

Heat Exchangers

Heat exchangers are used to transfer heat between two sources. The exchange can take place between a process stream and a utility stream (cold water, pressurized steam, etc), a process stream and a power source (electric heat), or between two process streams resulting in energy integration and reduction of external heat sources. Typically, a heat exchanger is used with two process streams. However, multistream heat exchangers are sometimes used with energy extensive processes, such as LNG processing, to reduce capital cost.

The term heat exchanger applies to all equipment used to transfer heat between two streams. However, the term is commonly used to equipment in which two process streams exchange heat with each other. In the other hand, the term heater or cooler is used when the exchange occurs between a process stream and a plant service stream. Other terms used to describe heating equipment include: vaporizer and reboiler (for vaporization) and evaporator (for stream concentration). Exchangers can also be classified as fired (heat source is fuel combustion) and unfired exchangers.

There are many types of heat exchangers applied in the process industry. These types include:

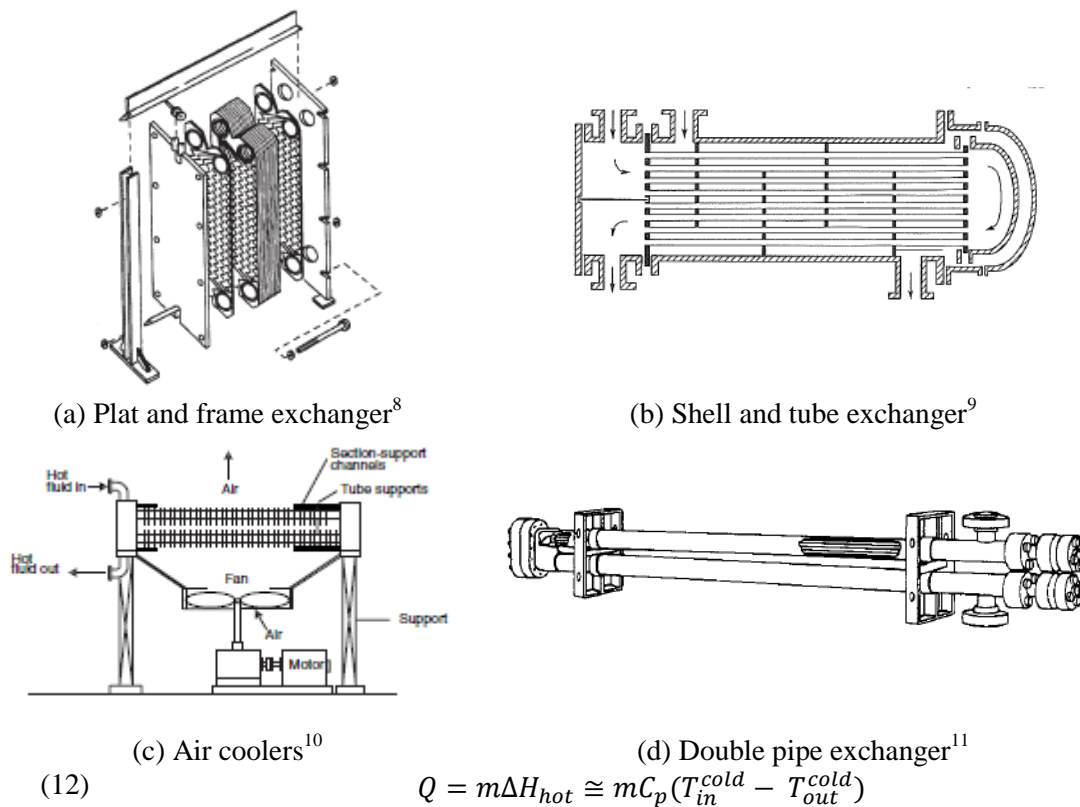
1. Hairpin/Double pipe exchangers
2. Shell and tube exchangers
3. Plate and frame exchangers
4. Plate-fin exchangers
5. Spiral heat exchangers
6. Air coolers and condensers
7. Direct contact (quenching towers)
8. Fired heaters

The selection of a heat exchanger depends on many factors including capital and operating costs, fouling, corrosion tendency, pressure drop, temperature ranges, and safety issues (tolerance to leakage). Different types of heat exchangers are shown in Figure 42.

In process calculations, the main objectives of heat exchanger calculations are to determine the heat duty (amount of energy to be transferred), temperature changes within the exchanger, and pressure drops. Depending on the degree of details available/needed, the calculations might be simple or thorough.

For an exchanger with a hot stream and a cold stream, the heat requirements are calculated as:

$$(11) \quad Q = m\Delta H_{hot} \cong mC_p(T_{in}^{hot} - T_{out}^{hot})$$



(12)

$$Q = m\Delta H_{hot} \cong mC_p(T_{in}^{cold} - T_{out}^{cold})$$

Figure 42. Different types of heat exchangers

In addition, the overall heat transfer equation for the exchanger must be solved simultaneously:

$$(13) \quad Q = UA\Delta T_{LM}$$

with U being the overall heat transfer coefficient, A the heat transfer area, and ΔT_{LM} is the log-mean temperature difference. Equation (13)(13) is used when simple counter or co-current flows exist. If the flow pattern is more complex (such as the case with most shell and tube heat exchangers), then a correction factor (F) term is used and the equation becomes:

$$(14) \quad Q = UAF\Delta T_{LM}$$

Depending on the complexity of the chosen model, the information needed in Equation (14) may vary from rough estimation to calculation based on the exchanger geometry.

⁸ R. K. Sinnott, John Metcalfe Coulson, and John Francis Richardson, *Coulson & Richardson's Chemical engineering Design*, vol. 6, 4th ed. (Butterworth-Heinemann, 2005).

⁹ Warren McCabe, Julian Smith, and Peter Harriott, *Unit Operations of Chemical Engineering (7th edition)*, 7th ed. (McGraw-Hill Science/Engineering/Math, 2004).

¹⁰ Ernst Schlünder et al., eds., *Heat Exchanger Design Handbook* (Washington: Hemisphere Publishing Corporation, 1983).

¹¹ Don Green and Robert Perry, *Perry's Chemical Engineers' Handbook, Eighth Edition*, 8th ed. (McGraw-Hill Professional, 2007).

The overall heat transfer coefficient represents the ease with which heat is transferred from one medium to another. For example, when heat is being transferred from a hot fluid inside a tube to a cold fluid outside of the tube (as shown in Figure 2), the

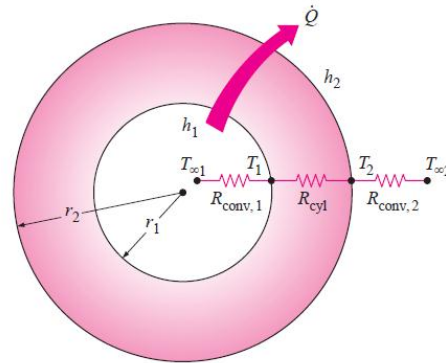


Figure 43. Heat transfer through tube.¹²

overall heat transfer coefficient is:

$$(15) \quad U = \left(\frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} \right)$$

with R_i being the resistance to heat transfer through each interface (hot fluid-inner tube wall, inner tube wall-outer tube wall, and outer tube wall-cold fluid). The resistance calculation depends on the phase from which heat is being transferred. For example, for R_1 (transfer at fluid-solid interface) the resistance is given by:

$$(16) \quad R = \frac{1}{(2\pi r L)h}$$

and for R_2 (transfer through solid media), the resistance is given by:

$$(17) \quad R = \frac{\ln(r_2/r_1)}{2\pi Lk}$$

All symbols here take their usual definition. As you can see from Equations (15) to (17), calculating U requires knowledge of the geometry, materials properties, and flow conditions. Geometry is also needed to calculate the heat transfer area (A). Material and flow information are needed to calculate the heat transfer coefficients (h and k). For example, the heat transfer coefficient h in the fluid can be calculated from general correlations according to fluid flow pattern and phases present. For example, for turbulent flow the heat transfer coefficient can be calculated using the general correlation:

$$(18) \quad Nu = \frac{hD}{k} = CRe^a Pr^b \left(\frac{\mu}{\mu_w} \right)^c$$

¹² Yunus A. Çengel, *Heat Transfer: A Practical Approach*, 2nd ed. (McGraw-Hill, 2002).

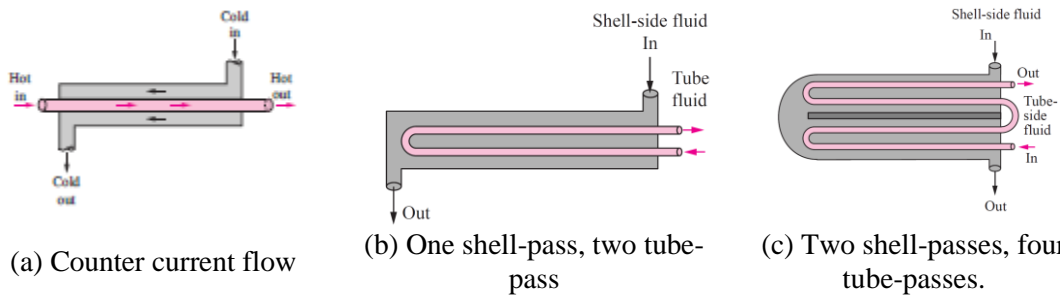


Figure 44. Different heat exchangers flow patterns.

Here Re is the Reynolds number (vD/ν) and Pr is the Prandtl number ($c_p\mu/k$). The parameters C , a , b , and c are constants and depend on the flow.

In addition to affecting flow, the geometry of the exchanger is necessary to calculate the heat transfer area. The area is calculated based on specifications of the dimensions of process streams contact area. For example, in a shell and tube exchanger, the pipe diameter and length are used for this purpose.

The correction factor is used in conjunction with the LMTD to account for the deviation from the ideal counter-current flow pattern. For example, shell and tube exchangers where the tubes make more than one pass or when two or more shells are used, as shown in Figure 44. Notice that in Figure 44(b) and (c), part of the flow resembles co-current flow rather than counter current. This flow pattern will cause a reduction in the driving force between the streams reducing the amount of heat that can be transferred. The LMTD represents the driving force between process streams and is given by:

$$(19) \quad \Delta T_{LM} = \frac{\Delta T_1 - \Delta T_2}{\ln\left(\frac{\Delta T_1}{\Delta T_2}\right)}$$

where ΔT_1 and ΔT_2 are the temperature differences between the two fluids at the two ends (inlet and outlet). The use of the LMTD represents an averaging of the driving force since the temperature difference between the two streams changes as it flows through the exchanger, as shown in Figure 45. The ΔT terms in Equation (19) represents the differences at the two ends of the plots in Figure 45. In the counter current flow, the driving force is almost constant; while in the counter current decreases as the fluids exchange heat. It is important to remember that it is not feasible for the two curves to cross or reach a pinch point. If the curves cross this means that heat transfer will switch direction which is physically impossible (the best that can happen is for both streams to reach the same temperature).

The LMTD can be problematic in cases where $\Delta T_1 = \Delta T_2$ or when either of the temperature differences is zero. While such cases are physically feasible, numerical calculations of Equation (19) are not possible. In such cases, other averaging techniques can be applied. For example, the arithmetic mean ΔT is given by:

$$(20) \quad \Delta T_{AM} = \frac{\Delta T_1 + \Delta T_2}{2}$$

can give good approximation of ΔT_{LM} when the ΔT ratios are closer to 1 but deviates largely as the ratio departs from 1.

As mentioned earlier, the correction factor is used to correct the LMTD from the ideal counter current flow. The magnitude of the correction depends on the temperature differences and the flow pattern. Two ratios are used to represent the temperature difference effect as follows:

$$(21) \quad P = \frac{T_2^t - T_1^t}{T_1^s - T_1^t}$$

and:

$$(22) \quad R = \frac{T_1^s - T_2^s}{T_2^t - T_1^t} = \frac{(\dot{m}C_p)_{tube}}{(\dot{m}C_p)_{shell}}$$

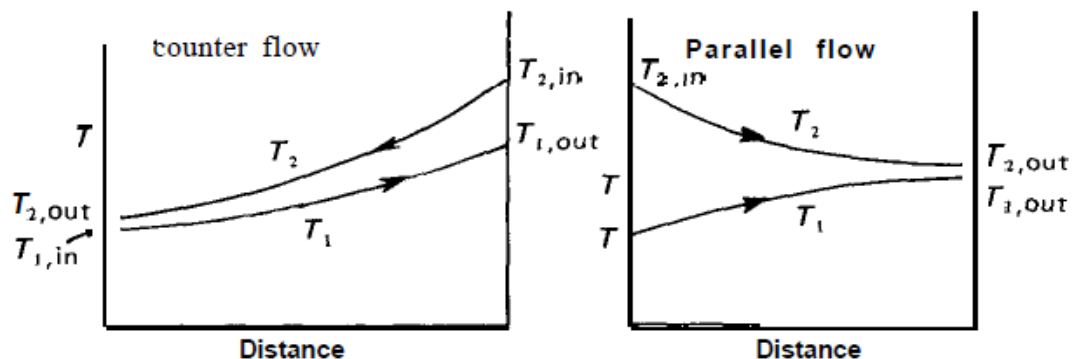


Figure 45. Temperature distribution inside counter and co-current (parallel) flow exchangers

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¹³ Schlünder et al., *Heat Exchanger Design Handbook*.

Calculations of the correction factors is then obtained from charts similar to that in Figure 46 for each the different flow patterns. Notice that the correction factor has a limiting value of one which occurs at low R and P values.

Pressure Drop Calculations

As the fluid passes through the exchanger its pressure will drop. Pressure drop in the

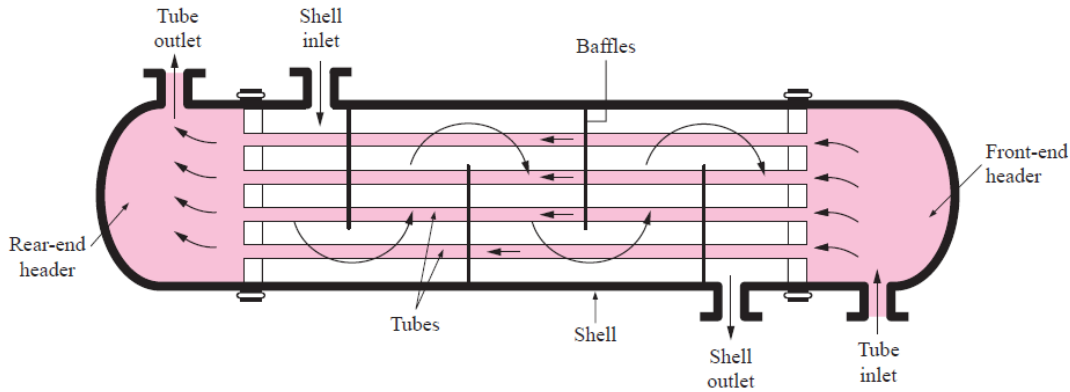


Figure 47. Main parts of the shell and tube heat exchanger.¹⁵

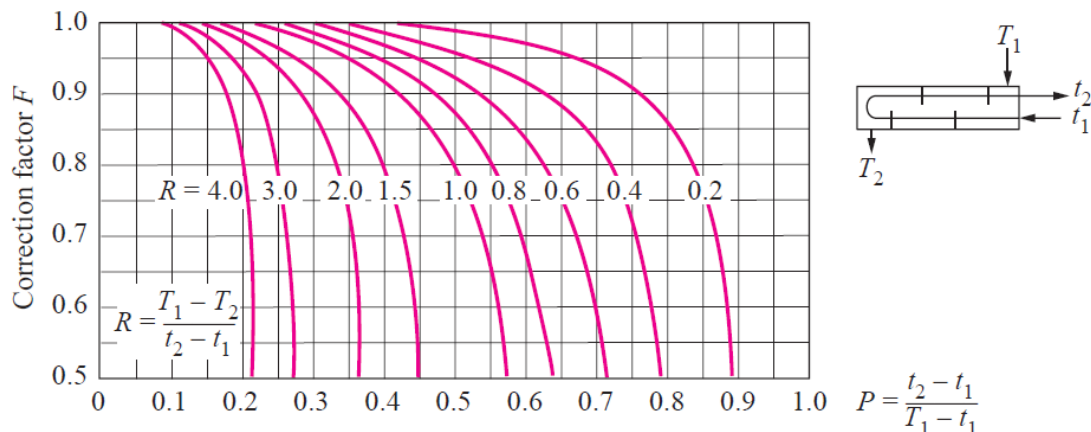


Figure 46. Correction factor chart for one-shell and multiple tube passes exchanger.¹⁴

tube side of heat exchangers can be calculated using correlations for pipeline pressure drop. Correlations such as Beggs-Brill can be used for this purpose. In addition, the pressure drop can be related directly to the flow rate through a flow rate dependent correlation. In the first case, information is needed on the geometry of the exchanger in order to calculate the flow regime and friction factors. The flow rate correlations do not require information about the geometry but lumps the heat exchanger effect on pressure in one parameter as follows:

$$(23) \quad \Delta P = \frac{K(\text{Mass flow})^2}{\text{density}} = kW^2 \frac{\left(\frac{1}{\rho_{in}} + \frac{1}{\rho_{out}}\right)}{2}$$

¹⁴ Çengel, *Heat Transfer*.

Shell & Tube Exchangers

The most commonly used unfired heat exchangers in the chemical-process plants are the shell and tube exchangers. These exchangers are made of a shell housing smaller tubes. One fluid is made to pass through the tubes (tube side) and the other is passed through the shell (shell side).

As shown in Figure 47, the shell and tube heat exchanger consists of the shell, which is a large vessel with one or more inlet and one or more outlet nozzles. Inside the shell, baffles are typically installed which help in holding the tubes and directing the shell fluid flow to some extent. The locations of the nozzles and the orientation of the baffles largely affect the flow pattern of the shell side. The shell fluid can be passed through the shell only once (single pass) or it can be passed multiple times (multi-pass).

Inside the shell, large number of tubes (sometimes several hundred) is placed. Again, the tubes may pass through the shell only once (single pass) or multiple times (multi-pass). The diameter (inside and outside) and length of the tubes determine the overall heat transfer area. The pattern (the way the tubes are arranged, see Figure 48) and the pitch (the center-to-center distance between the tubes) determine the number of heat tubes that can fit in the shell and affects the pressure drop. The tubes can be finned to increase the heat transfer area, but this will require a larger pitch, thus reducing the number of tubes. Fins are characterized by their height (or diameter), numbers, and efficiency (ability of the fin to transfer the heat).

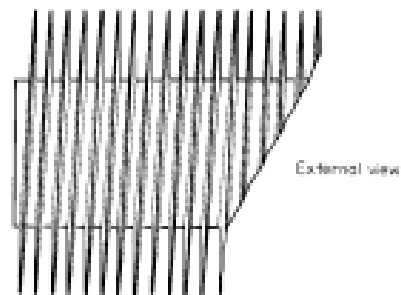


Figure 49. Finned tube.¹⁶

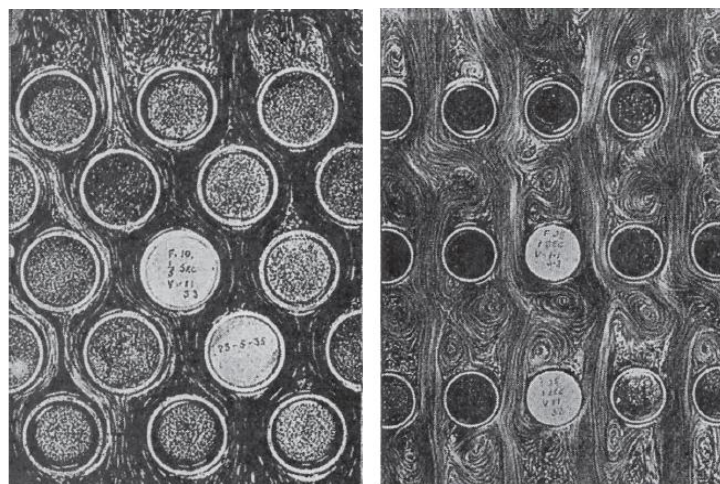


Figure 48. Triangular (left) and square (right) pitch.

¹⁵ Ibid.

¹⁶ Green and Perry, *Perry's Chemical Engineers' Handbook, Eighth Edition*.

Another part of shell and tube exchangers that affect its performance is the baffles. These are metal sheets used inside the shell for purposes of heat transfer (if heat transfer considerations are not important, baffles are replaced with tube supports to hold the tubes). A number of baffle configurations are available; some are shown in Figure 51. Important parameters for baffle design are its cut (percentage of shell diameter not covered by baffle), baffle spacing, and clearances left between the baffle and shell, and between the baffle and the tubes.

Finally, many of the features and designations of shell and tube exchangers have been standardized by the Tubular Exchanger Manufacturers Association (TEMA). This organization has put standard codes for the configurations of heat exchangers as shown in Figure 51 and as described in Perry's Handbook (section 11). The standards cover codes for front end, shell, and rear ends of the exchangers. These codes can be used to designating exchangers. For example, a fixed-tube sheet exchanger having stationary and rear heads integral with tube sheets, single-pass shell, 432 mm (17 in) inside diameter with tubes 4.9 m (16 ft) long. SIZE 17–192 TYPE CEN. Here, the 17 is the shell inside diameter, the 192 is the tube length in inches, and the CEN refers to the front, shell, and rear types from Figure 51. TEMA also provides standard

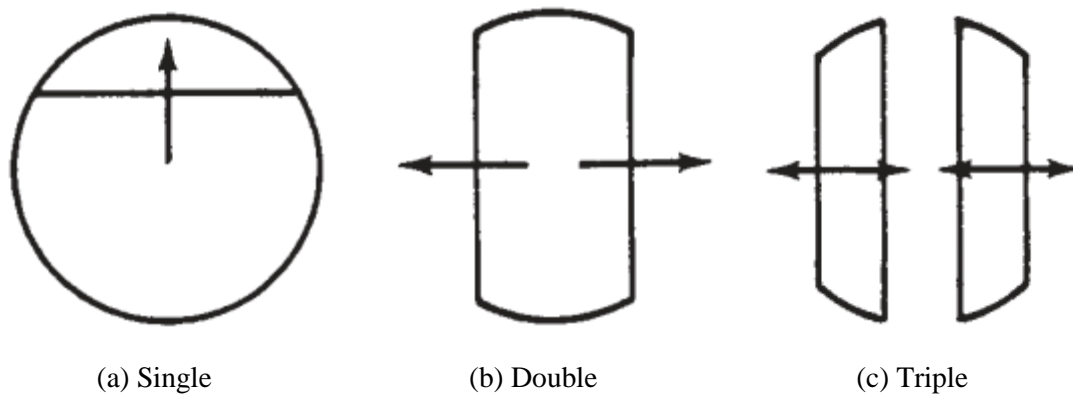


Figure 50. Different baffle configurations.¹⁷

specification sheets for the different types of heat exchangers. TEMA sheets are used by many process engineers to identify their exchangers and to communicate with heat exchanger manufacturers. A typical shell and tube exchanger TEMA sheet is shown in Figure 52.

Heat Exchangers in Aspen Plus

Under the heat exchangers library in Aspen Plus, there are four modules: the heater, heat exchanger, multistream exchanger, and heat flux. The first three modules correspond to the heat exchanger functionalities mentioned in page 66. The heat flux module is used to perform heat transfer calculations based on the use input. It does not have flowsheet connectivity, and used as a standalone module.

The Heater Block

¹⁷ Ibid.

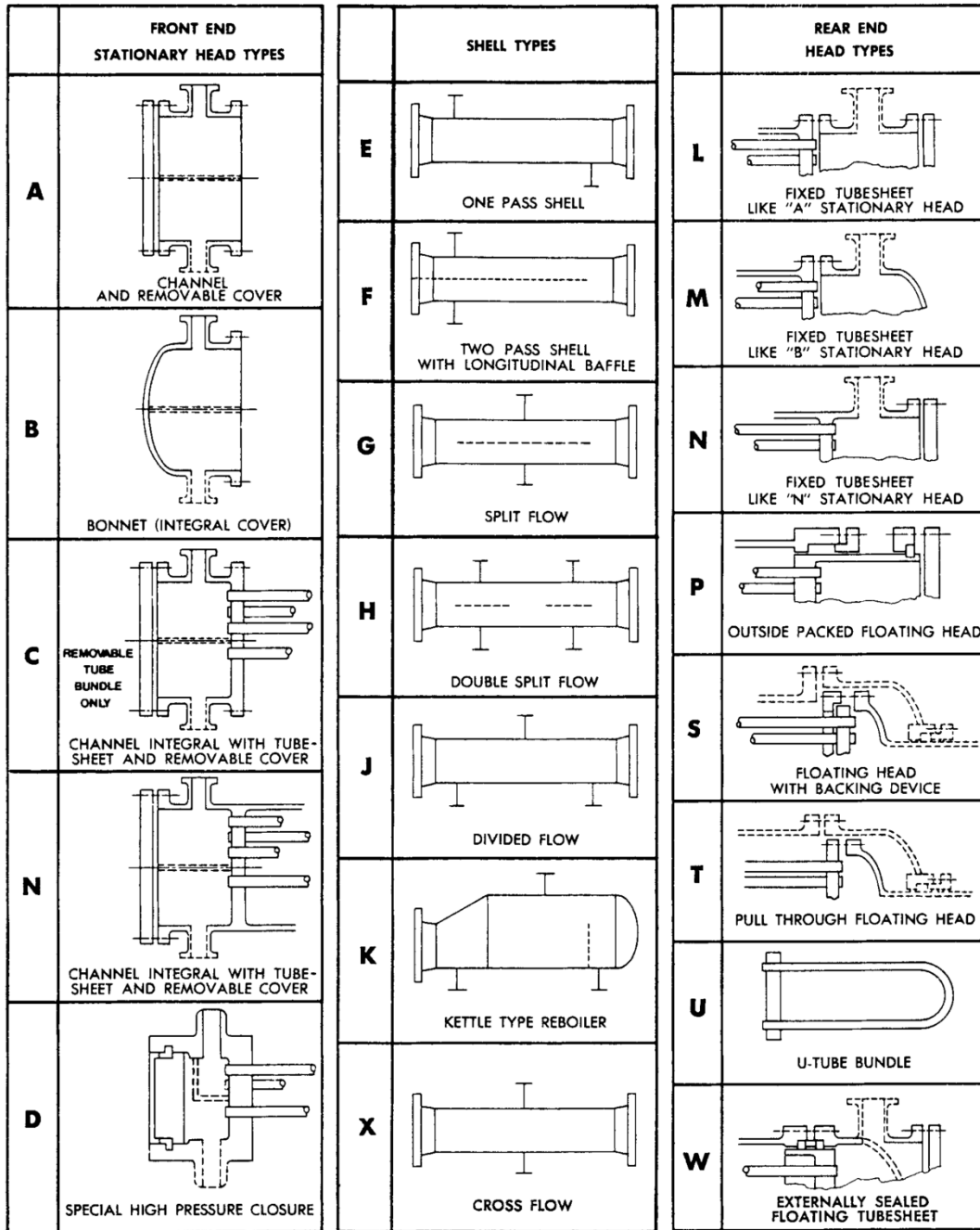
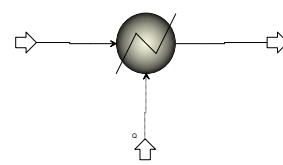


Figure 51. Shell and tube heat exchanger TEMA designs.¹⁸

The heater block is used for simple temperature or phase change applications where details of the heat transfer calculations are not important. The block can also be used as a pressure changer when the pressure drop is known. The heater block takes one or more inlet and one outlet material streams (plus optional water decant stream). It also takes an (optional) heat input and heat output streams.

¹⁸ Ibid.



Heat Exchanger Specification Sheet

1	Company: Jordan University of Science & Technology										
2	Location: Irbid, Jordan										
3	Service of Unit:					Our Reference:					
4	Item No.:					Your Reference:					
5	Date:	20/3/2011	Rev No.:	1	Job No.	P1-43					
6	Size	35	/	288	in	Type	AEL	Hor	Connected in	1 parallel 2 series	
7	Surf/unit(eff.)	10109.7	ft2	Shells/unit	2	Surf/shell (eff.)	5054.8	ft2			
8	PERFORMANCE OF ONE UNIT										
9	Fluid allocation			Shell Side				Tube Side			
10	Fluid name										
11	Fluid quantity, Total			899984				824984			
12	Vapor (In/Out)			0				0			
13	Liquid			899984				824984			
14	Noncondensable			0				0			
15											
16	Temperature (In/Out)			105				95			
17	Dew / Bubble point										
18	Density (Vap / Liq)			/ 62.075				/ 62.18			
19	Viscosity			/ 0.6468				/ 0.72			
20	Molecular wt, Vap										
21	Molecular wt, NC										
22	Specific heat			/ 1.0002				/ 1.001			
23	Thermal conductivity			/ 0.359				/ 0.354			
24	Latent heat										
25	Pressure (abs)			54.7				46.7			
26	Velocity			4.19				3.69			
27	Pressure drop, allow /calc.			8				8.79			
28	Fouling resist. (min)			0.001				0.002			
29	Heat exchanged			9E+06				MTD corrected			
30	Transfer rate, Service			154.1				Dirty			
31								165.13 Clean			
32								404.9			
33								BTU/(h*ft2F)			
34	CONSTRUCTION OF ONE SHELL										
35				Shell Side				Tube Side			
36	Design/vac/test pressure:			72.52 / /				130.5 / /			
37	Design temperature			F 176				167			
38	Number passes per shell			1				2			
39	Corrosion allowance			in 0.125				0.125			
40	Connections			In 1 10 / -				1 10 / -			
41	Size/rating			Out 1 10 / -				1 10 / -			
42	ID			Intermediate 1 10 / -				1 10 / -			
43	Tube No.			1088							
44	Tube type			Plain							
45	Shell			Carbon Steel				Material			
46	Channel or bonnet			Carbon Steel				Carbon Steel			
47	Tubesheet-stationary			Carbon Steel				Channel cover			
48	Floating head cover			-				Carbon Steel			
49	Baffle-crossing			Carbon Steel				Type			
50	Baffle-long			-				Double segm			
51	Supports-tube			-				Cut(%d) 19 H			
52	Bypass seal			-				Spacing: c/c 17.5			
53	Expansion joint			-				Seal type			
54	RhoV2-Inlet nozzle			3385				Inlet 19.4715			
55	Gaskets - Shell side			Flat Metal Jacket Fibe				Type			
56	Gaskets - Tube side			Flat Metal Jacket Fibe				Type			
57	Floating head			-				Exp.			
58	Code requirements			ASME Code Sec V/III Div 1				Tema class			
59	Weight/Shell			25996.6				R - refinery service			
60	Remarks			Filled with w ater				35378.6			
61								Bundle 17260.3			
62								lb			

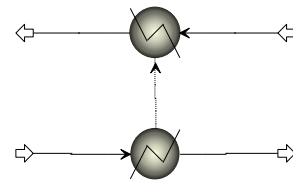


Figure 52. TEMA sheet of shell and tube exchanger.

The degrees of freedom for the heating block is 2 ($2C + 5$ variables minus $C + 2$ specified inlet conditions, minus C material balances, minus 1 energy balance). Therefore, we need two specifications for the heater block. These can be either the outlet temperature (or temperature change), outlet pressure (or pressure change), heat duty, or vapor fraction. These specifications are made in the Heater **Input | Specifications** sheet shown in Figure 53.

When vapor fraction is used, the value given indicates any point between the bubble and dew points. Thus, while a vapor fraction of 0 means a liquid with any degree of subcooling for any results stream, here it means *saturated* liquid. Similarly for a vapor fraction of 1 which indicates a saturated vapor.

Heat streams can be connected to the heater as an input or output. For input heat streams, the heat duty of that stream must be specified, and this will reduce the degrees of freedom by 1. For output heat streams, the heat extracted from the process stream is represented as heat flow through the heat stream. One advantage of using heat streams is that we can exchange heat between two process streams without using a heat exchanger block. To do so, just connect a heat stream between two heaters as shown.



When calculations are performed, the heat calculates the

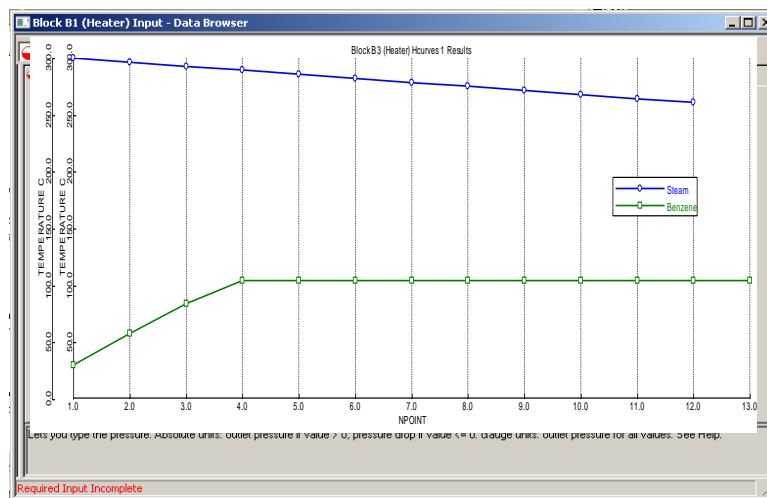


Figure 53. Heater specifications sheet.

outlet stream conditions and the heat duty balance. In addition, utilities can be specified and calculated from the **Input | Utility** tab, and the results will be calculated based on the user input. Heat curves, which are curves representing the change in temperature versus heat duty, can also be calculated. You can define heat curves under the **Hcurves** folder. Once you add a heat curve and run the simulation, the change in temperature, pressure, and vapor fraction versus heat duty will be presented in tabular format. These results can then be plotted using the **Plot** menu.

Consider a process in which 100 kg/min benzene is heated from 30 °C and 2 bar to its dew point using high pressure steam at 300 °C and 10 bar. This process can be specified using either two heaters connected with a heat stream or with one heater and utility specification. In the first case, the amount of stream needed must be specified, and the outlet conditions for this stream will be calculated based on the heat duty. In the second case, the steam inlet and outlet conditions are input and the required steam is calculated based on the heat duty. In both cases the heat duty will be the same. However, when heaters are used, the steam heater specifications will be overridden if the heat duty is not enough to achieve the specifications.

The heat curves for the two streams are shown in Figure 54. Notice that the temperature gas (or ΔT) is large for this system, which suggests that a more efficient heating can be applied using cooler utility or exchange with another process stream.

The Heat Exchanger Block

The heat exchanger block is used when two process streams are to exchange heat based on Equations (11) – (14). The exchanger takes one inlet and one outlet for hot fluid stream, and one inlet and one outlet for cold fluid stream. No heat streams are

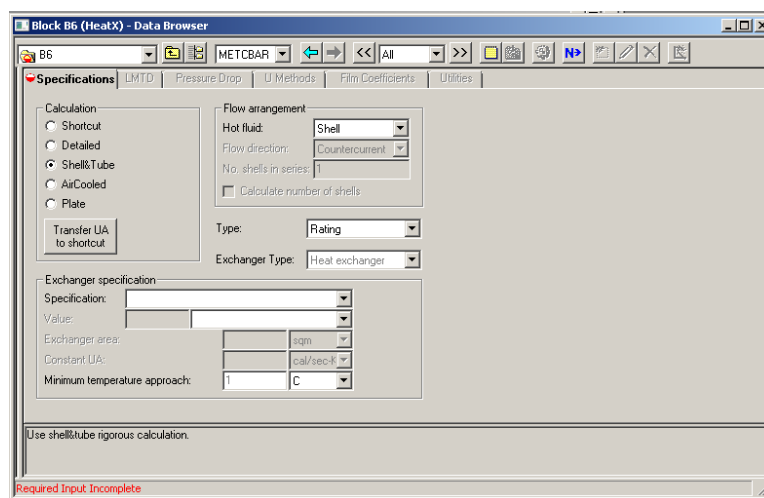
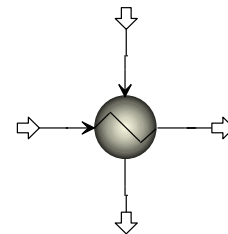


Figure 55. Heat exchanger specifications tab.

allowed with exchangers.

There are four degrees of freedom associated with adiabatic heat exchangers (assuming inlet conditions are known for the hot and cold streams). If we count the pressure drop correlations for each side (2 equations), and one heating or cooling specifications (which is the purpose of the exchanger), then we are left with one degree of freedom. This piece of information comes from that in Equation (14) through specifications of the heat exchanger geometrical factor.

There are three options to specifying heat exchangers in Aspen Plus: shortcut, detailed, and rigorous. Calculation selection can be made from the **Setup | Specifications** tab in the exchanger folder (Figure 55).

The shortcut method requires the minimum amount of information about the overall design of the exchanger. For this option, you need to input either the heat transfer area and specify how U will be calculated (constant, power law expression: $U_o q^n$, and phase specific). In the detailed calculations method, shell and tube exchangers geometry can be used to calculate variables such as the heat transfer area, U , and pressure drop. Detailed specifications of the shell, tubes, fins, baffles, and nozzles are required and can be input in the **Geometry** window of the heat exchanger. In addition to the geometry, one specification is needed and is usually specified based on temperature or phase requirements or heat duty.

Consider the previous example for benzene vaporization. In this case we will use an exchanger with the following specifications:

- Shell: type E, diameter 35 in, 1 tube pass
- Tubes: 1000 bare tubes, 24' length, pitch 0.975", 0.75" OD, thickness 0.085"
- Nozzles: 10"
- Baffles: 5 baffles, 19% cut

If you input the above information into the exchanger, we see that Aspen Plus will show results relating to the thermal performance (stream outlet conditions), exchanger details, pressure drops, in addition to other results available from the heat exchanger's **Thermal Results** and **Geometry Results** sheets. One of the important calculations for heat exchanger is the exchanger rating. By rating we mean to compare how the available heat transfer area compares to the required one. Based on this comparison, the exchanger may be under or over designed. For our example, the exchanger is highly over designed and much more area is available than needed. This will cause an unnecessary increase in the exchanger cost. Heat curves can also be calculated using the hot and cold **Hcurves** folders as in the heater block.

The third method, the rigorous design, requires the use of Aspen Exchanger Design and Rating (EDR) package. EDR gives an extended ability to design and rate several types of heat exchangers and perform mechanical analysis on the exchanger. Once the exchanger is design in EDR, the file is saving with .EDR extension.

Exercise 1: The Heater Block

Use two heater blocks with a heat stream transferring the heat between the blocks to cool the hot stream in the table below to 70 °F. The pressure drop in both sides can be neglected. Use the Wilson property method.

Component	Hot Feed (lb/hr)	Cold Feed (lb/hr)
Methanol	200	
Water	1800	
Ethylene glycol		400
Conditions		
Temperature (°F)	140 °F	40 °F
Pressure (psi)	14.6	14.6

Questions:

10. What is the outlet temperature from the cold stream?

.....

11. What is the heat duty for the exchangers, how is the sign convention for heat transfer in Aspen is defined?

.....

12. Prepare one plot containing the heat curves for the hot and cold stream.

13. What is the minimum temperature to which we can cool the hot stream?

.....

Exercise 2: Heat Exchanger

Repeat Exercise 1 using a HeatX block. Use a heat transfer coefficient of $100 \text{ Btu}/(\text{hr}\cdot\text{ft}^2\cdot^\circ\text{R})$.

Questions:

5. What is the outlet cold stream temperature in this case? How does it compare to that in Exercise 1?
.....

6. What is the required heat transfer area?
.....

7. Change the run type to Simulation and repeat the calculations using the UA value obtained in Question 2 and the given U in the U Methods form. What are the cold outlet temperature and the design rating (over/under design percentage) in this case?
.....
.....

Exercise 3: Detailed Heat Exchanger

An existing heat exchanger is to be used to cool 45,000 lb/hr of benzene at 390°F and 400 psia. The coolant is 490,000 lb/r n-dodecane at 100 °F and 200 psia. A heat exchanger with the following geometry is available:

TEMA type E: one shell pass, two tube passes

Countercurrent flow

Horizontal alignment

Hot fluid in the shell

2.75 ft inside shell diameter

0.5 in shell-to-bundle clearance

No sealing strips

U calculated from film coefficients

No fouling

200 tubes, length 32 ft, pitch 1.25 inches, square layout, carbon steel, ID 0.875 in, OD 1 in.

24 segmental baffles; baffle cut 0.2

Tubesheet-to-baffle spacing and baffle-to-baffle spacing 1.2 in.

Tubes in baffle window

Shell-side nozzles 6 in

Tube-side nozzles 8 in.

Simulate this system using the HeatX block in the simulation mode.

Questions:

5. What is the heat transfer coefficient and heat transfer area for this exchanger?

U: _____, *Area*: _____

6. What is the outlet stream temperatures?

Hot: _____, cold: _____

7. What is the pressure drop for the hot and cold sides?

Hot: _____, cold: _____

8. Repeat the calculations in the Rating mode, how is this exchanger rated for this process?
