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International Journal for Modern Trends in Science and Technology, 8(05):177-199, 2022

ISSN: 2455-3778 online
DOI: https://doi.org/10.46501/IJMTST0805028
Available online at: http://www.ijmtst.com/vol8issue05.html

Design, Modelling, Analysis and Manufacturing of Shell and Tube Heat Exchanger

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To Cite this Article
Rohan Kumar Malla, Gangu Shashank Reddy and Nikhil Kotha. Design, Modelling, Analysis and Manufacturing of Shell and Tube Heat Exchanger. International Journal for Modern Trends in Science and Technology 2022, 8(05), pp. 177-199. https://doi.org/10.46501/IJMTST0805028

Article Info
Received: 01 May 2022; Accepted: 05 May 2022; Published: 07 May 2022.

ABSTRACT

The fluids may be separated by a solid wall to prevent mixing or they may be in direct contact. They are widely used in space heating, refrigeration, air conditioning, power stations, chemical plants, petrochemical plants, petroleum refineries, natural-gas processing, and sewage treatment. The classic example of a heat exchanger is found in an internal combustion engine in which a circulating fluid known as engine coolant flows through radiator coils and air flows past the coils, which cools the coolant and heats the incoming air.

Heat exchangers are widely used in industry both for cooling and heating large scale industrial processes. The type and size of heat exchanger used can be tailored to suit a process depending on the type of fluid, its phase, temperature, density, viscosity, pressures, chemical composition and various other thermodynamic properties.

In many industrial processes there is waste of energy or a heat stream that is being exhausted, heat exchangers can be used to recover this heat and put it to use by heating a different stream in the process. This practice saves a lot of money in industry, as the heat supplied to other streams from the heat exchangers would otherwise come from an external source that is more expensive and more harmful to the environment.

A car radiator is another kind of heat exchanger. Water that cools the engine flows through the radiator, which has lots of parallel, aluminum fins open to the air. As the car drives along, cold air blowing past the radiator removes some of the heat, cooling the water and heating the air and keeping the engine working efficiently.

In power plants or engines, exhaust gases often contain heat that's heading uselessly away into the open air. That's a waste of energy and something a heat exchanger can certainly reduce (though not eliminate entirely, some heat is always going to be lost). The way to solve this problem is with heat exchangers positioned inside the exhaust tail pipes or smokestacks. As the hot exhaust gases drift upward, they brush past copper fins with water flowing through them. The water carries the heat away, back into the plant. saving the energy that would otherwise be needed to heat them up. Or it could be put to some other good use, for example, heating an office near the smokestack.

1. INTRODUCTION

Heat exchangers are used in many industries, including:

- Waste water treatment
- Refrigeration
- Wine and beer making
- Petroleum refining
- nuclear power

1.2 What are Industrial Heat Exchangers?

As their name implies industrial heat exchangers are pieces of industrial equipment which are designed to exchange or transfer heat from one medium to another.

The heat exchange may be for the primary purpose of heating up elements or cooling it down. Within the industrial sector, cooling tends to be the more prevalent function in order to prevent equipment or volatile substances from overheating. There are many different types of heat exchangers, each with their own advantages and drawbacks, yet tailored to best suit different purposes and industries.

1.3 Why are Heat Exchangers Needed?

Heat exchangers have a very broad range of industrial applications. They are used as components of air conditioning and cooling systems or of heating systems. Many industrial processes call for a certain degree of heat to function; however, typically great care must be taken to keep these processes from getting too hot. Within industrial plants and factories heat exchangers are required to keep machinery, chemicals, water, gas, and other substances within a safe operating temperature. Heat exchangers may also be used to capture and transfer steam or heat exhaust that is released as a byproduct of a process or operation so that the steam or heat can be put to better use elsewhere, thereby increasing efficiency and saving the plant money.

1.4 How do Heat Exchangers Work?

Different types of heat exchangers work in different ways, use different flow arrangements, equipment, and design features. One thing that all heat exchangers have in common is that they all function to directly or indirectly expose a warmer medium to a cooler medium, hence, exchanging heat. This is usually accomplished by using a set of tubes housed within some type of casing. Heat exchanger fans, condensers, belts, coolants, additional tubes and lines, along with other components and equipment work to increase heating and cooling efficiency or improve flow.

2. MODES OF HEAT TRANSFER

Heat is a form of energy which transfers between bodies which are kept under thermal interactions. When a temperature difference occurs between two bodies or a body with its surroundings, heat transfer occurs. In this article, we are going to deal with the different modes of heat transfer. Heat transfer occurs basically in three modes:

- Conduction
- Convection and
- Radiation

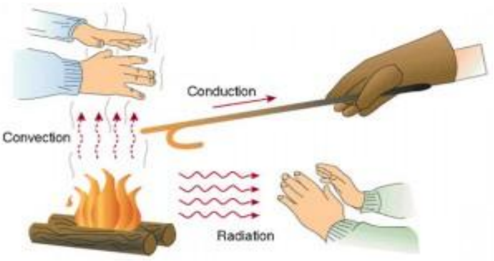


Fig 2.1 modes of heat transfer

2.1 Conduction

Conduction is the mode of heat transfer occurs from one part of a substance to another part of within the substance itself or with another substance which is placed in physical contact. In conduction, there is no noticeable movement of molecules. You might be thinking that then how this heat transfer occurs? The heat transfer occurs here by the two mechanisms happen.

1. By the transfer of free electrons. Good conductors like metals have a plenty of free electrons to make conductive heat transfer.
2. The atoms and molecules having energy will pass this energy they have with their adjacent atoms or molecules by means of lattice vibrations.

Now we can think how this conduction occurs in gases and liquids. In the cases of gases, the molecules having energy in the form of kinetic energy and during their random movements, they exchange their momentum and energy by colliding with others. By doing so, the first molecule loses the energy while the second one gains it. This is how energy is transferred in the case of gases. In the case of liquids also, the working is similar to that of gases. Here, the only difference is that, the molecules in liquids are more closely packed and hence inter molecular forces came into action in the case of liquids.

2.1.1 Fourier Law of Conduction:

$$Q = -kAdT/dx$$

Where: Q is the heat flow rate by conduction

K is the thermal conductivity of the material

A is the cross-sectional area normal to direction of heat flow and dT/dx is the temperature gradient of the section.

2.2 Convection

Conductive heat transfer occurs within a fluid itself and it is carried out by transfer of one fraction of the fluid to the remaining portion. Hence unlike conduction, transfer of molecules occurs during convection. Since movement of particles constitutes convection, it is the macro form of heat transfer. Also, convection is only [possible in fluids where the particles can move easily and the rate of convective heat transfer depends on the rate of flow to a great extent. Convection can be of two types:

2.2.1 Natural convection: In this type of convection, the movement of particles which constitutes convection occurs by the variation in densities of the fluids. As we already know, as temperature increases, the density decreases and this variation in density will force the fluid to move through the volume. This cause convection to occur.

2.2.2 Forced Convection: The difference between natural convection and forced convection is that in forced convection, a work is done to make movement in the fluid. This is done using a pump or blower.

2.2.3 Newton's Law of Cooling

Q = hA (Ts-T∞)

Where:

Ts is the surface temperature

T∞ is the fluid temperature

h is the heat transfer coefficient

equations more compact, you may use the solidus (/), the exp function, or appropriate exponents. Use parentheses to avoid ambiguities in denominators. Punctuate equations when they are part of a sentence, as in

$$\int_0^{r_2} F(r,\varphi)\, dr\, d\varphi = [\sigma r_2 / (2\mu_0)] \cdot \int_0^{\infty} \exp(-\lambda |z_j - z_i|)\, \lambda^{-1} J_1(\lambda r_2)\, J_0(\lambda r_i)\, d\lambda . \quad (1)$$

Be sure that the symbols in your equation have been defined before the equation appears or immediately following. Italicize symbols (*T* might refer to temperature, but T is the unit tesla). Refer

2.3 Radiation

Radiation is the third mode of heat transfer. This mode of heat transfer didn't require any medium to occur. Every matter having a temperature above absolute zero will emit energy in the form of electromagnetic waves and called radiation. It is the same way the energy of the Sun reaching us. The key features about radiation are it does not require any medium and also laws of reflection is applicable for radiation.

2.3.1 Stefan- Boltzmann Law:

The formula to know the amount of heat transferred by radiation is:

q = e σ A [(ΔT) ^4]

Where q is the heat transferred by radiation, E is the emissivity of the system, σ is the constant of Stephan-Boltzmann (5.6697 x 10^-8 W/m^2.K^4), A is the area involved in the heat transfer by radiation, and (ΔT)^4 is the difference of temperature between two systems to the fourth or higher power.

3. CLASSIFICATION OF HEAT EXCHANGERS

3.1 Based on relative direction of fluid motion

a) parallel flow
b) counter flow
c) cross flow

a) Parallel Flow Heat Exchanger

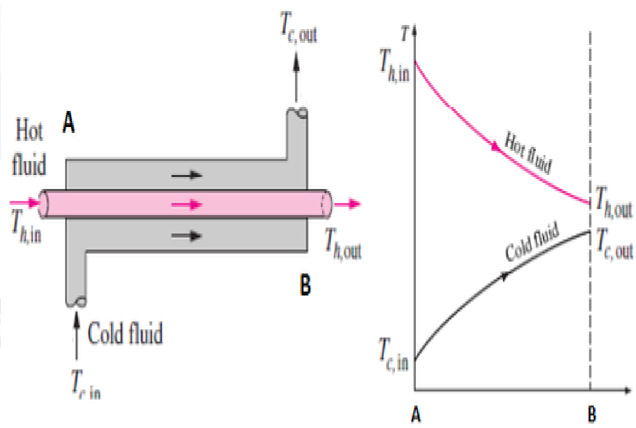


Fig 3.1 parallel flow heat exchanger

In a parallel flow heat exchanger, as the name suggest the two fluid streams (hot and cold) travel in the same direction. The two streams enter at one end and leave at the other end. The flow arrangement and variation of temperatures of the fluid streams in case of parallel flow heat whereas "Ni–Mn" indicates an alloy of some composition Ni_xMn_{1-x}.

exchangers are shown in the figure. It is evident from the figure that the temperature difference between the hot and cold fluids goes on decreasing from inlet to outlet. Since this type of heat exchanger needs a large area of heat transfer, it is rarely used in practice.

b) Counter-Flow Heat Exchangers

In a counter flow heat exchanger, the two fluids flow in opposite directions. The hot and cold fluids enter at the opposite ends. The flow arrangement and temperature distribution for such a heat exchanger are shown schematically in figure. The temperature difference between the two fluids remains more or less nearly constant

This type of heat exchanger, due to counter flow, gives maximum rate of heat transfer for a given surface area. Hence such heat exchangers are most favored for heating and cooling of fluids

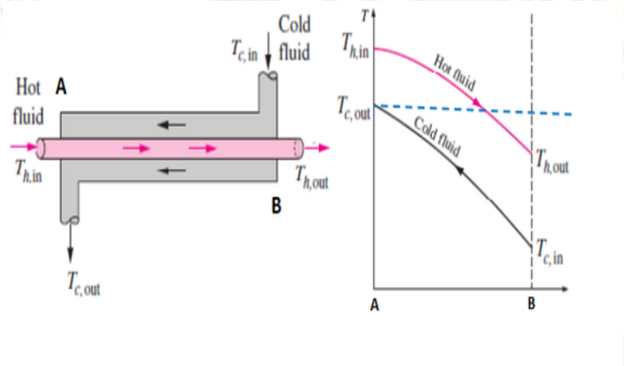


Fig 3.2 counter flow heat exchanger

c) Cross Flow Heat Exchanger

In cross-flow heat exchangers, the two fluids (hot and cold) cross one another in space, usually at right angles. Figure shows a schematic diagram of common arrangement of cross-flow heat exchangers

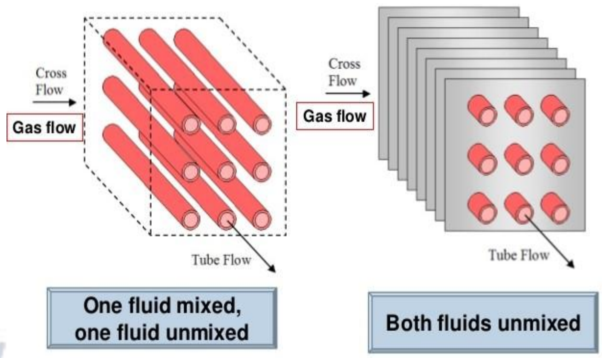


Fig 3.3 (a) fig 3.3 (b)

Fig (a) shows hot fluid flows in the separate tube and there is no mixing of the fluid streams. The cold fluid is perfectly mixed as it flows through the exchanger. The temperature of this mixed fluid will be uniform across any section and will vary only in the direction of flow.

Examples: the cooling unit of refrigeration system.

Fig (b) in this case each of the fluids follows a prescribed path and is unmixed as it flows through heat exchanger. Hence the temperature of the fluid leaving the heater section is not uniform.

Examples: automobile radiator.

3.2 Based on design and constructional features

a) Concentric tubes
b) Shell and tube
c) Compact heat exchangers

a) Concentric Tubes

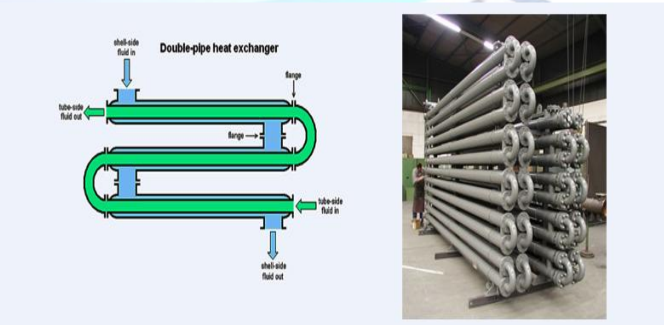


Fig 3.4 concentric tube heat exchanger

In this this type, two concentric tubes are used, each carrying one of the fluids. The direction of flow may be parallel or counter. The effectiveness of the heat exchanger is increased by using swirling flow.

a) Shell and Tube

In this type of heat exchanger one of the fluids flows through a bundle of tubes enclosed by a shell. The other fluid is forced through the shell and it flows over the outside surface of the tubes. Such an arrangement is employed where reliability and heat transfer effectiveness are important. With the use of multiple tubes heat transfer rate is amply improved due to increased surface area.

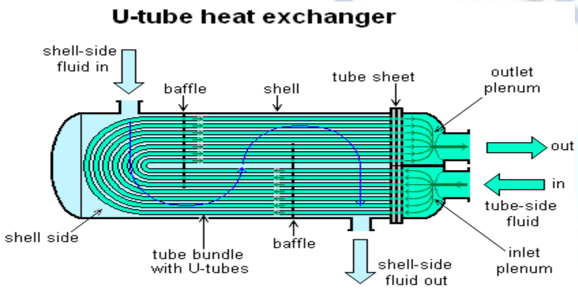


Fig 3.5 shell and tube heat exchanger

b) Compact Heat Exchangers

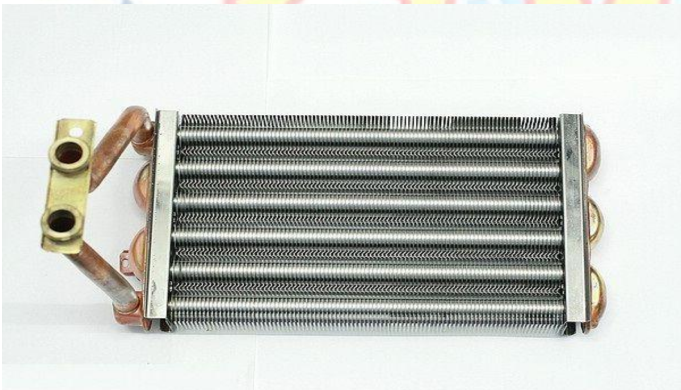


fig 3.6 compact heat exchanger

There are special purpose heat exchangers and have a very large transfer surface area per unit volume of the heat exchanger. They are generally employed when convective heat transfer coefficient associated with one of the fluids is much smaller than that associated with the other fluid.

Example: plate-fin, flattened fin tube exchangers etc.,

3.3 Based on the Nature of the Heat Exchange Process

This classification method refers to whether or not the substances between which the heat is being exchanged come into direct contact with each other or not, or whether they are separated by a physical barrier, such as the walls of their tubes.

a) Direct Contact Heat Exchangers

Direct contact heat exchangers bring the hot and cold fluids into direct contact with each other within the tubes rather than relying on radiant heat or convection. Direct contact is an extremely effective means of transferring heating since the contact is direct, but naturally for direct contact to be used it must be safe, or even desired to have the fluids come in contact with each other. Direct contact heat exchangers may be a good choice if the hot and cold fluids are merely different temperature variations of the same fluid, or if the fluid mixture is a desired or irrelevant part of the industrial process.

b) Indirect Contact Heat Exchangers

Indirect contact heat exchangers keep the hot and cold fluids physically separated from each other. Typically, indirect contact heat exchangers will keep the hot and cold fluids in different sets of pipes and instead rely on radiant energy and convection to exchange the heat. This is commonly done to prevent contamination or pollution of one fluid by the other.

3.4 Based on the Physical State of the Fluids

Heat Exchangers may also be classified based on the physical state of the hot and cold fluids. For instance:

- Liquid – Gas
- Liquid – Solid
- Gas – Solid

a) Condensers

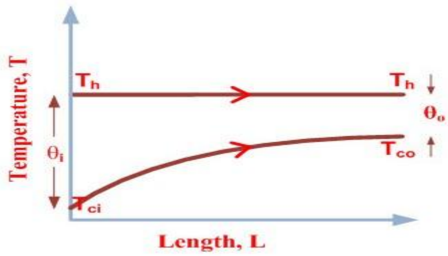


Fig 3.7 temperature distribution in condensers

In a condenser, the condensing fluid remains at constant temperature throughout the exchanger while the temperature of the colder fluid gradually increases from inlet to outlet. The hot fluid loses latent part of heat which is accepted by the cold fluid.

b) Evaporators

In this case, the boiling fluid (cold fluid) remains at constant temperature while the temperature of hot fluid gradually decreases from inlet to outlet, shown in figure

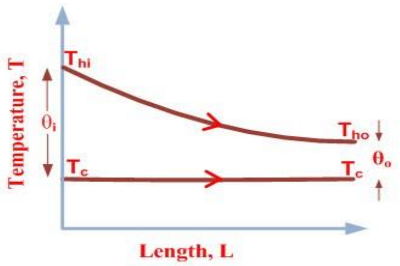


Fig3.8 temperature distribution in evaporators

4. SHELL AND TUBE HEAT EXCHANGER

4.1 Introduction

A shell and tube heat exchanger is a class of heat exchanger designs. It is the most common type of heat exchanger in oil refineries and other large chemical processes, and is suited for higher-pressure applications. As its name implies, this type of heat exchanger consists of a shell (a large.

pressure vessel) with a bundle of tubes inside it. One fluid runs through the tubes, and another fluid flows over the tubes (through the shell) to transfer heat between the two fluids. The set of tubes is called a tube bundle, and may be composed of several types of tubes: plain, longitudinally finned, etc.

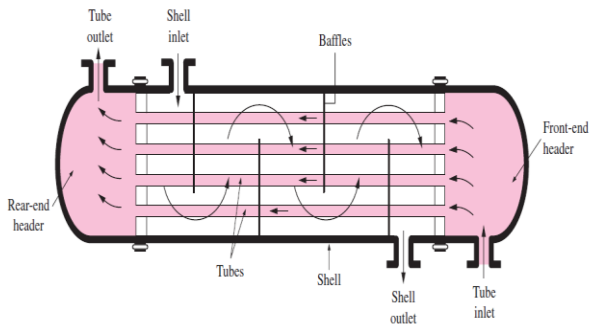


Fig 4.1 shell and tube heat exchanger

Two fluids, of different starting temperatures, flow through the heat exchanger. One flows through the tubes (the tube side) and the other flows outside the tubes but inside the shell (the shell side). Heat is transferred from one fluid to the other through the tube walls, either from tube side to shell side or vice versa. The fluids can be either liquids or gases on either the shell or the tube side. In order to transfer heat efficiently, a large heat transfer area should be used, leading to the use of many tubes. In this way, waste heat can be put to use. This is an efficient way to conserve energy.

4.2 Components of shell and tube heat exchanger

4.2.1 Tubes

The tubes are the basic component of the shell and tube exchanger, providing the heat transfer surface between one fluid flowing inside the tube and the other fluid flowing across the outside of the tubes. The tubes may be seamless or welded and most commonly made of copper or steel alloys. Other alloys of nickel, titanium, or aluminum may also be required for specific applications. The tubes may be either bare or with extended or enhanced surfaces on the outside. Typical tube will be extended surface. Extended or enhanced surface tubes are used when one fluid has a substantially lower heat transfer coefficient than the other fluid. Extended surfaces, (finned tubes) provide two to four times as much heat transfer area on the outside as the corresponding bare tube, and this area ratio helps to offset a lower outside heat transfer coefficient.

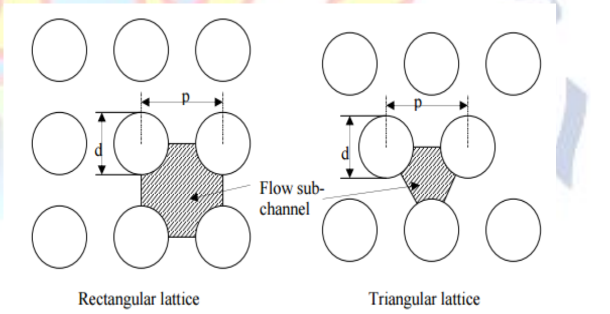


Fig 4.2 tube arrangement in heat exchanger

4.2.2 Tube sheets

The tubes are held in space by being inserted into holes in the tube sheet and there either expanded into grooves cut into the holes or welded to the tube sheet where the tube protrudes from the surface The tube sheet is usually a single round plate of metal that has been suitably drilled and grooved to take the tubes (in the desired pattern), the gaskets, the spacer rods, and the bolt circle where it is fastened to the shell. However, where mixing between the two fluids (in the event of leaks where the tube is sealed into the tube sheet) must be avoided, a double tube sheet such as is shown in figure may be provided. The space between the tube sheets is open to the atmosphere so any leakage of either fluid should be quickly detected. Exotic designs with inert gas shrouds and/or leakage recycling systems are used in cases of extreme hazard or high value of the fluid. The tube sheet, in addition to its mechanical requirements, must withstand corrosive attack by both fluids in the heat exchanger and must be electrochemically compatible with the tube and all tube-side material. Tube sheets are sometimes made from low carbon steel with a thin layer of corrosion-resisting alloy metallurgic ally bonded to onside.

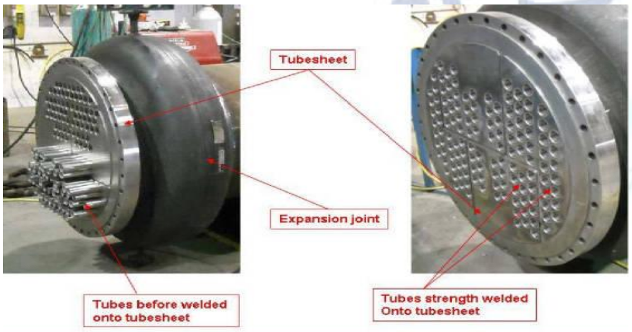


Fig 4.3 tube sheet

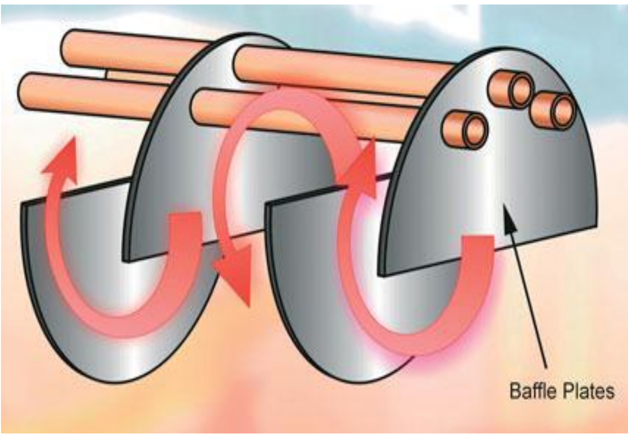


Fig 4.4 baffles

Baffles serve two functions most importantly, they support the tubes in the proper position during assembly and operation and prevent vibration of the tubes caused by flow-induced eddies, and secondly, they guide the shell-side flow back and forth across the tube field, increasing the velocity and the heat transfer coefficient. The most common baffle shape is the single segmental. The segment sheared off must be less than half of the diameter in order to ensure that adjacent baffles overlap at least one full tube row. For liquid flows on the shell side, a baffle cut of 20 to 25 percent of the diameter is common; for low pressure gas flows, 40 to 45 percent (i.e., close to the maximum allowable cut) is more common, in order to minimize pressure drop. The baffle spacing should be correspondingly chosen to make the free flow areas through the "window" (the area between the baffle edge and shell) and across the tube bank roughly equal. For many high velocity gas flows, the single segmental baffle configuration results in an undesirably high shell-side pressure drop.

4.2.4 Tie Rods and Spacers

Tie rods and spacers are used for two reasons:

1) Hold the baffle assembly together
2) Maintain the selected baffle spacing.

The tie rods are secured at one end to the tube sheet and at the other end to the last baffle. They hold the baffle assembly together. The spacers are placed over the tie rods between each baffle to maintain the selected baffle pitch. The minimum number of tie rod and spacers depends on the diameter of the shell and the size of the tie rod and spacers.

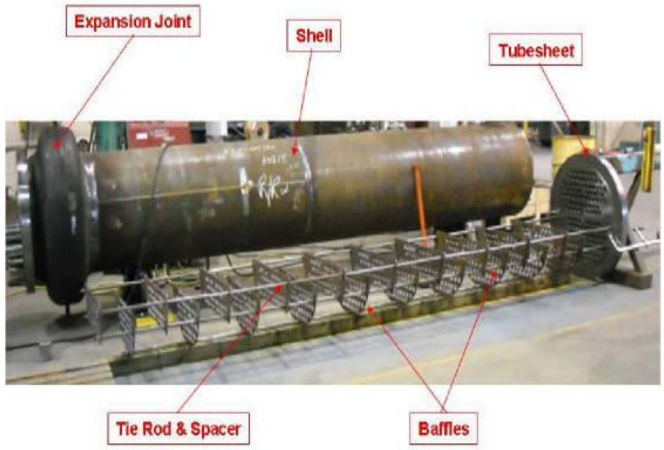


Fig 4.5 tie rods and spacers

4.2.5 Pass Divider

A pass divider is needed in one channel or bonnet for an exchanger having two tube-side passes, and they are needed in both channels and bonnets for an exchanger having more than two passes. If the channels or bonnets are cast, the dividers are integrally cast and then faced to give a smooth bearing surface on the gasket between the divider and the tube sheet.

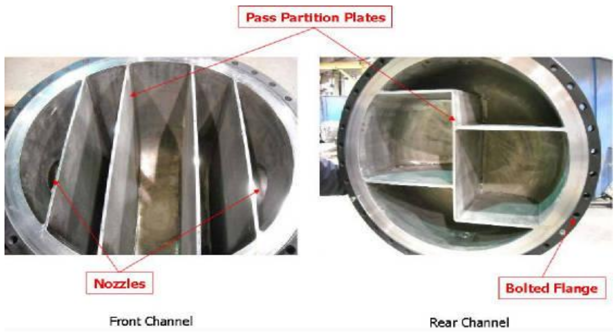


Fig 4.6 pass divider arrangement

If the channels are rolled from plate or built up from pipe, the dividers are welded in place. The arrangement of the dividers in multiple-pass exchangers is somewhat arbitrary, the usual intent being to provide nearly the same number of tubes in each pass, to minimize the number of tubes lost from the tube count, to minimize the pressure difference across any one pass divider (to minimize leakage and therefore the violation of the MTD derivation), to provide adequate bearing surface for the gasket and to minimize fabrication complexity and cost

4.2.6 Channels (heads)

Channels or heads are required for shell-and-tube heat exchangers to contain the tube side fluid and to provide the desired flow path. There are different types of heads are available.

The three (3) letters TEMA (Tubular Exchanger Manufacturers Association) designation is the standard method for identifying the type of channels and the type of shell of shell-and-tube heat exchangers. The first letter of the TEMA designation represents the front channel type (where the tube side fluid enters the heat exchanger), the second letter represents the shell type and the last letter represents the rear channel type. The TEMA channel types are shown below.

TEMA front heads

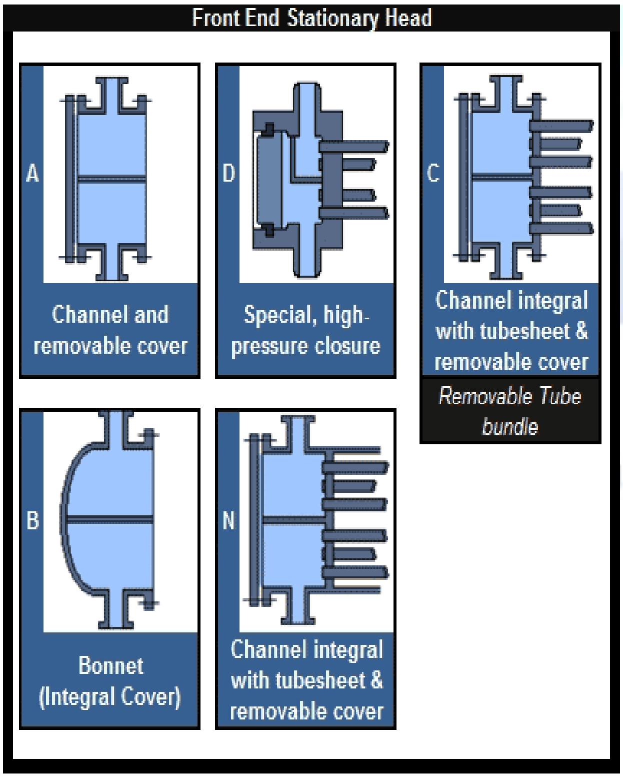


Fig: 4.7 TEMA front heads

TEMA Rear heads

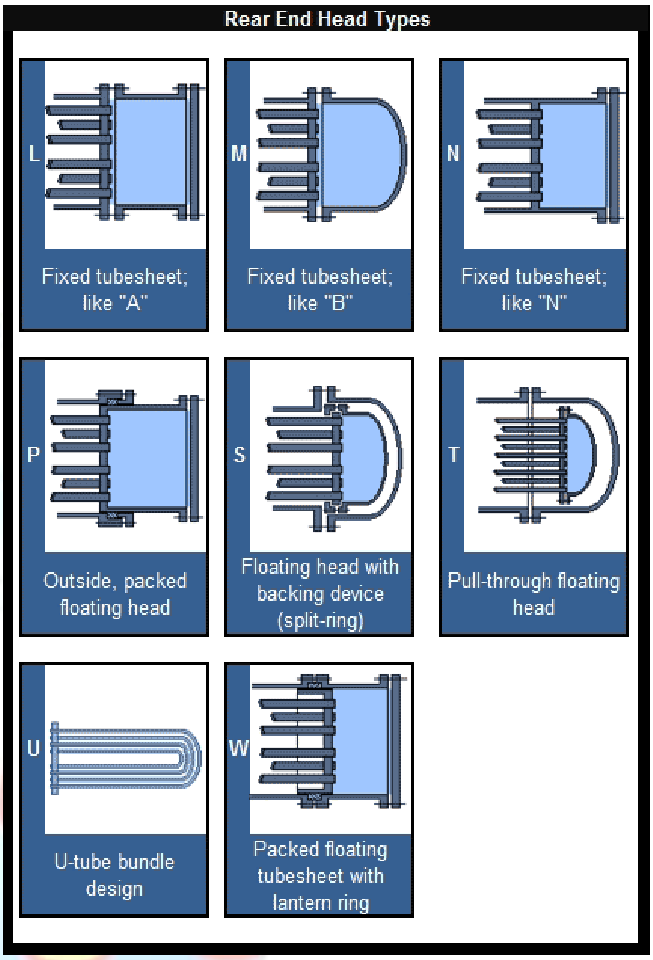


Fig: 4.8 TEMA rear heads

4.3 The proper selection of optimum heat exchanger depends on many factors

4.3.1 Heat Transfer Rate

This is the most important quantity in the selection of a heat exchanger. A heat exchanger should be capable of transferring heat at the specified rate in order to achieve the desired temperature change of the fluid at the specified mass flow rate.

4.3.2 Cost

Budgetary limitations usually play an important role in the selection of heat exchangers, except for some specialized cases where "money is no object." An off-the-shelf heat exchanger has a definite cost advantage over those made to order. However, in some cases, none of the existing heat exchangers will do, and it may be necessary to undertake the expensive and time-consuming task of designing and manufacturing a heat exchanger from scratch to suit the needs. This is often the case when the heat exchanger is an integral part of the overall device to be manufactured. The operation and maintenance costs of the heat exchanger are also important considerations in assessing the overall cost.

4.3.3 Pumping Power

In a heat exchanger, both fluids are usually forced to flow by pumps or fans that consume electrical power. Minimizing the pressure drop and the mass flow rate of the fluids will minimize the operating cost of the heat exchanger, but it will maximize the size of the heat exchanger and thus the initial cost. As a rule of thumb, doubling the mass flow rate will reduce the initial cost by half but will increase the pumping power requirements by a factor of roughly eight. Typically, fluid velocities encountered in heat exchangers range between 0.7 and 7 m/s for liquids and between 3 and 30 m/s for gases. Low velocities are helpful in avoiding erosion, tube vibrations, and noise as well as pressure drop.

4.3.4 Size and Weight

Normally, the smaller and the lighter the heat exchanger, the better it is. This is especially the case in the automotive and aerospace industries, where size and weight requirements are most stringent. Also, a larger heat exchanger normally carries a higher price tag. The space available for the heat exchanger in some cases limits the length of the tubes that can be used.

4.3.5 Type

The type of heat exchanger to be selected depends primarily on the type of fluids involved, the size and weight limitations, and the presence of any phase change processes. For example, a heat exchanger is suitable to cool a liquid by a gas if the surface area on the gas side is many times that on the liquid side. On the other hand, a plate or shell-and-tube heat exchanger is very suitable for cooling a liquid by another liquid.

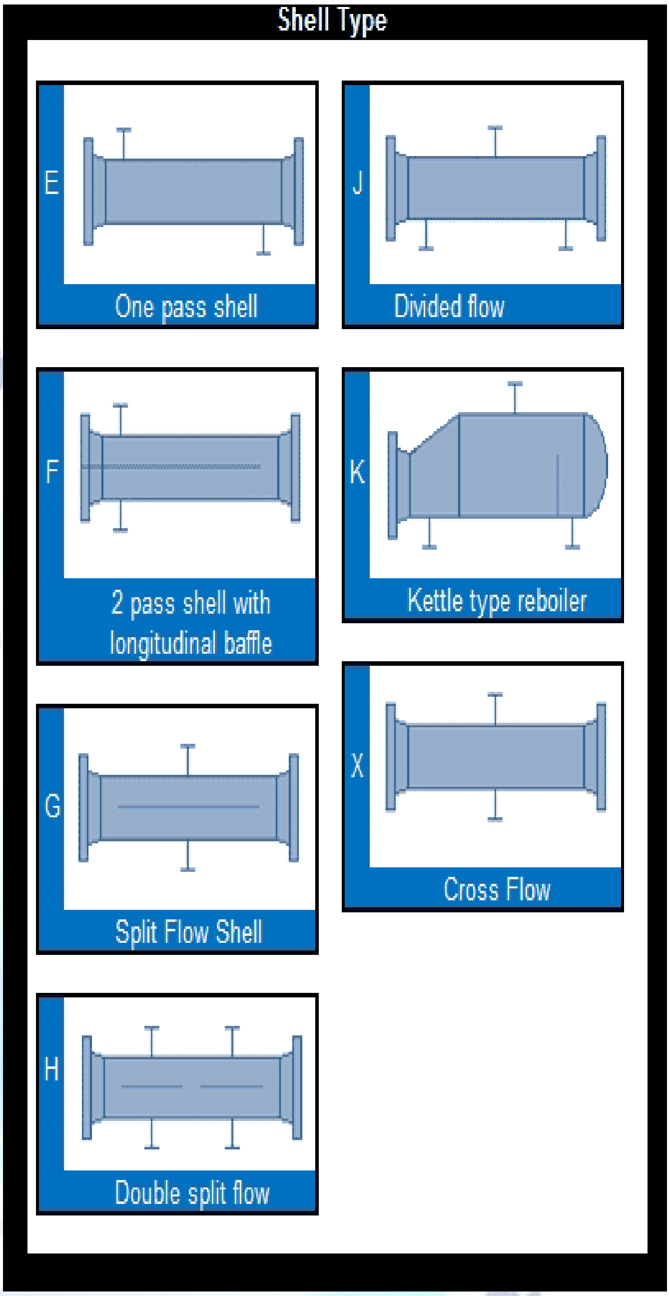


Fig: 4.9 TEMA shell types

4.3.6 Materials

The materials used in the construction of the heat exchanger may be an important consideration in the selection of heat exchangers. For example, the thermal and structural stress effects need not be considered at pressures below 15 atm or temperatures below 150°C. But these effects are major considerations above 70 atm or 550°C and seriously limit the acceptable materials of the heat exchanger. A temperature difference of 50°C or more between the tubes and the shell will probably pose differential thermal expansion problems and needs to be considered. In the case of corrosive fluids, we may have to select expensive corrosion-resistant materials such as stainless steel or even titanium if we are not willing to replace low-cost heat exchangers frequently.

4.3.7 Other Considerations

There are other considerations in the selection of heat exchangers that may or may not be important, depending on the application. For example, being leak-tight is an important consideration when toxic or expensive fluids are involved. Ease of servicing, low maintenance cost, and safety and reliability are some other important considerations in the selection process. Quietness is one of the primary considerations in the selection of liquid-to-air heat exchangers used in heating and air conditioning applications.

5. DESIGNING PROCEDURE OF SHELL AND TUBE HEAT EXCHANGER

5.1 Mechanical Design

The mechanical design of STHE includes

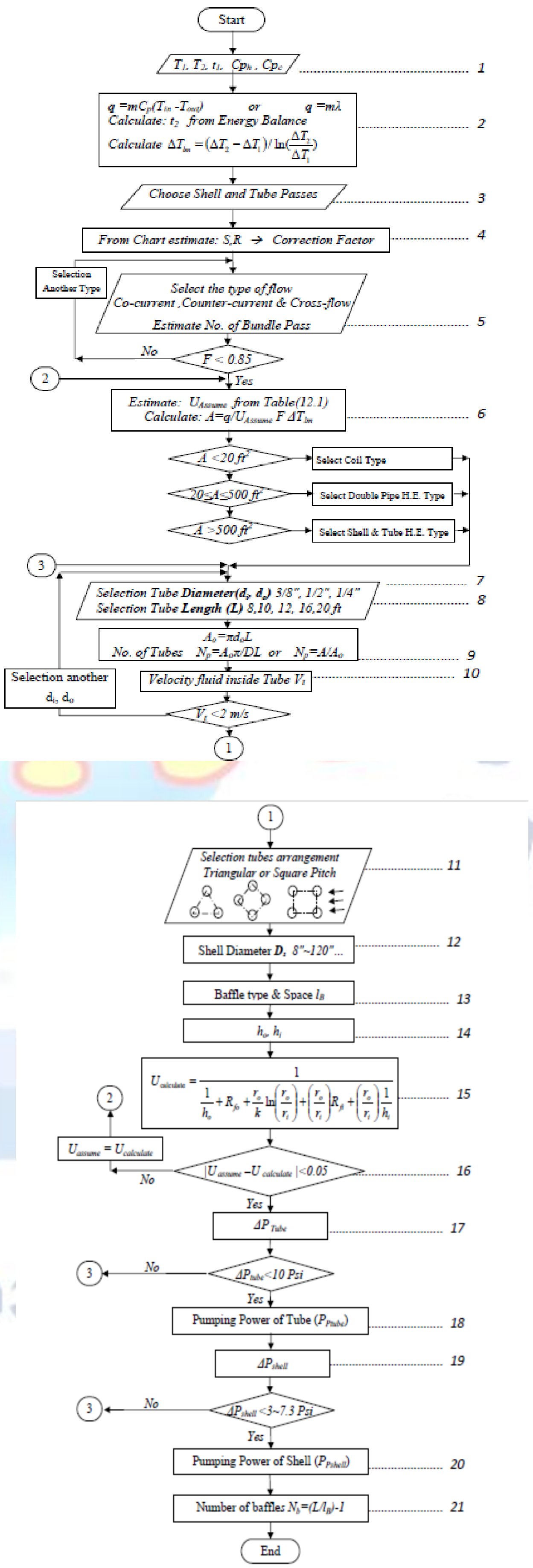
i) Selection of TEMA layout—based on thermal design
ii) Selection of tube parameters such as size, thickness, layout, pitch, material
iii) Limiting the upper and lower design on tube length
iv) Selection of shell side parameters such as material, baffle spacing, and clearances
v) Thermal conductivity of tube material
vi) Setting upper and lower design limits on shell diameter and baffle spacing

5.2 Thermal Design

The thermal design of STHE includes

i) Consideration of process fluids in both shell and tube side
ii) Selection of required temperature specifications
iii) Limiting the shell and tube side pressure drop
iv) Setting shell and tube side velocity limits
v) Finding heat transfer area including fouling factor.

5.3 General procedure of design (Kerns method)



5.4 Theoretical Background

- Logarithmic mean temperature difference

$$\Delta T_{1mean}=\frac{(T1-t2)-(T2-t1)}{\ln\left[\frac{(T1-t2)}{(T2-t1)}\right]} \quad \text{……………………………..……} \quad (1)$$

Where T1- hot fluid inlet temperature.

T2- hot fluid outlet temperature.

t1- cold fluid inlet temperature.

t2- cold fluid outlet temperature.

- $\Delta t = F * \Delta T_{1mean}$ ………………………………………………. (2)

$$R = \frac{(T1-T2)}{(t2-t1)} \qquad p = \frac{(t2-t1)}{(T1-t1)}$$

F= correction factor (R/P) (APPENDIX GRAPH)

5.4.1 Calculation of Tube Side

- Calculation of heat duty
  Heat duty = flow rate (kg/s) x specific heat (j/kg °c) x Δt_c (°c) ……. (3)

- Calculation of heat transfer area
  Let assume U
  Heat transfer area = $\frac{\text{heat duty}}{\text{assumed } U \times \Delta Tm}$ ……………………. …. (4)

- Surface area of one tube = $\pi \times d_0 \times L_{tube}$ ….…… ……………..…. (5)

- Calculation of no. of tubes needed (Nt)
  $$Nt=\frac{heat\ transfer\ area\ (m^2)}{surface\ area\ of\ one\ tube\ (m^2)} \text{……………………...} (6)$$

- Tube pitch (Pt)
  $Pt = 1.25 \times d_0$ …………………………………………… (7)
  d_0= outside diameter of tube (m)

- Bundle diameter (D_b)
  $$D_b = d_0 \times \left(\frac{Nt}{K1}\right)^{\frac{1}{n1}} \text{…………………………………………...} (8)$$
  Nt = no. of tubes
  d_0 = outside diameter of tube (m)
  k1, n1= constants

- Cross-sectional area of one tube

$$A_{tube} = \frac{\pi}{4} \times d_i^2 \quad \text{………………………………………………..} \quad (9)$$

- Total flow area in tubes (A_{flow})
  A_{flow} = no. of $\frac{\text{tube}}{\text{pass}}$ x A_{tube} ………………………………… (10)

- Tubes velocity = Volumetric flow rate (m^3 /s) x A_{flow} ………………….(11)

- Reynolds number (Re_{Tube})
  $$Re = \frac{\varrho \times V \times di}{\mu} \quad \text{………………………………………} \quad (12)$$
  Where ρ- density
  V- velocity
  d_i- tube inner diameter
  μ- viscosity

6. DESIGN AND MODELLING OF SHELL AND TUBE HEAT EXCHANGER

6.1 Design of Shell and Tube Heat Exchanger

6.1.1 Required data

Table 6.1.1.1 input parameters

Parameters	Shell side	Tube side
Flow rate (kg/h)	1,000	750
Inlet temperature	70	25
(°C)	55	45
Outlet temperature	974	1000
(°C)	1.165	1.16
Density ϱ (kg/m3)	0.364	0
Specific heat	0.6687	1.00
capacity, c (wh/kg		6
K)		0.59
Kinematic Viscosity,		78
υ (mm2/s)		
Heat conductivity, λ		
(w/m K)		

6.1.2 Determining the heat duty

Shell side Q= m × c ×Δt =1,000 × 1.165× (70-55) =17,400 W

Tube side Q = m × c ×Δt =750 × 1.160× (45- 25) =17,400 W

6.1.3 Temperature difference, CMTD

First the LMTD is determined for ideal countercurrent flow.

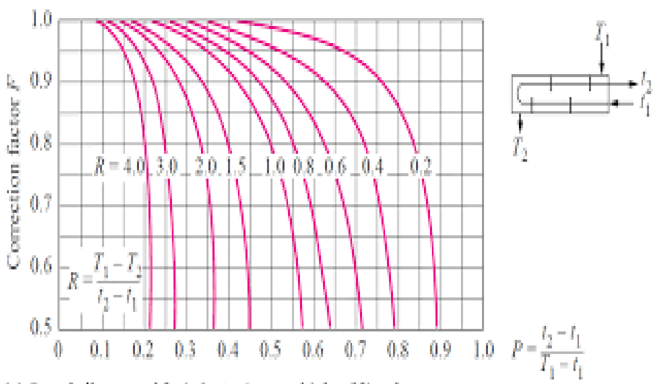
T1 → T2 70 → 55

t2 ≈ t1 45 ≈ 25

25 30

$$LMTD = \frac{30-25}{\ln\frac{30}{25}} = 27.42°C$$

Since we intend to use a multi pass heat exchanger, the temperature efficiency factor 'F' for the correction of the logarithmic temperature gradients LMTD must be used. F can be determined using below figure.



(a) One-shell pass and 2, 4, 6, etc. (any multiple of 2), tube passes

From figure Temperature efficiency factor, F, as a function of P and R

The parameters P and R are calculated from the temperatures T1, T2, t1, and t2.

P = 0.33 R = 0.75

From the diagram, the value of F is read off at the intersection of P and R: F = 0.948

CMTD = F × LMTD = 0.92 × 27.42 = 25.22 °C

6.1.4 Estimation of the required heat exchanger area, A

Heat load, Q = 17,400 W

Temperature gradient, CMTD = 25.22 °C

Estimated overall heat transfer coefficient, U = 716 W/m² K

Required heat exchanger area, A, is given below

$$A = \frac{Q}{U \times CMTD} = \frac{17400}{716 \times 25.22} = 0.96 \text{ m}^2$$

6.1.5 Selection of an appropriate heat exchanger

A heat exchanger type having the required area and sufficient flow velocities with the flows on the tube side and the shell side must be selected.

Chosen: Type 1DN 150 with 2 passes and 14 tubes of 25×2.

Determination of the heat exchanger area with 1m tube length:

A =1.1×1=1.1 m²

Table 6.1.5.1 Final Result of Optimum Heat Exchanger

Parameters	Units
Arrangement of tubes	Equilateral triangle
Tube diameter	25mm
Tube length	1000 mm
Nominal shell diameter (DN)	163mm
Surface area of heat transfer	1.1
(m²/m)	8.73
VR (m³/hr)	6.37
VM (m³/hr)	10
Number of baffles	14
Number of tubes (n)	1
Number of shell passes	2
Number of tube passes (z)	2
Tube thickness (mm)	174
Shell diameter (m)	100
Baffle spacing (mm)	

6.1.6 Determination of the flow velocity using the columns VR and VM (From the table 6.1.5.1)

The volumetric flows on the tube and shell side are listed in columns, VR and VM, which are required for a flow velocity of 1 m/s.

- Checking the tube side:

On the tube side there must be a flow of VR =8.73 m³/h for a flow velocity of 1 m/s.

In our example, the flow on the tube side is only V_{tube} =1 m³/h.

The resulting real flow velocity, W_t, is as follows:

$$W_t = \frac{V_{tube}}{VR} \times 1 = \frac{1}{8.73} \times 1 = 0.114 m/s$$

- Checking the shell side:

On the shell side VM = 6.37 m/h for 1 m/s with a baffle spacing, B = 100mm.
For B = 200 mm the flow is 2 × 6.37 = 12.74 m³/h for 1 m/s on the shell side.
In the example, the flow on the shell side, V_{sh} = 0.75 m/h.
This gives a real flow velocity, W_{sh}, as follows:

$$W_{sh} = \frac{V_{shell}}{VM} \times 1 = \frac{0.75}{6.37} \times 1 = 0.117 m/s$$

6.1.7 Calculation of the heat transfer coefficients on the tube side and the shell side

Using the found flow velocities on tube and shell side, the Reynolds numbers can be determined.

- **Tube-side: W_{tube} = 0.114 m/s**

$$Re = w \times \frac{d}{\nu} = 0.114 \times \frac{0.021}{1.006 \times 10^{-6}} = 2,379.7$$

$$Pr = \frac{c \times \nu \times \rho \times 3600}{\lambda} = \frac{1.16 \times 1.006 \times 10^{-6} \times 1000 \times 3600}{0.5978} = 7.03$$

$$Nu = 0.023 \times 2379.7^{0.8} \times 7.03^{0.33} = 22$$

$$\alpha_i = \frac{Nu \times \lambda}{di} = \frac{22 \times 0.597}{0.021} = 625.4 \text{ w/m}^2\text{k}$$

$$\alpha_{io} = 625.4 \times \frac{21}{25} = 525.3 \text{ w/m}^2\text{k}$$

- **Shell-side: W_{shell} = 0.117m/s**

$$Re = w \times \frac{d}{\nu} = 0.117 \times \frac{0.025}{0.364 \times 10^{-6}} = 8035.7$$

$$Pr = \frac{c \times \nu \times \rho \times 3600}{\lambda} = \frac{1.165 \times 0.364 \times 10^{-6} \times 974 \times 3600}{0.6687} = 2.224$$

$$Nu = 0.023 \times 8035.7^{0.8} \times 2.224^{0.33} = 39.83$$

$$\alpha_o = \frac{Nu \times \lambda}{do} = \frac{39.83 \times 0.668}{0.025} = 1064.2 \text{ w/m}^2\text{k}$$

6.1.8 Determination of the overall heat transfer coefficient U

Considering the resistances of the tube wall
Tube wall thickness, s = 0.002 m;
wall heat conductivity, l = 50 W/m K;

$$\frac{1}{U} = \frac{1}{\alpha_{io}} + \frac{1}{\alpha_o} + \frac{s}{\lambda} = \frac{1}{525.3} + \frac{1}{1064.2} + \frac{0.002}{50} = 0.0028$$

U = 357w/m²k

6.1.9 Calculation of the actual heat load of the selected heat exchanger and comparison with the U-value

Required heat load, Q_{req}

Q = U × A × CMTD = 357 × 1.1 ×25.22 = 9903.8 W

$$U_{req} = \frac{Q_{req}}{A \times CMTD} = \frac{17400}{1.1 \times 25.22} = 627.2 \text{ w/m}^2\text{k}$$

6.2 Modelling of shell and tube heat exchanger

Using table 6.1.5.1 a 3D is model is using Solidworks modelling software.
Initially the parts are modelled individually in Solidworks parts modelling. After each is modelled the parts are assembled in Solidworks assembly.
The main components made in modelling are

1) Tubes
2) Shell with flanges for mounting and inlet and outlet valve
3) Flower Baffles
4) Channel cover with inlet and outlets
5) Channel cover without inlets and outlets
6) M12 blots and nuts.

6.2.1 Tubes

A tube with 25mm outer dia and 2mm thickness with U shape length 1m as shown in figure is modelled by using Sweep extrude command.

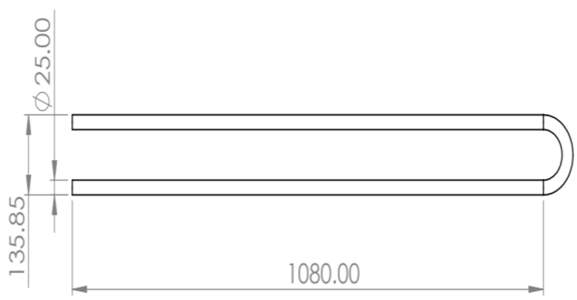


Fig 6.2.1.1 Orthographic view of tube

6.2.2 Shell with flanges for mounting inlet and outlet valve

Center member is modelled according to the dimensions in table 6.1.5.1 using the following commands

- Boss extrude
- Revolve extrude

Its orthographic view is shown in the figure 6.2.2.1

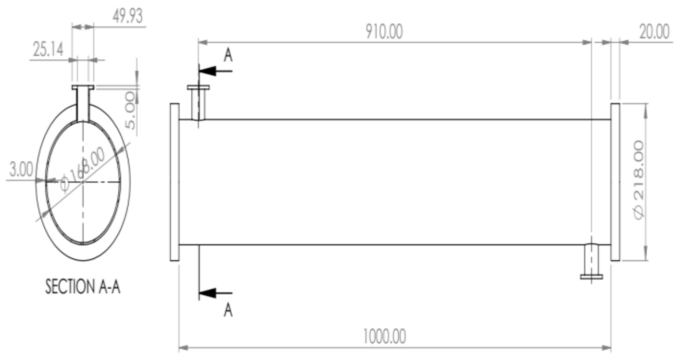


Fig 6.2.2.1 orthographic view of shell side.

6.2.3 Flower baffle plates

Baffle with a shape shown in the figure 6.2.3.1 with a thickness of 3mm is modelled with the following commands

- Boss extrude
- Trim

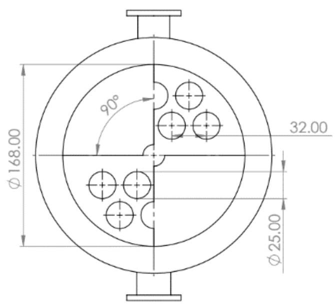


Figure 6.2.3.1 Orthographic view of flower plate

6.2.4 Channel cover with inlet and outlets

End channel cover are modeled with inlet and outlet valves as shown in the figure 6.2.4.1.A partition is made between the cover for the flow separation.

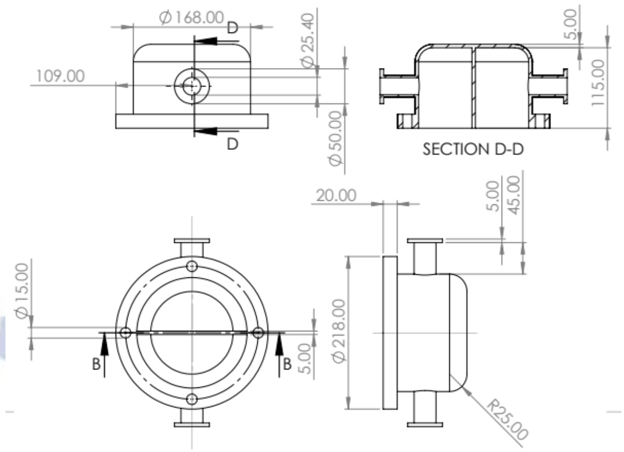


Fig 6.2.4.1 Orthographic view of channel cover.

6.2.5 M12 blots and nuts.

M12 bold with one-inch length is imported from the Solidworks library file.

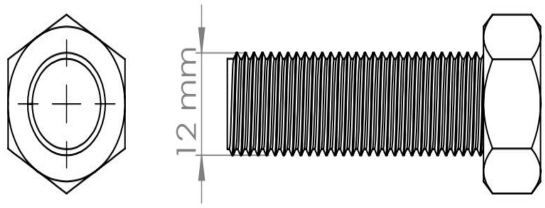


Fig 6.2.5.1 M12 Nut and bolt.

6.2.6 Assembly

The individual parts of shell and tube heat exchanger are assembled in Solidworks assembly module. The assembly is made by using mate option in solid works assembly module. The assembly drawing and bill of material is shown in the figure 6.2.6.1

Fig 6.2.6.1 Assembly and sectional view of shell and tube heat exchanger

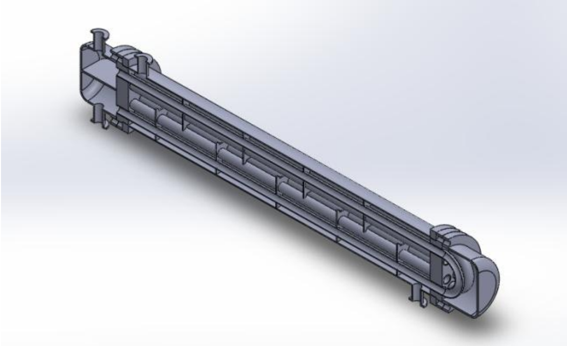


Fig 6.2.6.2 Isometric view of shell and tube heat exchanger

7. ANALYSIS OF SHELL AND TUBE HEAT EXCHANGER

7.1 Numerical analysis of shell and tube heat exchanger

This chapter includes CFD analysis of shell and tube heat exchanger. This analysis includes different steps which are discussed below.

Step 1 à 3D modelling

Step 2 à Preprocessing

Step 3 à Postprocessing

7.1.1 3D modelling

The 3D modelling of setup is made using any 3D modelling software. For this setup Solidworks is used to create 3D model. This is explained in detail in the previous chapter.so this chapter mainly concentrates of numerical setup.

7.1.2 Preprocessing

This stage consists of different stages which explained in below.

Step 1: - Geometry cleanup

In this step the complex geometry such as edge fillets, surface fillets are cleaned. This method is performed to decrease the processing time by making the mesh smoother.

Step 2: - Topology refinement

In this step the topology of the geometry is check before going to meshing. This will reduce the meshing errors.

Step 3: - Meshing

Meshing is the process which converts the 3D model into mathematical model. The accuracy of the solution depends on the type, size and order of the mesh. Before selecting the type of analysis, the science of the meshing is selected. For CFD analysis the science is CFD mesh.

Step 3: - Check mesh quality

Higher the mesh quality greater the accuracy of the solution. There are different techniques and fixed parameter to find the mesh quality.

Ste 4: - Creating named selection

This step is optional for the any type of analysis. This step helps to identify the parts easily during the post processing.

7.1.3 Postprocessing

This stage consists of different stages which explained in below.

Step 1: - Selecting solver

For CFD analysis Ansys fluent is used as a solver for the solving. In this step material properties, boundary conditions and magnitude of error is defined. After setting the necessary conditions the solution is started for solving.

Step 2: - Results

In this step graphs, temperature cantors are plotted for the visual reports.

7.2 Setting CFD simulation

7.2.1 Numerical solution model

B. Numerical simulation model The simulation code used in this study is ANSYS Fluent, it offers numerical simulations of thermal fields which allow the comparison of the characteristics of the multitubular heat exchanger in parallel-current and counter-current configuration in terms of heat transfer coefficient, flow rate, pressure and temperature, a cooling fluid passes through five central tubes and the fluid secondary passes into the annular space, the two fluids are separated by a copper wall through which the conductive exchange passes, the geometrical characteristics of the heat exchanger are table 6.1.5.1.

1) **3D Model**

   The model of shell and geometry is created according to the calculated dimensions.

2) **Geometry cleanup**

   The 3D model is simplified to improve solution accuracy and decrease the process time. The simplified geometry is shown in the following figure

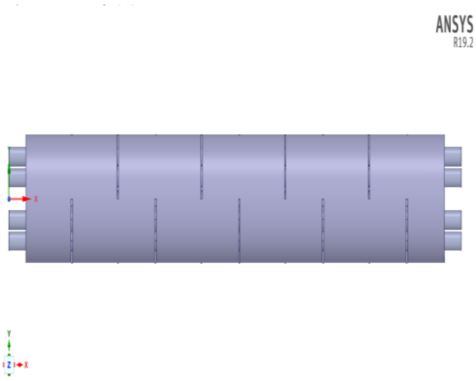


Figure 7.2.1.1 Geometry cleanup

3) Meshing

The simplified geometry is meshed using CFD mesh tool I Ansys workbench. Type of mesh chosen is first order tetrahedron. Later quality checks are done on the mesh model.

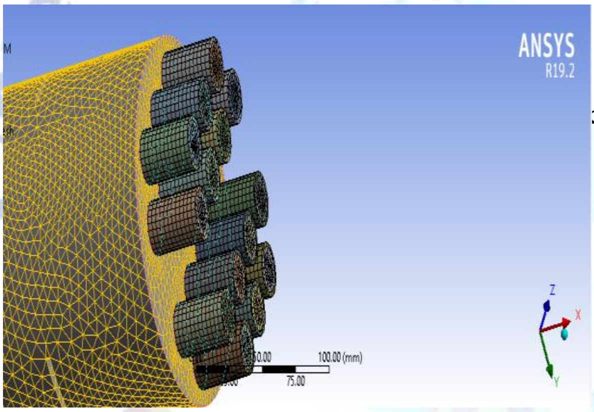


Fig 7.2.1.2 Mesh

4) Solution Setup

a) Modes

Here the governing equations are selected in the models menu. Energy and viscous equations are selected.

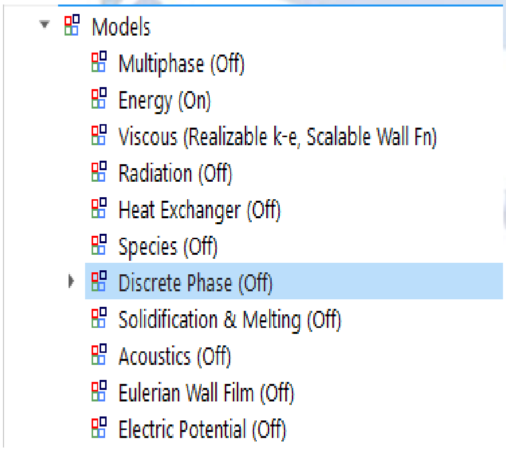


Fig 7.2.1.3 Model equations

b) Creating materials

In this tab materials like liquid and copper are created to assign for the geometry.

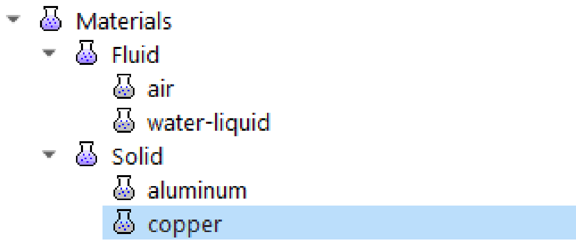


Fig 7.2.1.4 Material creation tab.

c) Cell zone condition

In this step the material is assigned to the geometry such as shell side liquid, tube side liquid and tube material as copper.

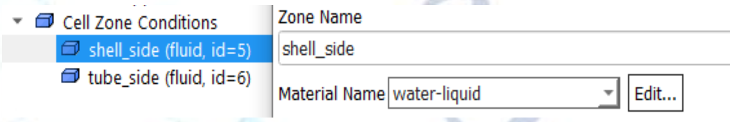


Fig 7.2.1.5 Cell zone conditions.

d) Boundary conditions

In this step boundary conditions like flow inlet temperatures, mass flow rates of shell side and tube side are defined according to the table 6.1.1.

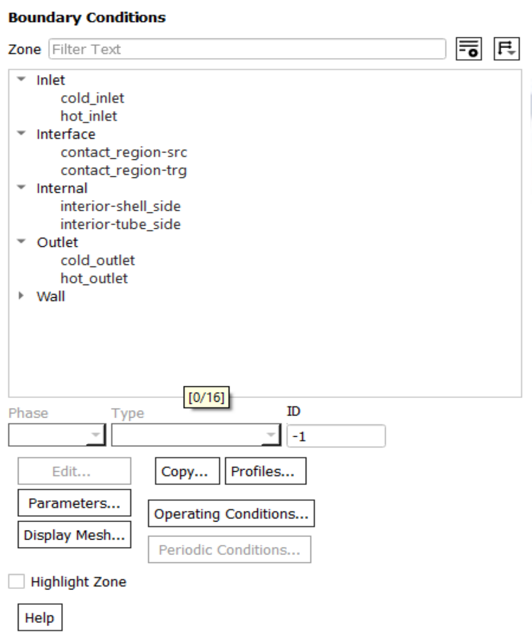


Fig 7.2.1.6 Boundary conditions

e) Defining mesh interface

In this step mesh interface such as coupled wall is defined between the hot fluid and cold fluid hence, heat transfer takes place between the fluids.

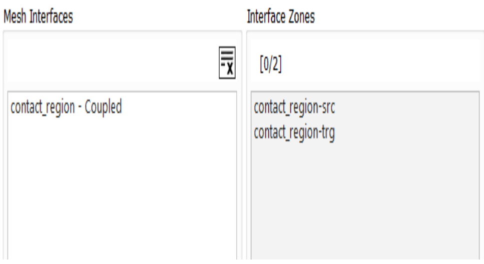


Fig 7.2.1.7 Mesh interface

f) Run Solution

After setting the complete setup the solution is calculated until the convergence is reached. So, then the approximate solution is reached. After this step temperature contours are plotted.

7.2.2 Solutions

To find the temperatures of outlets temperature contours are plotted for the above solved problem. The plotted results are shown below.

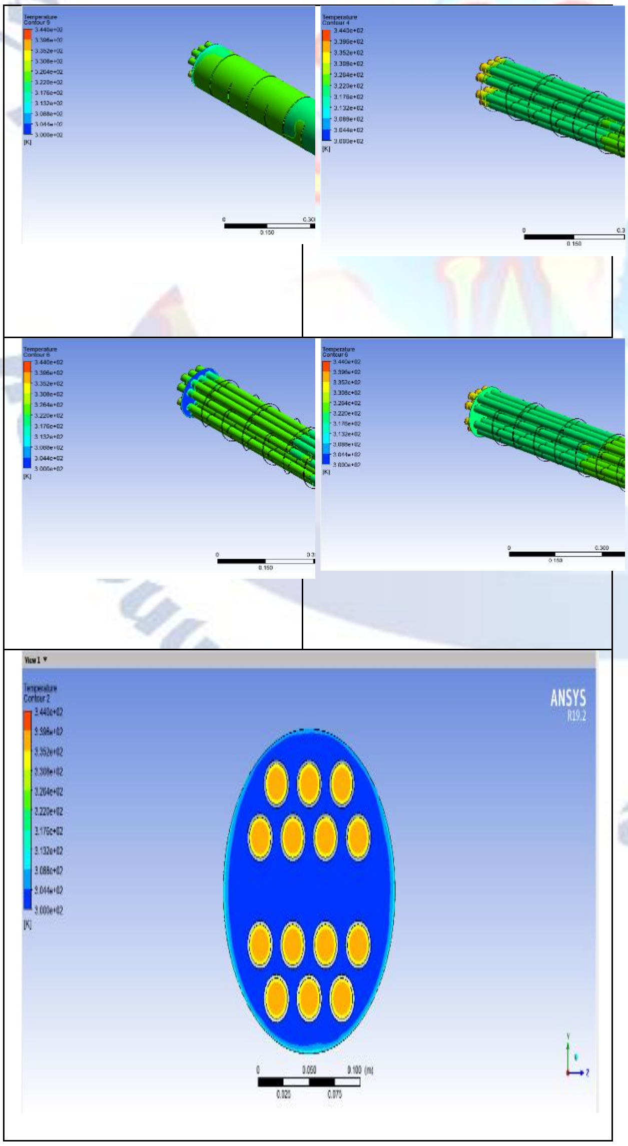


Fig 7.2.2.1 Temperature Contour plots

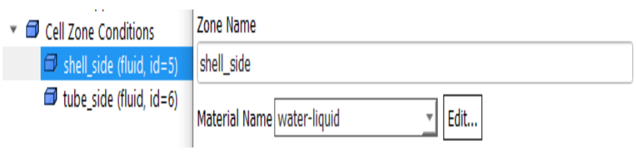


Fig 7.2.1.5 Cell zone conditions.

g) Boundary conditions

In this step boundary conditions like flow inlet temperatures, mass flow rates of shell side and tube side are defined according to the table 6.1.1.

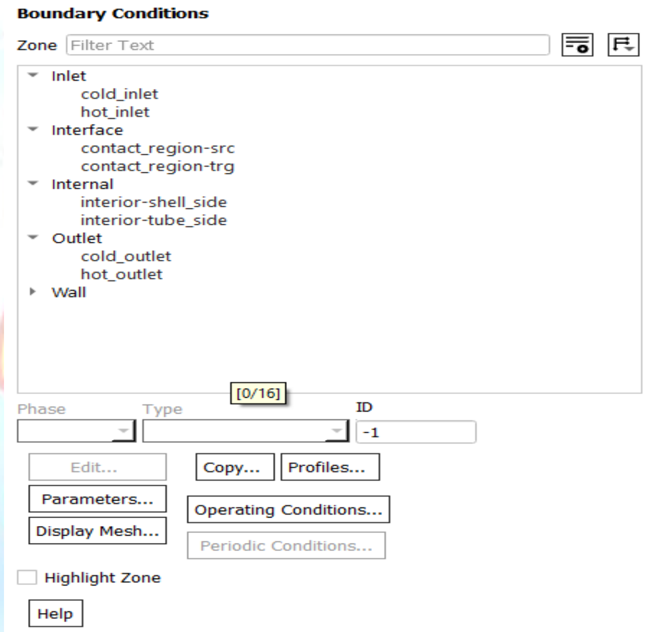


Fig 7.2.1.6 Boundary conditions

h) Defining mesh interface

In this step mesh interface such as coupled wall is defined between the hot fluid and cold fluid hence, heat transfer takes place between the fluids.

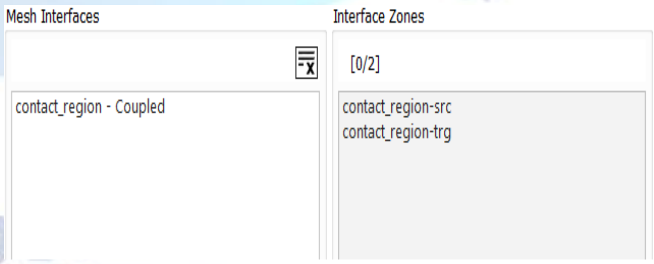


Fig 7.2.1.7 Mesh interface

i) Run Solution

After setting the complete setup the solution is calculated until the convergence is reached. So, then the approximate solution is reached. After this step temperature contours are plotted.

7.2.2 Solutions

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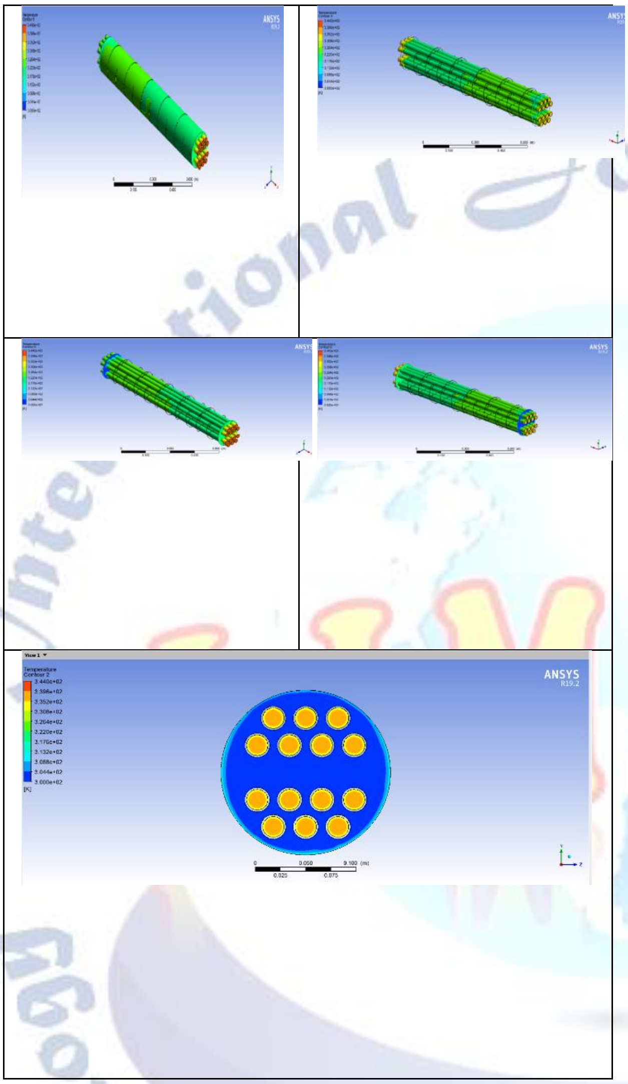

Fig 7.2.2.1 Temperature Contour plots

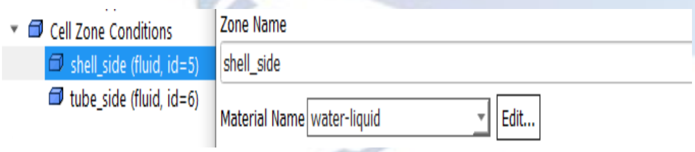

Fig 7.2.1.5 Cell zone conditions.

j) Boundary conditions

In this step boundary conditions like flow inlet temperatures, mass flow rates of shell side and tube side are defined according to the table 6.1.1.

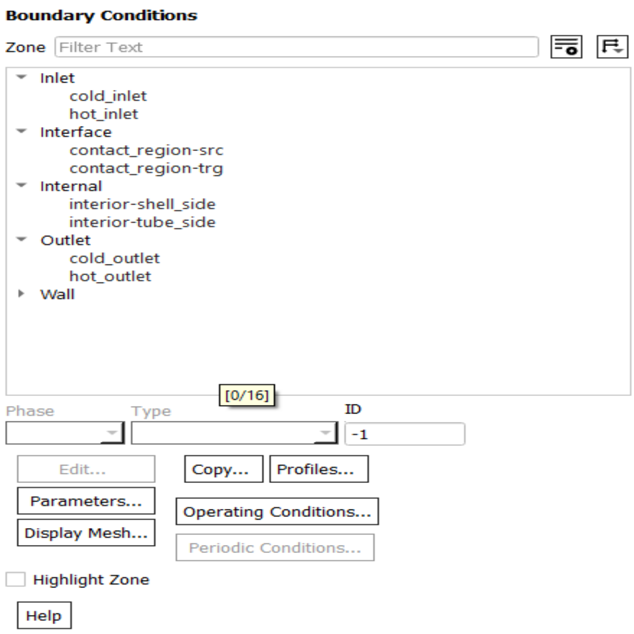

Fig 7.2.1.6 Boundary conditions

k) Defining mesh interface

In this step mesh interface such as coupled wall is defined between the hot fluid and cold fluid hence, heat transfer takes place between the fluids.

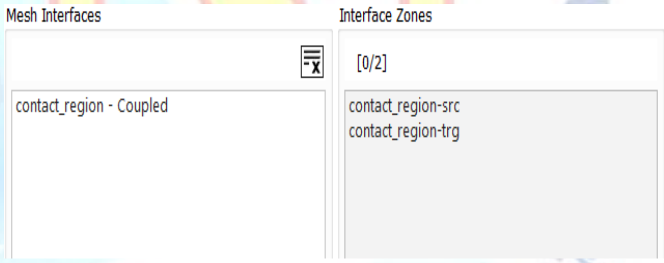

Fig 7.2.1.7 Mesh interface

l) Run Solution

After setting the complete setup the solution is calculated until the convergence is reached. So, then the approximate solution is reached. After this step temperature contours are plotted.

7.2.2 Solutions

To find the temperatures of outlets temperature contours are plotted for the above solved problem. The plotted results are shown below.

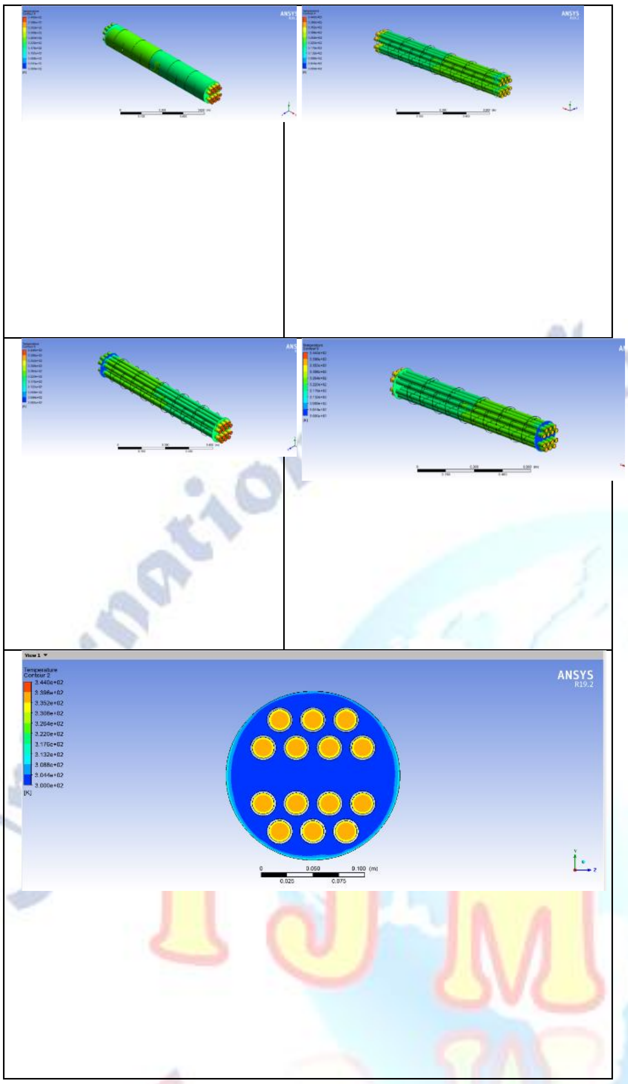

Fig 7.2.2.1 Temperature Contour plots

8. FABRICATION OF SHELL AND TUBE HEAT EXCHANGER

8.1 Material selection

Although there exists a wide range of designs and materials, some components are common to all. In all shell and tube heat exchangers, the tubes are mechanically attached to tube sheets, which are contained inside a shell with ports for inlet and outlet fluid or gas. They are designed to prevent the liquid flowing inside the tubes from mixing with the fluid outside the tubes. Tube sheets can be fixed to the shell or allowed to expand and contract with thermal stresses. In the latter design, an expansion bellows is used or one tube sheet is allowed to float inside the shell. The non-fixed tube sheet approach allows the entire tube bundle assembly to be pulled from the shell to allow cleaning of the shell circuit.

8.2 Components

8.2.1 Tubes

Heat exchangers with shell diameters of 10 to more than 100" typically are manufactured to the standards set forth by the Tubular Exchangers Manufacturers Association. Generally, the 0.625 to 1.5" tubing used in TEMA-sized exchangers is made from low carbon steel, copper.

Tubes are either drawn and seamless, or welded. High quality electro resistance welded tubes exhibit good grain structure at the weld. Extruded tube with low fins and interior rifling is specified for certain applications. Surface enhancements are used to increase the available metal surface or aid in fluid turbulence, thereby increasing the effective heat transfer rate. Finned tubing is recommended when the shell-side fluid has a substantially lower heat transfer coefficient than the tube-side fluid. Finned tubing is not finned in its landing areas, where it contacts the tube sheets. Also, the outside diameter of the finned portions of this tube design is slightly smaller than the un-finned areas. These features allow the tubes to be slid easily through the baffles and tube supports during assembly while still minimizing fluid bypass.

U-tube designs are specified when the thermal difference between the fluids and flows would result in excessive thermal expansion of the tubes. U-tube bundles do not have as much tube surface as straight tube bundles due to the bending radius, and the curved ends cannot be easily cleaned. Additionally, interior tubes are difficult to replace and often requiring the removal of outer layers or simply plugging the tubes. To ease manufacturing and service, it is common to use a removable tube bundle design when specifying U-tubes.

Fig 8.1 Tubes

8.2.2 Tube Sheets

Tube sheets usually are made from a round, flat piece of metal. Holes are drilled for the tube ends in a precise location and pattern relative to one another. Tube sheets are manufactured from the same range of materials as tubes. Tubes are attached to the tube sheet by pneumatic or hydraulic pressure, or by roller expansion. If needed, tube holes can be drilled and reamed, or they can be machined with one or more grooves. This greatly increases tube joint strength

The tube sheet is in contact with both fluids, so it must have corrosion resistance allowances and metallurgical and electrochemical properties appropriate for the fluids and velocities. Low carbon steel tube sheets can include a layer of a higher alloy metal bonded to the surface to provide more effective corrosion resistance without the expense of using the solid alloy.

The tube hole pattern, or "pitch," varies the distance from one tube to the other as well as the angle of the tubes relative to each other and to the direction of flow. This allows the fluid velocities and pressure drop to be manipulated to provide the maximum amount of turbulence and tube surface contact for effective heat transfer.

Fig 8.2 Tube sheet with holes drilled

Where the tube and tube sheet materials are joined by weld metals, the tube joint can be further strengthened by applying a seal weld or strength weld to the joint. In a strength weld, a tube is slightly recessed inside the tube hole or slightly extended beyond the tube sheet. The weld adds metal to the resulting lip. A seal weld is specified to help prevent the shell and tube liquids from intermixing. In this treatment, the tube is flush with the tube sheet surface. The weld does not add metal but rather fuses the two materials. In cases where it is critical to avoid fluid intermixing, a double tube sheet can be provided. In this design, the outer tube sheet is outside the shell circuit, virtually eliminating the chance of fluid intermixing. The inner tube sheet is vented to atmosphere, so any fluid leak is detected easily

8.2.3 Shell Assembly

The shell is constructed either from pipe up to 24" or rolled and welded plate metal. For reasons of economy, low carbon steel is in common use, but other materials suitable for extreme temperature or corrosion resistance often are specified. Roundness and consistent shell inner diameter are necessary to minimize the space between the baffle outside edge and the shell, as excessive space allows fluid bypass and reduces performance. Roundness can be increased by expanding the shell around a mandrel or double rolling after welding the longitudinal seam. In extreme cases, the shell can be cast and then bored to the correct inner diameter.

Fig 8.3 Shell cover

In applications where the fluid velocity for the nozzle diameter is high, an impingement plate is specified to distribute the fluid evenly to the tubes and prevent fluid-induced erosion, cavitation and vibration. An impingement plate can be installed inside the shell, eliminating the need to install a full tube bundle, which would provide less available surface. Alternatively, the impingement plate can be installed in a domed area (either be reducing coupling or a fabricated dome) above the shell. This style allows a full tube count and therefore maximizes utilization of shell space

8.2.4 End Channels and Bonnets

Used to control the flow of the tube-side fluid in the tube circuit, end channels or bonnets typically are fabricated or cast. They are attached to the tube sheets by bolting with a gasket between the two metal surfaces. In some cases, effective sealing can be obtained by installing an O-ring in a machined groove in the tube sheet

The head may have pass ribs that dictate whether the tube fluid makes one or more passes through the tube bundle sections. Front and rear head pass ribs and gaskets are matched to provide effective fluid velocities by forcing the flow through various numbers of tubes at a time. Generally, passes are designed to provide roughly equal tube-number access and to ensure even fluid velocity and pressure drop throughout the bundle. Even fluid velocities also affect the film coefficients and heat transfer rate so that accurate prediction of performance can be readily made.

Fig 8.4 End channel cover

Fig 8.5 Pass divider

Designs for up to six tube passes are common. Pass ribs for cast heads are integrally cast, then machined flat while pass ribs for fabricated heads are welded into place. The tube sheets and tube layout in multi-pass heat exchangers must have provision for the pass ribs. This requires either removing tubes to allow a low cost straight pass rib, or machining the pass rib with curves around the tubes, which is more costly to manufacture. Where a full bundle tube count is required to satisfy the thermal requirements, the machined pass rib approach may prevent having to consider the next larger shell diameter.

8.2.5 Baffles

Baffles serve two important functions. First, they support the tubes during assembly and operation and help prevent vibration from flow-induced eddies. Second, they direct the shell-side fluid back and forth across the tube bundle to provide effective velocity and heat transfer rates.

A baffle must have a slightly smaller inside diameter than the shell's inside diameter to allow assembly, but it must be close enough to avoid the substantial performance penalty caused by fluid bypass around the baffles. Shell roundness is important to achieve effective sealing against excessive bypass. Baffles can be punched or machined from any common heat exchanger material compatible with the shell side fluid. Some punched baffle designs have a lip around the tube hole to provide more surface against the tube and eliminate tube wall cutting from the baffle edge. The tube holes must be precise enough to allow easy assembly and field tube replacement yet minimize the chance of fluid flowing between the tube wall and baffle hole.

Fig 8.6 Tubes with Baffles

Fig 8.7 Flower Baffles

Single-segmental baffles force the fluid or gas across the entire tube count, where it changes direction as dictated by the baffle cut and spacing. This can result in excessive pressure loss in high velocity gases. To effect heat transfer yet reduce the pressure drop, double-segmental baffles can be used. This approach retains the structural effectiveness of the tube bundle yet allows the gas to flow between alternating tube sections in a straighter overall direction, thereby reducing the effect of numerous direction changes. This approach takes full advantage of the available tube surface. But reduced performance should be expected due to a reduced heat transfer rate. Because pressure drop varies with velocity, cutting the velocity in half using double-segmental baffles results in roughly one-quarter of the pressure drop seen in a single-segmental baffle space over the same tube surface

8.3 Welding and Machining Process

After the materials were purchased, as per the design parameters the dimensions on the materials have to make. Initially we marked the dimensions of the shell on the sheet metal. Then the sheet metal is cut to that shape. It's then rolled into a cylindrical shape of diameter 178mm. To join the ends the TIG welding is done. The shell of the heat exchanger is ready to process.

In this project we have used manual metal arc welding (MMAW) and gas welding for the fabrication of shell and tube heat exchanger. It is one of the most common types of arc welding. The consumable rod is often covered by a flux that creates vapor when it is melted. This gas will protect the weld from external contamination. Moreover, the flux will cover the weld with a layer of slag. This slag must be removed afterwards. Even if this welding type is simple, requires little training and inexpensive equipment, it is still a slow process, because the electrode has to be replaced frequently and the slag removed. Also, different electrodes are needed to weld different materials. This method is often used for construction of this shell and tube heat exchanger.

The tube which is of parallel type has to be arrange in a particular manner which is considered to be parallel flow process. The tube is placed by the supported enclosures on the both sides of the shell. The holes for inlet and outlet passage were also provided on both the ends of the shell perpendicular to each other. The problem which we faced is the insertion of tubes in to the shell. An improper insertion may cause leakages into the shell from tubes. A heater is provided to raise the temperature of the hot water and a pump is provide to circulate the water inside the tube and it is also coupled into the cold-water supply circulation.

Machining is any of various processes in which a piece of raw material is cut into a desired final shape and size by a controlled material-removal process. The processes that have this common theme, controlled material removal, are today collectively known as subtractive manufacturing, in distinction from processes of controlled material addition, which are known as additive manufacturing. Exactly what the "controlled" part of the definition implies can vary, but it almost always implies the use of machine tools (in addition to just power tools and hand tools)

Fig 8.9 Drilling

Fig 8.10 Cutting

8.4 ASSEMBLING

A heat exchanger assembly has an elongated shell provided with fluid inlet and fluid outlet openings. An elongated bundle assembly is received within the shell. The bundle assembly has a plurality of elongated tubes extending generally longitudinally and a plurality of generally parallel fin plates which are transversely oriented. The bundle assembly has a top sheet and a bottom sheet. The bundle assembly support is interposed between the bottom sheet and the shell.

A baffle is provided in the form of an elongated plate extending generally diagonally between the top sheet of the bundle assembly and the shell. In a preferred form, the baffle plate is provided with an underlying seal which is interposed between the baffle plate and the top sheet and has an upper edge which is of generally complementary curvature with respect to the adjacent portions of the shell and may take the form of a portion of a sine wave. The bundle assembly support may provide cooperation to facilitate insertion of the bundle assembly into the shell and removal of the same there from. The bundle assembly support may cooperate with the shell in defining a condensate receipt reservoir.

Fig 8.11 Assembled Shell

Conflict of interest statement

Authors declare that they do not have any conflict of interest.

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