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Thermal Design of Tube and Shell Heat Exchanger and Verification by HTRI Software

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***Abstract*— Heat exchangers are the devices used to transfer heat from one fluid to another. Fluids can be either gases or liquids. plate heat exchanger, Double pipe heat exchanger, shell and tube heat exchanger, condensers, evaporators and boilers are the most common types of heat exchangers. They are widely used in petroleum refineries, sewage treatment, air conditioning, power station, space heating and petrochemical plants. Tube and shell tube and shell heat exchanger is type of heat exchanger in which two fluids which are at different temperatures are separated by solid wall. this article includes thermal design calculation and verification of all the process parameters which are required for proper functioning of the compressor system as a whole. the design calculations of tube and shell heat exchanger are verified by HTRI(Heat Transfer Research Inc.) software. This is the software for the rating, design, and/or simulation of a wide variety of heat transfer equipment, including shell-and-tube and non-tubular exchangers, air coolers and economizers, and fired heaters.**

Keywords—Tube and shell heat exchanger, HTRI, temparature, compressor.

I. INTRODUCTION

Industries often use compressed gases such as air, hydrogen, acetylene, oxygen, methane, etc. The volume required of these compressed gases is very high so it is required to compress these gases efficiently. For this reason intercoolers are used. Intercoolers are placed after compression or between two stages of compression. Intercoolers can be placed horizontally or vertically but horizontal intercoolers are more effective thus horizontal intercoolers generally used.

Intercoolers are generally placed in between two stages of compression as it cools down the hot fluid before sending it to second compression. Thus volume of fluid decreases which increases the volumetric capacity and decreases the work done by motor.

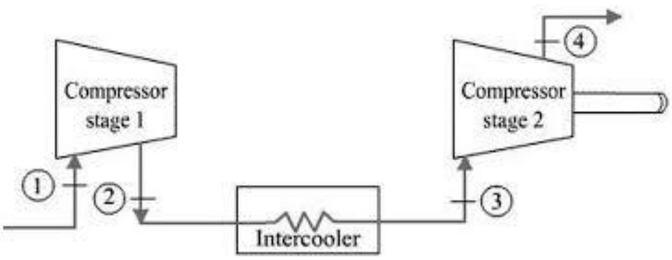

Fig 1: 2 stage compressor block diagram [6]

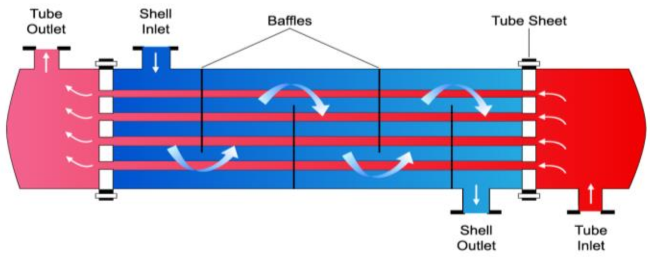

Fig 2: Tube and shell heat exchanger [12]

Following are the functions of an intercooler used in compressor:

- Atmospheric air contains moisture, and furthermore, the air may pick up oil vapor as it passes through some parts of the compressors. Cooling air down to or below its initial temperature will remove moisture down to the dew point, improving the quality of the air.
- Intercoolers improve the efficiency of compressor. As the volume of hot air reduces on cooling volumetric efficiency increases.
- Every 4 °C rise in inlet air temperature results in higher energy consumption by 1 percent to achieve equivalent output. Thus lower the temperature of intake air, more is the energy efficiency of a compressor.

II. METHODOLOGY

Problem identification

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Selection of a heat exchanger

↓

Thermal design

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Verification of design

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III. PROBLEM STATEMENT

To cool down the air from Thermal design of heat exchanger based on the input parameters which are given in the specification sheet and verification of design i.e. verification of the overall heat transfer coefficient also, finding out the acceptability of the pressure drop.

IV. SELECTION OF HEAT EXCHANGER

Thermal design of the heat exchanger (intercooler) is according to the Kern's method. It is simple to apply, accurate enough for preliminary calculations. The selection criteria for the heat exchanger, design procedure and its calculations are discussed in the subsequent sections Selection Criteria for Shell and Tube Heat Exchanger

- Materials of construction
- Operating pressure and temperature
- Flow rates
- Flow arrangements
- Fouling tendencies
- Maintenance, inspection, cleaning, extension
- Overall efficiency

1. Shell:

Shell is the cylindrical vessel container through which fluid flows and the tube bundle is placed inside the shell. Shells are usually casted from standard steel pipe with satisfactory corrosion allowance.

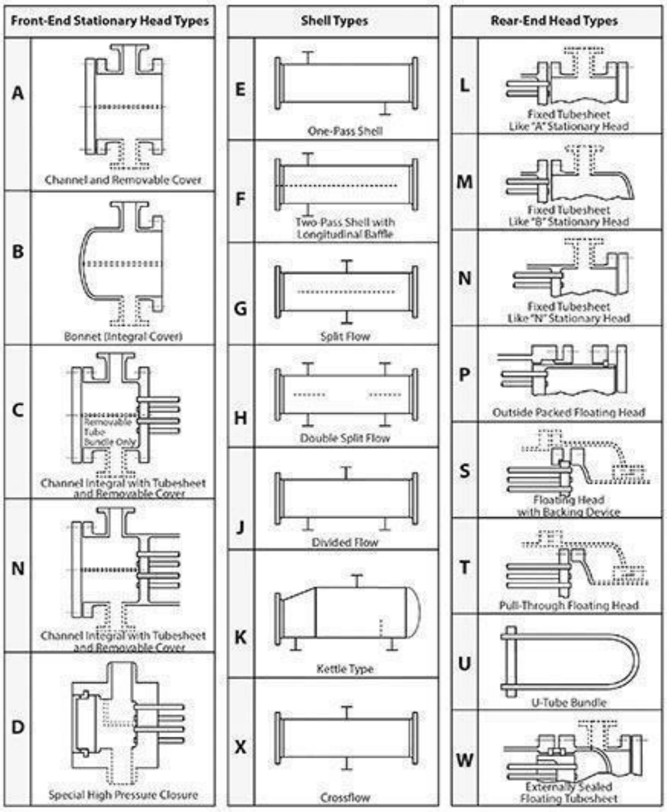

Fig 3: Shell Design [7]

BEW type shell type is selected. It is simple in construction and easy to clean as it has floating rare end head thus tube sheet can be easily removed for cleaning.

2. Tube and tube layout

The enough tube thickness ensures that it will bear the internal pressure along with the adequate corrosion allowance. Longer tube less is the shell diameter at the expense of higher shell pressure drop. Stainless steel, copper, bronze and alloys of copper- nickel are the commonly used tube materials.

The shortest center to center distance between the adjacent tubes is Pitch. The general pattern of tubes is square or triangular pattern. The tube count is the number of tubes that can be accommodated in a given shell ID.

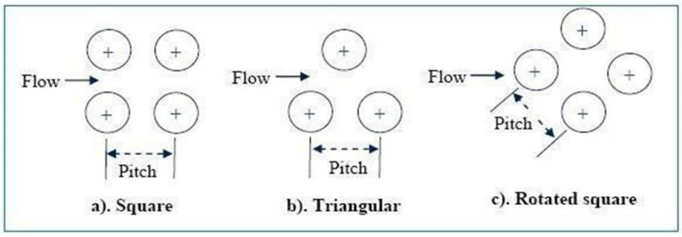

Fig 4: Tube Layout [1]

For this application triangular layout is selected as it is more effective and easy to clean

3. No of passes

To obtain greater heat transfer co-efficient and also to reduce scale formation, number of passes is chosen to get the required tube side fluid velocity. The tube passes vary from 1 to 16. A single tube pass is selected for the design.

4. Baffle

Liquid is maintained in a state of turbulence ensures the higher heat transfer coefficients. The turbulence is induced outside the tubes which cause the liquid to flow at right angles to the axes of the tubes. This causes considerable turbulence even when a small amount of liquid flows through the shell.

One from the various types of baffles is used to increase the fluid velocity by diverting the flow across the tube bundle to obtain higher transfer co-efficient. The distance

Between adjacent baffles is called baffle-spacing. The segmental baffle used in design shown in the figure 4..

The % cut for segmental baffle refers to the cut away height from its diameter.

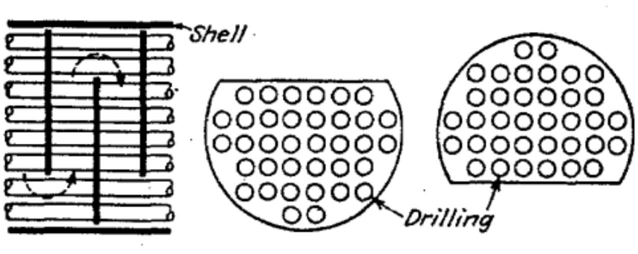

Fig 5: Segmental baffle [3]

V. PROBLEM IDENTIFICATION

TABLE I. REQUIREMENT SHEET

DATA CONSIDERED			
Gas Handled			Air
Capacity of compressor		M^3/hr	736.2
Suction Temperature		°C	35-38
Relative humidity (Min / Max)		%	70
Suct. Pres. at compr. flange		Bar (g)	1.01
Cooling Water Temp: In / O		° C	32/40
HEAT EXCHANGERS DATA			
Quantity required		Nos.	1 No.
Code of construction			TEMA – C
Flow	Air	kg/hr	792.6
Fluid		Tube side	Air
		Shell side	Water
Corrosion allowance	mm	Tube side	1.5
		Shell side	1.5
Pressure	Bar (g)	Tube side	2.82
		Shell side	3.965
Design Pressure	Kg/cm² (g)	Tube side	4
		Shell side	3.3
Hydro Test Pressure	Kg/cm² (g)	Tube side	6.0
		Shell side	5.0
Design Temperature	°C	Tube side	200
		Shell side	75
Max.permissible Pr .Drop	Kg/cm² (g) (By Vendor)	Tube side	0.1
		Shell side	0.5
Water consumption	kg/hr		5000
Air (Gas) Temperature	°C	In	147
		Out	40
No. of passes per Shell		Nos.	1
Material of construction		Tube	SA249TP304
		Tube Sheets	C.S.
		shell	C.S.
		Baffle Plates	C.S.
		Tie Rods	C.S.
		Heads	C.S.
Fouling factor	M2.Hr.°C/Kca	Tube side	0.0002
		Shell side	0.0004
Tube OD size		inch	3/8"
Tube thickness		SWAG	20G
Tube length		mm	1600
Tube pitch		mm	12.2

A. Thermo-Physical Properties Of Hot And Cold Fluids

- Inlet Condition Of Air (To L.P. Cylinder)

Pressure P_1= 1.0269 kg/cm^2
Temperature T_1= 38.0 °C.
RH = 0.7
Saturated pressure of vapour PV_1= 0.06689 kg/cm^2

Weight of air per kg of dry air:

= (0.622*PV1*RH1)/(P1- PV1*RH1) (1)

= (0.622*0.06689*0.7)/(1.0269- 0.06689*0.7)

= 0.0294 kg

- Outlet Condition Of Air (At Outlet Of intercooler)

Pressure P2= 2.8806 kg/cm^2
Temperature T2= 40.0 °C
RH = 1.00
Saturated pressure of vapour PV_2 = 0.0739 kg/cm^2

Weight of air per kg of dry air

= (0.622*PV2*RH2)/(P2- PV2*RH2)

= (0.622*0.0739*1)/(2.8806- 0.0739*1)

= 0.01637 kgs

- Temperature of air at the inlet of the intercooler (adiabatic compression)

$$T2/T1 = (P2/P1)^{(\gamma-1)/\gamma}$$

$$T2/38 = (2.8806/1.0269)^{(1.4-1)/1.4}$$

$$T2 = 144.56$$

T1, T2 = temperature at the i/p and o/t of L.P. cylinder resp.
P1, P2 = Pressure at the i/p and o/t of L.P. cylinder resp.

- Weight of dry air;

= P*V/R*T kgs/hr

= ((1.026-0.7*0.06689)*736.2*10^4)/29.271*311.0

= 792.60 kgs/hr

Weight of vapour in = 0.0294*792.60 = 23.30 kg/hr

- Heat duty = (flow rate * specific heat * temperature rise)

Dry air = 792.6*0.245(144.56-40) = 20304.19 kcal/hr

Vapour = 23.30*0.45(144.56-40) = 1096.311 kcal/hr

Total = 21400.5 kcal/hr

	Hot fluid	Cold fluid	Difference
High Temperature	Del t5=144.56	39.6	Del t2=104.56
Low temperature	40	Del t6=32.0	Del ta=8.0
Difference	Del t3=104.56	Del t4=8.0	

(Note- Temperatures in above table are in °C)

- LMTD

= (Del t2-Delt1)/ ln(Del t2/(Del t1)

= (104.56-8.0)/ ln(104.56/8.0)

= 37.56°C

B. Shell Side Calculations

- Flow Area

As = (Ds*C*Bp)/(144*Pt)

= (6*0.105*3.590)/(144*0.4803)

= 0.0327 ft^2

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Ds = Diameter of shell = 6 inch
Pt = Pitch of tubes = 0.480 inch
D_o = outer diameter of tube = 0.375 inch
Bp = baffle pitch = 3.59 inch
C = Pt-d_o = 0.480-0.375 = 0.105

- Mass Velocity

$$Gs = W/As$$
$$= 11025/0.0327$$
$$= 337155.96 \text{ lbs/hr.ft}^2$$

W = weight of water = 5000*2.205 = 11025 lbs/hr

- Reynolds No.

$$Res = Des*Gs/MYU$$
$$= 0.0248*337155.96/1.808$$
$$= 4624.70$$

Des = Equivalent Diameter

$$= 4*(Pt/2 * 0.86Pt – 1/2 * \pi d^2_o/4)1/2 * \pi d_o$$
$$= 0.2977 \text{ inch} = 0.0248 \text{ ft}$$

MYU = viscosity of water at 35 °C

$$= 0.7191 \text{ cp} = 1.808 \text{ lb/ft.hr}$$

- Shell Side Heat Transfer Coefficient Ho:

$$Ho = 0.36 * (K/Des) * (Des*Gs/MYU)^{0.55} * (C*MYU/K)^{0.33} * (MYU/MYUW)^{0.14}$$
$$=0.36 * (0.3630/0.0248) * (4624.70)^{0.55} * (1.0*1.808/0.3630)^{0.33} * 1^{0.14}$$
$$= 928.16 \text{ Btu/hr.ft}^2.°F$$

- Shell side thermal resistance

Ros = 1/Ho = 1/928.16 = $1.077*10^{-3}$

Shell side fouling factor, Rdo = 0.002

Thermal resistance Ro:

$$Ro = Ros + Rdo$$
$$= 1.077*10^{-3} + 0.002$$
$$= 3.077*10^{-3} \text{ hr.°F.ft}^2$$

C. Tube Side Calculations

- Flow area

$$At = (\text{No of tubes * flow area per tube})/(\text{No of passes *144})$$
$$= (94 * 0.0730)/(1*144)$$
$$= 0.0476 \text{ ft}^2$$

- Mass velocity :

$$Gt = M/At$$
$$= 1799.3/0.0476$$
$$= 37794.1 \text{ lbs/hr.ft}^2$$

M= weight of air = weight of dry air + weight of vapour

$$= (792.6+23.3) * 2.205 = 1799.3 \text{ lbs/hr}$$

- Reynolds No :

$$Res = d_i * Gt/MYU$$
$$= 0.02541 * 37794.1/0.0505$$
$$= 19016.79$$

MYU = viscosity of air

$$= 0.0208 \text{ cp} = 0.0505 \text{ lb/ft·hr}$$

- Tube Side Heat Transfer Coefficient Hi :

$$Hi = JH * (K/di) * (C*MYU/K)^{0.33} * (MYU/MYUW)$$
$$= 70 * (0.0183/0.02541) * (0.245*0.0505/0.0183)^{0.33} * 1^{0.14}$$
$$= 44.30 \text{ Btu/hr.ft}^2.°F$$

Referring to graph in Kern’s book fig.24 page 834, JH corresponding to the Reynold’s no 19016.79 is 70

- Tube side thermal resistance

Tube side fouling factor rdi = 0.001

$$ri = 1/ Hi$$
$$= 1/44.30 = 0.0225$$
$$Ri = ri + rdi$$
$$= 0.001 + 0.0225 = 0.0235$$

Tube wall resistance = rw

$$rw = d/(24*K) \ln(d/(d-2*t))$$
$$= 0.375/(24*117) \ln(0.375/(0.375-2*0.035))$$
$$= 2.75*10^{-5}$$

- Total resistance Rtotal :

$$= Ri * (Ao/Ai) + Ro + rw$$
$$= 0.0235 * (0.375/0.305) + 3.07*10^{-3} + 2.75*10^{-5}$$
$$= 0.03199$$

D. Overall heat transfer coefficient U

$$U = 1/\text{Total resistance}$$
$$= 1/0.03199$$
$$=31.258 \text{ Btu/hr.ft}^2\text{°F} = 152.61 \text{ kcal/hr·m}^2\text{·°C}$$

E. Pressure drop

- Pressure drop shell side Ps

Refer the graph figure 29 of kern: corresponding to Reynold’s No. friction factor F = 0.0025

$$Ps = F * G^2s * Ds * (N+1)/(5.22 * 10^{10} * s * De * PHIs)$$
$$= 0.0025 * 337155.96^2 * 0.5 * 13/(5.22 * 10^{10} * 1* 0.0248 *1)$$
$$= 1.45 \text{ psi} = 0.09983 \text{ kg/cm}^2$$

F = friction factor
N = no of baffles
s = sp. Gravity

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- Pressure drop tube side Pt

Refer the graph figure 26 of kern: corresponding to Reynolds No. friction factor F = 0.0002

$$Pt = F * Gt^{2} * L * N/(5.22 * 10^{10} * di * s * PHIt)$$

$$= 0.0002 * 37794.1^{2} * 5.25 *1/(5.22 *10^{10} * 0.025* 0.0027*1)$$

$$= 0.4 \text{ psi}$$

L = tube length per pass in ft
N = no of baffles
PHIt = MYU/MYUW = 1
s = sp. Gravity

$$Pr = 4 * (N/s) * V^{2}/(2 * g)$$

$$= 4 * 1/0.0027 * 0.16^{2}/(2 * 32.2) = 0.25 \text{ psi}$$

$$PTt = Pt + Pr$$

$$= 0.4 + 0.\ 25$$

$$= 0.65 \text{ psi} = 0.044 \text{ kg/cm}^{2}$$

VI. Design Verification

The software results look like figure no 6. The main parameter which will be verifies is the overall heat transfer coefficient, heat duty and pressure drop.

HTRI — HEAT EXCHANGER SPECIFICATION SHEET — Page 1 — MKH Units

		Job No.	
Customer	PCCOE	Reference No.	
Address		Proposal No.	
Plant Location		Date	11-12-2019 Rev
Service of Unit		Item No.	
Size	152 x 1600 mm Type BEW Horizontal	Connected In	1 Parallel 1 Series
Surf/Unit (Gross/Eff)	4.501 / 4.438 m2 Shell/Unit 1	Surf/Shell (Gross/Eff)	4.501 / 4.438 m2

PERFORMANCE OF ONE UNIT

Fluid Allocation		Shell Side		Tube Side	
Fluid Name		water		air	
Fluid Quantity, Total	kg/hr	5000.0		815.88	
Vapor (In/Out)				815.88	814.54
Liquid		5000.0	5000.0		1.3444
Steam				14.975	13.631
Water		5000.0	5000.0		1.3444
Noncondensables				800.91	800.91
Temperature (In/Out)	C	32.00	36.27	144.56	40.00
Specific Gravity		0.9945	0.9918		0.9916
Viscosity	cP	0.7645	0.7249	0.0222	0.0178 V/L 0.6524
Molecular Weight, Vapor					
Molecular Weight, Noncondensables					
Specific Heat	kcal/kg-C	1.0083	1.0104	0.2490	0.2460 V/L 1.0085
Thermal Conductivity	kcal/hr-m-C	0.5315	0.5337	0.0279	0.0218 V/L 0.5407
Latent Heat	kcal/kg	518.68	518.98	579.38	580.68
Inlet Pressure	kgf/cm2A	4.033		2.880	
Velocity	m/s	0.28		17.88	
Pressure Drop, Allow/Calc	kgf/cm2	0.500	0.049	0.100	0.053
Fouling Resistance (min)	m2-hr-C/kcal	0.000400		0.000200	
Heat Exchanged	21898 kcal/hr			MTD (Corrected)	34.7 C
Transfer Rate, Service	142.26 kcal/m2-hr-C	Clean	184.96 kcal/m2-hr-C	Actual	165.22 kcal/m2-hr-C

CONSTRUCTION OF ONE SHELL — Sketch (Bundle/Nozzle Orientation)

		Shell Side	Tube Side
Design/Test Pressure	kgf/cm2G	3.300 / 5.000	4.000 / 6.000
Design Temperature	C	75.00	200.00
No Passes per Shell		1	1
Corrosion Allowance	mm	1.500	1.500
Connections Size & Rating — In	mm	1 @ 35.052	1 @ 62.713
Out	mm	1 @ 35.052	1 @ 77.927
Intermediate		@	@

Tube No. 94 OD 9.525 mm Thk(Avg) 0.889 mm	Length 1600. mm Pitch 12.200 mm
Tube Type Plain	Material SA-249 TP304H Tube (W) S30409 Tube pattern 30
Shell Carbon steel ID 152.00 OD 168.30 mm	Shell Cover
Channel or Bonnet Carbon steel	Channel Cover Carbon steel
Tubesheet-Stationary Carbon steel	Tubesheet-Floating Carbon steel
Floating Head Cover Carbon steel	Impingement Plate None
Baffles-Cross Type Single-Seg.	%Cut (Diam) 35 Spacing(c/c) 91.200 Inlet 287.29 mm
Baffles-Long	Seal Type None
Supports-Tube	U-Bend Type None
Bypass Seal Arrangement 1 pairs seal strips	Tube-Tubesheet Joint Expanded (No groove)
Expansion Joint	Type
Rho-V2-Inlet Nozzle 2084.0 kg/m-s2	Bundle Entrance 21.09 Bundle Exit 21.15 kg/m-s2
Gaskets-Shell Side	Tube Side
- Floating Head	
Code Requirements	TEMA Class C
Weight/Shell 160.33 kg Filled with Water 191.56 kg	Bundle 38.09 kg

Fig 6: HTRI Result [13]

TABLE II. Comparison Of Parametrs

Parameter	Calculated value	HTRI value	remark
Overall heat transfer coefficient	152.61 kcal/hr·m²·°C	142.26 kcal/hr·m²·°C	Less than 10% of variation
Heat duty	21400.5 kcal/hr	21896 kcal/hr	Less than 10% of variation
Shell side pressure drop	0.09983 kg/cm²	0.049 kg/cm²	< 0.5 kg/cm²
Tube inside pressure drop	0.044 kg/cm²	0.053 kg/cm²	<0.1 kg/cm²

The difference between calculated value and HTRI value of overall heat transfer coefficient and Heat duty (heat exchanged) is less than 10% which is acceptable. Calculated value and HTRI value of shell side presure drop and tube inside presure drop are less than allowable pressure drop hence the values of the calculated parameters are varified.

VII. Conclusion

At first thermal design is done by using kern's method. The input parameters are taken from specification sheet. The values of Overall heat transfer coefficient, Heat duty, pressure drop, are obtained.

HTRI software is used to verify analytical thermal design. It gaves close results as that of obtain from thermal design. The comparision between calculated values and software obtained values concludes the varification of the parameters.

The proven theoretical methods are in good agreement with the software results.

Future Scope

HTRI incorporates a user-friendly interface that reduces time and increases efficiency. It can load a case from CD or a read only directory. If a user loads a case marked as read only, HTRI opens and runs the case. The results are given by the software are in less time as compared to manual calculations.

HTRI can estimate the shell weight. It has an approximation procedure for estimating the weight. It does not rigorously determine the material needed to construct the shell but rather divides the diameter into suitable portions. The values obtained are reasonable but not exact

Thus after all the input is put in the software, it generates the results which can further be used for analyzing them with required output. If found satisfactory user may move ahead with the design or he shall again change the input values and obtain the required results.

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