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MAIN TYPES OF HEAT EXCHANGERS AND THEIR PRIMARY COMPONENTS

Heat exchangers transfer heat from a hot fluid to a colder fluid through the combined mechanisms of conduction and forced convection. In most heat exchangers, a metal wall separates the two fluids. All heat exchangers are similar in their principle of operation; however, heat exchangers may differ in the specific fluids that are used in the heat transfer process, the layout of the metal tubes, and the configuration of the enclosure.

In order of usage, the main types of heat exchangers that are used by Saudi Aramco are as follows:

- Shell-and-tube heat exchangers
- Air-cooled heat exchangers
- Double-pipe heat exchangers
- Plate-and-frame heat exchangers

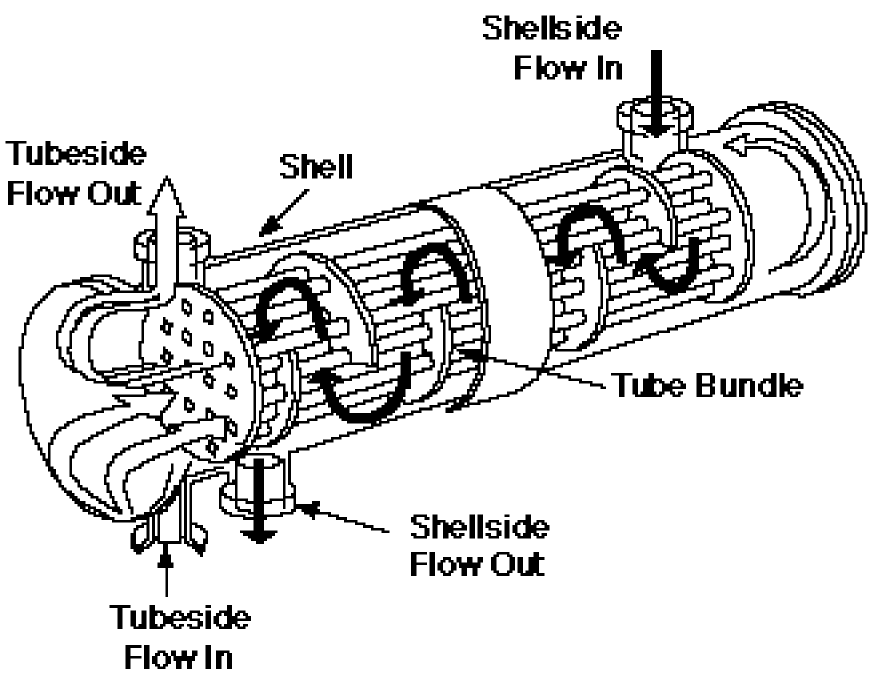
In addition to heat exchangers, other types of heat transfer equipment, such as cooling towers and process furnaces, are used in Saudi Aramco. Cooling towers are a special class of heat exchanger in which water is cooled by an evaporation process. Process furnaces transfer heat to a process fluid primarily through radiation. Cooling towers and process furnaces are not discussed in this course.

TEMA-Type Shell-and-Tube Heat Exchangers

The shell-and-tube heat exchanger is the type that is most commonly used in process plants. TEMA (the Tubular Exchanger Manufacturers Association) is an association that consists of companies who manufacture shell-and-tube heat exchangers. TEMA has developed an engineering standard that is used for the design of shell-and-tube heat exchangers. Specific design requirements that are contained in the TEMA standard will be discussed later. The phrase "TEMA-type shell-and-tube heat exchanger" refers to heat exchangers that are designed to meet TEMA requirements.

Figure 1 illustrates the basic arrangement of a shell-and-tube heat exchanger.

In shell-and-tube heat exchangers, one fluid, known as the "tubeside" fluid, flows inside a set of parallel tubes known as the "tube bundle." These tubes are enclosed within a metal shell. The other fluid, known as the "shellside" fluid, flows inside the shell but over the outside of the tubes. Both the metal shell and the tubes are pressurized, and they must withstand the specified design pressures during the intended lifetime of the equipment.



Shell-and-Tube Heat Exchanger

Figure 1

Design Standards

Saudi Aramco Engineering Standard SAES-E-001 - SAES-E-001, *Basic Design Criteria for Unfired Heat Transfer Equipment*, provides both the process designer and the Saudi Aramco Engineer with design criteria for four types of heat exchange equipment, including air-cooled, double-pipe, and plate type heat exchangers, and induced draft cooling towers. SAES-E-001 specifies the applicable codes, standards, and specifications for each of the four heat exchange equipment types. A copy of SAES-E-001 is in Course Handout 2.

Saudi Aramco Engineering Standard SAES-E-004 - SAES-E-004, *Design Criteria of Shell-and-Tube Heat Exchangers*, covers the requirements for the thermal and mechanical design of shell-and-tube heat exchangers for hydrocarbon, hydrogen, caustic, amine, wet sour, steam, and utility services. SAES-E-004 also covers the repair requirements for existing shell-and-tube exchangers. A copy of SAES-E-004 is in Course Handout 2.

Saudi Aramco Materials System Specifications - Saudi Aramco Materials System Specifications (SAMSSs) are technical specifications that accompany the purchase orders that are sent to equipment manufacturers. Each of the SAMSSs includes engineering requirements that are specific to Saudi Aramco and that modify or supplement the applicable industry standards. 32-SAMSS-007, *Heat Exchangers, Shell and Tube Type*, applies to TEMA-type shell-and-tube heat exchangers. A copy of 32-SAMSS-007 is in Course Handout 2.

ASME Pressure Vessel Code - All heat exchangers are typically built in accordance with a pressure vessel code. Saudi Aramco has adopted most of the United States codes and standards, and it requires all heat exchangers to be built in accordance with the American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel Code, Section VIII, Division 1 or 2. This compliance with the ASME Code ensures that the Saudi Aramco equipment is designed, fabricated, inspected, and tested in accordance with a widely accepted industry standard. Heat exchangers can therefore be considered as special purpose pressure vessels.

However, the design rules that are contained in the ASME Code are not sufficiently specific for the many types of heat exchangers that are in use. Therefore, a number of industry, manufacturer, and Company standards have been developed to clarify the design requirements for specific applications and environments.

TEMA Standard - TEMA has developed a standard that is entitled *Standards of the Tubular Exchanger Manufacturer's Association*. This standard covers the shell-and-tube heat exchangers that are built for use in the petroleum industry as well as in many other industries. Portions of the TEMA standard are discussed later in this module and in subsequent modules. A copy of the TEMA standard is in Course Handout 1.

API Standard 660 - In addition to the ASME Code and the TEMA standard, the American Petroleum Institute (API) has published a standard that is entitled API Standard 660, *Shell-and-Tube Heat Exchangers for General Refinery Service*. This document stipulates many of the design requirements for shell-and-tube heat exchangers that are used in oil refineries. A copy of API-660 is in Course Handout 1.

TEMA Classifications

Most process services in refineries require heavy-duty heat exchangers in order to achieve high reliability. Some process services are less severe and do not require such robust designs; therefore, the TEMA Standard 7th Edition (1988) specifies requirements for three different heat exchanger classifications, designated as Classes R, C, and B. These classifications cover a broad range of industrial services.

TEMA Class R - TEMA Class R specifies design and fabrication requirements for shell-and-tube heat exchangers that are in the severe service environments of petroleum refineries and related industries. Class R is generally selected by designers for applications where durability and safety are the primary concerns.

TEMA Class C - TEMA Class C specifies design and fabrication requirements for shell-and-tube heat exchangers that are in the generally moderate service environments of commercial and general process industries. Equipment that is fabricated in accordance with the Class C requirements are designed for maximum economy and overall compactness, and are, therefore, consistent with moderate safety and service requirements.

TEMA Class B - TEMA Class B specifies design and fabrication requirements for shell-and-tube heat exchangers that are in the chemical process industry. Class B is similar to Class R with respect to design requirements, but Class B is closer to Class C than to Class R with respect to minimum thickness and corrosion allowance.

Most Saudi Aramco shell-and-tube heat exchangers are Class R; however, there are service applications for which less expensive Class C exchangers may be used. SAES-E-004, Para. 7.5.1, indicates that a Class C exchanger may be used for nonhydrocarbon services, and for the lubricant and seal oil coolers that are included in standard packaged units.

Figure 2 compares some of the TEMA requirements for Class R, C, and B exchangers.

Design Item	Class/Service		
	R/Refinery	**C/General**	**B/Chemical**
Corrosion Allowance (carbon steel)	1/8 in.	1/16 in.	1/16 in.
Minimum Thickness of Shell	See Table R-3.13	See Table CB-3.13	See Table CB-3.13
Minimum Tie-Rod Diameter	3/8 in.	1/4 in.	1/4 in.
Gasket Contact-Surface Tolerance	±1/32 in., max.	None	None
Minimum Bolt Size	3/4 in.	1/2 in.	5/8 in.

TEMA Requirements for Class R, C, and B Exchangers

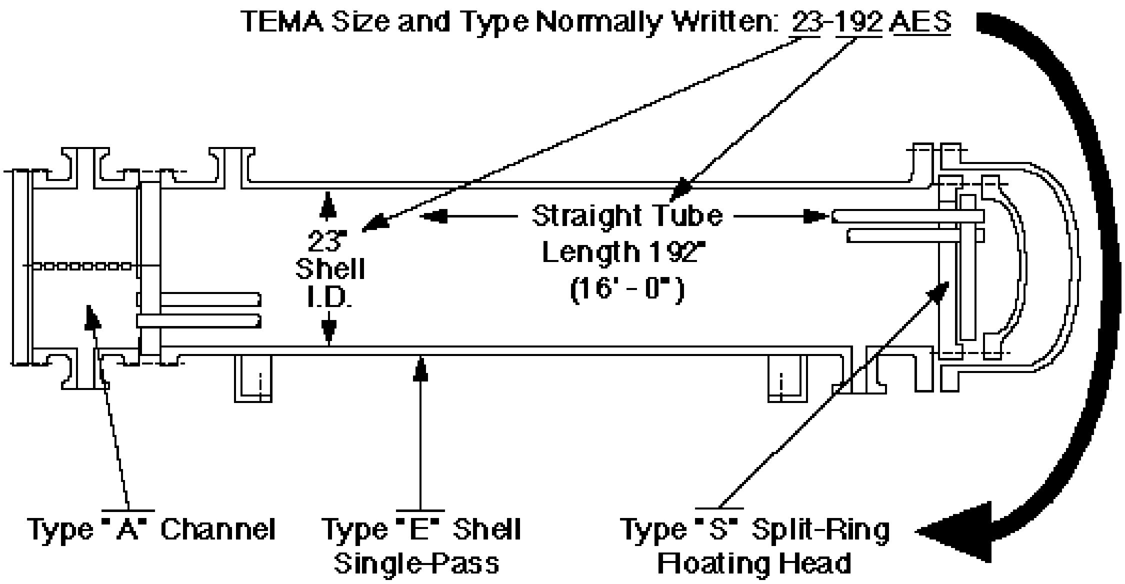
Figure 2

TEMA Designations

TEMA designations for shell-and-tube heat exchangers are used in the petroleum refining and chemical processing industries to identify exchanger sizes and types. The TEMA designation is usually made up of a two-part size designator and a three-letter type designator. The TEMA designation method is illustrated by the example that is shown in Figure 3.

TEMA Size Designation - The TEMA size designator consists of two numbers that are separated by a hyphen (-). The first number ('23' in the example of Figure 3) indicates the nominal shell diameter in inches, rounded to the nearest integer. The second number ('192' in the example of Figure 3) indicates the nominal tube length in inches. The three letters ('AES' in the example) indicate that the heat exchanger has a front-end type A, a shell type E, and a rear-end type S.

Note that the TEMA system of size designations for some types of heat exchangers, such as kettle-type reboilers, does not exactly follow this designation method. Refer to the TEMA standard for information on how the sizes of these heat exchanger types are designated.



TEMA Designation System Example

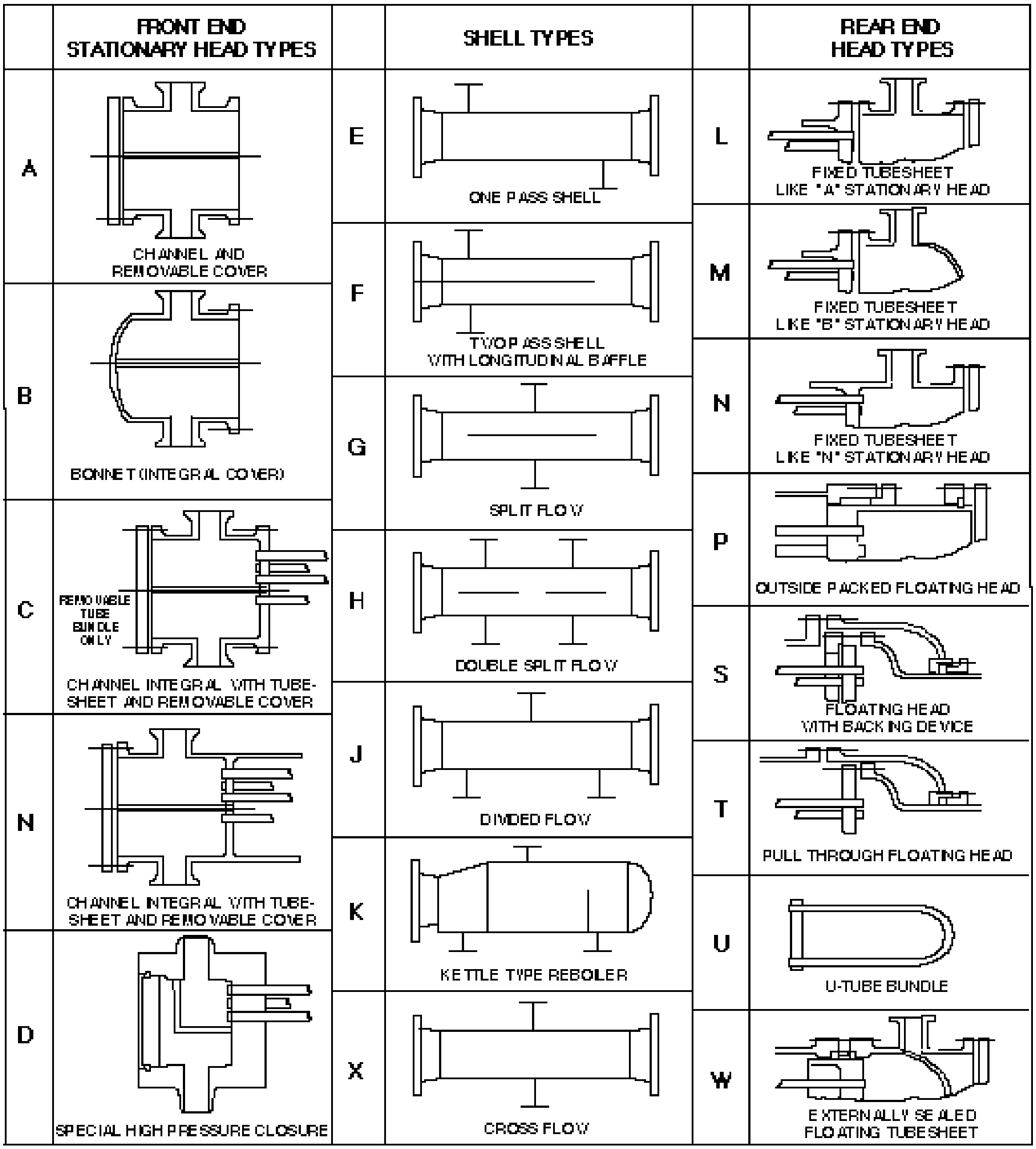
Figure 3

TEMA Type Designation - The standard TEMA shell-and-tube heat exchanger types are illustrated in Figure N-1.2 of the TEMA Standard, which is shown in Figure 4.

- The first letter of the three-letter TEMA-type designation describes the heat exchanger front-end or stationary head type. The first letter is selected from the five types that are illustrated in the first column of Figure N-1.2.

- The second letter of the three letter TEMA-type designator describes the heat exchanger shell, and it is selected from the seven types that are shown in the middle column of Figure N-1.2. This letter may be omitted in a specification or proposal if a shell is not included in the equipment that is to be purchased (for example, if the specification or a proposal is to be used for the purchase of a replacement tube bundle with tubesheet[s], only).

- The third letter of the three letter TEMA-type designator describes the heat exchanger rear-end or floating-head type, and it is selected from the eight types that are shown in the right-hand column of Figure N-1.2.



TEMA Figure N-1.2

Figure 4

Considerations for Selecting Exchanger Component Options

There are five stationary head types that are used in shell-and-tube exchangers. Figure 5 lists the considerations that are used to select the appropriate stationary head type for specific applications. Figure 6 lists the considerations that are used to select the appropriate shell design. Selection criteria for the rear end are listed in Figure 7.

Type	Description	Selection Consideration
A	Channel and Removable Cover	The most common type of head that is used in shell-and-tube heat exchangers. Used with fixed tubesheet, U-tube, and floating head exchangers. In most cases, the bundle is removable for mechanical cleaning.
B	Bonnet or Removable Channel with Integral Cover	Normally used only for low-fouling tubeside services. Used with fixed tubesheet, U-tube, and floating head exchangers. Less expensive than Type A head.
C	Channel Integral with Tubesheet and Removable Cover	Used with some types of fixed tubesheet exchangers and reboilers.
N	Channel Integral with Tubesheet, Shell, and Removable Cover	Shellside fluid must be relatively low-fouling so that chemical cleaning can be used. Not recommended for use with U-tube or floating head exchangers because of maintenance difficulties.
D	Special High Pressure Closure	Special high pressure head that is used when the tubeside design pressure exceeds approximately 10 340 kPa (1 500 psi).

Selection Considerations for Stationary Heads

Figure 5

Type	Description	Selection Consideration
E	Single Pass	The most common shell design.
F	Two Pass	Two pass affords slightly better heat transfer than single pass because two passes on the shell side more closely approximates counter-current flow. In order to avoid an excessively thick longitudinal baffle, two pass should not be used with a shellside pressure drop greater than approximately 70 kPa (10 psi). Shellside temperature range should be limited to 175°C (350°F) to avoid both excessive heat leakage through the baffle and thermal stress in the baffle, the shell, and the tubesheet.
G	Split Flow	Typically used in condensing and boiling services to reduce pressure drop and to enhance heat transfer duty.
H	Double Split Flow	
J	Divided Flow Shell	
X	Cross Flow	
K	Kettle-Type Reboiler	Typically used for boiling/vaporizing services. The large shell promotes heat transfer and vapor disengagement.

Selection Considerations for Shell Designs

Figure 6

Type	Selection Consideration
L	Used with fixed tubesheet exchangers when the tubes must be cleaned mechanically.
M and N	Used, if necessary, with fixed tubesheet exchangers when the tubes can be chemically cleaned.
P	Not recommended because of the tendency of packed joints to leak. Type P heads should never be used with shellside hydrocarbons or toxic fluids.
S and T	Removable bundle designs. The floating head in an S-type exchanger has a split backing ring that reduces shell diameter requirements and that maintains high thermal efficiency. For maintenance reasons, Saudi Aramco generally prefers the Type T head, which allows the bundle to be more easily removed.
U	Used with U-tube bundle where tubeside does not need mechanical cleaning. Typically, a formed head is used on the shell, although a bonnet-type head can be used also.
W	Uses a packed joint to separate the tubeside and shellside fluids. Not recommended because of tendency of packed joints to leak.

Selection Considerations for Rear Ends

Figure 7

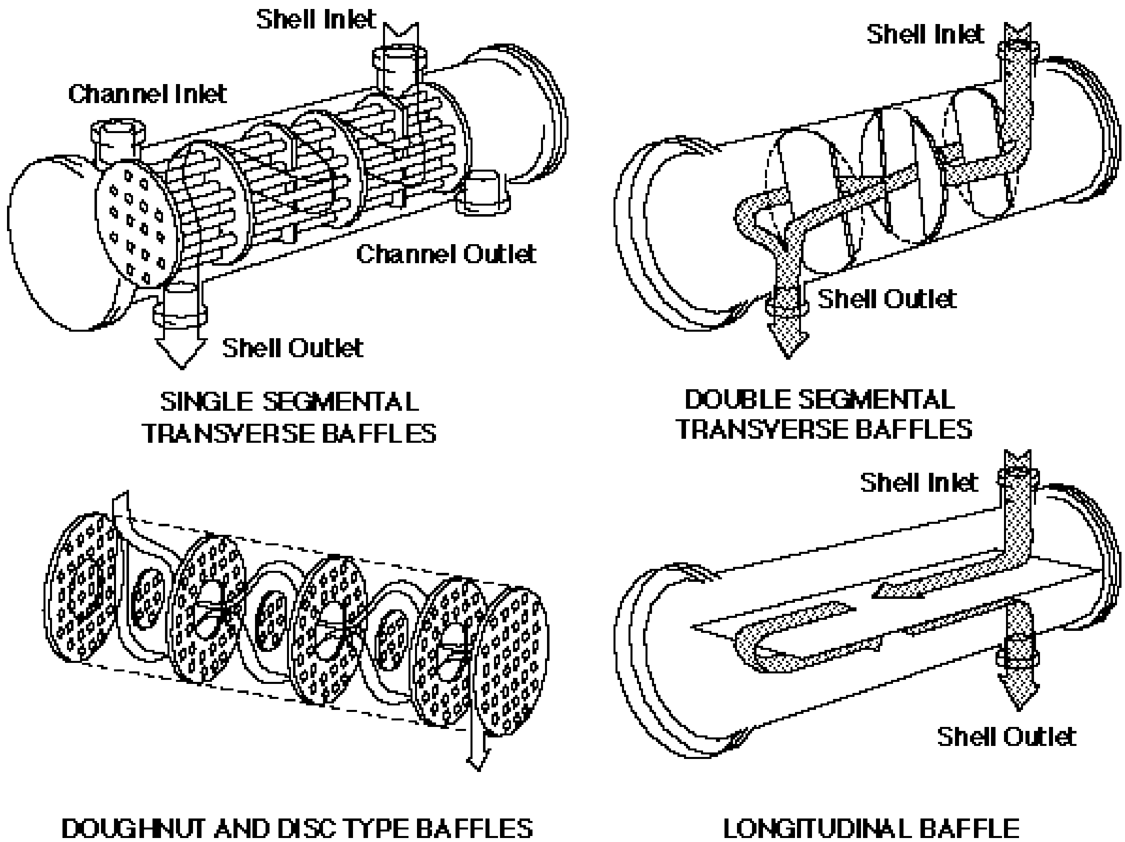
TEMA Component Nomenclature

TEMA has established standard terminology for the individual components of shell-and-tube heat exchangers. These components are shown in Section N of the TEMA Standard. Some of this nomenclature is used in this and later modules, and this nomenclature is discussed below.

Baffle Type - Baffles are installed on the shellside of heat exchangers to force the shellside fluid to flow across the tubes in a specific pattern. The modified flow improves heat transfer between the shellside and tubeside fluids. Baffles may be oriented either transversely (i.e., perpendicular to the axis of the heat exchanger) or longitudinally (i.e., parallel to the axis of the heat exchanger). Transverse baffles include segmental and "doughnut and disk" baffles. These baffle types are illustrated in Figure 8. The segmental transverse baffles can be single segmental, double segmental, or triple segmental.

Single segmental baffles have one fluid passage cut through the baffle. Double and triple segmental baffles have two and three passages, respectively. Single segmental baffles are prevalent in heat exchangers in which the shellside fluid is a liquid. Double and triple segmental baffles are generally used when the shellside fluid is a gas. Segmental baffles can be cut horizontally or vertically. Vertical cut baffles are illustrated in Figure 8.

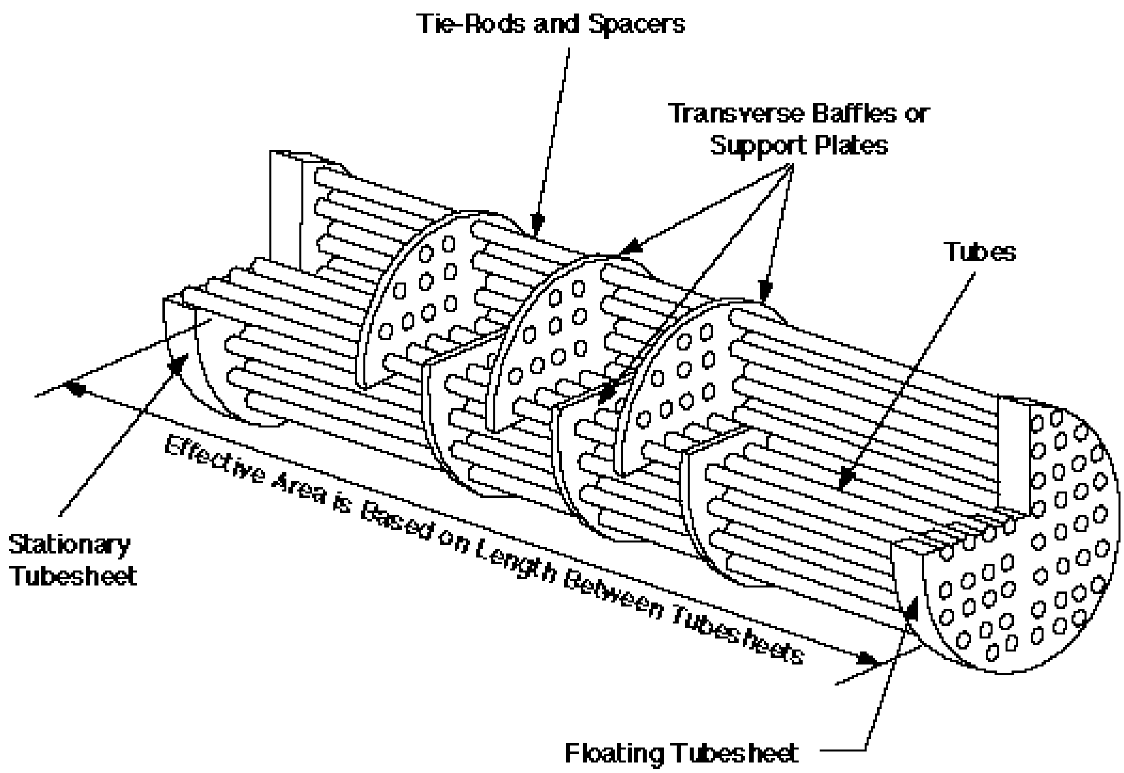
In some cases, such as when tube vibration is a concern, a *no tube in the window* baffle design is used. In a *no tube in the window design*, the bundle is laid out in such a way that there are no tubes located in the window of the baffle (i.e., the region where a particular baffle does not support the tubes). In this manner, every tube is supported by each baffle, and the lowest mechanical natural frequency of the tube bundle is increased. The *no tube in the window* design greatly increases the size of shell that is required, because a larger number of tubes are needed in order to achieve the necessary heat transfer.



Typical Baffle Configurations

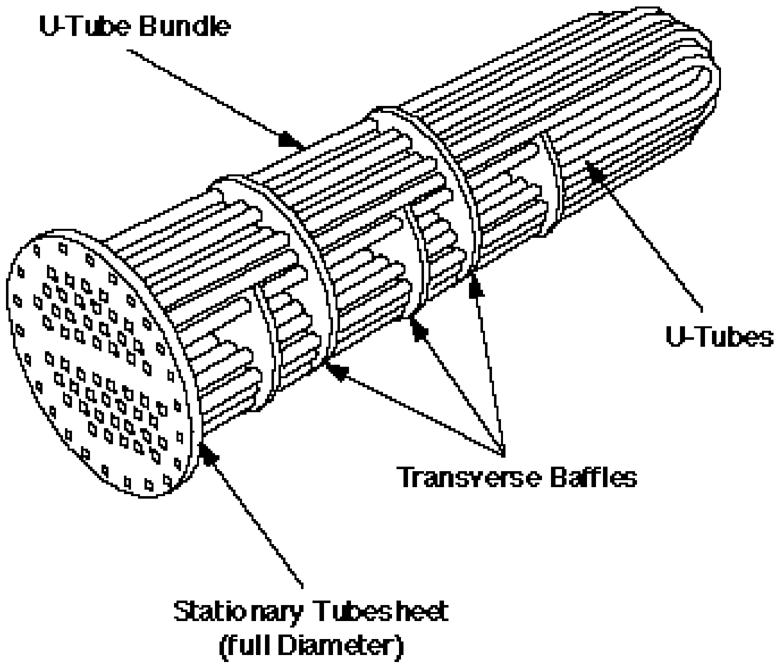
Figure 8

Bundle (or Tube Bundle) - In heat exchangers with removable bundles, the bundle consists of the tubesheet (or tubesheets), tubes, baffles and/or supports, tie-rods, and spacers. The bundle of a straight-tube, split-ring, floating-head-type heat exchanger is shown in Figure 9. The bundle of a U-tube heat exchanger is shown in Figure 10. For fixed tubesheet exchangers, the bundle refers to the part of the exchanger that extends from tubesheet to tubesheet, exclusive of channels and bonnets.



Bundle for a Straight-Tube, Split-Ring, Floating Head Heat Exchanger

Figure 9



Bundle of a U-Tube Heat Exchanger

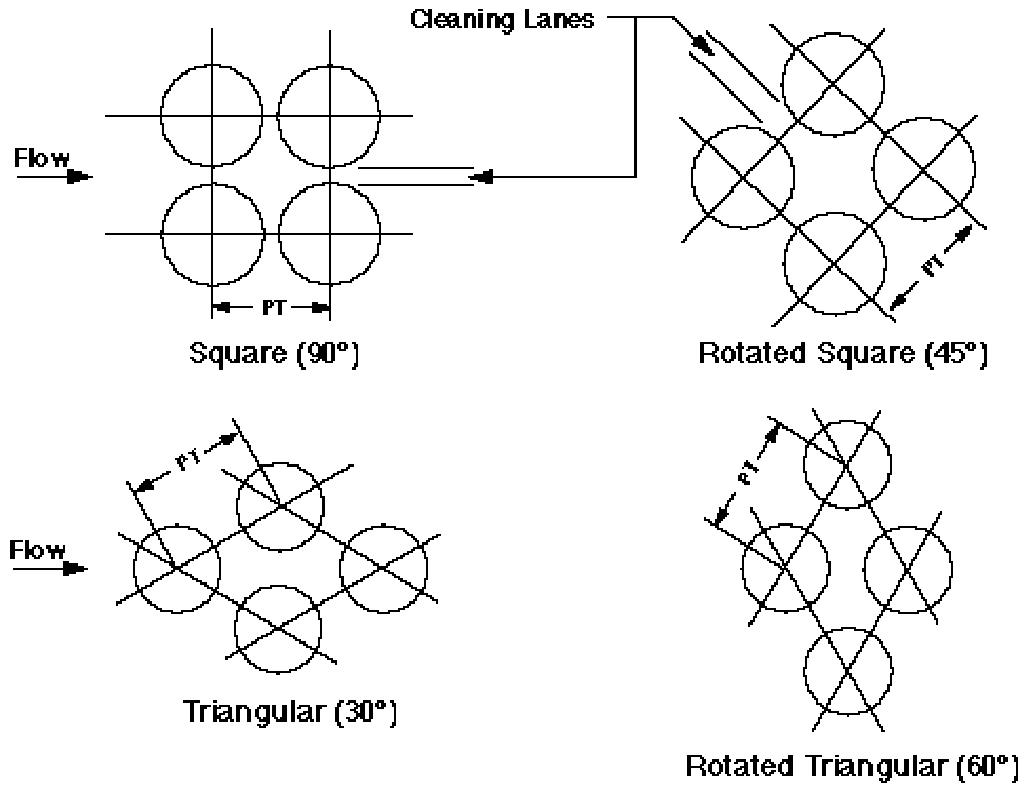
Figure 10

Tube Cleaning Lanes - Tube cleaning lanes are the spaces that are between rows of tubes in a removable-bundle heat exchanger and that are large enough to permit entry of brushes and other cleaning devices, such as hydroblast equipment. Cleaning lanes are typically provided when the tubes are arranged on a square or rotated square pitch, as shown in Figure 11.

Tube Pitch Pattern - The tube pitch pattern describes the arrangement or layout of tubes as the tubes pierce the tubesheets, baffles, and supports.

Typical pitch patterns are illustrated in Figure 11. These patterns include:

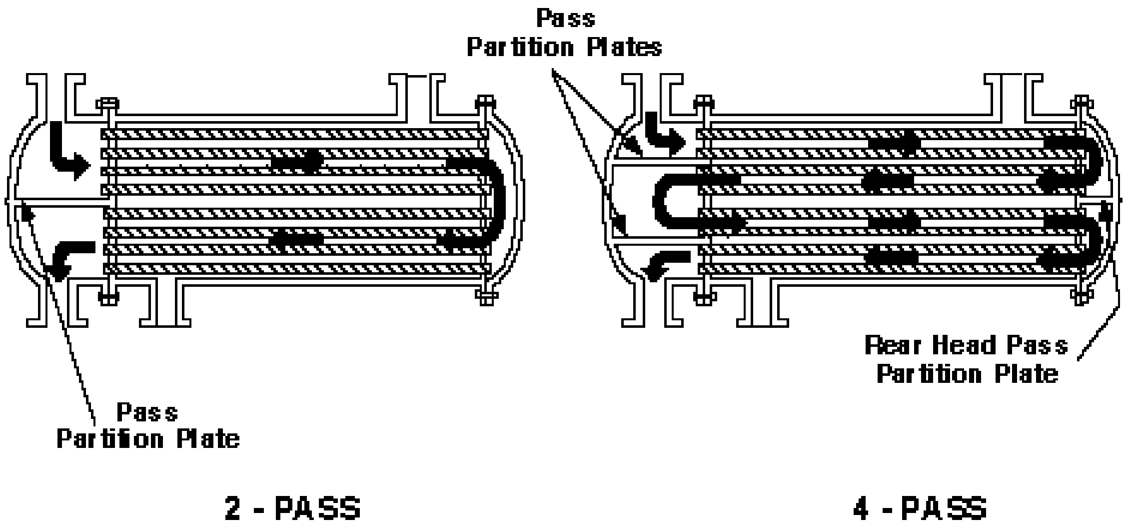
- Square
- Rotated square
- Triangular with flow parallel to the base of an equilateral triangle
- Triangular with flow that enters at the apex of an equilateral triangle



Tube Pitch Patterns

Figure 11

Tubeside Passes - Tubeside passes refer to the number of times that the fluid flows from one end of a bundle to the other end. In heat exchangers that have more than a single tubeside pass, a number of tubes are grouped together in the channel. Pass partition plates, which separate the individual groups of tubes, are located in the channel. Pass partition plates are also sometimes located in the floating head as well, depending on the number of tubeside passes that are required. Each group of tubes in a pass receives the full flow from the inlet of the heat exchanger. Figure 12 illustrates two-pass and four-pass tubeside heat exchanger designs.



Two-Pass and Four-Pass Tubeside Flows

Figure 12

TEMA Shell-and-Tube Heat Exchangers Used by Saudi Aramco

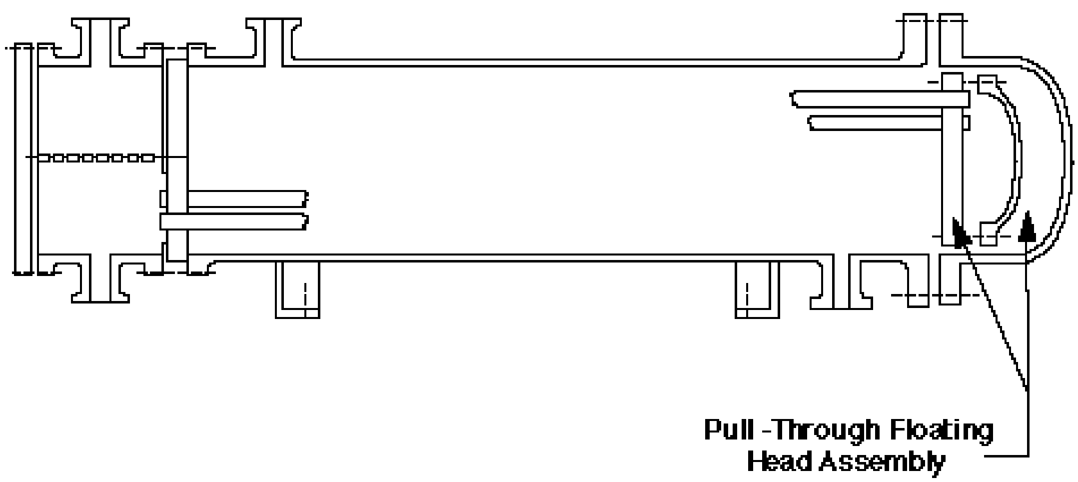
This section discusses the primary types of shell-and-tube heat exchangers that are installed in Saudi Aramco facilities. These types include the following:

- Split-Ring Floating Head
- Pull-Through Floating Head
- U-Tube
- Kettle-Type
- Fixed Tubesheet
- Special High Pressure
- Double Tubesheet

Split-Ring Floating Head (Example: TEMA-Type AES) - Split-ring floating head heat exchangers are standard units that were purchased by Saudi Aramco several years ago. To remove the tube bundle from this type of exchanger, the shell head, the floating head cover, and the split-ring backing device must be removed.

A standard TEMA-Type AES exchanger is illustrated in Figure N-2 of the TEMA Standard. (See the TEMA Standard in Course Handout 1.)

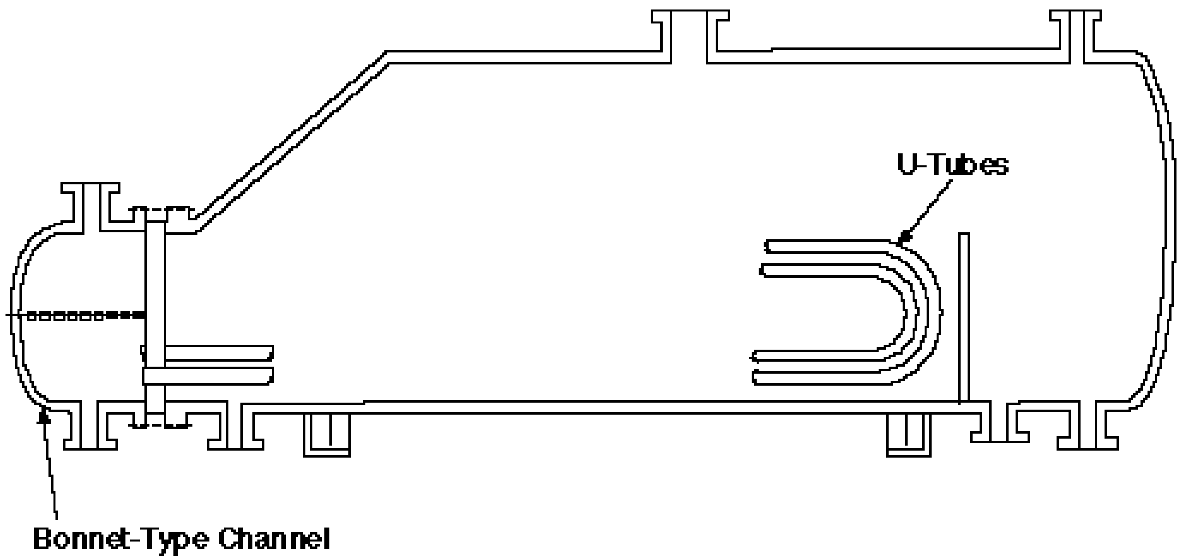
Pull-Through Floating Head (Example: TEMA-Type AET) - TEMA-Type AET heat exchangers have pull-through floating head tube bundles, and they are the current standard design that is used in most Saudi Aramco facilities. Figure 13 illustrates the standard TEMA-Type AET heat exchanger. The shell is slightly larger and more expensive than the AES shell; however, it is not necessary to disassemble the shell cover and the floating head for purposes of removing the bundle from the shell. Thus, the AET design reduces field maintenance and turnaround time.



TEMA-Type AET Heat Exchanger

Figure 13

U-Tube Kettle Reboilers (Examples: TEMA-Type AKU and BKU) - The AKU kettle reboiler has a removable channel cover. The BKU kettle reboiler, illustrated in Figure 14, has an integral welded channel cover. The BKU design is used when the tubeside fluid is clean (e.g., steam applications). The BKU design is also specified when it is necessary to minimize heat loss to the atmosphere. The entire bonnet channel can be insulated to conserve heat.



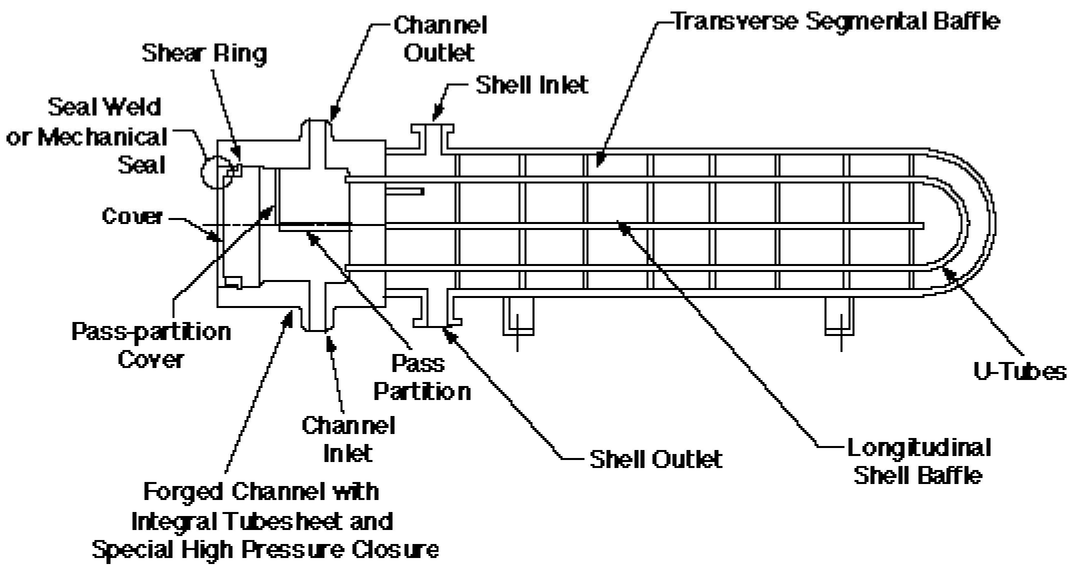
TEMA-Type BKU Heat Exchanger

Figure 14

Pull-Through Kettle-Type (Example: TEMA-Type AKT) - These kettle-type reboilers have pull-through floating heads. The AKT is normally used when excessive fouling on the tubeside requires mechanical cleaning inside the tube bundle. The AKT heat exchanger is illustrated in Figure N-2 of the TEMA Standard. (See the TEMA Standard included in Course Handout 1.)

Fixed Tubesheet (Example: TEMA-Type BEM) - The TEMA-type BEM exchanger has bonnet heads on both channels. This exchanger type is typically used in a single tube pass arrangement as a vertical thermosyphon reboiler. The tubesheets are integrally welded to the shell. If temperature differences between the tubes and the shell exceed 30°C (50°F), an expansion joint in the shell may be needed. Figure N-2 of the TEMA Standard illustrates a BEM-type exchanger with a modified conical rear head. (See Figure N-2 in the TEMA Standard included in Course Handout 1.)

Special High Pressure U-Tube (Example: TEMA-Type DFU) - Figure 15 illustrates a TEMA-type DFU exchanger. The TEMA-type DFU exchanger has special high pressure closures on the channel (or tube) side. These closures are used when the tubeside pressure is approximately 10 340 kPa (1 500 psi) or higher. The channel is usually made from a forged steel ring, and the tubesheet is usually welded to the channel. The tubesheet also may be forged integrally with the channel through the use of a "cup" forging. The channel cover is designed with a shear-key ring that is held in place, usually by a key backing ring flange that is bolted to the channel. Many high-pressure closures incorporate proprietary designs of the manufacturers.



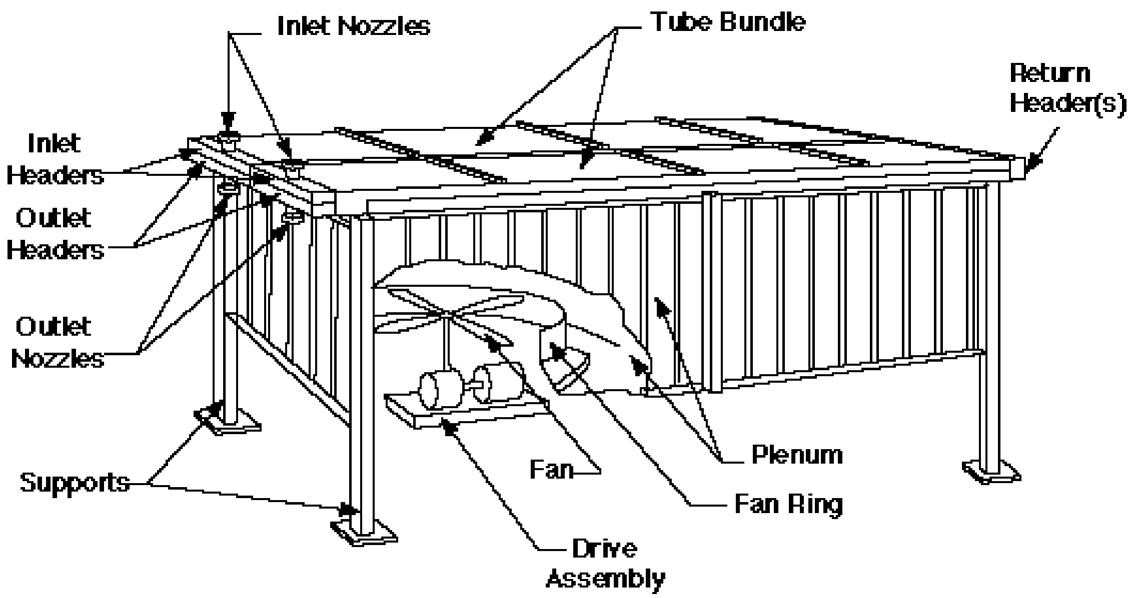
TEMA-Type DFU Heat Exchanger

Figure 15

Double Tubesheet - A double tubesheet design uses two tubesheets between the tubeside and shellside fluids rather than one tubesheet, and the tubes must pass through both of these tubesheets. This type of construction is sometimes used in applications that have very high tubeside pressures, or where any leakage of one side's fluid into the other side's fluid is unacceptable. Double tubesheet configurations include a number of manufacturers' proprietary designs.

Air-Cooled Heat Exchangers

Air-cooled heat exchangers are used to cool process fluids that flow through tubes. The tubes are fitted with external cooling fins in order to enhance the transfer of heat from the fluid to the ambient-temperature air. A typical forced-draft air-cooled heat exchanger is illustrated in Figure 16.



Typical Forced-Draft Air-Cooled Heat Exchanger

Figure 16

Air-cooled heat exchangers are used when it is impractical to exchange heat between two process fluids. Exchanging heat between two process streams is usually not practical when a second process fluid is not available at the temperature that is required to achieve useful heat transfer. In such cases, a shell-and-tube design would require water to cool the single process fluid. Because it is uneconomical to use water for cooling purposes in many Saudi Aramco facilities, air-cooled heat exchangers are recommended when a second process fluid of the right temperature is not available. The ultimate selection between a water-cooled or an air-cooled heat exchanger is normally governed by economic considerations, which include both initial investment costs and long-term operating costs.

Design Standards

Saudi Aramco Engineering Standards - SAES-E-001, previously introduced, is a general design standard that also is applied to air-cooled heat exchangers. SAES-E-001 references the code and industrial standards that are listed below. 32-SAMSS-011, *Air Cooled Heat Exchangers*, is a Saudi Aramco Materials System Specification that is applicable to air-cooled heat exchangers, and it is written with paragraph numbers that correspond to the paragraph numbers of API-661. This arrangement facilitates incorporation of the Saudi Aramco supplementary requirements into the design of air-cooled heat exchangers. A copy of 32-SAMSS-011 is in Course Handout 2.

ASME Boiler and Pressure Vessel Code - The design and fabrication of air-cooled heat exchangers are subject to the requirements of the ASME Boiler and Pressure Vessel Code, Section VIII, Division 1. The ASME Code is supplemented by the requirements of API-661, *Air Cooled Heat Exchangers for General Refinery Service,* and Saudi Aramco SAESs and SAMSSs.

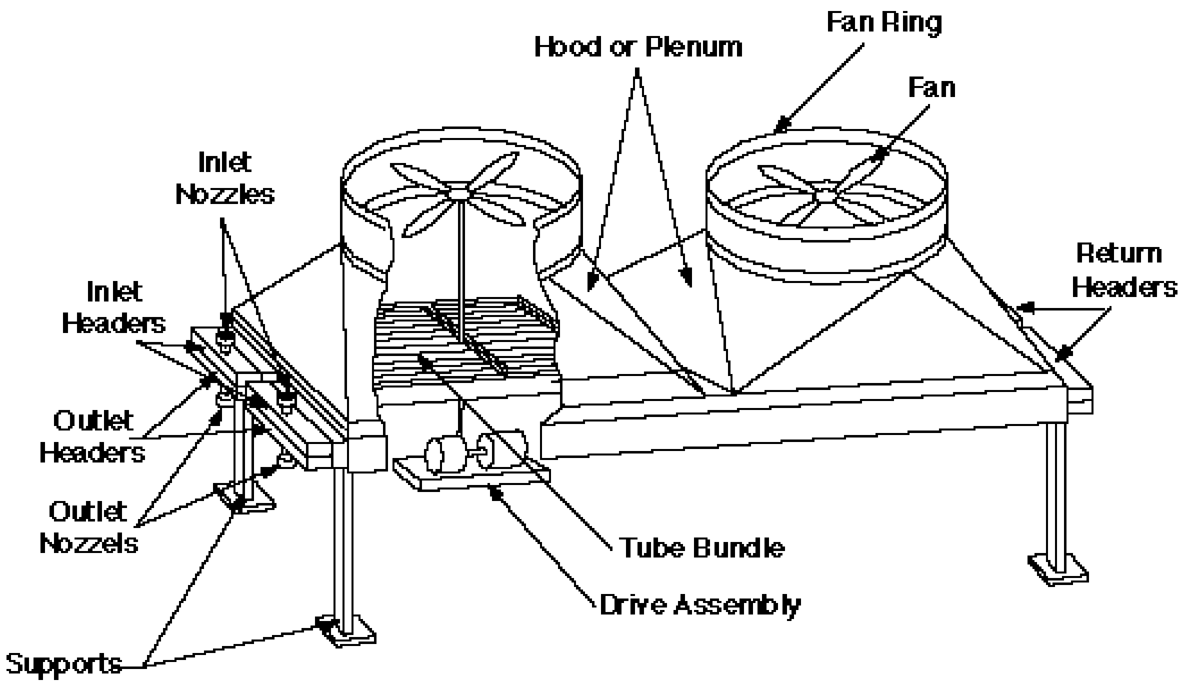
API Standards - API has developed API Standard 661, *Air Cooled Heat Exchangers for General Refinery Service*. API-661 augments the ASME Code in the areas of design, manufacture, and product reliability, and it provides requirements for air-cooled exchangers in refinery and petrochemical service. A copy of API-661 is in Course Handout 1.

Types of Air-Cooled Heat Exchangers

Three principal types of air-cooled heat exchangers are used in Saudi Aramco: forced draft, induced draft, and humidified forced-draft.

Forced Draft - In a forced draft heat exchanger, air is forced across the tube bundle by a fan that is located in an air plenum below the bundle. The fan pressurizes the entire bundle. Figure 16 illustrates a horizontal tube, forced-draft, air-cooled heat exchanger.

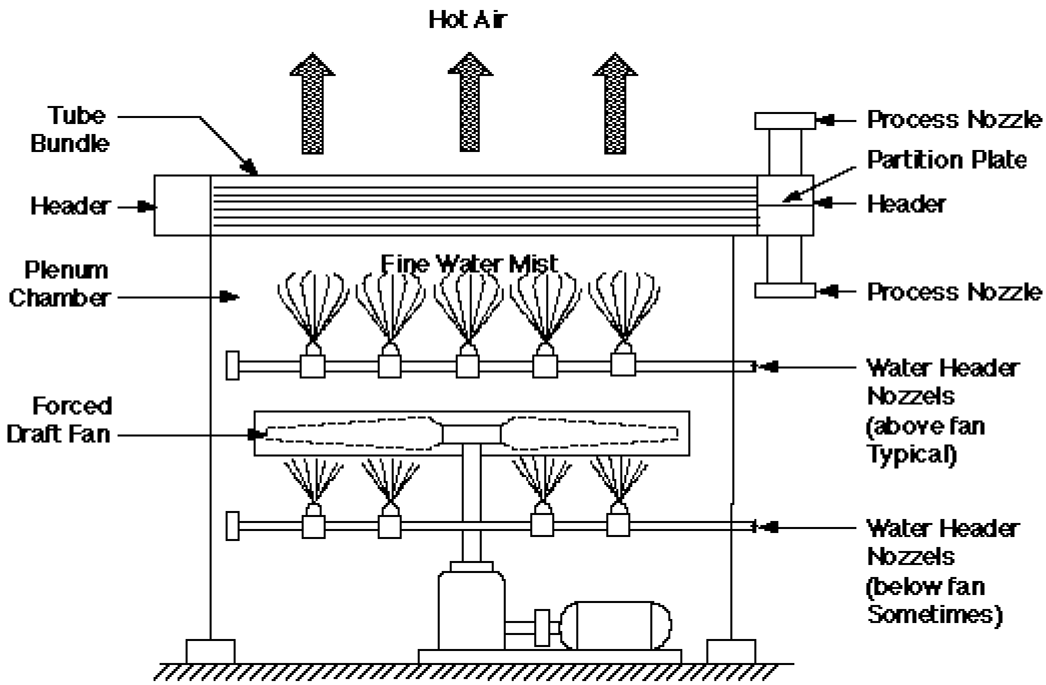
Induced Draft - In an induced draft heat exchanger, the fan is located above a hood that covers the tube bundle. The air is pulled across the tube bundle and is exhausted through the hood. Figure 17 illustrates the horizontal tube, induced-draft, air-cooled heat exchanger. Except for the fan location, the exchanger is similar to the forced-draft design.



Horizontal Tube, Induced-Draft, Air-Cooled Heat Exchanger

Figure 17

Humidified Forced-Draft - The humidified forced-draft heat exchanger is illustrated in Figure 18. The tube bundle of the humidified exchanger is similar to the forced-draft and induced-draft exchangers, except that the air is humidified before it is forced to flow across the rows of tubes. The water that is sprayed into the air evaporates as it passes through the tube bundle. The evaporation process draws heat out of the air, and it thereby cools the air to a temperature that is below the temperature of the process fluid that is in the tubes. The increased temperature differential between the humidified air and the process fluid enhances the cooling effectiveness of the heat exchanger.



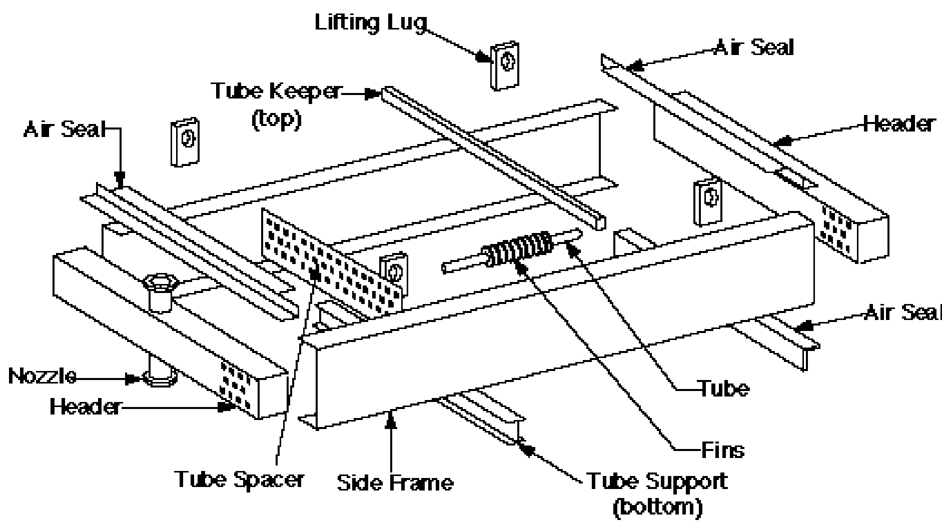
Humidified Forced-Draft Heat Exchanger

Figure 18

Component Nomenclature

Some of the major component parts of air-cooled heat exchangers are shown in Figures 16 through 18, and they are defined below. A complete list of air-cooled heat exchanger component nomenclature is listed in Section 1.4 of API-661. Refer to the copy of API- 661 that is included in Course Handout 1.

Tube Bundle (Coil Assembly) - Tube bundle refers to an assembly of tubes, header boxes, side frames, and other components. Figure 19 illustrates the tube bundle of an air-cooled heat exchanger. The tube bundles for both forced-draft and induced-draft heat exchangers are rectangular, and they contain many rows of tubes that are arranged in a triangular pitch. A rectangular pressurized header box usually is located at each end of the bundle. The tubeside fluid enters and leaves the tubes through nozzles that are welded to the header boxes.



Typical Air-Cooled Heat Exchanger Tube Bundle Components

Figure 19

Heat transfer in air-cooled heat exchangers is generally counter-current, which means that the hot fluid enters the top of the bundle, and air enters from the bottom. The air flows over the tubes to cool the fluid that is within the tubes. Typically, the tubes are finned to increase heat transfer to the air.

Inlet Header Box - The inlet header box is a rectangular pressurized box that is used to distribute the process fluid from the inlet nozzle equally to all of the tubes in the bundle.

Outlet Header Box - The outlet header box collects all of the process fluid from the exchanger tubes and directs the fluid to the outlet nozzle.

Return Header Box - In a multiple-pass bundle, the return header box collects, turns, and redistributes the flow between the multiple tube passes.

Header Box Options

Typical tube bundle header box construction options are shown in API-661 as follows:

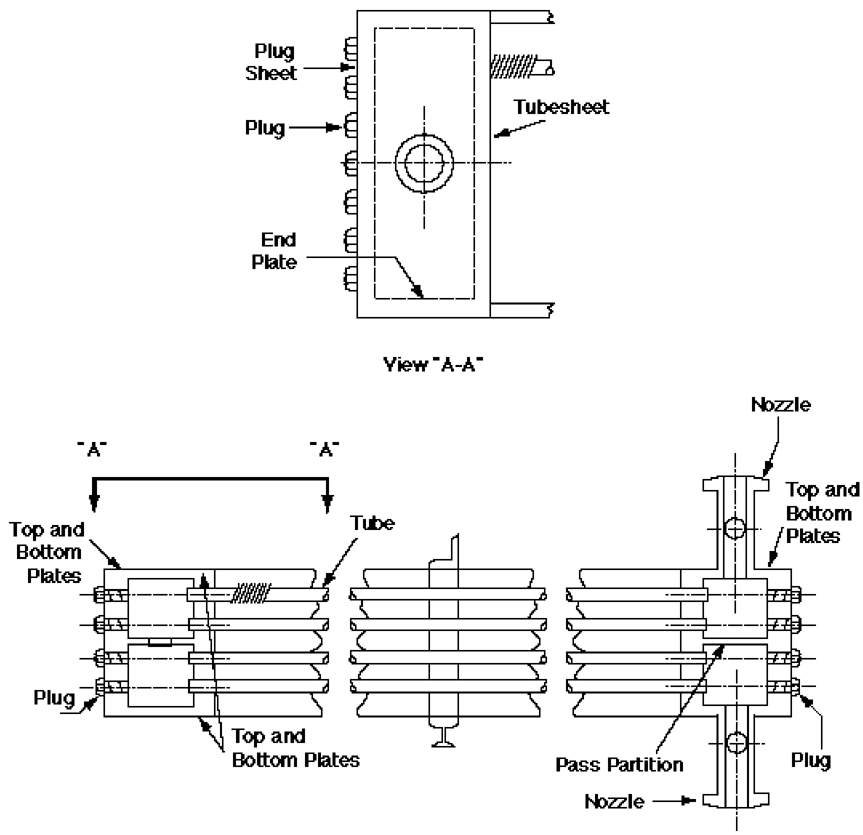
Figure 3a - With removable coverplate

Figure 3b - With removable bonnet headers

Figure 5 - Assembled, with plug headers

Refer to the copy of API-661 in Course Handout 1. These different types of header boxes are selected on the basis of the maintenance and cleaning requirements of the process service.

32-SAMSS-011, Paragraph 5.1.5.7, requires that plug-type headers be used for all process applications. Other types of headers may be used for lube oil and seal oil coolers. Figure 20 illustrates a typical plug-type header box. Note that, in this design, threaded/gasketed plugs are in the header box end plates and that they are aligned with the tubes. This arrangement permits individual inspection and cleaning of the tubes.



Tube Bundle with Plug Headers

Figure 20

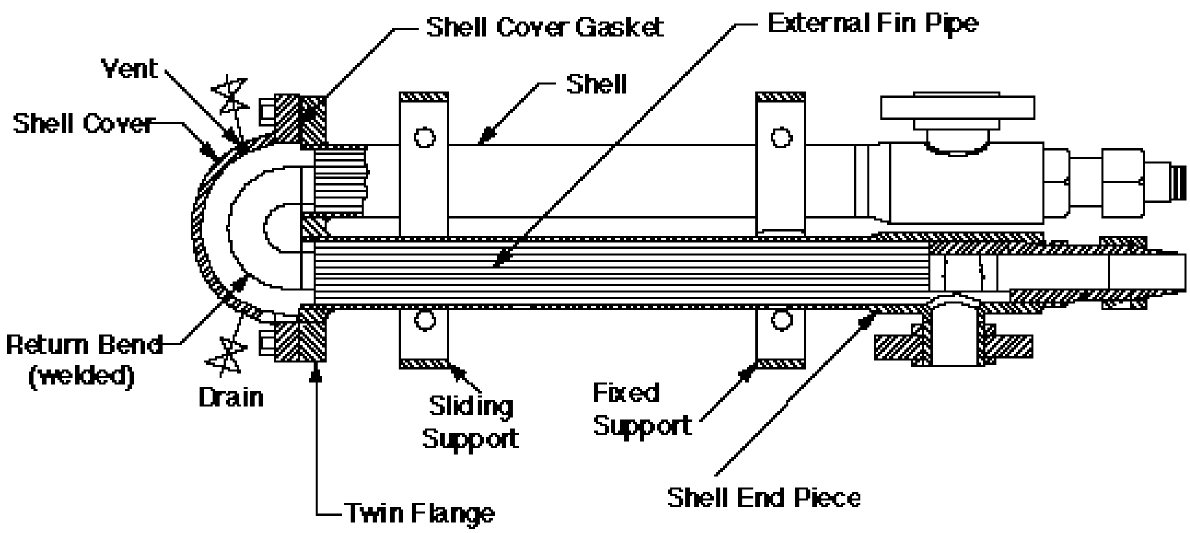
Other Types of Heat Exchangers

Double-Pipe Heat Exchangers

Figure 21 illustrates a double-pipe heat exchanger, which is a special type of shell-and-tube heat exchanger. Double-pipe heat exchangers often are used when the required heat transfer surface is less than approximately 10 square meters (100 square feet). Typically, a double-pipe heat exchanger is used to cool lubricants and hydraulic fluids for large machines. Sometimes, double-pipe heat exchangers are used to cool samples and liquids for process analyzers.

A double-pipe heat exchanger consists of a tube-within-a-tube. One of the fluids flows inside the inner tube, and the other fluid flows in the annulus between the tubes. Tubes in a double-pipe heat exchanger are occasionally long, and they may be U-shaped. Typically, the inner tube has external longitudinal fins. In very clean services, the inner and outer tubes can be a single forging, or the inner tube can be welded to the outer tube. In other services, the tubes can be made with packed or gasketed joints between the inner and outer tubes. The packed or gasketed joints enable the inner tubes to be removed to be cleaned. For U-shaped tubes, the inner tubes are made with bolted-on covers on the U-bend end of the shell to make it easier to clean the tubes.

Specifications for double-pipe heat exchangers are covered in SAES-E-006 and in 32-SAMSS-028.



Double-Pipe Heat Exchanger

Figure 21

Plate-and-Frame Heat Exchangers

Plate-and-frame heat exchangers generally are used in applications in which a high overall heat transfer coefficient is required and where high-alloy materials, rather than carbon steel, must be used for the heat transfer surface. Plate-and-frame heat exchangers provide a large heat transfer surface area in a relatively compact package. Figure 22 is an illustration of a plate-and-frame heat exchanger.

As specified in SAES-E-014, plate-and-frame heat exchangers may be used as an alternative to shell-and-tube type heat exchangers when the operating pressures and temperatures do not exceed 1 380 kPa gage (200 psig) and 150°C (300°F), respectively, and when a material other than carbon steel is required for contact with the fluid.

Further, SAES-E-014 indicates that plate-and-frame heat exchangers should be designed with 10% excess thermal capacity when they are used in clean services. A 15% excess thermal capacity is required when the exchanger is to be used in fouling services, such as to cool crude oil, emulsions, or heavy hydrocarbon processing streams. Also, the frames of plate-and-frame heat exchangers should be designed to permit the addition of 20% more plates in order to permit a future increase in exchanger capacity. Single pass counter-flow arrangements are the preferred arrangement for plate-and-frame heat exchangers.

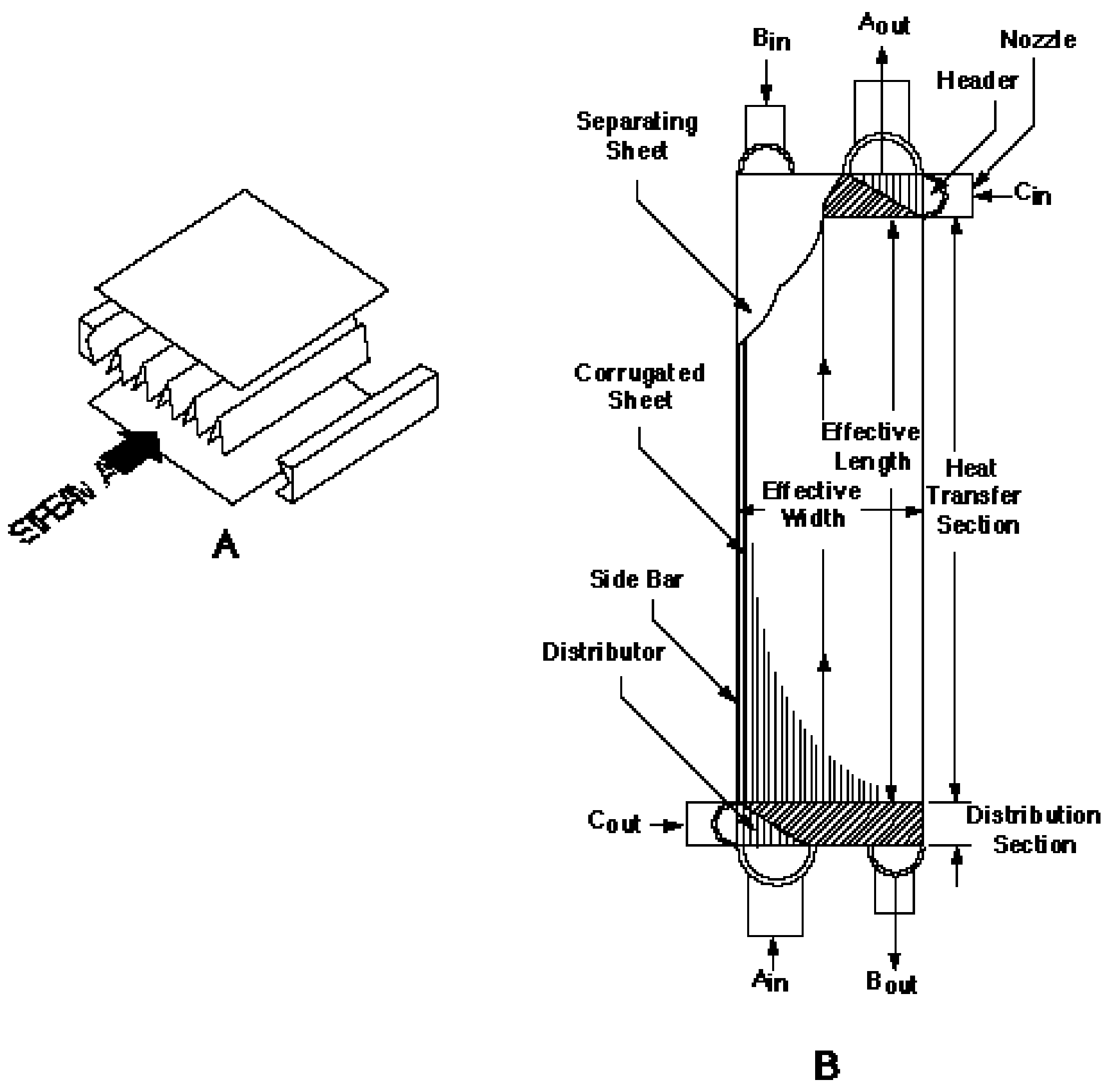


Plate-and-Frame Heat Exchanger

Figure 22

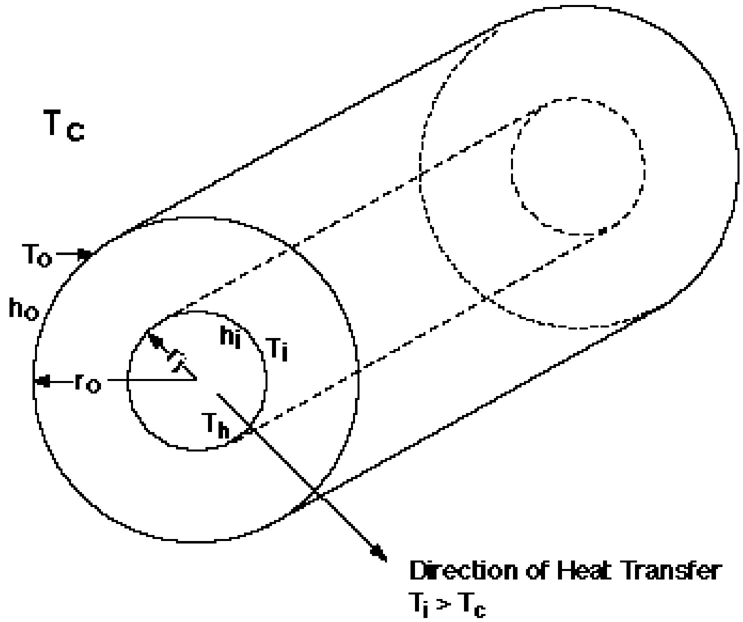
PRIMARY PROCESS FUNCTIONS OF HEAT EXCHANGERS

The two main process functions of heat exchangers are as follows:

- To change the temperature of a fluid by the exchange of heat from a higher temperature fluid to a lower temperature fluid.
- To change the phase of a fluid from liquid to vapor or from vapor to liquid at constant temperature.

Change in Temperature

Heat transfer in heat exchangers involves the combined mechanisms of conduction and convection. As shown in the sample model of a heat exchanger tube in Figure 23, heat flows by convection from the hotter fluid inside the tube to the inner surface of the tube. The heat then flows by conduction through the tube wall and by convection from the outer surface of the tube to the outside (colder) fluid. Note that it is also possible for the hotter fluid to be on the outside of the tube and for the colder fluid to be on the inside of the tube. When the hotter fluid is on the outside of the tube, the direction of heat transfer is from the outside to the inside of the tube. In the case shown, as the hot fluid flows through the inner tube and heat is transferred from the fluid, the temperature of the fluid inside the tube is lowered. Similarly, as the colder fluid outside of the tube flows over the tube, heat is transferred to the fluid, and its temperature is increased.



T_h = Inside Fluid Temperature

T_c = Outside Fluid Temperature

T_i = Inside Surface Temperature

T_o = Outside Surface Temperature

h_i = Inside Convection Coefficient

h_o = Outside Convection Coefficient

k = Thermal Conductivity of the Tube Material

Simplified Heat Exchanger Model

Figure 23

Change in Phase

Some heat exchangers are designed to change the phase of a fluid that passes through the exchanger. These exchangers can either vaporize a liquid or condense a vapor. A liquid vaporizes in a heat exchanger when sufficient heat is transferred to the fluid such that it is heated to fluid saturation temperature (i.e., boiling point). A vapor condenses in a heat exchanger when sufficient heat is transferred from the vapor such that it is cooled to its saturation temperature (i.e., condensation point). Note that the boiling point and condensation point are actually the same temperature for a pure fluid.

Figure 24 summarizes the terminology that is used by the process engineer to identify the primary process functions of heat exchangers. It is helpful if the mechanical design engineer is generally familiar with this terminology.

Terminology	Primary Function
Condenser	Condenses vapors in a process stream that enters the exchanger.
Cooler	Cools a process stream, usually by water, but can use air or other process fluid.
Chiller	Cools a process stream by refrigerant to a temperature that is lower than the prevailing water temperature.
Evaporator/ Vaporizer	Evaporates a process fluid by use of a heating medium such as steam.
Reboiler	Heats a liquid in a recirculating cycle to the boiling point.
Steam Generator	Produces steam from boiler feedwater.
Heater	Heats fluid but does not vaporize. Heating medium is usually steam or another hot fluid.
Waste-Heat Boiler	Produces steam from condensate or boiler feedwater by removal of heat from high-temperature process or waste gas stream.

Primary Process Functions of Heat Exchangers

Figure 24

PRINCIPAL APPLICATIONS AND SIZE LIMITATIONS OF SHELL-AND-TUBE AND AIR-COOLED HEAT EXCHANGERS

The following sections briefly summarize the principal applications and limitations of shell-and-tube and air-cooled heat exchangers.

Shell-And-Tube Heat Exchangers

Principal Applications

The shell-and-tube heat exchanger is one of the most common types of heat exchanger that is used in refineries and chemical plants. Shell-and-tube exchangers can either heat or cool a process fluid.

Size Limitations

The size of shell-and-tube heat exchangers is normally limited to the maximum size that can be transported and erected conveniently. Saudi Aramco has published preferred limits for exchanger sizes in SAES-E-004. These limits are intended to simplify the logistics and the maintenance that is associated with Saudi Aramco heat exchangers. The preferred maximum bundle size is 1.2 m (48 in.), and the preferred maximum tube length is 6.1 m (240 in.).

Air-Cooled Heat Exchangers

Principal Applications

Air-cooled heat exchangers are used primarily to cool or condense a process stream to a temperature that is slightly higher than the ambient air temperature. In general, air-cooled exchangers are selected for locations where water is not economically available in the quantity or quality that is required to support a water-cooled shell-and-tube heat exchanger.

Air-cooled exchangers operate efficiently when the condensing temperature and/or outlet temperature of the process fluid is at least 10°C (18°F) above the maximum dry-bulb temperature of the ambient air. Compared to water, air has only about one-fourth the heat capacity per kilogram (or pound) mass; therefore, if the temperature differential between the process fluid and the ambient air is too small, a very large cooling fin surface area is required to cool the process fluid to the desired temperature. Because the cost of an air-cooled heat exchanger is highly dependent on the size of the cooling surface area, an air-cooled heat exchanger can be prohibitively expensive when the outlet process fluid/air temperature differential is less than 10°C (18°F). The 10°C (18°F) cutoff differential above the dry-bulb temperature can be reduced to 10°C (18°F) above the wet-bulb temperature through the use of a humidified air-cooled exchanger.

Because the maximum dry-bulb air temperature varies geographically, different design conditions are required for the various Saudi Aramco plant locations. SAES-A-012 provides the design dry-bulb temperatures for all Saudi Aramco plant locations and the design factors that apply to different types of air-cooled exchangers and services.

Size Limitations

The size of air-cooled heat exchangers is normally limited to the maximum size that can be transported and erected conveniently. Saudi Aramco has published a table of preferred exchanger sizes in 32-SAMSS-011, which is intended to simplify the logistics and the maintenance that is associated with Saudi Aramco heat exchangers. The maximum tube length is 12.2 m (40 ft.), unless otherwise approved.

Heat Exchanger Applications and Limitations Summary

Figure 25 summarizes some of the applications for which various exchanger designs are best suited, and some of the principal limitations of each type.

The choice between an air-cooled or a shell-and-tube heat exchanger is usually based on economic considerations. Both the initial investment in the exchanger installation and the long-term cost of its operation must be considered in order to decide whether to install an air-cooled or a shell-and-tube heat exchanger.

TYPE DESIGNATION	PRINCIPAL APPLICATIONS	PRINCIPAL LIMITATIONS
Floating Head or Tubesheet (Removable and nonremovable bundles)	High temperature differential between tube and shell. Multipass tubeside units. Dirty fluids require that the shellside and tubeside be cleaned.	Internal gaskets create danger of leaks. Corrosiveness of fluids on shellside parts that float. Usually confined to horizontal units.
U-Tube	High temperature differentials that can require provision for expansion in fixed-tube units. Clean service on tubeside. Multipass tubeside.	Bends must be carefully made, or mechanical damage and danger of rupture can result. Very high tubeside velocities can cause erosion of bends. Fluid should be free of suspended particles.
Fixed Tubesheet	Condensers; liquid-liquid; gas-gas; gas-liquid; cooling and heating, horizontal or vertical, reboiling. Single pass tubeside.	Tube-to-shell temperature difference over 27°C (50°F) usually requires an expansion joint in the shell.
Kettle	Boiling of process fluid on shell side that is to be vaporized.	Limited to horizontal installation. Physically large in most applications.
Air-Cooled; plain or finned tubes	Condensing or cooling a process fluid well above ambient air temperature when cooling water is either not available or its use is not cost effective due to the use of expensive ally materials.	Low heat transfer coefficient; can be improved with forced airflow across the tubes; initial cost is high.

Principal Applications and Limitations of Heat Exchangers

Figure 25

PRIMARY FACTORS AFFECTING HEAT TRANSFER DUTY

This section addresses the primary factors that affect heat transfer duty in heat exchangers, and it highlights the importance of these factors in heat exchanger design. This section does not address the fundamentals of fluid flow, thermodynamics, or heat transfer. Participants are directed to ChE 101, *Plant Engineering*, or pertinent college courses for a review of these fundamentals, as necessary.

The primary factors that affect heat transfer duty include:

- Flow arrangement
- Temperature distribution
- Heat transfer coefficient
- Effects of fouling

Flow Arrangement Factors for Shell-and-Tube Heat Exchangers

Flow arrangement factors that affect the heat transfer duty of shell-and-tube heat exchangers can be subdivided into shellside and tubeside factors.

Shellside Flow Arrangement Factors

Tube Layout - The process designer usually specifies the tube layout based on heat transfer and pressure drop considerations. The triangular layout is generally preferred for clean shellside service (i.e., where the fouling factor is low), and for applications in which the deposit can be chemically cleaned. The rotated triangular layout has a slightly lower pressure drop, but it is seldom used because the heat transfer characteristics are poor. An exchanger with a triangular layout costs less and transfers more heat per measure of tube surface area (i.e., m^2 or $ft.^2$) than a square or a rotated square layout. Figure 11 illustrates these different tube layouts.

Typically, a square or rotated square tube pattern is specified for the following cases:

- For high shellside fouling factors
- When mechanical cleaning of the outside of the tubes is required

In most cases, rotated square layouts are preferred to square layouts because of the higher heat transfer coefficient that is induced by the turbulence associated with the rotated square layout; however, for pressure-drop limited applications, the square layout is preferred to the rotated square, because the pressure drop is lower for the square layout.

Cross Baffles - The process designer usually specifies that the baffle cut or window area for flow be consistent with thermal and pressure drop considerations in the shell. Single segmental baffles usually are cut at about 25% of the shell diameter, although the maximum practical cut for tube support is approximately 48%. For double segmental baffles, the area for the central baffle and the area of the window between the two adjacent chordal baffles are both about 40% of the exchanger cross-sectional area. This percentage of baffle cut allows a baffle overlap of approximately 10% of the exchanger's cross section; however, there must be enough overlap so that at least one row of tubes is supported by adjacent baffles. Double segmental baffles typically cost more than single segmental baffles, but they result in lower pressure drop on the shell side. Figure 8 illustrates typical baffle configurations.

Baffle Pitch - If there is no phase change of the shellside fluid, the baffle pitch (i.e., the distance between baffles) usually does not exceed the shell inside diameter; otherwise, the fluid would tend to flow parallel with the tubes, which would result in poor heat transfer. With shellside condensation or vaporization, the maximum pitch is limited by TEMA to ensure adequate tube support. Minimum baffle pitch is set by TEMA requirements. The minimum allowable baffle pitch is the greater of 50 mm (2 in.) or 20% of the inside diameter of the shell. A very tight baffle pitch tends to force the shellside fluid into leakage and bypass streams, which reduces heat transfer.

Baffle pitch is specified by the process engineer, and it is usually based on thermal performance and pressure drop considerations. In general, a close baffle pitch improves heat transfer, but it increases shellside pressure drop. Care is required in the specification of baffle pitch because the baffles support the tubes, and improper spacing of the baffle can overstress tubes or cause the tubes to vibrate. In some cases, where tube vibration is a concern, the baffle pitch must be decreased to raise the tube's natural frequency.

Tubeside Flow Arrangement Factors

In general, shell-and-tube heat exchangers have more than one tube pass. Multiple tube passes are necessary to keep the tubeside fluid velocity high in order to achieve a high heat transfer rate and to reduce fouling. In exceptional cases, only one tube pass is used (e.g., if only a small differential temperature is needed, or if using vertical thermosyphon reboilers).

Flow Arrangement Factors for Air-Cooled Heat Exchangers

Air-cooled heat exchangers normally feature two or four tube passes and counter-current flow. Counter-current flow means that the direction of temperature change for the fluid is opposite to the direction of temperature change for the air; for example, if the hot fluid enters at the top of the exchanger and the cooler fluid exits at the bottom, cool air enters the exchanger at the bottom and exits hotter at the top.

Some header boxes include a pass partition plate to separate the inlet and outlet fluids. However, if the temperature difference between the inlet and outlet fluids is over 100°C (200°F), the pass partition plate is likely to distort. When the temperature difference is above the 100°C range, separate header boxes (i.e., split headers) are used to prevent pass partition plate distortion.

In condensing service, air-cooled heat exchanger tubes are usually sloped (typically 10 mm per meter; 1/8 in. per foot) to drain the condensate that collects in the tubes and in the header boxes.

Flow Arrangement Factors in Multiple Exchangers

If an excessively large surface area is required to achieve the desired heat transfer, the use of multiple exchangers, arranged in series and/or in parallel, is preferable to the use of a single, large exchanger. Multiple small exchangers are easier to inspect and maintain than are large exchangers. These inspection and maintenance considerations apply equally to both shell-and-tube and air-cooled exchanger designs. Sometimes, shells in series are necessary when the exit temperature of the hotter fluid is lower than the exit temperature of the colder fluid.

Multiple exchanger configurations can be piped in parallel or in series so that individual units may be taken out of service for maintenance or for purposes of adjusting flow or heat duty, as necessary. When one of the units in a multiple exchanger arrangement is out of service, the other units continue to operate at reduced throughput.

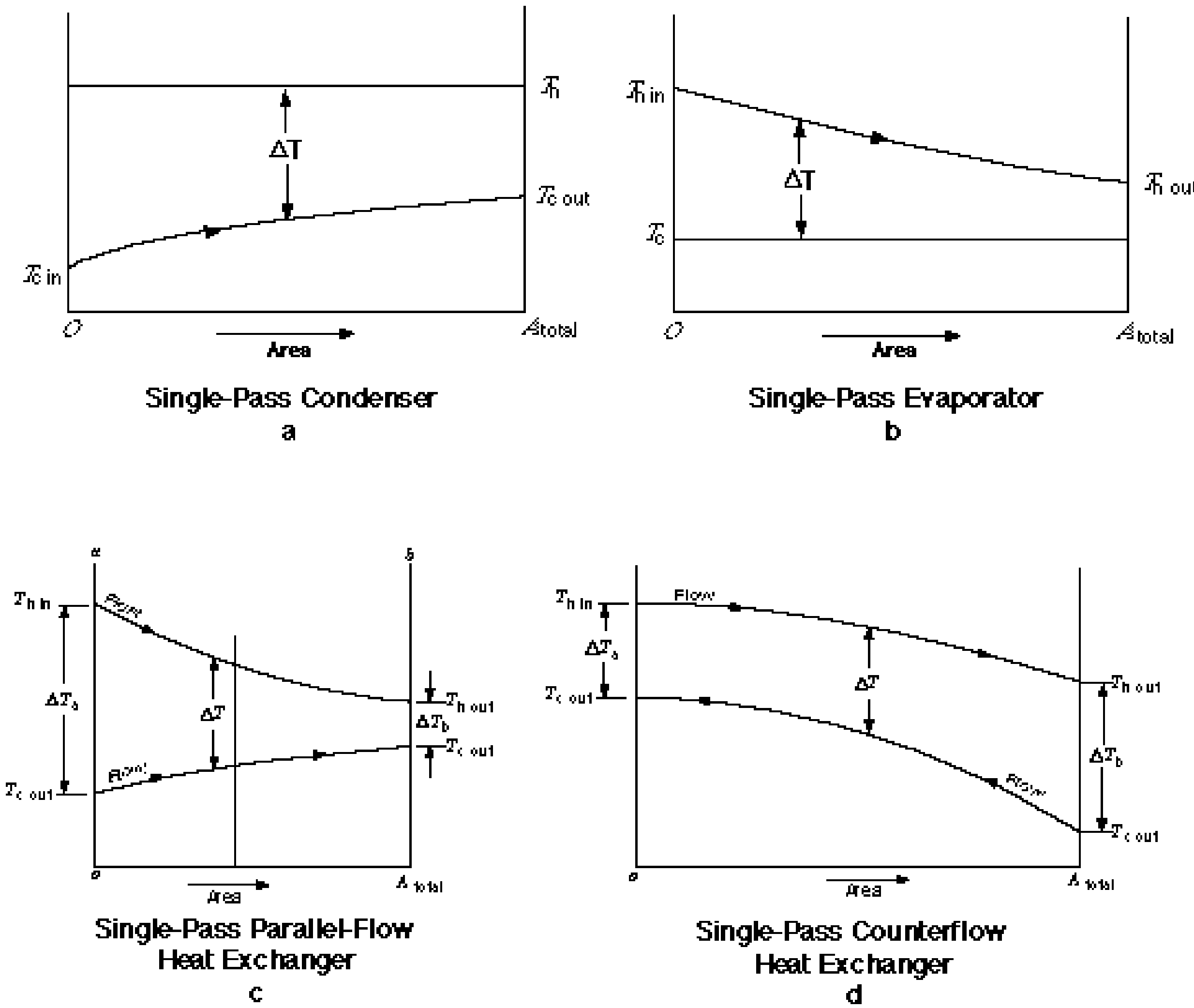
Temperature Distribution

The temperatures of fluids in a shell-and-tube heat exchanger are generally not constant; instead, they vary from point to point along the exchanger as heat flows from the hotter fluid to the colder fluid. The transfer of heat to or from a fluid changes the temperature of the fluid if there is no change in phase of the fluid.

Figure 26 illustrates the changes in temperature that may occur in either or both fluids in four types of shell-and-tube heat exchangers. The distances between the solid lines are proportional to the temperature differences, ÆT, between the two fluids.

Figure 26a illustrates the case of a vapor that condenses at a constant temperature as the other fluid is heated. Figure 26b depicts a fluid that evaporates at constant temperature while heat flows from a warmer fluid whose temperature decreases as the fluid passes through the exchanger. For both of these cases, the direction of flow of either fluid is immaterial, and the constant-temperature fluid may also be at rest.

Figure 26c depicts a parallel-flow exchanger and Figure 26d depicts a counter-flow exchanger. No phase change occurs in either case. No matter how long the exchanger of Figure 26c is constructed, the colder fluid can never reach the exit temperature of the hotter fluid in parallel flow. For counter-flow, the final temperature of the cooler fluid may exceed the outlet temperature of the hotter fluid because a favorable temperature gradient exists all along the heat exchanger. An additional advantage of the counter-flow arrangement is that, for a given rate of heat flow, less surface area is required than in a parallel flow arrangement.



Temperature Distributions in Four Types of Heat Exchanger

Figure 26

Heat Transfer Coefficients

Figure 27 is a repeat of the simplified heat exchanger model that was illustrated in Figure 23. When the fluid temperatures on the inside and outside of the tube are known, the overall amount of heat transferred, Q, can be calculated through the use of the following equation:

$$Q = UA_o \left(T_h - T_c\right) \qquad (1)$$

Where:

Q = Overall amount of heat transferred

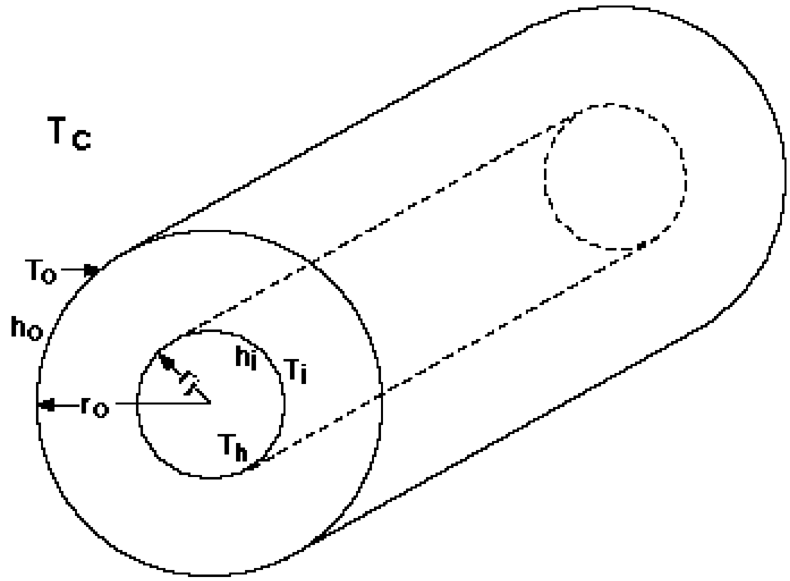
U = Overall heat transfer coefficient

A_o = Heat transfer area based on the outside area of the tube

T_h = Hot fluid temperature

T_c = Cold fluid temperature

The overall heat transfer coefficient, U, is a function of the individual inside and outside film coefficients, heat exchanger geometry, and the material thermal conductivity (usually a known function of the material temperature). The film coefficients and U are usually determined by the process engineer. Determination of these two items is outside the scope of this course.



T_h = Inside Fluid Temperature

T_c = Outside Fluid Temperature

T_i = Inside Surface Temperature

T_o = Outside Surface Temperature

h_i = Inside Convection Coefficient

h_o = Outside Convection Coefficient

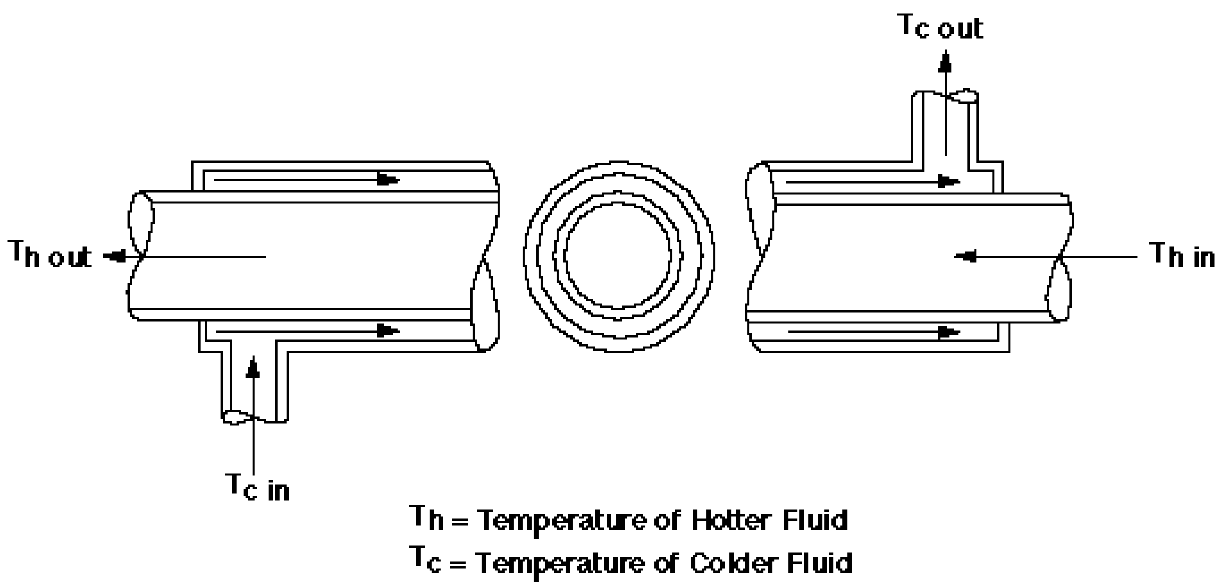
k = Thermal Conductivity of the Tube Material

Simplified Heat Exchanger Model

Figure 27

The heat flow calculation in an actual heat exchanger is more complicated than the simplified heat flow model that was illustrated previously. In a typical heat exchanger, the temperature of the fluid sometimes varies from the inlet to the outlet of the exchanger. The temperature variation is illustrated in the double-pipe heat exchanger of Figure 28, which represents the more realistic case of two-dimensional heat flow.

In Figure 28, hot fluid enters the inner tube on the right, and cold fluid enters the outer tube on the left. As the two fluids flow through the exchanger, the hot fluid warms the cold fluid and becomes cooler while the cold fluid becomes warmer. These changes in the fluid temperatures produce a variable temperature difference between the inner and outer fluids. This temperature difference varies with the position along the length of the exchanger. The value of the (T_h -T_c) term in Equation 1 varies with the length. As a result, an effective temperature differential that takes into account the variation in temperature along the length of the exchanger tube must be determined. The convection heat transfer coefficient, h, also depends on temperature, which causes h_i and h_o to vary with the position along the exchanger length. This variation of h complicates the determination of U and makes it necessary to employ averaging techniques to calculate heat flow in actual heat exchangers.



Two-Dimensional Heat Flow Model

Figure 28

Averaging techniques consider the temperature gradients of an actual exchanger to determine a corrected mean temperature difference, $Æt_m$. Some of the items that are considered in the averaging process include the exchanger geometry, the direction of flow, fluid properties, and flow velocity. These averaging techniques are discussed in the Section 7, *Thermal Relations*, of the TEMA Standard. The required calculations, which are usually made by the process engineer, are not covered in this course; however, these calculations are made after a corrected mean temperature differential, $Æt_m$, and an overall heat transfer coefficient, U, have been found through the use of averaging techniques. Equation 1 can be used to calculate heat transfer, Q.

Effects of Fouling

The performance of heat exchangers under service conditions, especially in the process industry, cannot be predicted from a theoretical analysis alone. With most liquids and some gasses, a dirt film gradually builds up on the heat-transfer surface during operation. This deposit may be rust, boiler scale, silt, coke, or any number of other substances.

The effect of these deposits, which are referred to as fouling, is to increase the thermal resistance. The manufacturer usually cannot predict the nature of the dirt deposit nor the rate of fouling; therefore, only the performance of clean exchangers can be guaranteed. In general, the thermal resistance of the deposit can be obtained only from actual tests or from experience. If performance tests are made on a clean exchanger and repeated after the unit has been in service for some time, the thermal resistance of the deposit (i.e., the fouling factor) can be determined from the relation:

$$R_f = \frac{1}{U_f} - \frac{1}{U} \qquad (2)$$

Where:

U = Overall heat transfer coefficient of clean exchanger

U_f = Overall heat transfer coefficient after fouling has occurred

R_f = Unit thermal resistance (i.e., fouling factor) of the scale

Fouling factors (i.e., resistances) for various applications are provided in SAES-E-001, Table 1, and also in TEMA. The fouling resistances are applied as indicated in Equation 3**,** which gives the expression for the overall heat transfer coefficient.

$$U = \frac{1}{\left[\left(\frac{1}{h_o} + r_o\right)\left(\frac{1}{E_f}\right) + r_w + r_i\left(\frac{A_o}{A_i}\right) + \frac{1}{h_i}\left(\frac{A_o}{A_i}\right)\right]} \quad (3)$$

Where:

U	=	Overall heat transfer coefficient (fouled)
h_o	=	Film coefficient of shellside fluid
h_i	=	Film coefficient of tubeside fluid
r_o	=	Fouling resistance on outside surface of tubes
r_i	=	Fouling resistance on inside surface of tubes
r_w	=	Resistance of tube wall
A_o/A_i	=	Ratio of outside tube surface to inside tube surface
E_f	=	Fin efficiency (where applicable)

GLOSSARY

baffle, transverse baffle	One of a series of drilled or perforated plates that are slightly smaller in diameter than the shell inside diameter. Baffles, through which tubes pass, are located between the front and rear tubesheets, or between the stationary tubesheet and the return end of a U-tube bundle. The baffles direct the flow of fluid in the shell and support the tubes.
baffle cut	Expressed as a percent of the shell inside diameter, the fraction of a segmental baffle that is cut off to allow passage of the shellside fluid.
baffle pitch	Center-to-center distance between adjacent baffles or tube supports.
baffle spacing	Distance between adjacent segmental baffles. The baffle spacing is equal to the baffle pitch minus one-half of the thickness of the baffles.
bundle	(1) In a removable-bundle heat exchanger, the assembly of tubesheet(s), baffles and /or supports, tie-rods, spacers, tubes, and any other appurtenances that are not connected to the shell. (2) In a fixed tubesheet exchanger, the part of the unit that extends between the outer tubesheet faces.
cleaning lane	Space that is located between adjacent rows of tubes in removable-bundle heat exchangers and that is large enough to permit entry of cleaning devices. To form cleaning lanes, tubes are arranged on a square pitch or on a rotated square pitch.
conduction	A mode of heat transfer in which heat flows from a region of higher temperature to a region of lower temperature within a medium (solid, liquid, or gas), or between different media that are in direct physical contact.
conductivity	A measure of the ability of a material to conduct heat.

convection	A mode of heat transfer in which heat flows by means of the combined action of heat conduction, energy storage, and the mixing motion of a fluid.
doughnut and disk baffle	Baffle system in which the center is removed from a full circle and located one baffle pitch away from the remaining annulus. The center is the disk; the annulus is the doughnut.
double tubesheet	Two tubesheets at the tube ends. The outer face of the outer tubesheet is exposed only to the tubeside fluid. The inner face of the inner tubesheet is exposed only to the shellside fluid.
double-segmental baffle	Cross-flow baffle system that consists of alternate A-section and B-section segmental baffles. A-sections are opposite sectors of a circle; B-sections are sections of a circle that remain after opposite sections have been cut off.
dry bulb temperature	The temperature of air as measured by a thermometer with a dry bulb.
floating head	Floating tubesheet and its attached floating cover.
fouling factor	A numerical value that represents the resistance to heat flow that is caused by objects such as dirt, sludge, and other deposits that form on the tube surfaces while the exchanger is in service.
horizontal cut	Segments that are cut off from cross-flow baffles alternately at the top of one baffle and at the bottom of the adjacent baffle, in order to direct shellside flow up and down over the tubes.
longitudinal baffle	Shellside pass partition.
pass	(1) A group of tubes that are combined together in the tubesheet that receives the full flow from the inlet. (2) One transit of fluid through the straight tube length in a tube pass.

pitch pattern The arrangement of tubes that pierce the tubesheets, baffles, and supports. Also known as tube layout.

single-segmental baffle Cross-flow baffles.

tie-rods	Round bars that pierce the cross-flow baffles or tube supports. Tie-rods are attached to the stationary tubesheet at one end and to the last baffle or tube support at the other end.
tube bundle	See "bundle."
tubesheet	A plate into which a heat exchanger tube is connected at its end.
vertical cut	Segments that are cut off from cross-flow baffles alternately to the left of one baffle and to the right of the adjacent baffle in order to direct shellside flow side-to-side over the tubes.
wet-bulb temperature	The temperature of air as measured with a wet-bulb thermometer. A wet-bulb thermometer has a bulb that is covered by a cotton wick that is saturated with water.