Module III

HEAT-EXCHANGE EQUIPMENT

Course material Adapted from:

1. Warren. L, McCabe, Julian ,C. Smith and Peter Harriott, "Unit Operations of Chemical Engineering", 7th Edn., McGraw Hill International Edition, NewYork 2005.

2. Holman. J.P., "Heat Transfer" , 9th Edn., Tata McGraw Hill Book Co., New Delhi, 2008.

3. R.C.Sachdeva, "Fundamentals of Engineering Heat and Mass Transfer", 4th Edition, New Age International Publishers,2010

4. http://www.slideshare.net/vatsalpateln/new-shell-tube-heat-exchanger

5. http://www.slideshare.net/rijumoniboro/heat-exchangers-12606868

CONTENTS

Typical heat exchange equipment, counter current and parallel-current flows, enthalpy balances in: heat exchanges, total condensers. Double pipe exchanger, single-pass 1-1 exchanger, 1-2 parallel-counterflow exchanger, 2-4 exchanger, heat-transfer coefficients in shell-and-tube exchanger, coefficients for crossflow, correction of LMTD for crossflow.

Condensers: shell-and-tube condensers, kettle-type boilers,

Introduction

In industrial processes heat energy is transferred by a variety of methods, including conduction in electric resistance heaters; conduction –convection in exchangers, boilers and condensers; radiation in furnaces and radiant heat dryers; and by special methods such as dielectric heating

3.1. Types of heat exchangers

Double pipe heat exchanger, Shell and tube heat exchanger Single pass: 1-1 heat exchanger multi pass: 1-2 exchanger, 2-4 exchanger, Plate type heat exchanger, extended surface heat exchanger, Compact heat exchanger

The design and testing of practical heat exchange equipment are based on the general principles. From the material and energy balances, the required heat transfer rate is calculated. Tubular exchangers are in general designed in accordance with various standards and codes, such as the standards of the Tubular Exchanger Manufacturers Association (TEMA) and the American Society of Mechanical Engineers, ASME – API Unfired Pressure Vessel Code. Standards devised and accepted by TEMA are available covering in detail the materials, methods of construction, technique of design, and dimensions for exchangers. In designing an exchanger many decisions must be made to specify the materials of construction, tube diameter, tube length, baffle spacing, number of passes, and so forth.

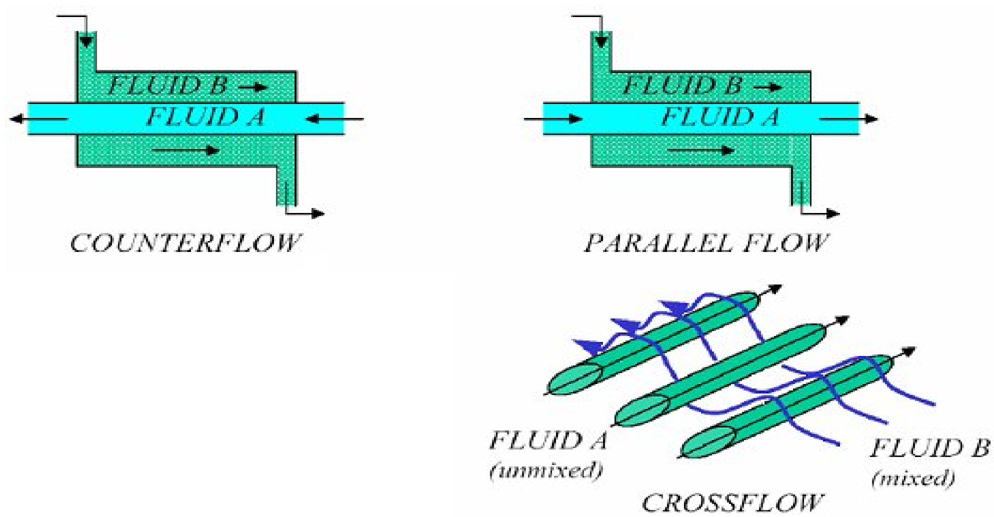
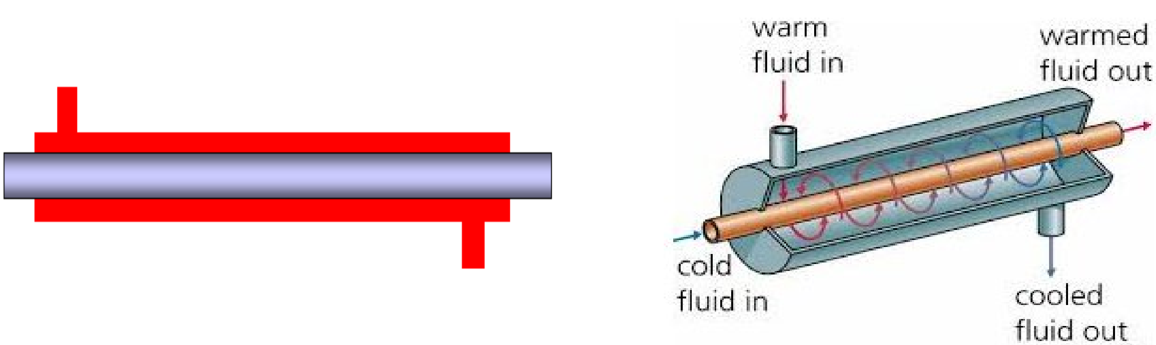


Fig.1. Flow pattern

3.2. **DOUBLE PIPE HEAT EXCHANGER**

It is the simplest type has one tube inside another. The inner tube may have longitudinal fins on the outside. The simple double pipe exchanger is inadequate for flow rates that cannot readily be handled in a few tubes.



(a) **(b)**

Fig.2. Double Pipe Heat Exchanger

3.3. SHELL AND TUBE HEAT EXCHANGERS

Tubular heat exchangers are so important and so widely used in the process industries that their design has been highly developed. Tubular exchangers are in general designed in accordance with various standards and codes, such as the standards of the Tubular Exchanger Manufacturers Association (TEMA) and the American Society of Mechanical Engineers, ASME – API Unfired Pressure Vessel Code. Standards devised and accepted by TEMA are available covering in detail the materials, methods of construction, technique of design, and dimensions for exchangers.

Single pass 1-1 exchanger:

The exchanger with one shell side pass and one tube side pass is a 1-1 exchanger. In an exchanger the shell side and tube side heat transfer coefficients are of comparable importance. The velocity and turbulence of the shell side liquid are as important as those of the tube side fluid. To promote crossflow and raise the average velocity of the shell side fluid, baffles are installed in the shell. Common practice is to cut away a segment having a height equal to one fourth the inside diameter of the shell. The baffles are perforated to receive the tubes.

Tubes and tube sheets

Tubes are arranged in a triangular or square layout known as triangular pitch or square pitch. Pitch is the distance between the centers of adjacent tubes. It should not be less than one-fifth the diameter of the shell.

Square pitch gives a lower shell side pressure drop than triangular pitch. In triangular pitch more heat transfer area can be packed into a shell of given diameter than in square pitch. Tubes in triangular pitch cannot be cleaned by running a brush between the rows. But Square pitch allows cleaning of the outside of the tubes.

Shell and Baffles

Shell diameters are standardized. The diameter is fixed in accordance with American Society for Testing and Materials (ASTM) pipe standards. The distance between the baffles is the baffle pitch or baffle spacing. It should not be less than one fifth the diameter of the shell or more than the inside diameter of the shell

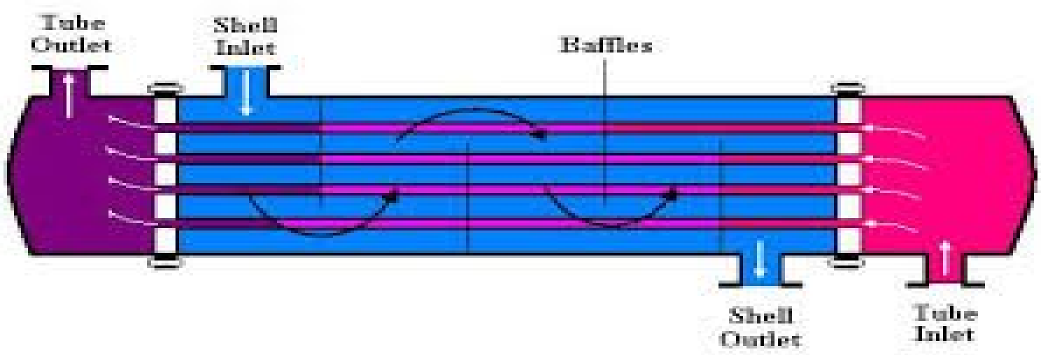


Fig.3. 1-1 Shell and tube Heat Exchanger

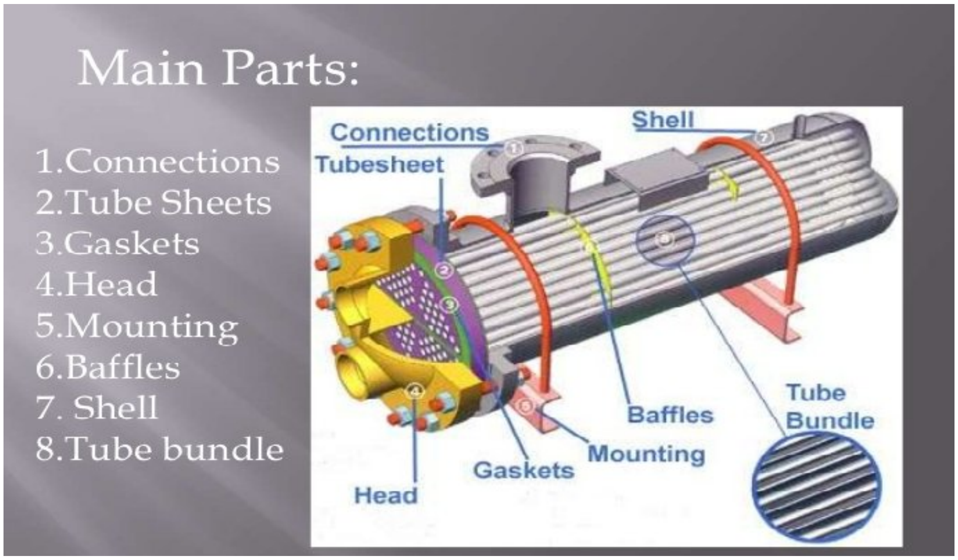


Fig.4. Main Parts of Shell and Tube Heat Exchanger

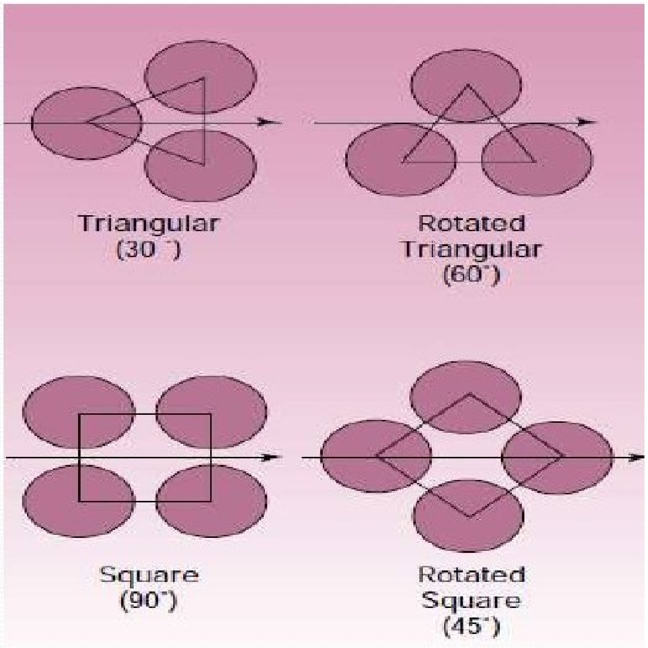


Fig.5. Tube Layout

Multipass Heat Exchangers

The 1-1 exchanger has limitations, because when the tube side flow is divided evenly among all the tubes, the velocity may be quite low, giving a low heat transfer coefficient. Using multi pass construction with two, four or more tube passes permits the use of standard length, while ensuring a high velocity and high tube side coefficient. The disadvantages are that (1) the construction of the exchanger is slightly more complicated (2) some sections in the exchanger have parallel flow, which limits the temperature approach and (3) the friction loss is greatly increased. For example, the average velocity in the tubes of a four pass exchanger is four times that in a single pass exchanger having the same number and size of tubes and operated at the same liquid flow rate. An even number of tube side passes are used in multipass exchangers. The shell side may be either single pass or multi pass.

1-2 Shell and Tube Heat Exchanger

A common construction is the 1-2 shell and tube heat exchanger in which the shell side liquid flows in single pass and the tube side liquid in two passes. The tube side liquid enters and leaves through the same head, which is divided by a baffle to separate the entering and leaving tube side streams. The 1-2 exchanger is arranged so that the cold fluid and the hot fluid enter at the same end of the exchanger, giving parallel flow in the first tube pass and counter flow in the second. This permits the closer approach at the exit end of the exchanger than if the second pass were parallel

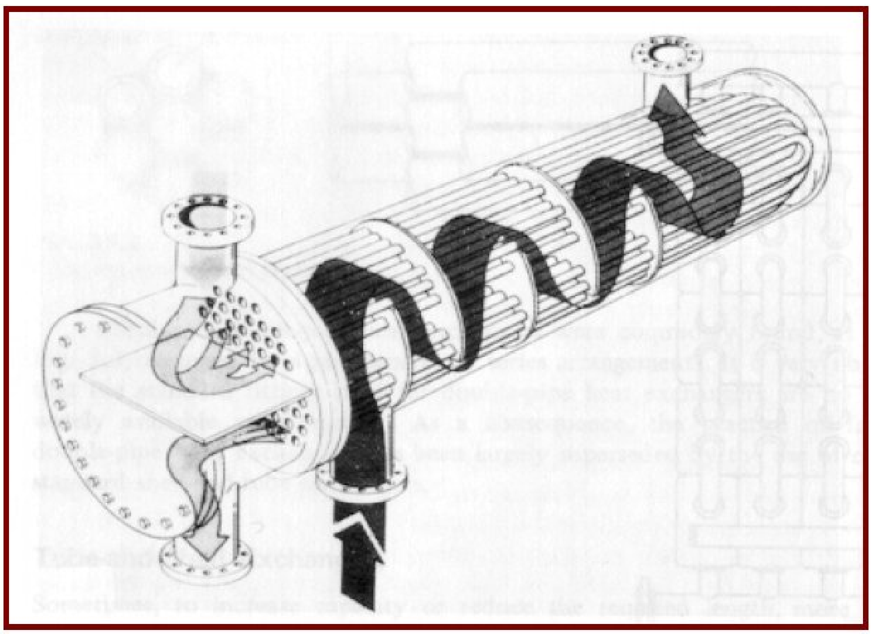


Fig.6. 1-2 Shell and Tube Heat Exchanger

2-4 Shell and Tube Heat Exchanger

The 1-2 exchanger has an important limitation. Because of the parallel flow pass, the exchanger is unable to bring the exit temperature of one fluid very near to the entrance temperature of the other. More common is 2-4 exchanger which has two shell side pass and four tube side passes. This type of exchanger also gives higher velocities and a larger overall heat transfer coefficient than 1-2 exchanger having two tube side passes and operating with the same flow rates.

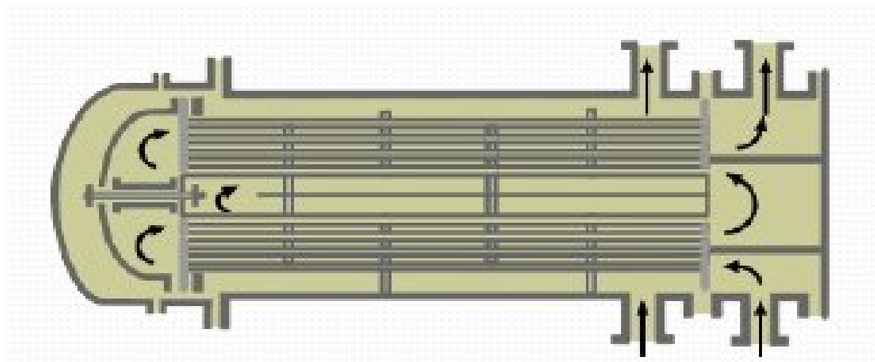
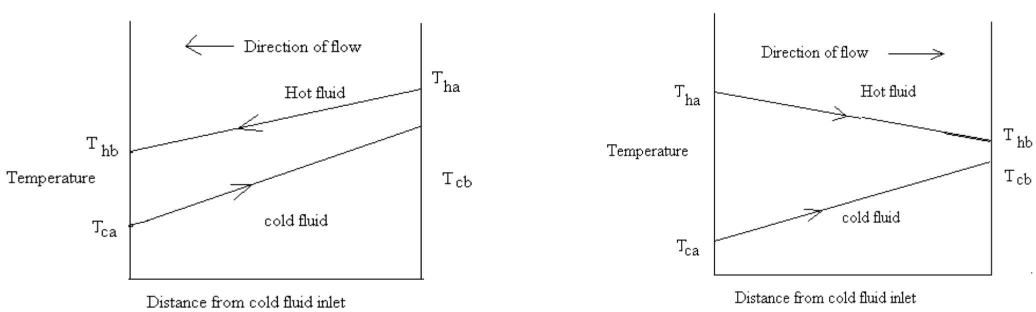


Fig.7. 2-4 Shell and Tube Heat Exchanger

Temperature patterns in heat exchanger:

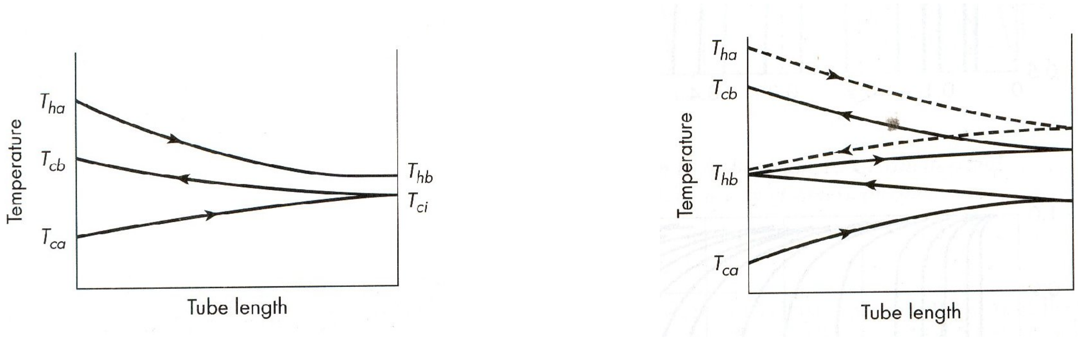
(i) Single pass Heat exchanger



(a) (b)

Fig.8. (a) Countercurrent flow (b) Parallel flow

(ii) Multipass Heat exchanger



(a) (b)

Fig.9. (a) 1-2 Shell and tube Heat exchanger (b)2-4 shell and tube heat exchanger

T_{ha}, T_{hb} – inlet and outlet temperatures of hot fluid respectively

T_{ca},T_{cb} – inlet and outlet temperatures of cold fluid respectively.

Range and approach in heat exchangers:

Range: The change in temperature of the fluid,T_{cb}-T_{ca}, T_{hb}-T_{ha}, in the heat exchangers is called the temperature range.

Approach: The point temperature differences, $T_{ha} – T_{ca}$, $T_{hb} – T_{cb}$ (or) $T_{hb} – T_{ca}$, $T_{ha} – T_{cb}$ are called the approaches.

LMTD:(Logarithmic mean temperature difference)

The local heat flux is related to the local value of ΔT by the equation

$$dQ/dA = U\,\Delta T \qquad (1)$$

where, U = overall heat transfer coefficient

To apply this equation to the entire area of a heart exchanger the equation must be integrated. This can be done formally where certain simplifying assumptions are accepted. The assumptions are that (i)overall heat transfer coefficient U is constant(ii) the specific heat of hot and cold fluid are constant (iii) heat exchange with the ambient is negligible (iv) the flow is steady and either parallel or counter current.

Assumptions (ii) and (iv) imply that if T_c and T_h are plotted against Q,as shown in figure.10, straight lines are obtained. Since T_c and T_h vary linearly with Q, ΔT does likewise and d(ΔT)/dQ, the slope of the graph of ΔT versus Q is constant. Therefore

$$\frac{d(\Delta T)}{dQ} = \frac{\Delta T_2 - \Delta T_1}{Q} \qquad (2)$$

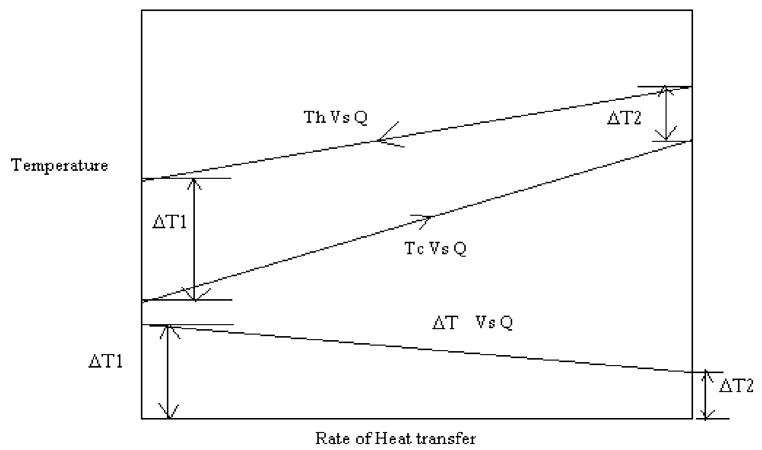


Fig.10. Temperature versus heat flow rate in counter current flow

Where ΔT_1 and ΔT_2 = approaches

Q = rate of heat transfer in entire exchanger

Elimination of dQ from equns (1) and (2) gives

$$\frac{d(\Delta T)}{U\, dA\, \Delta T} = \frac{\Delta T_2 - \Delta T_1}{Q} \qquad (3)$$

The variables ΔT and A can be separated, and if U is constant, the equation can be integrated over the limits 0 and A for A and ΔT_1 and ΔT_2 .

$$\int_{\Delta T_1}^{\Delta T_2} \frac{d(\Delta T)}{\Delta T} = \frac{U(\Delta T_2 - \Delta T_1)}{Q} \int_0^A dA \qquad (4)$$

$$\ln \frac{\Delta T_2}{\Delta T_1} = \frac{UA(\Delta T_2 - \Delta T_1)}{Q}$$

$$Q = \frac{UA(\Delta T_2 - \Delta T_1)}{\ln \frac{\Delta T_2}{\Delta T_1}} = UA\overline{\Delta T_L} \qquad (5)$$

Where, $\overline{\Delta T}_L = \frac{(\Delta T_2 - \Delta T_1)}{\ln \frac{\Delta T_2}{\Delta T_1}}$ (6)

Equation (6) defines the logarithmic mean temperature difference(LMTD).

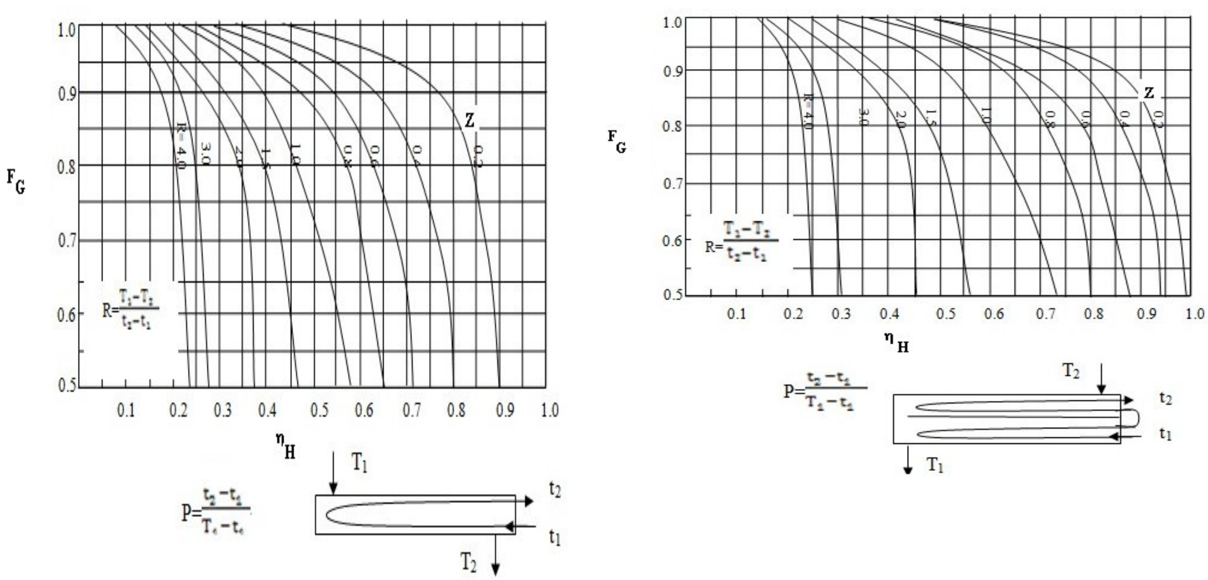
Correction of LMTD in multipass Heat exchangers:

The LMTD as given by equation(6) does not apply to the exchanger as a whole, nor to the individual tube passes using ($T_{hb} - T_{ci}$) as one of the driving forces in the LMTD. The reason is that the ΔT for each tube pass is not a linear function of the heat transferred. If the temperature of both the fluids in the heat exchanger change, the temperature conditions do not correspond to either counter current or parallel flow. When flow type other than counter current or parallel appear, it is customary to include a correction factor F_G with the LMTD. This F_G is called as LMTD correction factor. F_G is multiplied with LMTD to get the true average temperature drop. Factor F_G is always less than unity. The F_G can be calculated using two parameters Z and η_H through graph.

Where

$$Z = \frac{T_{ha} - T_{hb}}{T_{cb} - T_{ca}} \qquad \eta_H = \frac{T_{cb} - T_{ca}}{T_{ha} - T_{ca}}$$

The factor Z is the ratio of the true drop in temperature of the hot fluid to the rise in temperature of the cold fluid. The factor η_H is the heating effectiveness, or the ratio of the actual temperature rise of the cold fluid to the maximum possible rise if the warm end approach, based on counter current flow is zero.



(a) **(b)**

Fig.11. LMTD corrector factor chart for (a) 1-2 Shell and Tube Heat Exchanger

(b) 2-4 Shell and Tube Heat Exchanger

3.4. PLATE-TYPE EXCHANGERS

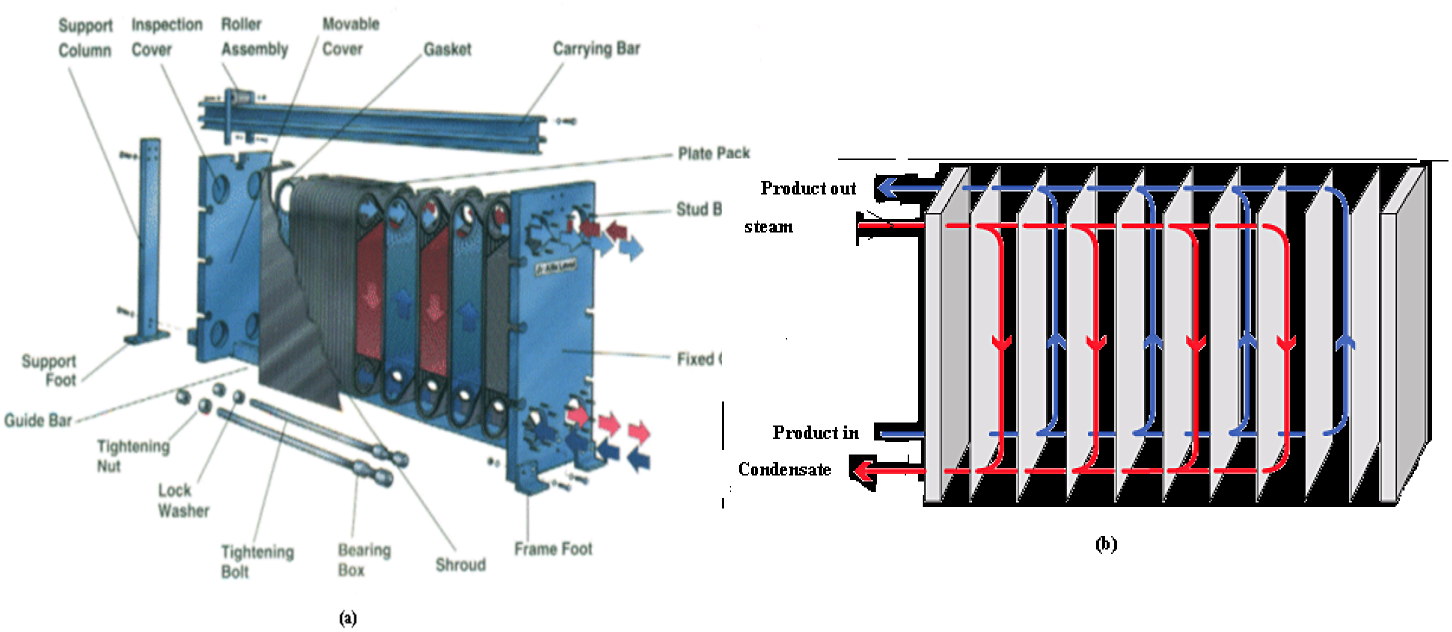


Fig.12. Plate type Heat Exchanger

For many applications at moderate temperature and pressure, an alternative to the shell-and-tube exchanger is the gasketed plate exchanger, which consists of many corrugated stainless steel sheets separated by polymer gaskets and clamped in a steel frame. Inlet portals and slots in the gaskets direct the hot and cold fluid to alternate spaces between the plates. The corrugations induce turbulence for improved heat transfer, and each plate is supported by multiple contacts with adjoining plates, which have a different pattern or angel of corrugation. The space between plated is equal to the depth of the corrugation and is usually 2 to 5 mm. A typical plate type heat exchanger is shown in fig.12.

With water or aqueous solutions on both sides, the overall coefficient for a clean plate type exchanger may be 3000 to 6000 W/m^2K, several times the normal values for a shell and tube exchanger. Because of high shear rates, the fouling factors experienced are much lower than those for shell and tube exchangers and the designer may just add 10 percent to the calculated area to allow for fouling. The units can be easily taken apart for thorough cleaning.

Plate exchangers are widely used in the dairy and food processing industries because they have high overall coefficients and are easily cleaned or sanitized. For example, the high temperature short time process for pasteurizing milk uses a plate exchanger with three or four sections. In the first regeneration section, raw milk is heated to 68ºC by exchange with hot pasteurized milk. In the next section hot water raises the milk temperature to 72ºC, the pasteurization temperature. The hot milk is held for at least 15 seconds in an external coil and then returned to the regenerator. In the last section chilled brine rapidly cools the product to 4ºC.

3.5. Condensers

Shell-and-tube condensers

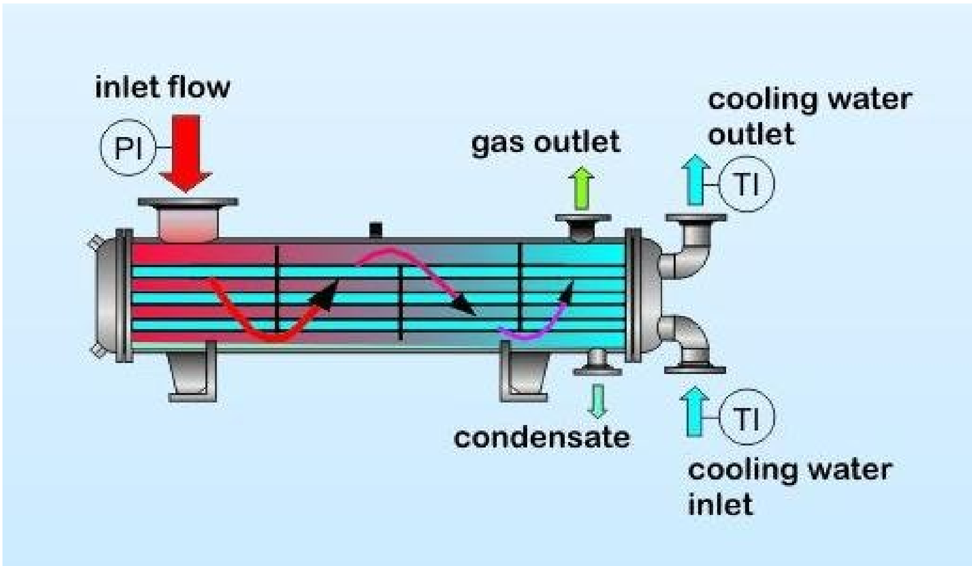
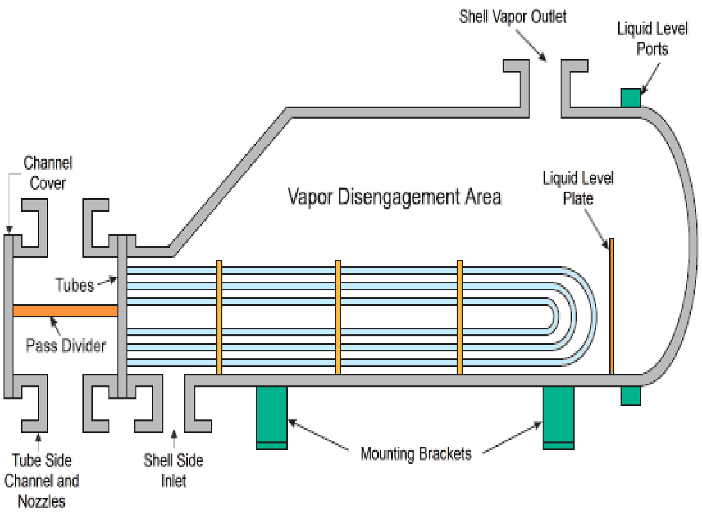


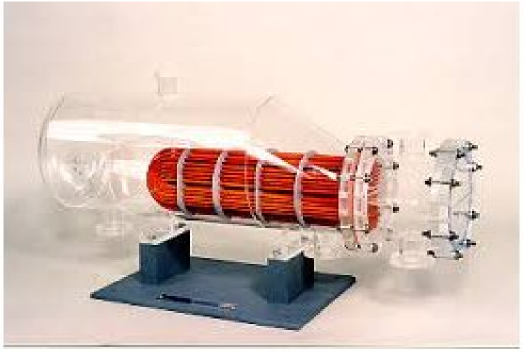
Fig.13. Shell and tube condenser

Heat transfer devices used to liquefy vapours by removing their latent hat are called condensers. The latent heat is removed by absorbing it in a cooler liquid called the coolant. Since the temperature of the coolant is increased in a condenser, the unit also acts as a heater, but functionally it is the condensing action that is important and the name reflects this fact. Condensers fall into two classes. I n the first, called shell and tube condensers, the condensing vapour and coolant are separated by a tubular heat transfer surface. In the second called contact condensers, the coolant and vapour streams both of which are usually water are physically mixed and leave the condenser as a single stream. The condenser shown in fig.13. is a single pass unit

kettle-type Reboiler



(a)



(b)

Fig.14. Kettle type Reboiler

Kettle type reboiler shown in fig.14. contains a bundle of horizontal tubes submerged in the liquid and arranged to provide some clearance between the lowest tubes and the reboiler shell. Vapour generated at the lower rows of tubes rises and affects the heat transfer rate from the upper tubes. Vapour blanketing of the tube bundle occurs at lower temperature differences, and the maximum heat flux is much lower than that for a single tube. The maximum flux for the tube bundle is only about one fourth that for the single tube.

PROBLEM

P.No.1. Water at the rate of 4 kg/s is heated from 38°C to 55°Cin a shell and tube heat exchanger. The water is to flow inside tubes of 2cm diameter with an average velocity of 35 cm/s. hot water available at95°C and the rate of 2 kg/s is used as the heating medium on the shell side. if the length of the tubes must not be more than 2m calculate the no. of tube passes , the no. tubes over pass and the length of the tubes for one shell pass, assuming U_o=1500 w/m^2k. Cp of water= 4186 J / kg K.

Solution:

Cold fluid

$\dot{m}_c$ = 4 kg/s

C_{pc} = 4186 J/kg K

T_{ca} = 38ºC ; T_{cb} = 55ºC

Hot fluid:

$\dot{m}_h$ = 2 kg/s

C_{ph} = 4186 J/kg K

T_{ha} = 95ºC

$Q = U\,A\,\overline{\Delta T_L}$

Enthalpy balance equation:

Q = $\dot{m}_c\, C_{pc}\left(T_{cb} - T_{ca}\right) = \dot{m}_h\, C_{ph}\left(T_{ha} - T_{hb}\right)$ = 284648 W

$4x\,4186(55-38) = 2x\,4186(95 - T_{hb})$

T_{hb} = 61 °C

$$\overline{\Delta T_L} = \frac{\Delta T_2 - \Delta T_1}{\ln\left(\frac{\Delta T_2}{\Delta T_1}\right)} = 30.72\ ^{o}C$$

$\Delta T_1 = T_{ha} - T_{cb}$ = 40 °C

$\Delta T_2 = T_{hb} - T_{ca}$ = 23 °C

Assumption ; Single pass shell and tube heat exchanger

$Q = U\,A\,\overline{\Delta T_L}$

A = 6.177 m^2 = NnπDoL

$\dot{m}_c = \rho\ u\ s$

$s = n\ (\pi D_i^2 /4)$

$D_i = 0.02m$

n = 36

A = NnπDoL

N = 1

L = 2.73m

Length is greater than 2m.So our assumption is not correct.

Assumption: 1-2 shell and tube heat exchanger

$Q = U\ AF_G\ \overline{\Delta T_L}$

Assumption: $F_G = 0.95$

$A = 6.5\ m^2$

A = NnπDoL

Answer:

N = 2

n = 36

L = 1.43 m

Assignment

1. A counter flow shell and tube heat exchanger is used to heat water at the rate of 0.8 kg/s from 30^{o}C to 80^{o}C with hot oil entering at120^{o}C and leaving at 85^{o}C. The overall heat transfer coefficient is 125 W/m^{2o}C. Calculate the heat transfer area required.
2. Water at the rate of 68kg/min is heated from 35 to 75°C by oil having a specific heat of 1.9kJ/kgK. The fluids are used in counter flow double pipe heat exchanger and the oil enters the exchanger at 110°C and leaves at 75°C. The overall heat transfer coefficient 320W/m^{2}K.Calculate the heat transfer area.
3. An oil cooler for a large diesel engine is to cool engine oil from 60^{o}C to 45^{o}C, using sea water at an inlet temperature of 20^{o}C with a temperature rise of 15^{o}C. The design heat load is 140kW and the mean overall heat transfer coefficient based on outer surface area of the tubes is 70 W/m^{2o}C. Calculate the heat transfer surface area for single pass (a) counter flow and (b) parallel flow arrangement.
4. In a double pipe counter flow heat exchanger 10,000 kg/h of an oil having a specific heat of 2095 J/kgK is cooled from 80^{o}C to 50^{o}C by 8000kg/hr of water entering at 25^{o}C.Determine the heat exchanger area for an overall heat transfer coefficient of 300W/m^{2}k.c_p of water=4180 J/kg K.
5. A counter flow tubular heat exchanger is used to cool engine oil(c_p=2130 J/kg K) from 160^{o}C to 60^{o}C with water, available at 25^{o}C as the cooling medium. The flow rate of cooling water through the inner tube of 0.5m dia is 2kg/s while the flow rate of oil through the outer annulus O.D=0.7 is also 2kg /s. If the value of the overall heat transfer coefficient is 250W/m^{2}K, how long must the heat exchanger be to meet its cooling requirement?
6. Crude oil flows at a rate of 2000 Kg/hr thro' the inside pipe of a double pipe heat exchanger and is heated from 45^{o}C to 100^{o}C. The heat is supplied by a hot fluid initially at 225^{o}C flowing thro' the annular space. If the temperature. of approach (min temperature. difference between the fluids) at the leaving end of hot fluid is 10^{o}C, determine the heat transfer area and the required hot fluid flow rate for co- current and counter current flow patterns. Data : U_O = 454 W/m^{2o}C ; Cp of crude oil= 2.34 kJ/kg K ; Cp of hot fluid= 2.51 kJ/kg K .
7. A heavy hydrocarbon oil is cooled in a counter current double pipe heat exchanger from 100°C to 75°C. The oil is flowing thro' inner tube at a rate of 1000 kg/hr. cold water enters the annulus at 15°C with a rate of 2000kg/ hr. Estimate the heat transfer area. Data:

overall heat transfer coefficient = 500 W/m^2K; specific heat of oil= 2.0 kJ/kg K; specific heat of water=4.00 kJ/kg K.

8. Saturated steam at 120^oC is condensing on the outer tube surface of a single pass heat exchanger. The heat transfer coefficient is u_o= 1800 W/m^2K. Determine the surface area of a heat exchanger capable of heating 1000kg/h of water from 20^oC to 90^oC. Also calculate the rate of condensing of steam. λ_s= 2200 kJ/kg.
9. Water at the rate of 4080 kg/hr is heated from 35^oC to 75^oC by an oil having a specific heat of 1900 J/kg K. The exchanger is of a counter flow double pipe design. The oil enters at 110^oC and leaves at 75^oC. Determine the area of the heat exchanger necessary to handle this load if the overall heat transfer coefficient is 320 W/m^2K.
10. A pipe (k=59 w/mk) with an I.D. of 3.175 cm and wall thickness of 0.318 cm is externally heated by steam at a temperature. of 180^oC . The water flows thro' the pipe with a velocity of 1.22 m/s. calculate the length of the pipe required to heat water from 30^oC to 90^oC assuming the heat transfer coefficient on the steam side to be 11.3 kW/m^2K. Data: ρ=982.3 kg/m^3 ; μ= 453 $\times10^{-6}$ $N.s/m^2$; k=656$\times10^{-3}$ w/mk; p_r=2.88
11. A shell and tube steam condenser is to be constructed of 2.5 cm O.D., 2.2cm I.D., single pass horizontal tubes with steam condensing at 54^oCoutside the tubes. The cooling water enters each tube at 18^oC with a flow rate of 0.7 kg/s per tube and leaves at 36^oC . The heat transfer coefficient for the condensation of the steam is 8000 $W/m^{2o}C$. Calculate the tube length and the condensation rate per tube. The properties of water at 27^oC are, C_p=4180 J/kg K; μ=0.86$\times10^{-3}$ kg/m.s; p_r= 5.9; k=0.61 W/mK; λ_s=2372.400 kJ/kg.
12. Hot engine oil available at 150°C flowing through the shell side is used to heat 2.4kg/s of water from 20°C to 80°C in a shell and tube heat exchanger. Water flows through eight tubes of 25mm diameter. Each tube makes six passes through the shell. The exit oil temperature is 90°C. Neglecting the tube wall resistance, find the oil flow rate and length of the tubes. Take the oil side heat transfer coefficient as 400 W/m^2K.For engine oil at 140°C; Cp = 2.34 kJ/kg K. For water at 50°C; Cp = 4.181kJ/kg K; μ = 548 x 10^{-6} Ns/m^2; k = 0.643 W/mK and Pr = 3.56
13. The condenser of a large steam power plant is a shell and tube heat exchanger having a single shell and 30000 tubes, with each tube making two passes. The tubes are thin walled with 25mm diameter and steam condenses on the outside of the tubes with ho= 11 kW/m^2K. The cooling water flowing through the tubes is 30000kg/s and the heat transfer rate is 2 x 10^9W.Water enters at 20°C while steam condenses at 50°C. Find the length of

the tubes in one pass. Properties of water at bulk mean temperature are Cp = 4.18 kJ/kg K; μ = 855 x 10^{-6} Ns/m^2; k = 0.613 W/mK and Pr = 5.83

14. Warm water is required at rate of 500 kg/hr for washing a filter cake, and it is decided to use a 25 mm steam heated tube for the purpose. The wall is maintained at 130^{o}C by condensing steam on the outside surface . Calculate the length of the tube required to heat water from 30^{o}C to 50^{o}C at the required rate. Use the Dittus- Boelter eqn to calculate the heat transfer coefficient. The I.D. of the tube is 21.2mm. Data; μ=6.82×10^{-4} kg/ms; κ=0.63 W/m^{o}C, c_p= 4.174 k J/kg K. Neglect the resistance of the tube wall.
15. In a food processing plant, water is to be cooled from 18^{o}C to 6.5^{o}C by using brine solution entering at the inlet temperature of -1.1^{o}C and leaving at 2.9^{o}C. What area is required when using a shell and tube heat exchanger with the water making one shell pass and the brine making two tube passes. Assume an average overall heat transfer coefficient of 850 W/m^2K and a design heat load of 6000W.
16. Water at the rate of 4 kg/s is heated from 38^{o}C to 55^{o}C in a shell and tube heat exchanger. The water is to flow inside tubes of 2cm diameter with an average velocity of 35 cm/s. hot water available at95^{o}C and the rate of 2 kg/s is used as the heating medium on the shell side. If the length of the tubes must not be more than 2m, calculate the no. of tube passes , the no. tubes over pass and the length of the tubes for one shell pass, assuming U_o=1500 W/m^2K. Cp of water= 4186 J/kg K.
17. Determine the area of one shell pass and 2 tube pass heat exchanger to heat water with a mass flow rate of 68 kg/min. from 35^{o}C to 75^{o}C by oil having a specific heat of 1.9 k J/kg K. The oil flowing thro' the tubes, enters the exchanger at 110^{o}C and leaves at 75^{o}C. The overall heat transfer coefficient is 320 W/m^2K.
