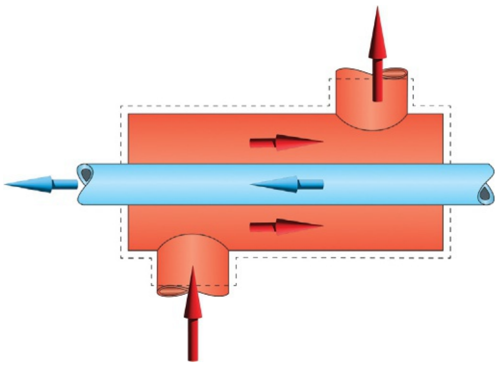
1.4 Classification of heat exchangers according to the fluid flow direction

The direction of hot and cold flows inside an exchanger can have three arrangements:

- Parallel flow (co-current)



- Counterflow (countercurrent)



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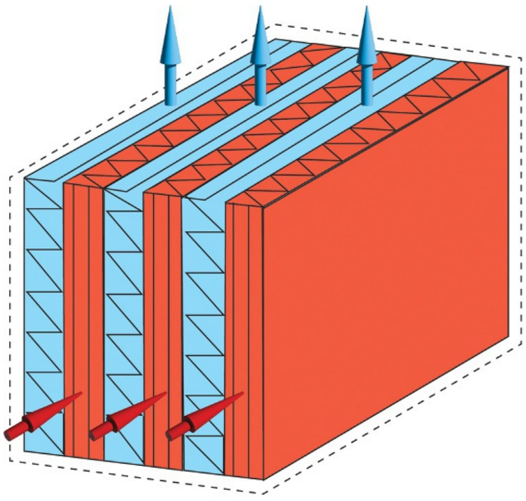
- Cross-flow



In parallel flow, the two fluids flow parallel to each other in such a way that both the hot and cold fluids enter from the same side; thereby, at the entrance, the coldest fluid is exposed to the hottest fluid, and both fluid temperatures gradually move towards the same temperature along the exchanger length (Fig. 1.1). In counterflow, the hot and cold fluids are still parallel to each other; but, they enter the exchanger from opposite sides. Therefore, the fluid temperature difference will not undergo severe changes across the exchanger length (Fig. 1.1).

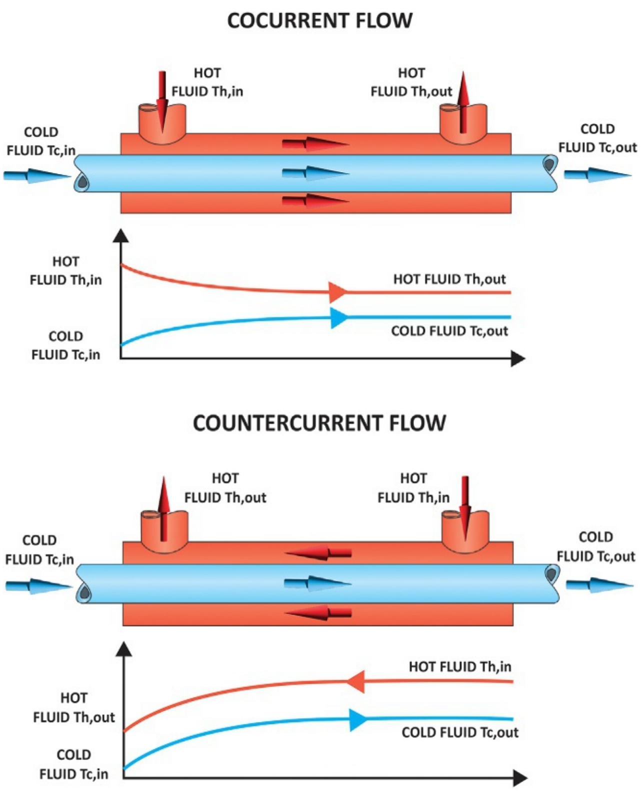


FIG. 1.1 A comparison of parallel and counterflows.

From a thermodynamic viewpoint, the best heat transfer case occurs in a completely counterflow arrangement, and the lowest amount of heat is transferred in a completely parallel flow arrangement. Furthermore, since the maximum temperature difference in counterflow is lower than parallel flow, there is a lower risk of thermal shocks (sudden temperature fluctuations) occurring in the exchanger. Therefore, it is more suitable to use a counterflow pattern in heat exchangers to the extent possible. However, since the temperature of the separating wall is more uniform in parallel flow, when the wall temperature must be kept below a specific limit, parallel flow must be considered. In a cross-flow arrangement, the two fluids flow perpendicular to each other. It should be noted that, in certain exchangers, such as a shell-and-tube heat exchanger, both parallel and cross-flow patterns could occur simultaneously, i.e. the flows are parallel in some sections and crossed in others (Fig. 1.2).

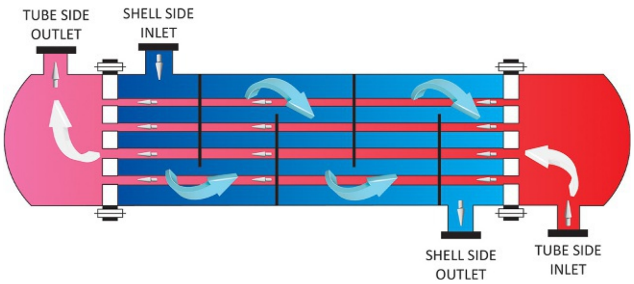


FIG. 1.2 Single-pass countercurrent in a shell-and-tube exchanger.

In many cases, the fluid will not reach the requested temperature after passing the length of the exchanger once. Therefore, the fluid must flow throughout the exchanger a few more times without exiting the exchanger. Each time a total fluid stream passes through the entire length of the exchanger, it is called one pass.

Therefore, a cross-parallel or a cross-counterflow pattern exists in an exchanger with cross-flow arrangements and more than one pass. In other words, if the entrances of hot and cold fluids were in the same side, the flow would be a cross-parallel flow, and otherwise, it would be a cross-counterflow (Fig. 1.3).

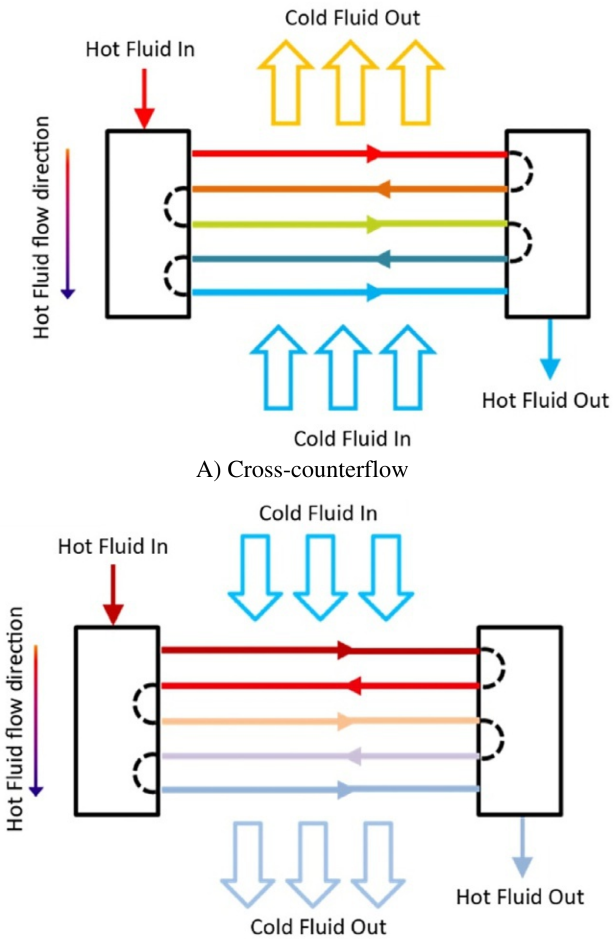


FIG. 1.3 Cross-counter- and cross-parallel flows.

1.5 Classification of heat exchangers according to the surface compactness

Surface compactness is one of the crucial factors in choosing heat exchanger types. The surface compactness factor in an exchanger refers to the ratio of the heat transfer area to the volume of the exchanger. Therefore, the larger this factor is, the smaller and lighter the heat exchanger will be. This factor can also have an impact on the initial manufacturing costs of an exchanger. In other words, lighter exchangers often cost less to manufacture. It is worth noting that in cases where the volume or weight of the exchanger is a determining factor, such as in marine and/or offshore heat exchangers, considering surface compactness is crucial. If the surface compactness of a given exchanger in services with one gaseous flow is over $700\,m^2/m^3$, then the exchanger is a compact heat exchanger. In other services, the criterion for compactness of an exchanger is a surface compactness of $400\,m^2/m^3$. All plate heat exchangers discussed in the present book are compact exchangers. Nevertheless, some of the widely used heat exchangers such as air-cooled or shell-and-tube exchangers are not considered as compact exchangers.

1.6 Classification of heat exchangers according to the structure

Generally, recuperator heat exchangers fall into the following two groups:

- Plate heat exchangers
- Tubular heat exchangers

Although there are other categories in this context, they are not mentioned here since there are no clear boundaries in categorising the heat exchangers according to those definitions.

Plate heat exchangers refer to the class of exchangers in which the wall separating the fluids is made up of plates or sheets, while in tubular exchangers, tubes are used as a separating wall. In both types of exchangers, secondary surfaces such as fins can be added in order to extend the overall heat transfer area.

The plate heat exchangers discussed in this book are as follows:

- Gasketed plate-and-frame exchangers
- Double-wall plate exchangers
- Semi welded plate exchangers
- Brazed plate exchangers
- Bavex exchangers
- Compabloc exchangers
- Packinox exchangers
- Lamella exchangers
- Spiral exchangers
- Plate-fin exchangers

Due to the universality of gasketed plate-and-frame heat exchangers and their close structural similarity to other plate exchangers, only the gasketed plate-and-frame exchanger is discussed in detail separately, while the other types of plate exchangers are all described in one single chapter. Although there are a wider variety of plate exchangers than the ones discussed, this book only covers the most commonly used types. Regarding the tubular exchangers, only the most common types are discussed, which are:

- Air-cooled exchangers
- Cooling towers
- Shell-and-tube exchangers
- Double-pipe (hairpin) exchangers
- Heat pipe exchangers

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Chapter 2

Gasketed plate-and-frame heat exchangers

(From TGT Co.)

2.1 Introduction

It should be noted beforehand that Part 1 of the API 662 standard, or ISO 15547-1, is used for the discussion of the topic at hand. This standard, which is one of the leading standards for gasketed plate-and-frame heat exchangers, covers a portion of the necessary requirements and recommendations for the design, materials selection, fabrication, inspection, testing, and preparation for the shipment of gasketed plate-and-frame heat exchangers used in the petrochemical, petroleum, and natural gas industries. To facilitate the use of this book, wherever this standard is applied, it is explicitly specified in the text.

2.2 Structure of gasketed plate-and-frame exchangers

As demonstrated in Fig. 2.1, gasketed plate-and-frame exchangers (simply gasketed plate heat exchanger or gasketed plate exchanger) are generally composed of a series of thin rectangular corrugated plates, through which the fluids flow. The plate pack is clamped between two frames, and the gap between each two plates is sealed with a gasket. One of these frames is fixed (headpiece) and attached to the inlet and outlet nozzles, while the other is moveable (pressure plate, tailpiece, or the follower) and responsible for compressing the plates and keeping them in place. Since these frames are not in contact with the fluids inside the exchanger, they are usually made of painted carbon steel, stainless steel, or in some cases, carbon steel coated with stainless steel. All plates hang from an upper carrying bar and are fitted into their appropriate positions by a lower carrying bar. These bars are designed to support 1.5 times the weight of the exchanger when filled with water (API 662). Under operating conditions, in order to prevent fluid leakage, the two frames are compressed together using long bolts (tie rods) 16 mm in diameter (API 662), which results in the plate pack being pressed between them. Therefore the length of the plate pack is shorter under operating conditions than when the plates are not compressed together, thereby the length of the carrying bars should also allow enough space for the plates to move under nonoperating conditions. In addition to adequate spacing for the movement of plates, each exchanger must have the capacity to install additional plates by at least 20% of the initial number of plates (API 662).

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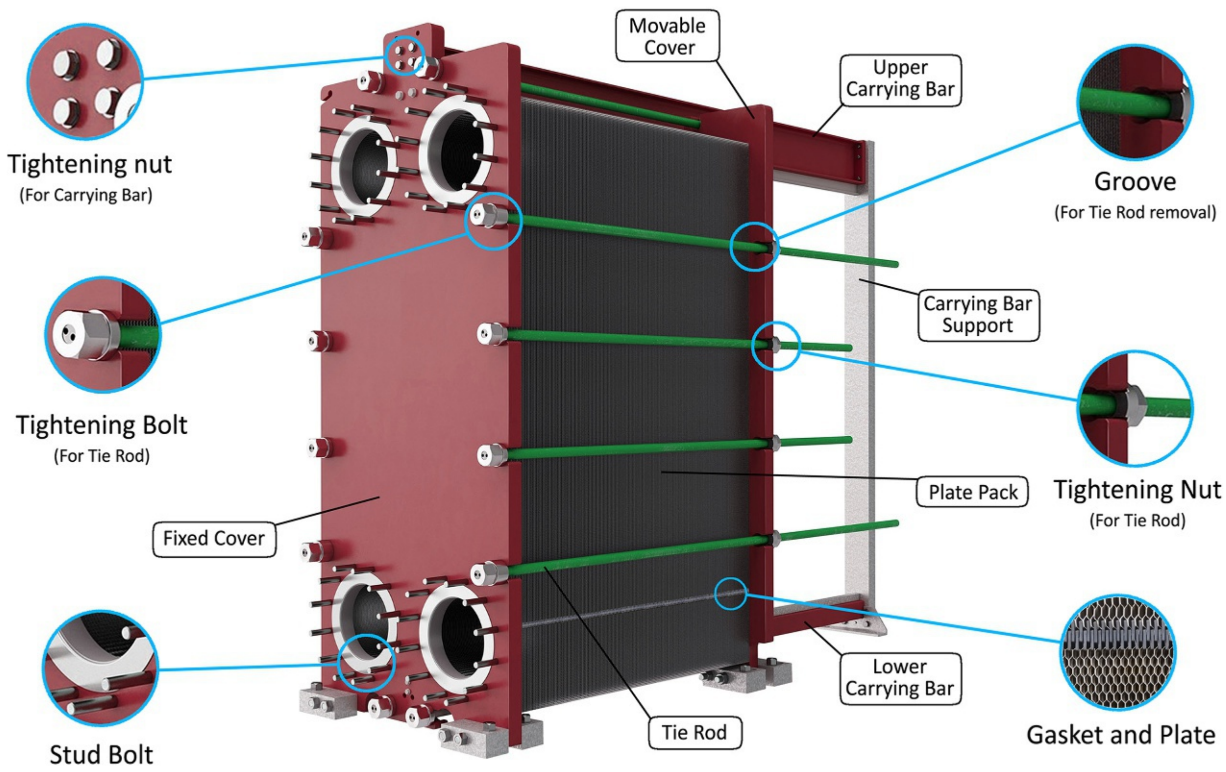

Schematic of a packed gasketed plate heat exchanger

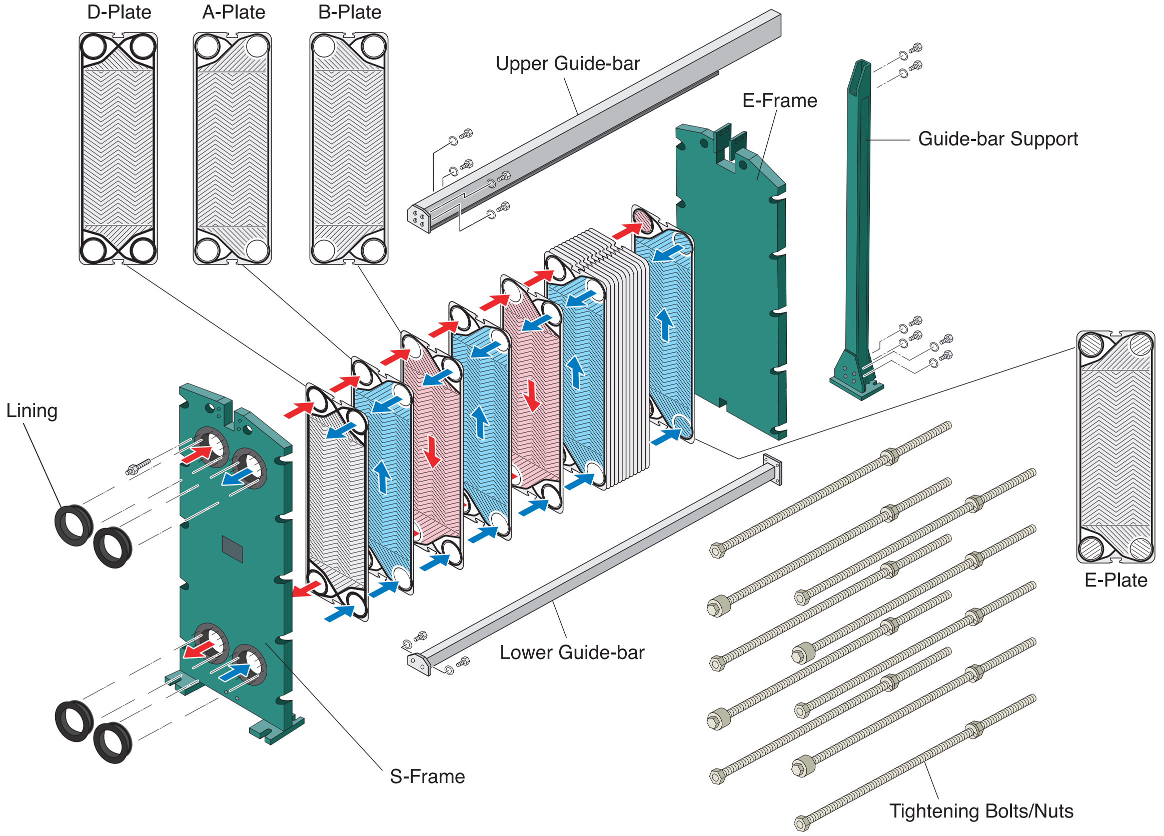

FIG. 2.1 Schematic depicting a disassembled gasketed plate heat exchanger. *(From Hisaka Works, Ltd.)*

The empty spaces in between the plates act as channels for the fluids to flow through. The plates are arranged in such a way that would allow the hot and cold fluids to flow alternately through these channels, enabling the transfer of heat from the hot fluid to the cold one. There are four ports on the four corners of each plate, which allow the passage of fluids through the empty spaces in between plates. The number and dimensions of these plates are determined according to the fluid flow rate, heat transfer rate, allowable pressure drop, fluid phase, and thermophysical properties of the fluid. These types of exchangers were first patented by Albrecht Dracke in 1878 and became popular in 1923 after Dr. Richard Seligman created the first industrial model. Fig. 2.2 shows a gasketed plate heat exchanger from before World War II.

The earliest models of gasketed plate exchangers fabricated before 1923 were made of bronze, which limited their effectiveness, but paved the way for the wide application of these exchangers.

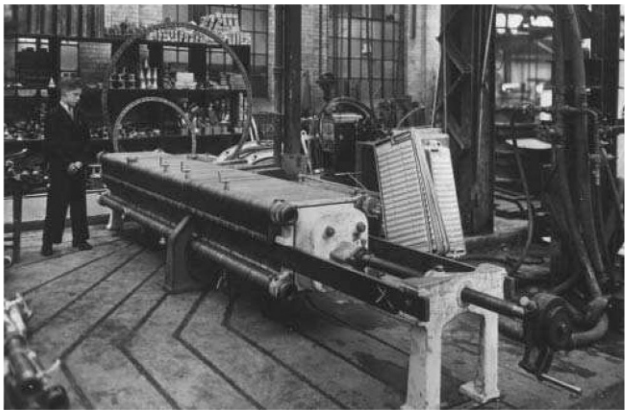

FIG. 2.2 A photograph depicting one of the first models of gasketed plate heat exchangers. *(From SPX Flow Co.)*

The switch to stainless steel as the plates' material, the ease of cleaning, and the possibility of increasing the capacity of these exchangers by adding extra plates have turned them into one of the most commonly used types of heat exchangers, especially in food industries. Although these plates are produced on a large scale, their design requires much research and consideration. The operating capacity of early exchangers was limited to a pressure of 2 bar and a temperature of 60°C due to sealing problems and the limitation of gasket materials. Even though the operating principles of these exchangers have not changed much, technological advancements in their fabrication have increased their allowable working pressure up to 30 bar and their temperature up to 250°C.

The corrugation of plates causes a higher turbulence or the occurrence of a secondary flow in the fluid, which will eventually increase the heat transfer coefficient and reduce sedimentation. Fig. 2.3 presents a sample of such corrugations. In addition, these corrugations play a crucial role in increasing the mechanical strength of the plates, making them capable of easily withstanding a differential pressure between 0.25 bar and 10 bar on both sides. Since these corrugation patterns are created on thin plates by cold working in one stage, the plates must be made of materials that have adequate resistance to corrosion, in addition to being suitable for cold working. The most common material used for this purpose is stainless steel (S.S. 316 or S.S. 304), although materials such as titanium, Incoloy, or Hastelloy are also used in certain cases. In cases where corrosion is a determining factor, nonmetal materials such as polymers or graphite/fluoroplastic composites can be used. Table 2.1 presents some of the usable materials in this area along with their thermomechanical properties. The maximum size of these plates is about 1.1 m (width) × 4.3 m (height), and their

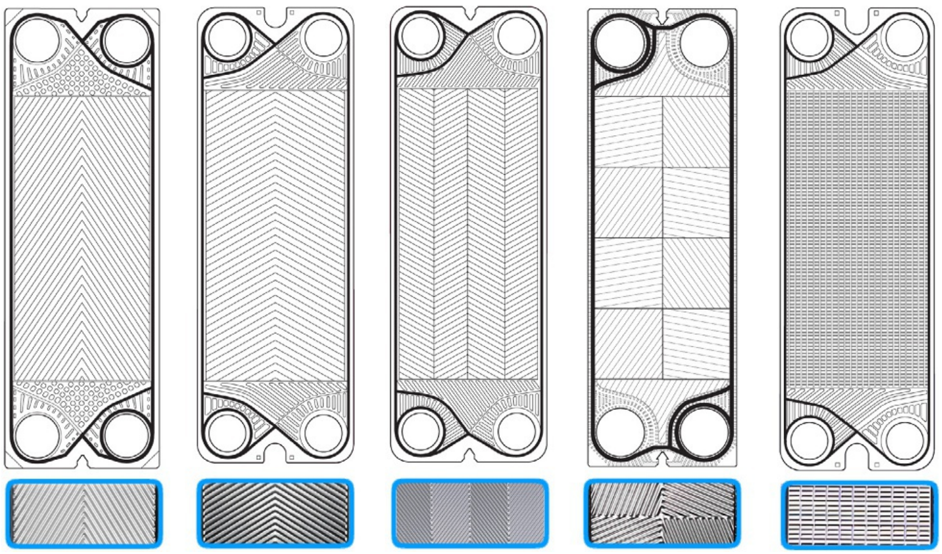

FIG. 2.3 Various plate designs.