

# An Optimal Design Procedure For Heat Exchangers From Process Plants

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**ABSTRACT** - Heat Exchangers are now a days one of the main equipments used in industries. It finds wide applications in the field of thermal science such as cooling , heating and so on. Inorder to make use of these applications, performance characteristics, different co-relations of heat exchangers are to be studied. This paper tells us different design aspects and shows an optimal , user friendly and a simplest design procedure mainly intended to tackle heat transfer requirements in chemical industries. The present study focuses on selection and design of an optimal heat exchanger for cooling Ethyl Benzene, mainly used as a solvent in paint industry., obtained as a distillate from the column. The capacity of the plant was 50 TPD. The temperature of the Ethyl Benzene obtained from the column is 1350C which is not recommended for the production of paints. From detailed studies, it is clear that a temperature of 400C is very much ideal, desired and a warm temperature for the production of paints. Availability of cooling water is 10000 Kg/hr at 300C. For meeting the prescribed requirement, a suitable heat exchanger has to be designed .This paper is very important for both petroleum and petrochemical industries which are day to day indulged in meeting specific heat transfer requirements.

**Keywords:** chemical industries; Optimal design; performance parameters; heat transfer coefficient.

## 1 . INTRODUCTION

Heat exchangers may be defined as the equipment which transfers energy from a hot fluids to cold fluid with maximum rate and minimum investment and running costs. The present work deals in design of shell and tube heat exchanger. Heat exchangers are classified into direct contact and indirect contact heat exchangers, parallel and counter, cross flow heat exchangers. In shell and tube heat exchangers, one of the fluid 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 tube. The main parts are tube, shells, baffles, tube sheet and channel covers etc. It is apparent that higher heat transfer coefficient result when a liquid is maintained in a state of turbulence. The centre to centre distance between baffles is called baffle spacing or baffle pitch. In this work , we have dealt with various aspects in designing a heat exchanger and various problems faced during design. This plays an important role in modern industry which deals with process like heat transfer , heat recovery and conservation of energy also. Hence this design and study of heat exchangers give a variety of application in developing industries and future generations.

## 2. LITERATURE SURVEY

A large amount of works had been conducted in fields of shell and tube type heat exchangers (STHE). Some of the worth noting contribution are described for supporting present work are as followed. Ahmad Fakheri[1] in his paper shows that how to calculate the efficiency of the heat exchangers with the concept of 2nd law of TD and explained the relevance of AMTD calculation and entropy generation and irreversibility analysis. That is he has tried a thermodynamic analysis in his work.. Ahmad Fakheri[2] provided one user friendly equation which can be deployed for the efficiency calculation of heat exchangers in networks. It too helps in finding out effectiveness and efficiency for of individual heat exchangers. V.K. Patel and R.V. Rao made use of particle swarm optimization (PSO), for design optimization of shell-and-tube heat exchangers with a view to minimize total annual cost which was taken as the objective function from economic view point. Minimization of total annual cost is considered as an objective function. shell side internal diameter, outer tube diameter and closer baffle side internal diameter and closer baffle spacing are taken for optimization.

Tube layouts namely triangle and square are also taken as reference for optimization purpose. A clear cut idea of low finned tube Heat Exchangers and its advantages over plain tube units and spotted several technical issues as shell side and tube side pressures, cost size etc. had been contributed by Shiv Kumar Rathore and Ajeet Bergaley. A well known scientist A. Pignotti established a strong relationship between the effectiveness of two heat exchanger configurations and provided the way by which the effectiveness of one combination could be expressed in terms of specific heat capacity rate ratio and number of transfer units and it was a well noted contribution in the field of design of heat exchangers. M. S. Bohn delivered a method in calculating the electric power by a thermoelectric heat exchangers and he found it as an extension of the transfer units method and effectiveness of thermoelectric power is established.

### 3. DESIGN METHODOLOGY AND MATERIAL AWARENESS

Material selection is very important in design of heat exchangers. Criteria in selection of proper material based on properties such as mechanical, thermal, chemical, electrical and material cost. Corrosion resistance, thermal conductivity, material cost, sufficient strength and non reactive with flowing fluid are the desirable characteristics of a tube material. So commonly used tube material are copper tubes. Common material used for shells and baffles are Carbon steel due to availability, low cost, high strength and non corrosiveness with flowing fluid.

### 4. TASKS IN DESIGN OF SHELL AND TUBE HEAT EXCHANGER.

1. Problem specification
2. Conducting a detailed literature survey if necessary.
3. Collect necessary thermo physical properties of hot and cold fluids
4. Perform energy balance and heat transfer rate.
5. Select tentative number of shell and tube passes and find out LMTD
6. Take reasonable value of overall heat transfer coefficient.
7. Select tube diameter, tube length and calculate number of tubes
8. Select tube pitch. select the shell diameter which can accommodate the required number of tubes. A tube sheet layout table is used for this purpose
9. Estimate the tube side and shell side heat transfer coefficients.

10. Calculate overall coefficient UD by selecting . . .
- . the dirt factor applicable in the given system and .
- . service and found out area based on this UD value.

### 5. PROBLEM SPECIFICATION

It is an important step in the heat exchanger design process. In an industry, ethyl benzene is commercially prepared by the alkylation of benzene with ethylene. The reaction products are separated in series of distillation column. Ethyl benzene is obtained as a distillate from the last column called ethyl benzene column at 1350C. Capacity of the plant is 50tpd. For fulfilling the purpose, ethyl benzene has to be cooled from 1350C to 400C and stored in a storage tank. This 400C is ideal and desirable temperature for the production of paints. For cooling, availability of cooling water is 10000 Kg/hr at 300C. For this purpose, a heat exchanger has to be designed. Studies revealed that the criteria for selection of heat exchanger are on the basis of plant capacity, heat transfer rate etc. and the shell and tube heat exchanger possess such features and is selected to fulfil the requirement. For the design purpose, High viscosity fluid flows through the tube and water is highly viscous when compared with ethyl benzene. Therefore water flows through tube. Here in the problem, a chance of corrosion is more in tubes due to direct contact with water and fouling is more in tubes than shell. So cleaning of tube is very easy by passing fluid with high force. If water flows through the shell, it is difficult to clean inside shell. There are several heat exchangers which shows multi tube passes. This finds exact use of LMTD correction factor that may be used in finding out mean temperature difference in the Heat Exchanger. While computing the tube side coefficient, it is strictly to be assumed that all tubes in the exchanger are exposed to the same thermal and hydraulic conditions. The value of coefficient will come to be same for all tubes and thereafter calculations may be done for a single tube.

#### 5.1 CHANCES FOR TUBE FAILURE

Corrosion products such as rust may build up in walls resulting in reduced heat transmission and eventually the tube fails. This fouling problem can be minimized or can be eliminated by properly choosing corrosion resistant materials of construction in the process of design. There are chances of Crystallisation which may be occurring in cooling water streams contains sulphates and carbonates and the solubility of these salts decreases with increase in temperature and they will precipitate on heat transfer surface when water is heated leading to scale formation. This

problem can be avoided by restricting outlet water temperature to desired ranges depending up on safe design. The necessary table for designing shell and tube heat exchanger are as given below. vibration by baffles such as segmental baffles .

**5.2 TABLE SHOWING PROPERTIES OF TUBE SIDE FLUID**

W A T E R  A s  L I Q U I D	Tempa- ture K	Density, Kg/m <sup>3</sup>	Thermal Conductivity W/mK	Specific Heat in J/Kg	Prantl Number
	0	100	0.5524	4216	1.3
20	1000	0.5978	4178	7.02	
40	995	0.6280	4178	4.34	
60	985	0.6513	4183	3.02	
80	974	0.6687	4195	2.22	
100	961	0.6804	4216	1.740	
120	945	0.6757	4215	1.4	
140	928	0.6638	4283	1.241	
160	909	0.6804	4342	1.099	
180	889	0.6757	4417	1.044	
200	867	0.6652	4505	0.937	
220	842	0.6534	4610	0.891	
240	815	0.6350	4756	0.871	
260	786	0.6106	4949	0.874	
280	752	0.5803	5208	0.910	
300	714	0.5396	5728	1.019	
-50	704	0.5466	4463	2.6	
-40	691	0.5466	4467	2.280	
-30	979	0.5489	4476	2150	

**5.2 TABLE SHOWING PROPERTIES OF SOME COMMON SHELL SIDE FLUIDS**

Sl no.	Substance	Boiling Point in Degree Celsius	Density in kg/m <sup>3</sup>	Melting Point in Degree celsius
1	Ethyl Benzene	137	840	95
2	Ethylene	169.4	577	169
3	Benzene	80.12	878.6	5.5
4	Pentane	36	626.2	129
5	Ethylene Glycol	198	103	129
6	Propane	-42	649	189.7
7	Ethyl Alcohol	78.4	789	114.3
8	Methyl Alcohol	64.7	791.8	97
9	Toluene	173	897	34

**5.2 TABLE SHOWING PROPERTIES OF ETHYL BENZENE**

Properties on degree celsius	Viscosity in Kg/ms	Thermal Conductivity in W/mk
-50	23.98 x 10 <sup>-4</sup>	0.1472
-10	10.71 x 10 <sup>-4</sup>	0.1372
10	7.84 x 10 <sup>-4</sup>	0.1372
40	5.33 x 10 <sup>-4</sup>	0.1256

**5.2 TABLE SHOWING TYPICAL RANGES OF OVERALL HEAT TRANSFER COEFFICIENTS**

Hot fluid	Cold fluid	kcal/h m <sup>2</sup> k
Steam	water	1250-3800
Steam	Light Oils	250-750
Steam	Organic Solvents	50-400

Water	water	750-1400
Organic Solvents	water	250-750

## 5.2 TABLE SHOWING TUBE OUTSIDE DIA- . . METER AND OTHER RELEVANT DETAILS

Tube OD	BWG	Wall Thickness inch	ID, inch	Flow Area Per Tube, inch
½	12	0.180	0.282	0.0625
½	16	0.065	0.70	0.1076
¾	16	0.134	0.482	0.182
¾	10	0.065	0.620	0.302
¾	16	0.049	0.652	0.334

## 5.3 DIMENSIONS OF STEEL PIPE

Nominal Pipe Size, inch	OD, inch	Schedule No.	ID, inch	Flow Area Per Pipe,
1/8	0.405	4080	0.2690.215	0.0580.36
3/8	0.675	4080	0.4930.423	0.1920.141
½	0.640	4080	0.620.546	0.3040.235
¾	1.05	4080	0.8240.742	0.5340.432
1	1.32	4080	1.0480.957	0.8640.718

## 5.4 NECESSARY THERMO PHYSICAL . . . PROPERTIES

### 1. PROPERTIES OF WATER

Since the inlet and outlet temperatures of water are 40°C and 30°C. So the properties are calculated at an average temperature of 35°C

Density = 996Kg/m<sup>3</sup>  
 Specific Heat = 4.175 KJ/KgK  
 Viscosity = 8 x 10<sup>-4</sup> Kg/ms  
 Thermal Conductivity = 0.623 W/Mk  
 = 0.536 Kcal/hrmK

### 2. PROPERTIES ETYL BENZENE

Since the inlet and outlet temperatures of ethyl benzene is 135°C and 40°C. So the properties are calculated at an average temperature of 87.5°C.

Density =840kg/m<sup>3</sup>  
 Specific heat =2.093kJ/kgK  
 Viscosity =0.33 centipoise  
 =3.3x10<sup>-4</sup>kg/ms  
 Thermal Conductivity =0.1156W/mK

## 3.ENERGY BALANCE

plant capacity =50 tpd

m = 50x1000/24  
 =2083kg/hr  
 Heat transfer rate =2083x2.093x (.135-40)  
 =414173kJ/hr  
 =98920kcal/hr

Heat lost by ethyl benzene =heat gained by water

$$Q_w = m C_p \Delta T$$

$$\Delta T = Q_w / m C_p$$

$$= T_{co} - T_{ci}$$

$$= 414173 / (10000 \times 4.175)$$

$$= 10^{\circ}C$$

$$T_{co} - 30 = 10^{\circ}C$$

$$\text{So, } T_{co} = 30 + 10$$

$$= 40^{\circ}C$$

4. Let us try a 1 – 1 Pass Counter flow Heat . .  
 . Exchanger

### 4.1 LMTD CALCULATION

$$LMTD = T_{hi} - T_{co} = 135 - 40 = 95^{\circ}C$$

$$= T_{ho} - T_{ci} = 40 - 30 = 10^{\circ}C$$

$$LMTD = 95 - 10 / \ln(95 / 10) = 38^{\circ}C$$

Taking an average heat transfer co efficient of 350 Kcal/m<sup>2</sup>hrK from HMT tables

$$\text{So area required , } A = Q / ( U \times LMTD )$$

$$= 98920 / ( 350 \times 38 ) = 7.44 \text{ m}^2$$

5. Select ¾ , 16 BWG, 1 – inch 60<sup>0</sup> triangular pitch and 3000 mm long, putting ethyl benzene on shell side and cooling water on tube side

$$\text{Outer surface area of tube , } a = d l$$

$$= \pi \times 0.019 \times 3$$

$$= 0.179 \text{ m}^2$$

$$\text{So number of tubes required } = A/a$$

$$= 7.44 / 0.179$$

$$= 42$$

$$\text{Flow area } = n \times (\pi / 4) \times d_i^2 = 0.00813 \text{ m}^2$$

So linear velocity of water = Flow rate / Flow area

$$= 10/3600 \times 0.00813$$

$$= 0.3417 \text{ m/s}$$

In this case, the linear velocity of water is too low (usually velocity should remain 1 m/sec). So it should be increased at least by about 4 times. So let us go for 1-4 pass exchanger. So trial exchanger 1-4 pass heat exchanger  $\frac{3}{4}$  inch outer diameter, 16 BWG, 3000 mm long and 1 inch  $60^0$  triangular pitch. In the above step, the number of tubes is equal to 42, So in 1-4 exchanger, the number of tube in each pass =  $42/4=10.5=11$ .

$$\text{So total number of tube in 1-4 exchanger} = 11 \times 4$$

$$= 44$$

From tube count table corresponding to  $\frac{3}{4}$  inch 44 number of tubes, 1 inch triangular pitch, inside diameter of the shell can be taken as 10 inch and schedule 40

6. Select 25% cut segmental baffles with 0.15 m baffle space

6.1 Estimation of heat transfer coefficient Tube side

$$\text{Flow area} = (\pi/4) d_i^2 \times 11$$

$$= 0.00213 \text{ m}^2$$

$$\text{Linear velocity} = \text{Water flow rate} / \text{flow area}$$

$$= 10 / (3600 \times 0.00213)$$

$$= 1.303 \text{ m/sec}$$

$$\text{Reynold number} = 996 \times 1.303 \times 0.0157 / (8 \times 10^{-4})$$

$$= 2.54 \times 10^4$$

$$\text{Colburn factor, } j_H = h_i d_i / K \times C_p \mu / K)^{-1/3} = 85$$

$$\text{Now prantl number, } P_r = C_p \mu / K$$

$$= 4.175 \times 1000 \times 8 \times 10^{-4} / 0.623$$

$$= 5.36 \text{ Therefore,}$$

$$h_i = 5075 \text{ Kcal/hm}^2 \text{Oc}$$

6.2 Shell side Calculation

$$\text{Flow area} = a_s = \text{CBD}_S / p$$

$$C = \text{Clearance between two adjacent tubes}$$

$$= P - d_o$$

$$= 0.254 - 0.019$$

$$= 6.4 \times 10^{-3} \text{ m}$$

$$\text{Baffle Spacing} = 0.15 \text{ m}$$

$$\text{Where Pitch} = 0.0254 \text{ m}$$

$$\text{Inside diameter of the shell} = 0.254 \text{ m}$$

$$\text{Flow area} = \text{CBD}_S / p$$

$$= 0.0096 \text{ m}^2$$

$$\text{Flow area} = a_s = \text{CBD}_S / p$$

$$C = \text{Clearance between two adjacent tubes}$$

$$= P - d_o$$

$$= 0.254 - 0.019$$

$$= 6.4 \times 10^{-3} \text{ m}$$

$$\text{Baffle Spacing} = 0.15 \text{ m}$$

$$\text{Where Pitch} = 0.0254 \text{ m}$$

$$\text{Inside diameter of the shell} = 0.254 \text{ m}$$

$$\text{Flow area} = \text{CBD}_S / p$$

$$= 0.0096 \text{ m}^2$$

$$\text{Mass flow rate of the shell fluid, } G_s = W/a_s$$

$$\text{Where } W = \text{Flow rate}$$

$$G_s = 2083 / 0.0096$$

$$= 2.17 \times 10^5 \text{ Kg/m}^2 \text{hr}$$

Finding equivalent diameter for shell side cross flow

$$D_H = 4(0.5P)(0.8P) - (\pi/4)d_o^2/8 / (\pi/4)d_o/2$$

$$= 4(0.5 \times 2.54)(0.8 \times 2.54) - (\pi/4) \times 1.9^2/8 / (\pi/4) \times 1.9/2$$

$$= 1.82 \text{ cm}$$

$$\text{Reynold number} = D_H G_s / \mu$$

$$= 1.82 \times 10^{-2} \times 2.17 \times 10^5 / 3600$$

$$\times 3.3 \times 10^5$$

$$= 3324$$

From calculation and charts,  $j_H = 32$

$$\text{Heat transfer co-efficient outside} = 317 \text{ Kcal/hm}^2 \text{Oc}$$

Calculating overall heat transfer coefficient ( $U_D$ )

by selecting dirt factor,  $R_d$

$$1/U_D = 1/h_o + R_{do} + (A_o/A_i) R_{di} + A_o/A_i h_i$$

$$\text{Here } A_o/A_i = 1.21.$$

$$\text{Take } R_{do} = 0.21 \times 10^{-3} \text{ hm}^2 \text{oC/Kcal}$$

$$R_{di} = 0.35 \times 10^{-3} \text{ hm}^2 \text{oC/Kcal}$$

$$\text{Therefore } U_{Do} = 248 \text{ Kcal/hm}^2 \text{oC}$$

Compare the value of  $U_D$  and  $U$ , the value of  $U_D$  is considerably lower than the trial overall coefficient 350 Kcal/hm<sup>2</sup>Oc. So the second trial is necessary.

7. Second Trial

Based on the above result, modifying the trial heat exchanger by considering the following 1. Use a smaller baffle space to increase shell side  $Re$  and hence  $h_o$  2. Use 4500mm tube length to increase area of per tube

3. From tube count table, it is seen that 48 tubes can be accommodated if a square pitch tube layout is selected.

7.1 Trial exchanger

1-4 pass 19 tubes on square pitch 254 mm shell and 4500 mm tube length, number of tube = 48, 12 tube per pass. Also select 25% cut segmental baffles with 0.1 m spacing

Estimation of Heat Transfer Coefficient

7.2 Tube side and implying same formulae, the following parameters are obtained.

1. Flow area per pass = .00232m<sup>2</sup>
2. velocity= 1.196m/s
3.  $R_e = 2.33 \times 10^4$
4.  $j_H = 83$

Therefore  $h_i = 4960 \text{ Kcal/hm}^2\text{°C}$

Shell side  $C = 25.4 - 19 = 6.4 \times 10^{-3}$

$B = 0.1 \text{ m}$  ;  $P = 2.54 \text{ cm}$  ;  $D_S = 0.254 \text{ m}$

Flow area , $a_s = .0064 \text{ m}^2$

$G_s = W/a_s = 2083 / 0.0064 = 3.25 \times 10^5 \text{ Kg/mhr.}$

With tubes on square pitch , the equivalent shell diameter is  $D_H = 2.42\text{cm.}$

Reynold number for shell side cross flow is 6620.

$j_H = 48$

Therefore outside heat transfer coefficient ,  $h_o =$

$$358 \text{ Kcal/hm}^2\text{°C}$$

So overall heat transfer coefficient,

$$U_D = 272 \text{ kcal/hm}^2\text{°C}$$

This is less than the assumed overall heat transfer coefficient .Further calculation is necessary to determine whether the design is acceptable or not. We have to take into account the LMTD correction factor for the 1 -4 pass exchanger . So we shall now calculate the area required and area available.

So calculating area required based on

$U_D = 272 \text{Kcal/hm}^2\text{°C}$ , we need the LMTD correction factor , $F_T$ . This can be found out by using normal calculation.

$$T_c = T_{CO} - T_{CI} / T_{HI} - T_{ci} = 40 - 30 / 135 - 30 = .095$$

$$R = T_{hi} - T_{HO} / T_{CO} - T_{CI} = 135 - 40 / 40 - 30 = 9.5$$

$$\text{So } F_t = 0.8$$

Area required =  $Q / U_D F_t \text{ LMTD}$

$$= 98920/272 \times 0.8 \times 38 = 12 \text{ m}^2$$

Area available =  $\pi \times 0.019 \times 4.5 \times 48 = 12.9 \text{ m}^2$

Percentage excess area =  $\text{area available} - \text{area required} / \text{area required} = 12.9 - 12 / 12. = 0.075 = 7.5 \%$

## 8. RESULTS AND DISCUSSIONS

Now a days the study and design of different kinds of heat exchangers are a usual practice in many of the industries . As designed , high viscosity fluid flows through the tube and water is highly viscous when compared with ethyl benzene..Therefore water flows through tube..Here in the problem, a chance of corrosion is more in tubes due to direct contact with

water and fouling is more in tubes than shell. So cleaning of tube is very easy by passing fluid with high force . If water flows through the shell , it is difficult to clean inside shell. higher viscous fluid was selected for tube material. Hence designed shell and tube heat exchanger would be having following specifications and dimensions and is given below.

Serial No.	Specification	Dimensions
1.	Length of the tube	4500mm
2.	Diameter of the Shell	19mm
3.	Diameter of the tube	254mm
4.	Tube material	Copper
5.	Shell and baffle material	Carbon steel
6.	Number of baffles	44
7.	Number of tube	48
8.	Baffle Spacing	100mm
9.	Type	1-4 pass
10.	Type of pitch	25.4 mm square pitch
11.	Flowing fluid through tube	Water
12.	Flowing fluid through shell	Ethyl benzene

The optimal values for designing a new heat exchanger is found out and hence the design is acceptable.

## 9. CONCLUSION

The study revealed that shell and tube heat exchangers are preferred for higher plant capacities.If the estimated shell side coefficient appears to be small , closer baffle spacing should be tried and the outside film coefficient should be recalculated . If the tube side coefficient is low,adjust the number of tube passes to increase the Reynold number and thereby heat transfer coefficient.If the assumed heat exchanger configuration gives about 10% excess area than that required , it is accepted. Otherwise a new configuration in terms of number , size of the tube , tube passes, shell diameter etc are to be assumed and calculations to be repeated from previous steps. Here water is safely selected to flow through tubes for multi objective purpose due to easy cleaning and its high viscosity when compared with shell side fluid.

And more over the shell diameter found out are on the safer side to accommodate the number of tubes . The selected material for tube was copper and carbon steel for shell side and baffles were up to the mark.

#### 10. APPENDIX

$C_p$  - specific heat at constant pressure

$\mu$  - viscosity;  $K$  - Thermal Conductivity

$m$  - Mass

$T_{Hi}$  ,  $T_{Ho}$ ,  $T_{ci}$ ,  $T_{CO}$  - Temperatures of hot and cold fluids. in K

$Q$  – Heat gained / heat lost.in KJ/Kg

LMTD – logarithmic mean temperature difference.in degree Celsius.

$A_s$  - Flow surface area.in  $m^2$

$D_s$  ,  $D_o$  – Diameters of shell and tube sides in ms

$h_i$  ,  $h_o$  - heat transfer coefficient at inner and outer side in  $W/m^2C$

$Re$ ,  $Pr$  ,  $j_H$  - Reynold , Prantl numbers and Colburn factor.

$V$  - Velocity in m/sec

$B$  – Baffle spacing in m

$P$  – pitch in m.

$U$  - Overall heat transfer coefficient in  $Kcal/hrm^2oC$

#### ACKNOWLEDGEMENT

First of all , We would like to thank almighty for blessing us to complete the prescribed work. We take this opportunity to thank research experts who helped us in making the work successful.

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