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HEAT EXCHANGER DESIGN OPTIMISATION

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Abstract- In this paper, an optimized model of Shell and Tube Parallel Flow Heat Exchanger of water and oil type is proposed using C++ programming language. Shell and tube heat exchangers are of special importance in boilers, oil coolers, condensers, pre-heaters etc. They are also used in high pressure operations, refrigeration and air conditioning industry and process applications. In this paper, a number of practical cases of shell and tube heat exchangers are taken and the analysis of thermal and constructional design of every case is done. The optimised design is obtained by minimising the pressure drop by maximising the heat exchanger area to reduce pumping and running cost. Also considering that large sizes lead to increased capital cost, heat exchanger area is also optimised to overcome this problem. Effect of design parameters on pressure drop and heat exchanger area is also explained.

Keywords – Heat Exchanger, C++, Parallel Flow, Shell and Tube, Pressure drop

Abbreviations-

H.E.= heat exchanger , LMTD= log mean temperature difference , P-F= parallel flow, C-F= counter flow, S&T= shell and tube, NTU- number of transfer units, LMTD- log mean temperature difference, ε- effectiveness of P-F HE, f= friction factor, Re –reynolds number.

I. INTRODUCTION

A. *Heat Exchanger:-*

A heat exchanger is a piece of equipment built for efficient heat transfer from one medium to another. The media may be separated by a solid wall, so that they never mix, or they may be in direct contact. They are widely used in space heating, refrigeration, air conditioning, power plants, chemical plants, petrochemical plants, petroleum refineries, natural gas processing, and sewage treatment.

There are three primary classifications of heat exchangers according to their flow arrangement. In parallel-flow heat exchangers, the two fluids enter the exchanger at the same end, and travel in parallel to one another to the other side. In counter-flow heat exchangers the fluids enter the exchanger from opposite ends. In a cross-flow heat exchanger, the fluids travel roughly perpendicular to one another through the exchanger.

B. *Shell and tube :-*

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 large power plants with steam-driven turbines, shell-and-tube surface condensers are used to condense the exhaust steam.

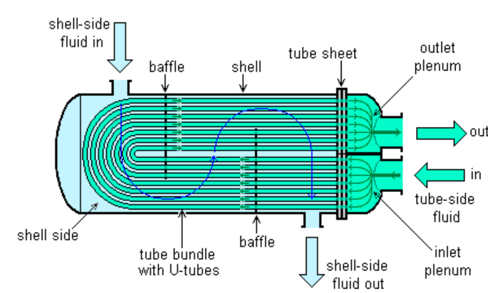

Fig. 1.1 SHELL & TUBE HE

C. *Pressure drop in HE-*

HE size can be reduced by forcing the fluid through it at higher velocities. But due to higher velocities there will be large pressure drops resulting in larger pumping costs. The smaller diameter pipe, for a given flow rate, may involve less initial capital cost but definitely higher pumping costs for the life of the exchanger.

D. *C++ language-*

It is a programming language developed at AT&T Bell Laboratories in early 1980s by Bjarne Stroutstrup. 'C' lacked in simulations and extended the language by adding features from Simula 67. The name "C++" was coined by Rick Mascitti. It is case sensitive. It supports control loops like if , if else, while etc. for conditions. The inclusion of header files used for different operations are an important part.

II. LITERATURE REVIEW

A. Previous work-

Simplified model of study of thermal analysis of shell and tube heat exchanger of water & oil type[1][2] is proposed. It used C code[1] and MATLAB[2] for theoretical calculations of a practical problem of counter flow HE. The data obtained is used for designing HE using Pro-e[1][2]. Also the research include the comparison of above results with the results obtained from thermal analysis performed using ANSYS[1] and FLOEFD[2] softwares.

B. Scope of work-

In this research, the same case of shell and tube HE of water & oil type is taken as in [1] & [2] but for parallel flow and for different design parameters. Multiple practical problems are chosen in place of one[1][2] and analysed using only C++ programming unlike C[1], MATLAB[2], ANSYS[1] and FLOEFD[2]. Results obtained from thermal and constructional analysis of the multiple problems are used for extracting an optimised design unlike comparing the results of C[1], MATLAB[2] & Pro-e[1][2] with ANSYS[1] and FLOEFD[2]. Also Tc2 and N are a part of given design parameters in the research but in earlier research[1][2], these parameters are calculated .

III. OBJECTIVES

TABLE 3.1. UNITS AND SYMBOLS

PARAMETER	SYMBOL	SI UNIT
mass flow rate of hot fluid	Mh	Kg/s
hot fluid capacity rate	Ch	kJ/s ºC
overall heat transfer coefficient between two fluids	U	W/m² ºC
capacity ratio	R	
specific heat capacity of hot fluid	Cph	kJ/kg ºC
mass flow rate of cold fluid	Mc	Kg/s
cold fluid capacity rate	Cc	kJ/kg ºC
specific heat capacity of cold fluid	Cpc	kJ/kg ºC
rate of heat transfer	Q	(J/sec)
length of tube per pass	L	M
area of shell	Ashell	m²
area of tube	Atube	m²
outer diameter of shell	Do	M
fluid velocity in tube	V	m/s
pressure drop	P	N/m²
minimum fluid capacity rate	Cmin	kJ/s ºC
maximum fluid capacity rate	Cmax	kJ/s ºC
hot fluid temperature at inlet	Th1	ºC
hot fluid temperature at outlet	Th2	ºC
cold fluid temperature at inlet	Tc1	ºC
cold fluid temperature at outlet	Tc2	ºC

diameter of tube	D	M
number of tubes	N	

In the designing process, the known design parameters are-

- Th1= 380ºC
- Th2= 360ºC
- Tc1=300ºC
- Tc2=340ºC
- Cpc= 4.18 kJ/kgºC
- Mh=2.5kg/s
- Mc= 3.5 kg/s
- Cph=2.5 kJ/kgºC
- E= 0.00004572 m
- U= 350 W/m² ºC
- ϱ(water)=1000 kg/m
- ϱ(oil)=850 kg/m

A. *Design Analysis of multiple cases of HE-*

Various design cases are considered for the thermal and constructional analysis.

TABLE 3.2. VALUES OF d, N AND L

d1	0.025m
d2	0.035m
d3	0.045m
N1	20
N2	25
N3	30
L1	3.5m
L2	4.5m
L3	5.5m

Evaluation of all cases is performed by taking one parameter as variable and other two parameters as constants from above given values using C++ programming.

B. *Study influence of design parameters on As & P*-The effect of d, N & L on As and P are described with the help of Graphical representation performed in MS Excel. The graphs are made for the following design cases:

- When d & N constant-
  1. L vs As
  2. L vs P
- When d & L constant-
  1. N vs As
  2. N vs P
- When N & L constant-
  1. d vs As
  2. d vs P

D. Obtain an optimised design-

The optimum value of design parameters are calculated by the program by maximising the HE area. These optimum values are then put in the objective function P and the other design attributes to obtain the whole optimised design.

IV. METHODOLOGY

A. *Design of HE using thermal and constructional formulas-*

The values of known parameters are fed in the following thermal and constructional formulas fed in the program.

- Thermal formulas-

a. Cc=$Mc\times Cpc$
b. Ch= $Mh \times Cph$
c. R= $Cmin \div Cmax$
d. T1= Th1- Tc1
e. T2= Th2- Tc2
f. LMTD=$(T1-T2)\div \ln(T1\div T2)$
g. Q=$Mh\times Cph\times(Th1-Th2)$
h. ε= $(Th1-Th2)\div(Th1-Tc1)$ *when $Cc>Ch$*
i. ε = $(1-\{-NTU\times(1+R)\})/((1+R))$
j. NTU= $(-\ln\ [1-\varepsilon(1+R)])/(1+R)$

- Constructional formulas-

a. Atube =$(N\pi d^2)/4$
b. Ashell =$N\pi dL$
c. Do = $Ashell/\pi L$
d. V = $(4\ Mc)/(\pi d^2\ \varrho N)$
e. Re = $\varrho Vd/(\mu)$ *where* μ=0.000596 Ns/m^2
f. f1= E/d
g. f=$[1.14+2\log(d/E)]$ ^(-2)
h. P= $f2\varrho V^2L/d$

B. *Performing calculations for multiple design cases-*

The various design cases taken into consideration by taking one parameter as variable and other two parameters as constants are given below-

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- d1= constant & N1= constant
a. d1= 0.025m, N1= 20, L1= 3.5m
b. d1= 0.025m, N1= 20, L2= 4.5m
c. d1= 0.025m, N1= 20, L3= 5.5m
- d2= constant & N2= constant
a. d2= 0.035m, N2= 25, L1= 3.5m
b. d2= 0.035m, N2= 25, L2= 4.5m
c. d2= 0.035m, N2=25, L3= 5.5m
- d3=constant & N3=constant
a. d3= 0.045m, N3= 30, L1= 3.5m
b. d3= 0.045m, N3= 30, L2= 4.5m
c. d3= 0.045m, N3= 30, L3= 5.5m
- d1=constant & L1=constant
a. d1= 0.025m, N2= 25, L1= 3.5m
b. d1= 0.025m, N3= 30, L1= 3.5m
- d2=constant & L2=constant
a. d2= 0.035m, N1= 20, L2= 4.5m
b. d2= 0.035m, N3= 30, L2= 4.5m
- d3=constant & L3=constant
a. d3= 0.045m, N1= 20, L3= 5.5m
b. d3= 0.045m, N2= 25, L3= 5.5m
- N1=constant & L1=constant
a. d2= 0.035m, N1= 20, L1= 3.5m
b. d3 = 0.045m, N1= 20, L1= 3.5m
- N2=constant & L2=constant
a. d1= 0.025m, N2= 25, L2= 4.5m
b. d3= 0.045m, N2= 25, L2= 4.5m
- N3=constant & L3=constant
a. d1= 0.025m, N3= 30, L3= 5.5m
b. d2= 0.035m, N3= 30, L3= 5.5m

Program of this part is only for calculations. It performs the Design analysis of all the cases without taking any input. One of the case study is shown below:

Case study for d1= 0.025m, N3= 30, L3= 5.5m

- Thermal design values :
a. Cc= $Mc \times Cpc$ =3.5×4.2×1000=14700 kJ/ºC
b. Ch= $Mh \times Cph$= 2.5×2.5×1000=6250 kJ/ºC
c. Cmin= 6250 kJ/ºC
d. Cmax= 14700 kJ/ºC
e. R= $Cmin \div Cmax$ =6250÷14700=0.4251
f. T1= Th1- Tc1 =380-300=80 ºC
g. T2= Th2- Tc2 =360-340=20 ºC
h. LMTD= $(T1-T2) \div \ln(T1 \div T2)$=(80−20)÷ ln(80÷20)=43.2808
i. Q=Mh×Cph×1000$(Th1-Th2)$=6250×(380−360)=125000 " J/s"
j. ε= $(Th1-Th2) \div (Th1-Tc1)$ =(380−360)÷(380−300)=0.25
k. NTU= (− ln [1−ε(1+R)])/(1+R)= (−ln [1−0.25(1+0.4251))/(1+0.4251)= 0.309
- Constructional design values:
a. Atube = $(N\pi d^2)/4$= (30×π×0.025²)/4 = 0.01472m²
b. Ashell = $N\pi dL$= 30×π×0.025×5.5= 12.959m²
c. Do = $Ashell/\pi$ = 12.959/(π×5.5) = 0.75m
d. V = $(4\,Mc)/(\pi d^2\,\varrho N)$ = (4×3.5)/(π×0.025²×1000×30) = 0.2376m/s
e. Re = $\varrho Vd/(\mu)$ = (1000×0.2376×0.025)/0.000596 = 9969.43
f. f1= E/d = (0.00004572)/0.025 = 0.0018288
g. f= [1.14+2 log(d/E)] ^(−2) = [1.14+2 log(0.025/0.00004572)] ^(−2) = 0.0228
h. P= $f2\varrho V^2L/d$=(0.0228×2×1000×0.2376²×5.5)/0.025 = 567.337N/m²

C. Study the influence of design parameters on As & P-

TABLE 4.1. GRAPHS AND DESIGN CASES

	Constant parameters		
Case no.	Graph 1 & 2	Graph 3 & 4	Graph 5 & 6
1	N1L1	d1L1	d1N1
2	N2L2	d2L2	d2N2
3	N3L3	d3L3	d3N3
4	N1L2	d1L2	d1N2
5	N2L1	d2L1	d2N1
6	N2L3	d2L3	d2N3
7	N3L2	d3L2	d3N2
8	N1L3	d1L3	d1N3
9	N3L1	d3L1	d3N1

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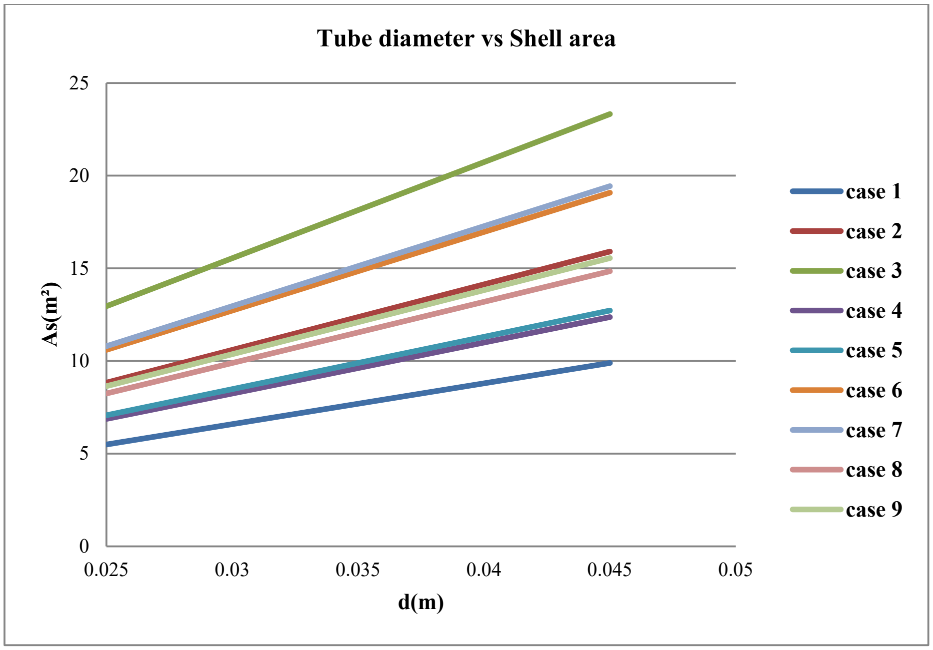

CHART 1. d vs As

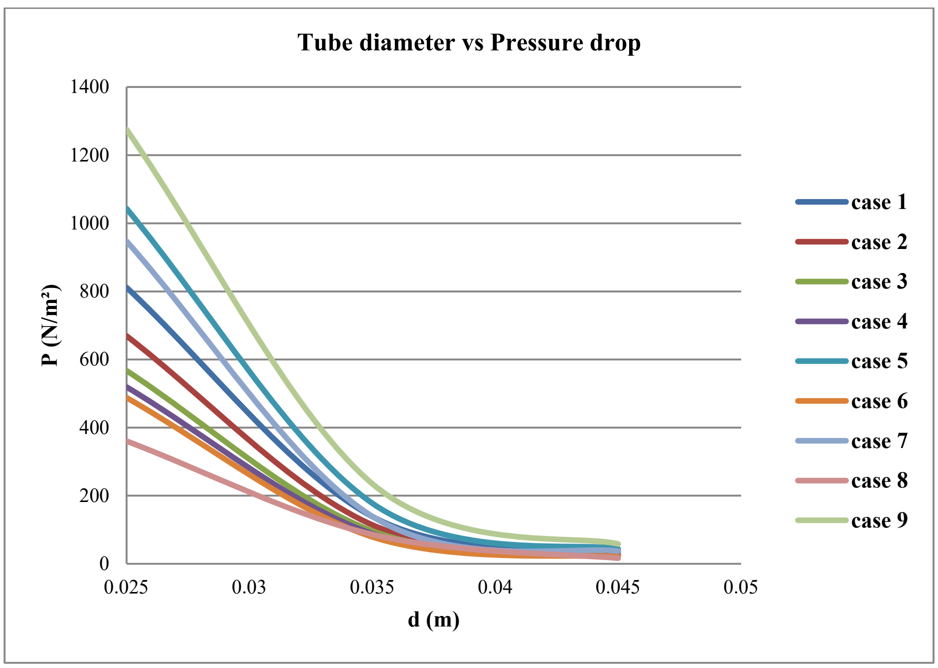

CHART 2. d vs P

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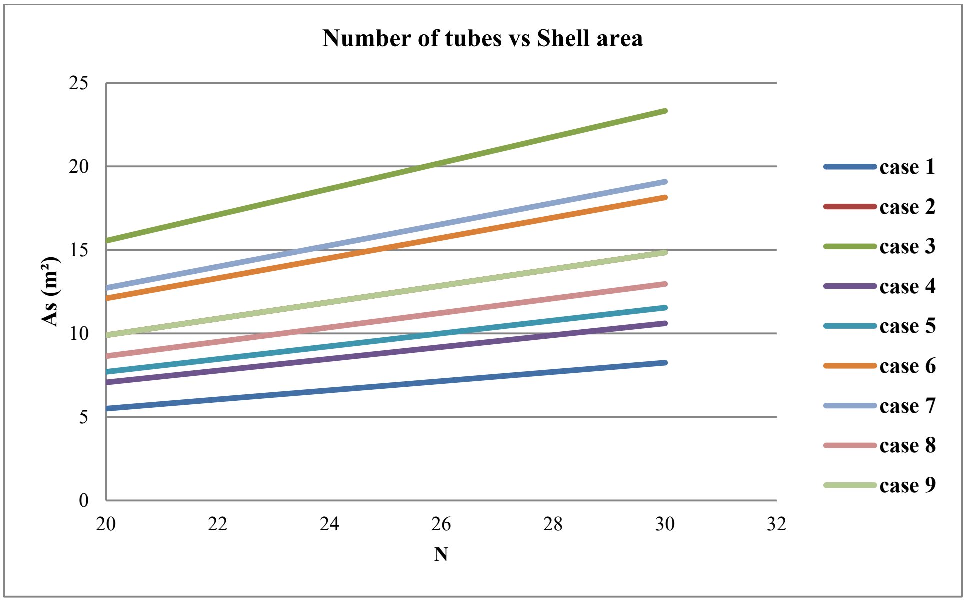

CHART 3. N vs As

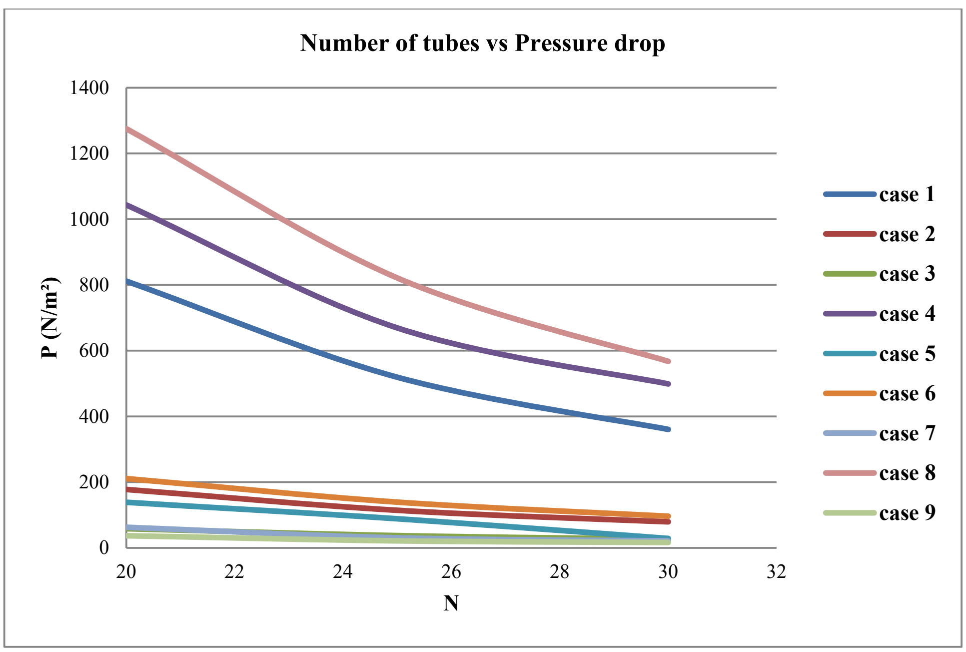

CHART 4. N vs P

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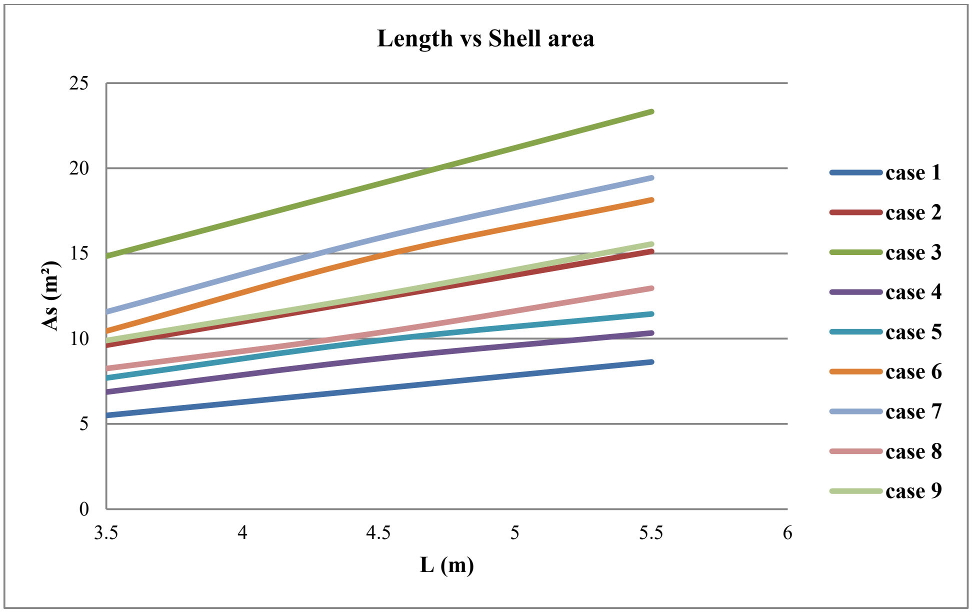

CHART 5. L vs As

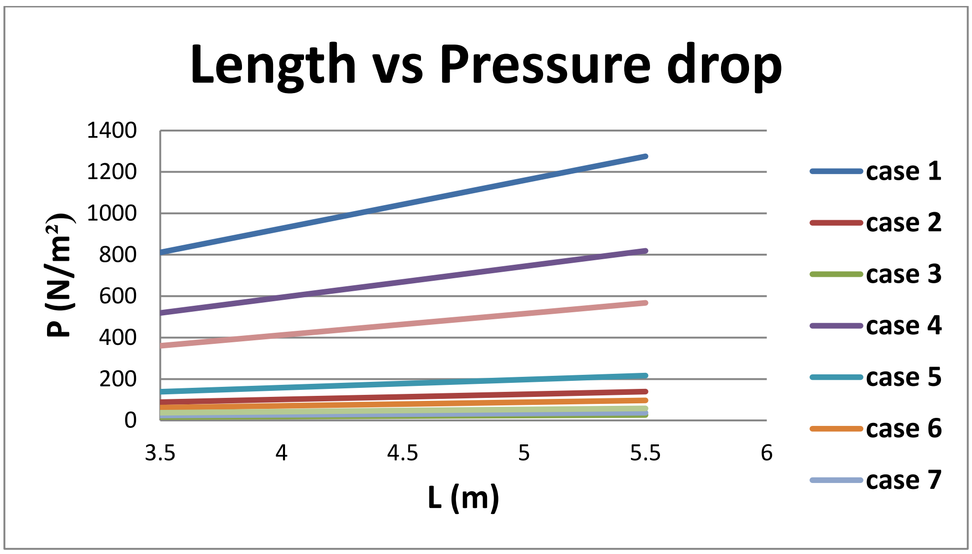

CHART 6. L vs P

D. Obtain an optimised design-

Optimisation procedure is done as follows:

- Selection of minimum value of HE area from the result data obtained for every design case so as to increase its value to the maximum.
- Calculating the values of d, N and L for every design case .
- Finding the optimum values of d, N & L for which value of P is minimum and maximising HE area also taking into consideration the capital cost.

Objective – Minimise $P=\frac{0.212\,L}{d}$

- Putting the optimum values of d, N & L in other design attributes to obtain optimised design.

V. RESULTS

- Simple design of S&T HE is shown in the output screen of C++.

```
Temperature of cold fluid(water) at outlet( in degree celsius)=340
Overall heat transfer coefficient( in W/metre square degree celsius)=350
Specific heat capacity of hot fluid(oil)( in kJ/kg degree celsius)=2.5
Specific heat capacity of cold fluid(water)( in kJ/kg degree celsius)=4.2

Select the number of tubes from the following options

  20
 25
 30
Enter your choice=20

Select the diameter of tube( in metres)from the following options

  0.025
   0.035
   0.045
Enter your choice=0.035

Select the length of tube (in metres) from the following options

 3.5
  4.5
  5.5
Enter your choice=4.5_
```

Fig. 5.1. INPUT OF DESIGN DATA

```
Mass of hot fluid(oil)( in kg/sec)=2.5
Mass of cold fluid(water)( in kg/sec)=3.5
Temperature of hot fluid(oil) at inlet( in degree celsius)=380
Temperature of hot fluid(oil) at outlet( in degree celsius)=360
Temperature of cold fluid(water) at inlet( in degree celsius)=300
Temperature of cold fluid(water) at outlet( in degree celsius)=340
Overall heat transfer coefficient( in W/metre square degree celsius)=350
Specific heat capacity of hot fluid(oil)( in kJ/kg degree celsius)=2.5
Specific heat capacity of cold fluid(water)( in kJ/kg degree celsius)=4.2
Tube diameter (in metres)=0.035
Tube length (in metres)=4.5
Number of tubes=20
Log mean temperature difference( LMTD)=43.280849
Rate of heat transfer( in Joule/sec)=125000
Effectiveness of heat exchanger=0.25
Number of transfer units(NTU)=0.309094
Area of tube is=0.019233
Area of Shell is=9.891
Shell outer diameter is=0.7
Fluid velocity=0.181984
Reynolds Number=10741.023593
friction factor=0.020956
Pressure drop=178.461281_
```

Fig 5.2. THERMAL & CONSTRUCTIONAL DESIGN OF S&T HE

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- Design table for all cases of d, N & L-

TABLE 5.1 DESIGN ANALYSIS

PARAMETER	**d1N1L1**	**d2N2L2**	**d3N3L3**	**d1N2L2**	**d1N3L3**	**d1N1L2**	**d1N1L3**
Atube (m^2)	0.0098	0.02405	0.0477	0.01227	0.01472	0.0098	0.0098
Ashell (m^2)	5.497	12.37	23.326	8.8357	12.959	7.0685	8.6393
Do (m)	0.5	0.625	1.35	0.625	0.75	0.5	0.5
V (m/s)	0.3565	0.1455	0.07335	0.2852	0.2376	0.3565	0.3565
Re	14954.1	8544.46	5538.57	11963.3	9969.43	14954.1	14954.1
f1	0.00182	0.0013	0.00101	0.00182	0.00182	0.00182	0.00182
F	0.0228	0.0209	0.01969	0.0228	0.0228	0.0228	0.0228
P (N/m^2)	811.356	114.0726	26.0038	669.043	567.337	1043.17	1274.98

TABLE 5.2 DESIGN ANALYSIS

PARAMETER	**d1N2L1**	**d1N3L1**	**d2N1L1**	**d2N3L3**	**d2N2L1**	**d2N2L3**	**d2N1L2**
Atube (m^2)	0.01227	0.01472	0.01924	0.02886	0.02405	0.02405	0.01924
Ashell (m^2)	6.8722	8.2466	7.6969	18.1426	9.6211	15.1189	9.896
Do (m)	0.625	0.75	0.7	1.05	0.875	0.875	0.7
V (m/s)	0.2852	0.2376	0.1818	0.1212	0.1455	0.1455	0.1818
Re	11963.3	9969.43	10681.5	7121.02	8545.23	8545.23	10681.5
f1	0.00182	0.00182	0.0013	0.0013	0.0013	0.0013	0.0013
F	0.0228	0.0228	0.0209	0.0209	0.0209	0.0209	0.0209
P (N/m^2)	519.26	360.4	138.523	96.488	88.49	139.058	177.626

TABLE 5.3 DESIGN ANALYSIS

PARAMETER	**d2N3L2**	**d3N1L1**	**d3N2L2**	**d3N3L1**	**d3N3L2**	**d3N1L3**	**d3N2L3**
Atube (m^2)	0.02886	0.03180	0.03976	0.04771	0.04771	0.03180	0.03976
Ashell (m^2)	14.844	9.896	15.9043	14.844	19.0851	15.5508	19.4386
Do (m)	1.05	0.9	1.125	1.35	1.35	0.9	1.125
V (m/s)	0.1212	0.11	0.08802	0.07335	0.07335	0.11	0.08802
Re	7121.02	8307.86	6646.29	5538.57	5538.57	8307.86	6646.29
f1	0.00130	0.00101	0.00101	0.00101	0.00101	0.00101	0.00101
F	0.0209	0.01969	0.01969	0.01969	0.01969	0.01969	0.01969
P (N/m^2)	79.023	37.064	30.5097	16.479	21.1873	58.2386	37.2896

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- Optimized design-

From the above analysis of design cases, an optimised design is obtained which has optimised value of P and As

.*TABLE 5.4. FINAL DESIGN*

Cc (kJ/ºC)	14700	**NTU**	0.309
Ch (kJ/ºC)	6250	**d(m)**	0.0262
Cmin (kJ/ºC)	6250	**N**	29
Cmax (kJ/ºC)	14700	**L(m)**	3.5
R	0.4251	**Atube (m²)**	0.01563
T1 (ºC)	80	**Ashell (m²)**	8.3544
T2 (ºC)	20	**Do (m)**	0.7598
LMTD	43.2808	**V (m/s)**	0.2238
Q (J/s)	125000	**P (N/m²)**	28.3
ε	0.25		

VI. CONCLUSION

- The optimum value of design parameters d, N & L is between the maximum and minimum value hence design is safe.
- The optimum value of other design attributes Ashell, Atube, Do, V & P is between the maximum and minimum values hence design is safe.
- P is proportional to L and inversely proportional to d & N^2 hence decrease in L and increase in d and N will give a favourable design.

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