Production of Sulfuric Acid

A project report Submitted to the Engineering Department

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Chapter One
Introduction

1.1 Introduction

Sulfuric acid : sulfuric acid is a chemical compound , colorless , odorless , extremely , oily liquid and highly corrosive strong mineral acid with the molecular formula H_2SO_4 and molecular weight 98.079 g/mol . which is soluble in water at all concentrations and sometimes called oil of vitriol.

History :

Sulfuric acid has been an important item of commerce since the early to middle 1700 s . It has been known and used since the Middle Ages . In the eighteenth and nineteenth centuries it was produced almost entirely by the chamber process in which oxides of nitrogen (as nitrosyl compounds) are used as homogeneous catalysts for the oxidation of sulfur dioxide . The product made by this process is of rather low concentration (77-78 wt % H_2SO_4) . This is not high enough for many of the commercial uses of the 1990 s . The chamber process is therefore considered obsolete for primary sulfuric acid production . However, more recently modifications to the chamber process have been used to produce sulfuric acid from metallurgical off-gases in several European plants . During the first part of the twentieth century , the chamber process was gradually replaced by the contact process . The primary impetus for development of the contact process came from a need for high strength acid and oleum to make synthetic dyes and organic chemicals . The contact process employing platinum catalysts began to be used on a large scale late in the nineteenth century. The pace of its development was accelerated during World War I in order to provide concentrated mixtures of sulfuric and nitric acid for explosives production . In 1875 a paper by Winkler awakened interest in

the contact process first patented in 1831. Winkler claimed that successful conversion of SO_2 to SO_3 could only be achieved with stoichiometric undiluted ratios of SO_2 and O_2 . Although erroneous this belief was widely accepted for more than 20 years and was employed by a number of firms . Meanwhile other German firms expended a tremendous amount of time and money on research . This culminated in 1901 with Knietsch's lecture before the German Chemical Society revealing some of the investigations carried out by the Badische Anilin-und-Soda-Fabrik . This revealed the abandonment of Winkler's theory and further described principles necessary for successful application of the contact process . in 1915 an effective vanadium catalyst for the contact process was developed and used by Badische in Germany .

This type of catalyst was employed in the United States starting in 1926 and gradually replaced platinum catalysts over the next few decades . Vanadium catalysts have the advantages of exhibiting superior resistance to poisoning and being relatively abundant and inexpensive compared to platinum . After World War II , the typical size of individual contact plants increased dramatically in the United States and around the world in order to supply the rapidly increasing demands of the phosphate fertilizer industry . The largest sulfur burning plants as of the mid-1990 s produce approximately 3300 metric tons of acid per day . Plants using sulfur in other forms especially SO_2 from smelting operations (metallurgical plants) have also increased in size . One metallurgical plant has been built to produce 3500 metric tons of acid per day . Another significant change in the contact process occurred in 1963 , when Bayer AG announced the first large-scale use of the double-contact (double-absorption) process . In this process SO_2 gas that has been partially converted to SO_3 by catalysis is cooled passed through sulfuric acid to remove SO_3 reheated , and then

passed through another one or two catalyst beds . Through these means, overall conversions can be increased from about 98% to 99.7% , there by reducing emissions of unconverted SO_2 to the atmosphere . Because of world wide pressures to reduce SO_2 emissions , most plants as of the mid — 1990 s utilize double-absorption . An early U.S . patent disclosed the general concept of this process but apparently was not reduced to practice at that time .
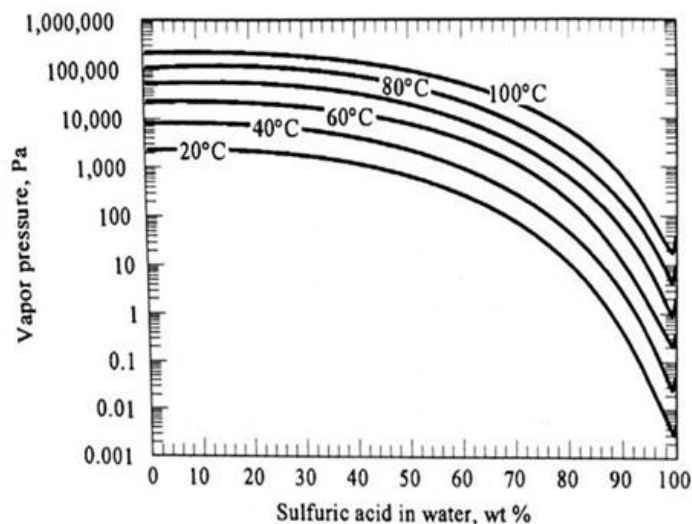
Uses of sulfuric acid :

The important uses of sulfuric acid are :-

1 - Production Fertilizer

2 - Paints and dyes .

3 – Uses in water treatment .

4 - Making Detergents

5 - A Dehydrating agent.

6 - Metal treatment and <u>anodizing</u> .

7- A Catalyst .

8- The acid in a car battery .

1.2 Physical properties of sulfuric acid:

- It is colorless, heavy and only liquid .
- It has specific gravity of 1.84 .
- It is odorless dilute solution it has sour taste.
- It is extremely corrosive to skin and all body tissues hence causes sever burns .
- Its boiling point is 348 ℃ .
- Its M.P is 10-15 ℃ .
- It is soluble in water in all preparations with the evolution of a large amount of heat .
- Pure H_2SO_4 is non-conductor of electricity as it is not dissociated .
- With addition of water it becomes good conductor .

There are many fingers shows the gravity with concentration , viscosity with concentration , boiling points with concentrations and other bellow :
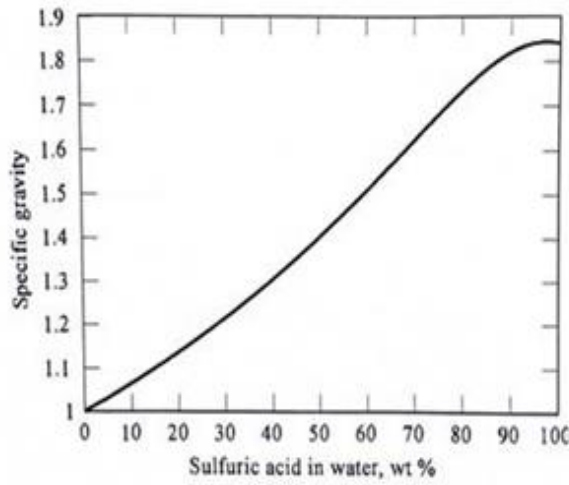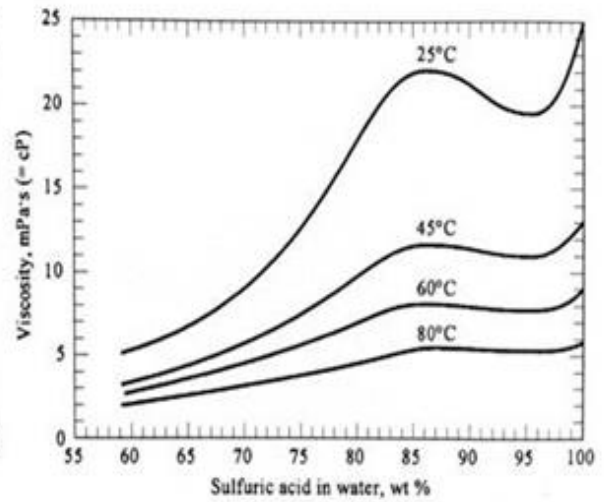
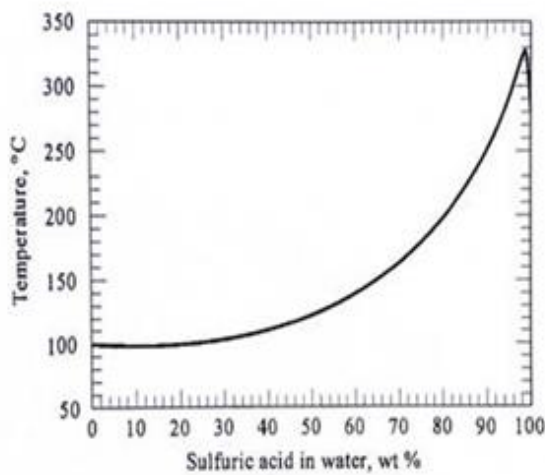fig. 1.1 Specific gravity of Sulfuric acid

Fig .1.2 Viscosity of Sulfuric acid

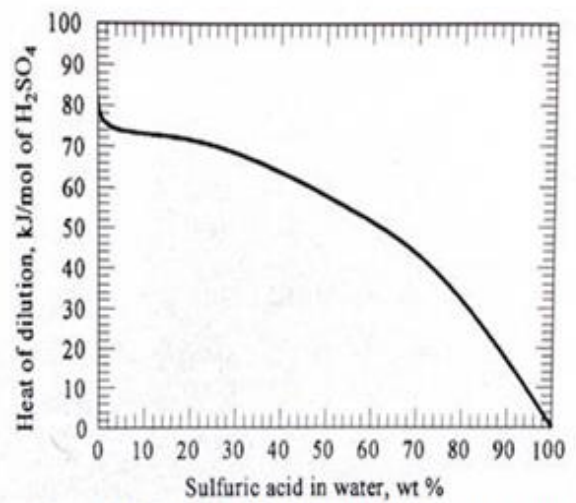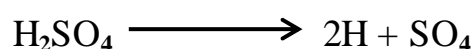Fig. 1.3 Normal boiling point of Sulfuric acid

Fig. 1.4 Heat of dilution of Sulfuric acid in water

1.3 Chemical Properties Of H_2SO_4 :

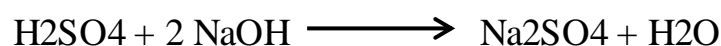The Chemical properties of Sulfuric acid are as under.

1.3.1. Reaction with water:

Sulfuric acid is a di basic acid i-e when dissolved in water one molecule produces two hydrogen atoms.
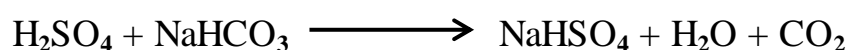
$$H_2SO_4 \longrightarrow 2H + SO_4$$

1.3.2. Reaction with alklies:

As it is di-basic acid as it forms two series of salts with bases i-e hydrogen sulfates and sulfates.

$$H_2SO_4 + NaOH \longrightarrow NaHSO_4 + H_2O$$
$$H2SO4 + 2 NaOH \longrightarrow Na2SO4 + H2O$$

1.3.3. Reaction with Carbonates and Bicarbonates :

Sulfuric Acid reacts with Carbonates, bicarbonates to form salts and CO_2.
$$H_2SO_4 + Na_2CO_3 \longrightarrow Na_2SO_4 + H_2O + CO_2$$
$$H_2SO_4 + NaHCO_3 \longrightarrow NaHSO_4 + H_2O + CO_2$$
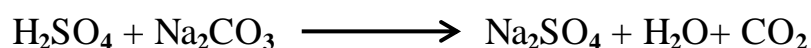
1.3.4. Reaction with Metals

Action of sulfuric acid is different under different conditions. Cold and dilute acid gives hydrogen with metals like Zn,Mg,Al, Fe ….. etc.
$$Zn + H_2SO_4 \text{ (dil)} \longrightarrow ZnSO_4 + H_2$$
$$Mg + H_2SO_4 \text{ (dil)} \longrightarrow MgSO_4 + H_2$$
$$Al + H_2SO_4 \text{ (dil)} \longrightarrow Al_2 (SO_2)_3 + 3 H_2$$
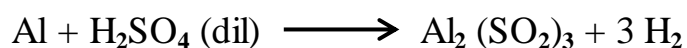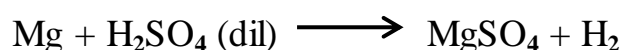
Hot and concentrated acid gives SO_2, with metals like Cu, Hg, Ag and Pb …. Etc.

$$Cu + 2H_2SO_4 \longrightarrow CuSO_4 + H_2O + SO_2$$

$$Pb + H_2SO_4 \longrightarrow PbSO_4 + H_2O + SO_2$$

1.3.5. Dissociation of H_2SO_4

H_2SO_4 dissociates into SO_3 and H_2O on boiling .

1.3.6 Oxidation Agent :

Sulfuric acid is a powerful oxidizing agent . some of its oxidizing properties are as under :

I - It oxidizes carbon, to Co_2 and sulfur to So_2
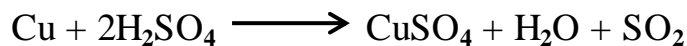
$$C + H_2SO_4 \longrightarrow CO_2 + SO_2 + H_2O$$
$$S + 2 H_2SO_4 \longrightarrow 2 SO_2 + H_2O$$

II - it oxidizes " HI " and " HBY " to iodien " I " and bramine " Br_2"
$$HI + H_2SO_4 \longrightarrow I_2 + SO_2 + H_2O$$
$$HBr + H_2So_4 \longrightarrow Br_2 + SO_2 + H_2O$$
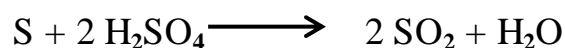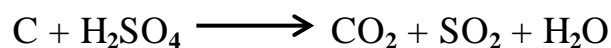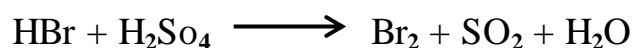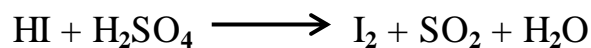
III - It oxidizes " H_2S " to "S".
$$H_2S + H_2SO_4 \longrightarrow S + SO_2 + H_2O$$

1.3.7 Drying and Dehydration Agent

Concentrated sulfuric acid has a strong attraction towards water due to this property, the acid is not only used in drying the wet substances but can also extract water from compounds.

Examples to Drying and Dehydration :-

- Blue copper sulfate (penta hydrated) is dehydrated and is changed into white anbydrous copper sulfate :

$$CuSO_4 . 5 H_2O \longrightarrow CuSO_4 + 5 H_2O$$
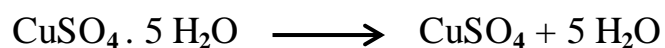
- Sugar is dehydrated to carbon :

$$C_{12}H_{22}O_{11} \longrightarrow C + 11 H_2O$$
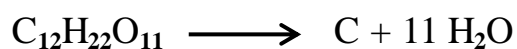
- Formic acid is dehydrated to carbon monoxide :

$$HCOOH \longrightarrow CO + H_2O$$
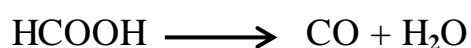
1.4 Methods of Production :

There are two major processes for production of sulfuric acid (H_2SO_4) :-
1-lead chambers
2-contact process
this processes available commercially.

1.4.1 The lead chambers process :
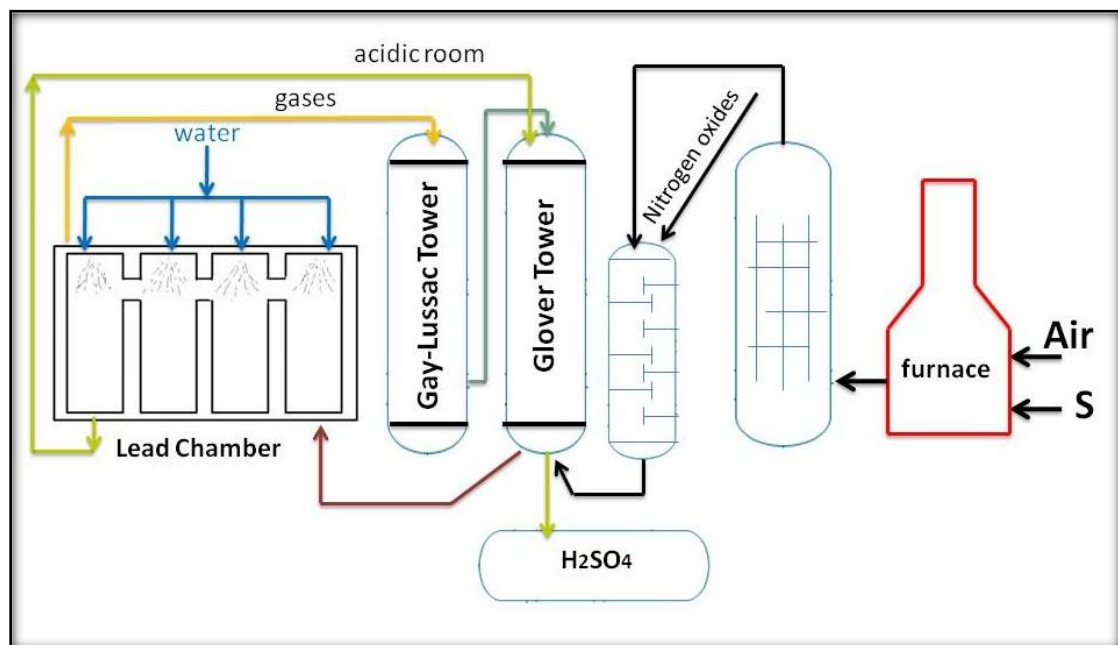
Fig. 1.5 lead chambers process

It is the older of the two processes , is used to produce much of the acid used to make fertilizers it produces a relatively dilute acid (62% – 78% H_2SO_4) . In this process sulfur enters to the furnace with amount of air (burin sulfur) and produce sulfur dioxide (SO_2) , the hot sulfur dioxide gas go to the (Dust Trap) to purification from dust and other impurities and mixed with nitrogen oxides in specific tower then the mixture enters the bottom of tower called " Glover Tower " where flaking chambers acid from the top of this tower like spray to form tower acid or

" Glover acid " (about 78% H_2SO_4 or less) this tower contain Ceramic or Porcelain rings as packing . From the bottom Glover Tower a mixture of hot gases (including sulfur dioxide and trioxide , nitrogen oxides , nitrogen , oxygen , acid vapor and steam) is transferred to a lead-lined chambers in which sulfur dioxide (SO_2) oxidize to sulfur trioxide (SO_3) where it is reacted with more water . The chambers may be a large boxes like rooms .

Notes the gases is colorless in the first room due to it do not contain higher nitrogen oxides where , reciting the gas mixture to the color red italic to brown due to higher nitrogen oxides forming the spray water from Ceilings of rooms make on dissolved some gases and acid vapor which released from oxidize (SO_2) to (SO_3) and collected the acid formed and is condenses on the walls and collects on the floor of the chambers . The gases that interring Champers passes through each in succession . The acid produced in the chambers , often called chambers acid or fertilizer acid , contains 62% to 68% H_2SO_4 . After the gases (including sulfur oxides , nitrogen oxides and nitrogen gas that produced from air used in sulfur burning) have passed through the chambers they are passed into a reactor called the Gay-Lussac Tower where they are washed with cooled dilute sulfuric acid , the nitrogen oxides and un reacted sulfur dioxide (SO_2) dissolve in the acid to form the nitrous vitriol used in the Glover tower .

1.4.2 Contact process :
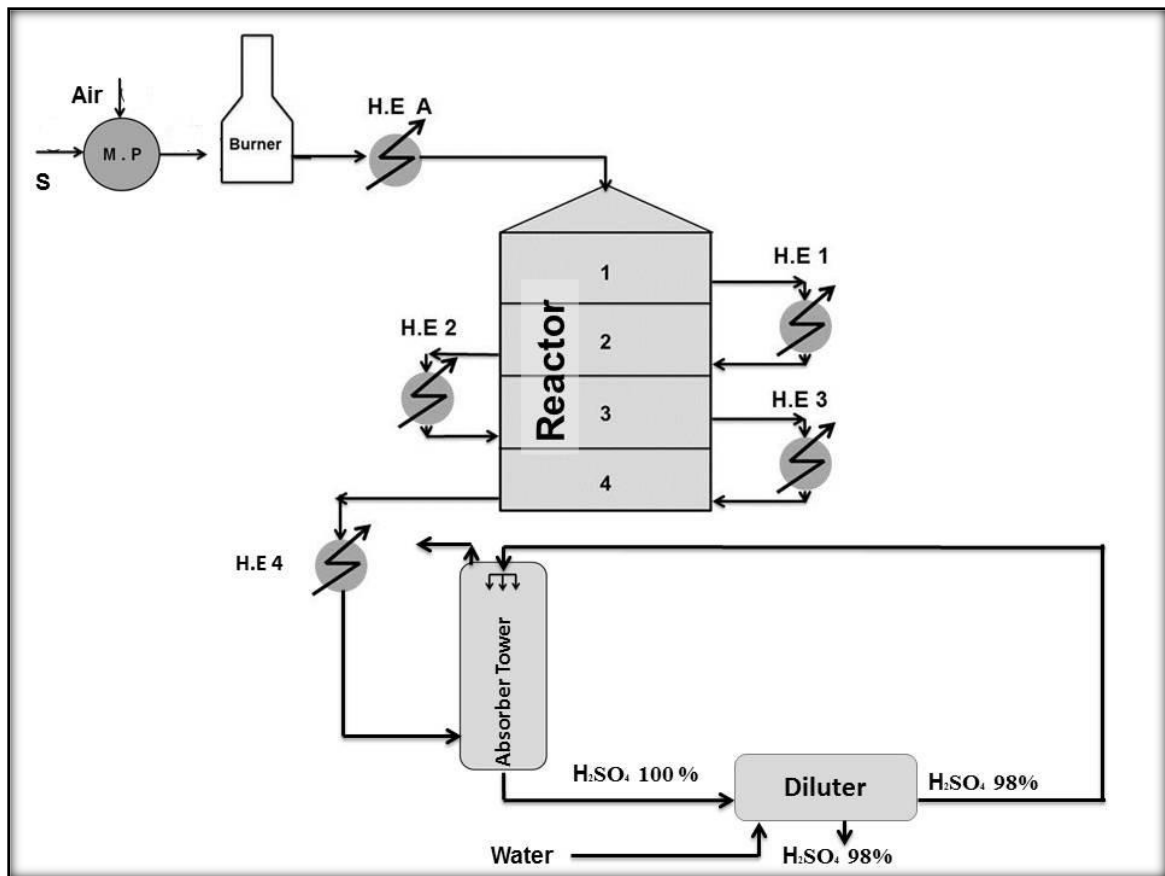
Fig. 1.6 Contact Process .

This method discovered the first one in 1831 by Englishman his name **Phillips** included his patent the basic features for modern contact process , even in 1900, it has not built a factory in a manner of contact in the United States , even though this method has gained importance in Europe duties by the urgent need for Oleum and acid with high concentration for slfonation and especially in the manufacture of dyes . And the basic principle of the process begin by burning sulfur with an abundance of air to produce sulfur dioxide (SO_2) the increase in oxygen useful to the contact process because it make the process more efficient. In both processes (contact process and lead chambers) sulfur dioxide (SO_2) is oxidized to sulfur trioxide (SO_3) . The sulfur dioxide

is obtained by burning sulfur by burning pyrites (iron sulfides) by roasting nonferrous sulfide ores preparatory to smelting , or by burning hydrogen sulfide gas H_2S . Then in contact process convert sulfur dioxide (SO_2) to sulfur trioxide (SO_3) with vanadium oxide V_2O_5 as a catalyst which is in the form of tiny cylinders packaged the reaction tower . In the final stage , sulfur trioxide is converted to sulfuric acid . The sulfur trioxide gas is absorbed into very concentrated sulfuric acid (a 98 per cent solution of H_2SO_4 in water) , producing a thick fuming liquid called oleum . The oleum is mixed carefully with water , and the sulfuric trioxide in the oleum reacts with the water to formed sulfuric acid with 98% concentration as follows :

$$SO_{3\,(g)} + H_2O_{\,(L)} \longrightarrow H_2SO_{4\,(L)}$$
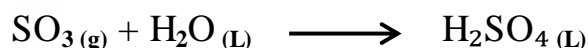
1.5 Selection of production method :

The contact process is the selected method commercially for sulfuric acid production because it is the newer method and in which the sulfuric acid produced purely and in high concentrations , more safety , less pollute , low cost and the equipment in this process is available . The Contact Process is important because it plays a big role in manufacturing . Without The Contact Process , manufacturing would be much more expensive and time consuming .

1.6 Selection of production capacity :

We will take a ten tons per day as production capacity which mean 3000 tons per year .

Chapter Two
Material And Energy Balance

2.1 Material balance
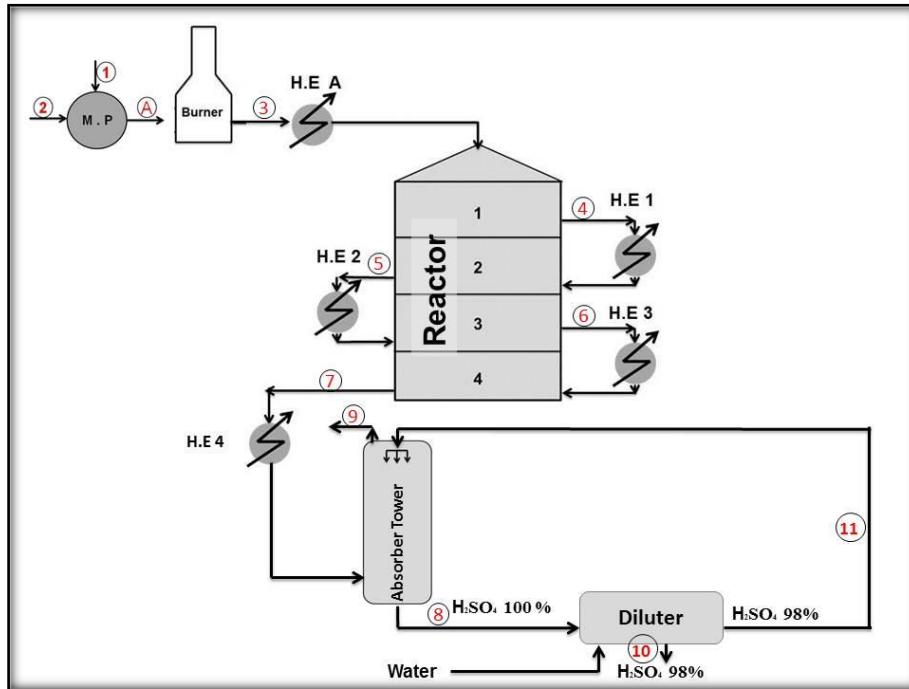
Fig. 2.1 Contact process with number of streams

given :

To design a 10 TPD capacity H_2SO_4 acid plant

Purity :

Product which is to be manufactured is assumed to have strength of 98% acid .

10 TPD implies that we have $10 * 10^3 / 24 = 416.666$ (kg / hr) of Acid With 98% purity

Basis :

1 hour of operation .

the acid that is produced per hour = (0.98 * 416.666 = 408.332 kg

kmoles of Sulfuric acid to be produced = 408.332 / 98 = 4.166 kmole

It's assumed that overall absorption of the acid is 100 %

$$SO_{3\,(g)} + H_2O_{(L)} \rightleftharpoons H_2SO_{4\,(L)}$$
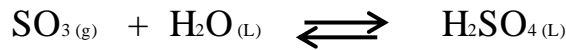
Then, SO_3 required $= 4.166$ kmole

Also its assumed that the overall conversion of SO_2 to SO_3 in the reactor is 99.8%

$$SO_{2\,(g)} + \tfrac{1}{2} O_{2\,(g)} \rightleftharpoons SO_{3\,(g)}$$
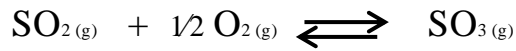
Then SO_2 required $= 4.166 / 0.998 = 4.174$ kmole

Assuming 100% combustion of Sulfur ,

$$S_{(L)} + O_{2\,(g)} \longrightarrow SO_{2\,(g)}$$
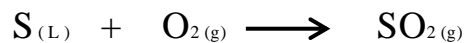
Then S required $= 4.174$ kmole $= 133.568$ kg (liquid)

Amount of oxygen required to convert (1) kmole of S to SO_3

$= 1.5$ kmole according to the equations below :

$$S_{(L)} + O_{2\,(g)} \longrightarrow SO_{2\,(g)} \qquad 1 \;\text{kmole of } O_2$$
$$SO_{2\,(g)} + \tfrac{1}{2} O_{2\,(g)} \rightleftharpoons SO_{3\,(g)} \qquad 0.5 \;\text{kmole of } O_2 \qquad 1.5\,\text{kmole}$$
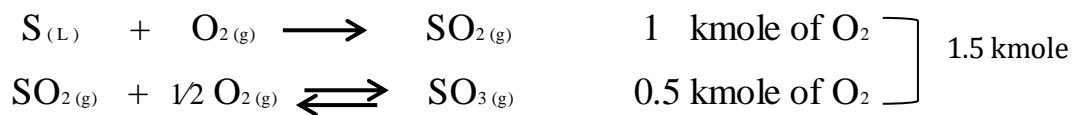
Then, amount of Oxygen required $= 4.174 \times 1.5 = 6.261$ kmole

As cited in the literature that some amount of excess oxygen must be used

Using 20% excess

O_2 required to process $= 6.261 * 1.2 = 7.5132$ kmole

From this, the total dry air that is coming in can be calculated as :

Air	O_2
100	21
X	7.5132

$X = (7.5132* 100)/ 21 = 35.777$ kmole of Dry air inlet to process

$$= 35.777 * 29 = 1037.533 \text{ kg}$$

$Q = 1036.421$ kg

Sulfur burner :

The combustion reaction takes place inside the burner where Sulfur is oxidized to Sulfur Dioxide .

Dry air entering to burner = 1037.533 kg / 29 (kg / kmole)

= 35.777 kmole

Sulfur entering (S) = 4.174 kmole

Oxygen entering O_2 = 7.5132 kmole

As mentioned before we have assumed 100% combustion of sulfur,

SO_2 leaving the burner = 4.174 kmole

Oxygen leaving the burner = 7.5132 - 4.174 = 3.339 kmole

Nitrogen leaving the burner = 35.777 * 0.79 = 28.263 kmole

SO_2 percentage in the stream leaving the burner = 0.116 and this value is nearly to note in the reference by author **" NORMAN SHREVE "** which was say the percentage of SO_2 not more than 0.12 .

Sulfur (S)
4.174 kmole
①

Dry Air   ②   Ⓐ
35.777 kmole   M . P

S = 4.174 kmole
O_2 = 7.5132 kmole
N_2 = 28.263 kmole

Ⓐ   ③
Burner

S = 4.174 kmole
O_2 = 7.5132 kmole
N_2 = 28.263 kmole

SO_2 = 4.174 kmole
O_2 = 3.339 kmole
N_2 = 28.263 kmole
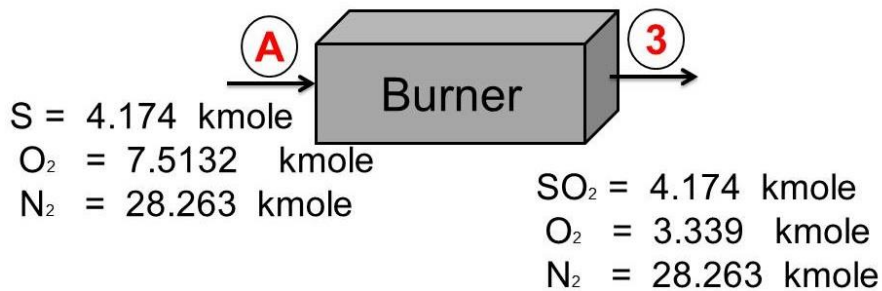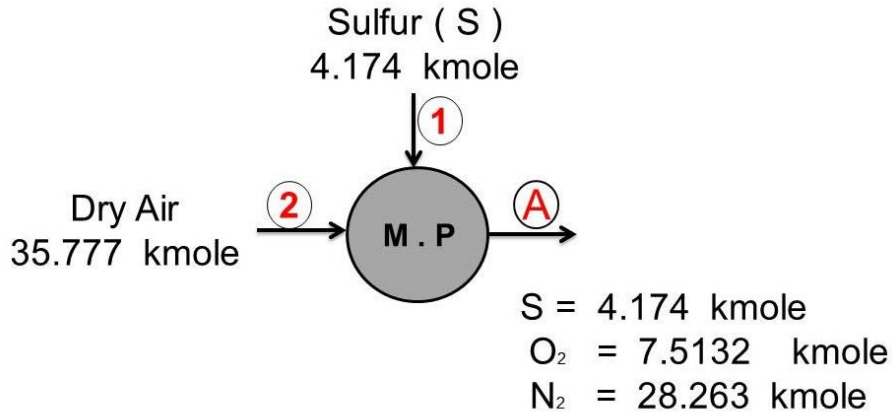
Comp.	equipment	Stream	m (Kg)	no. moles (Kmole)
S	Burner	1	133.568	4.174
O_2	Burner	2	240.4224	7.5132
N_2	Burner	2	395.682	28.263
SO_2	Burner	3	133.568	4.174
O_2	Burner	3	106.848	3.339
N_2	Burner	3	395.682	28.263

Reactor :

O_2 entering reactor   = 3.339   kmole

N_2 entering reactor   = 28.263   kmole

SO_2 entering reactor = 4.174   kmole

SO_3 entering reactor = 0.0   kmole

In the reactor the reaction below is take place :

$$SO_{2 (g)} + \frac{1}{2} O_{2 (g)} \rightleftarrows SO_{3 (g}$$
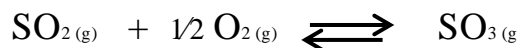
From chemical equation above we can find O_2 required for this reaction :

$$\underline{SO_2} \qquad \underline{O_2}$$

1   0.5

  4.174   X

X = 2.087 kmole of O_2 required for the reaction

O_2 leaving the reactor   = 3.339 − 2.087 = 1.252 kmole

N_2 leaving the reactor   = 28.263 kmole

SO_2 leaving the reactor = 4.174 * 0.002 = 0.008 kmole

SO_3 leaving the reactor = 4.174 * 0.998 = 4.166 kmole

In let

O₂ = 3.339 kmole
N₂ = 28.263 kmole
SO₂ = 4.174 kmole
SO₃ = 0.0 kmole

Converter
(Reactor)

O₂ = 1.252 kmole
N₂ = 28.263 kmole
SO₂ = 0.008 kmole
SO₃ = 4.166 kmole

Out let
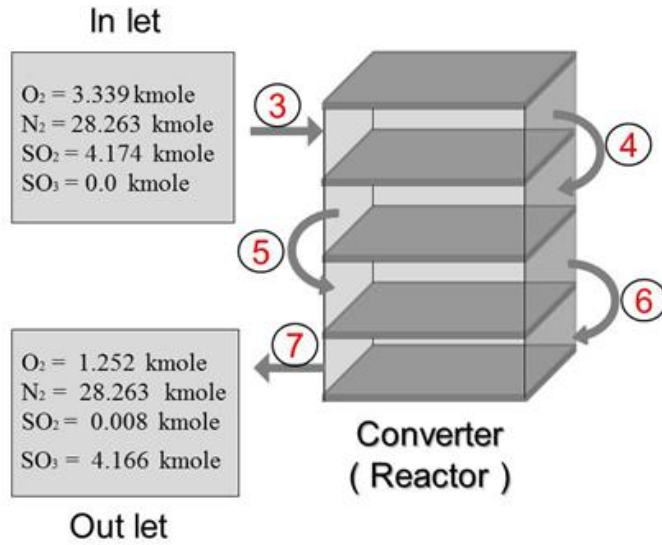
Comp.	equipment	stream	m (Kg)	no. moles (Kmole)	state
SO2	converter	3	267.136	4.174	In to stage 1
O2	converter	3	106.848	3.339	In to stage 1
N2	converter	3	395.682	28.263	In to stage 1
SO2	converter	4	69.45536	1.08524	In to stage 2
O2	converter	4	57.42784	1.79462	In to stage 2
N2	converter	4	395.682	28.263	In to stage 2
SO3 gen.	converter	4	247.1008	3.08876	In to stage 2
SO3 total	converter	4	247.1008	3.08876	In to stage 2
SO2	converter	5	20.30234	0.317224	In to stage 3
O2	converter	5	45.13958	1.410612	In to stage 3
N2	converter	5	395.682	28.263	In to stage 3
SO3 gen.	converter	5	61.44128	0.768016	In to stage 3
SO3 total	converter	5	308.5421	3.856776	In to stage 3
SO2	converter	6	8.815488	0.137742	In to stage 4
O2	converter	6	42.26787	1.320871	In to stage 4
N2	converter	6	395.682	28.263	In to stage 4
SO3 gen.	converter	6	14.35856	0.179482	In to stage 4
SO3 total	converter	6	322.9006	4.036258	In to stage 4
SO2	converter	7	0.512	0.008	Out from stage 4
O2	converter	7	42.13987	1.316871	Out from stage 4
N2	converter	7	395.682	28.263	Out from stage 4
SO3 gen.	converter	7	10.35152	0.129394	Out from stage 4
SO3 total	converter	7	333.2522	4.165652	Out from stage 4

Absorber tower :

In absorber tower the sulfur trioxide (SO_3) absorbed by sulfuric acid with purity 98% and leaving the as a product with purity 100% but we Must be cooled to avoid disintegration the acid to SO_3 gas and water in acid boiling point . also mentioned in the literature that " its required to take the strength of the solvent H_2SO_4 for absorption of SO_3 not to increase by more than 1 – 2 % and the best absorption will occur when the absorbing acid has the strength between the range 97.5 to 99 % " .

$$SO_{3\,(g)} + H_2O_{\,(L)} \rightleftarrows H_2SO_{4\,(L)}$$
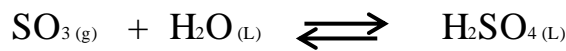
From chemical equation above we can find H_2O required for this reaction :

SO_3	H_2O	H_2SO_4
1	1	1
4.166	4.166	4.166

$H_2O = 4.166$ kmole required for the reaction to produce H_2SO_4

Solvent acid entering A.T	H_2O in solven	H_2SO_4 in solvent
100 kmole	2 kmole	98 kmole
(X + 4.166) kmole	4.166 kmole	X

$X = 204.134$ kmole H_2SO_4 in solvent acid entering

Solvent entering $= 4.166 + 204.134 = 208.3$ kmole

$= 840.572$ Kg

West Gas

Absorber

9

11   H_2SO_4 = 204.134 kmole
      H_2O = 4.166 kmole
      Σ = 208.3 kmole

7   SO_3 = 4.166 kmole

8   H_2SO_4 = 204.134 kmole
     (Added)
     H_2SO_4 = 4.166 kmole
     (Formed)
     Σ = 208.3 kmole
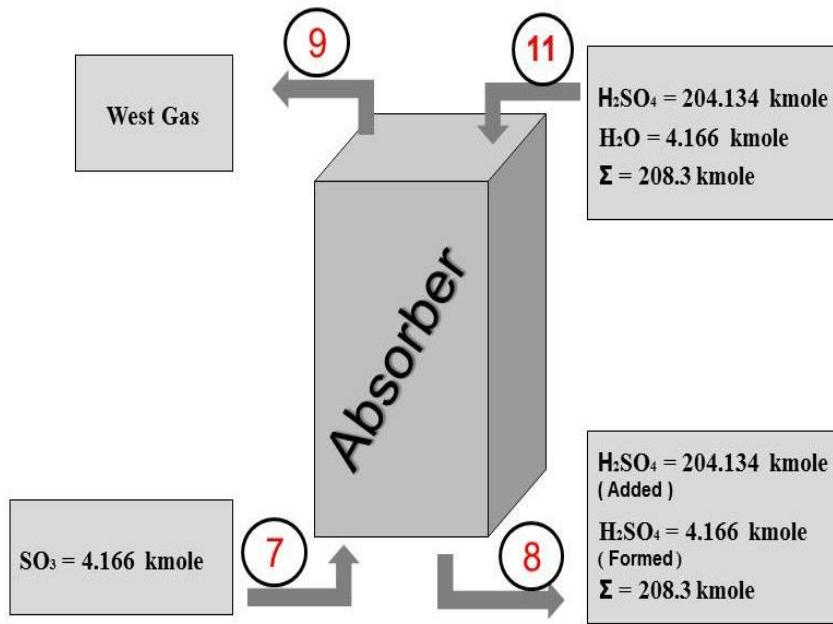
Comp.	equipment	Stream	m (Kg)	no. moles (Kmole)
SO_2	absorber	7	0.512	0.008
O_2	absorber	7	40.064	1.252
N2	absorber	7	395.682	28.263
SO_3	absorber	7	333.28	4.166
H_2SO_4	absorber	8	20413.4	208.3
SO_2	absorber	9	0.512	0.008
O_2	absorber	9	40.064	1.252
N_2	absorber	9	395.682	28.263
H_2SO_4	absorber	11	20005.13	204.134
H_2O	absorber	11	74.988	4.166

Diluter :

Dilution water is added in the tank to bring down the concentration to the desired 98% and this is calculated as

In = Out

840.572 Kg + G + W = D + K + P

W : Water

K : amount of H_2SO_4 go to Absorber Tower with 98 % purity

P : H_2SO_4 Product with 98 % purity

H_2O balance :

In = Out

W = K * 0.02 + P * 0.02

K = 840.572 Kg

P = 416.666 Kg

W = 840.572 * 0.02 + 416.666 * 0.02

= 16.811 + 8.333 = 25.144 kg water
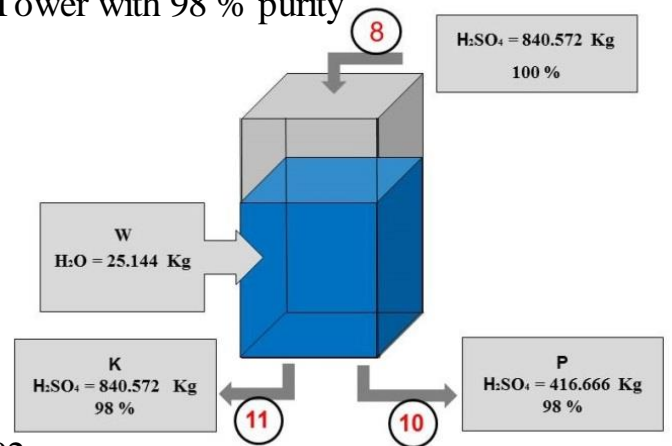
Comp.	equipment	Stream	m (Kg)	no. moles (Kmole)
H_2SO_4	diluter	8	20413.4	208.3
H_2SO_4	diluter	10	80728.48	823.76
H_2O	diluter	10	302.598	16.811
H_2SO_4	diluter	11	20005.13	204.134
H_2O	diluter	11	74.988	4.166

2.2 Energy balance :

Fig. 2.1 Contact process with number of streams

Burner :

$\Delta H_{in} = m\, cp\, \Delta T$

$\Delta H_{O2,\,N2,\,S} = m \int_{115}^{25} a + bT + cT + cT\, dT$

$\Delta H_{O2,\,N2,\,SO2} = m \int_{25}^{1100} a + bT + cT + cT\, dT$

We can solve the equation above by using Excel application to make the calculation easier , we ginned the resultant show in table below :

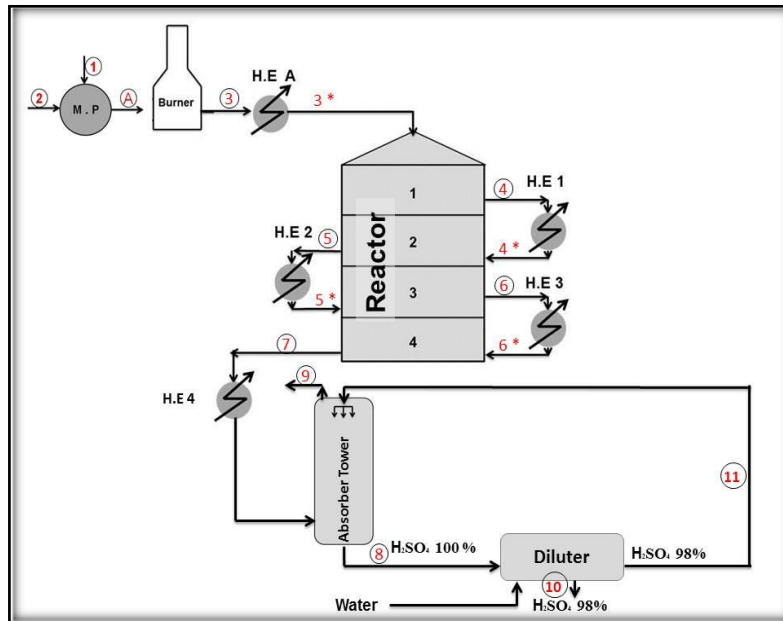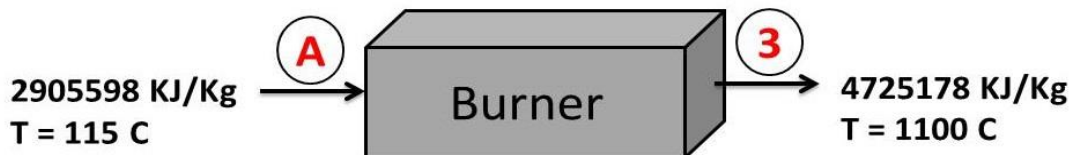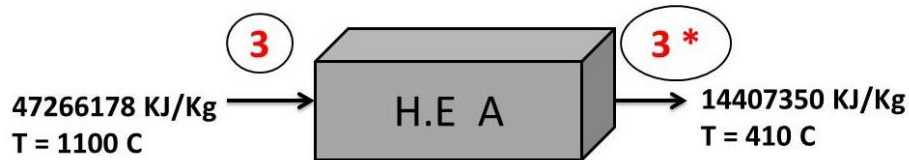| Comp.	M.wt	a	b	c	d	T1	T2	No.Stream	m (mole)	m (Kg)	ΔH	ΔH r	Q lost
S	32	15.2	0.000000027	0	0.0000000000	25	115	A	4.174	133.568	182721.0466		
O2	32	29.1	0.01158	-0.00000607	0.0000000013	25	115	A	7.5132	240.4224	646487.5566		
N2	28	29	0.002199	0.00000572	-0.000000029	25	115	A	28.233	790.524	2076389.117		
											2905597.721	-1212991808	-1162821032
SO2	64	38.91	0.0039	-0.00003104	0.0000000861	25	1100	3	4.174	267.136	16539827.67		
O2	32	29.1	0.01158	-0.00000607	0.0000000013	25	1100	3	3.339	106.848	3854179.903		
N2	28	29	0.002199	0.00000572	-0.0000000029	25	1100	3	28.233	790.524	26871170.74		
											47265178.31		

Heat Exchanger A :

$$\text{In} : \Delta H_{O2,\,N2,\,SO2} = m \int_{25}^{1100} a + bT + cT + cT \ \mathrm{dT}$$

$$\text{Out} : \Delta H_{O2,\,N2,\,SO2} = m \int_{25}^{410} a + bT + cT + cT \ \mathrm{dT}$$

$$\Delta H_{H2O} = m \int_{25}^{65} a + bT + cT + cT \ \mathrm{dT}$$

Comp.	M.wt	a	b	c	d	T1	T2	No.Stream	m (mole)	m (Kg)	ΔH	Q lost
SO2	64	38.91	0.0039	-0.00003104	0.0000000861	25	1100	3	4.174	267.136	16539827.67	
O2	32	29.1	0.01158	-0.00000607	0.0000000013	25	1100	3	3.339	106.848	3854179.903	
N2	28	29	0.002199	0.00000572	-0.0000000029	25	1100	3	28.233	790.524	26871170.74	
											47265178.31	-32857827.94
SO2	64	38.91	0.0039	-0.00003104	0.0000000861	25	410	3 *	4.174	267.136	4060985.278	
O2	32	29.1	0.01158	-0.00000607	0.0000000013	25	410	3 *	3.339	106.848	1286772.923	
N2	28	29	0.002199	0.00000572	-0.0000000029	25	410	3 *	28.233	790.524	9059592.177	
H2o	18	18.2964	0.47212	-0.0013388	0.0000013142	298	338	.	10909.59561	14407350.38		

Amount of service water = 10909.5 Kg / hr

Reactor Stage 1 :

$$\Delta H_{in} + \Delta H_r = \Delta H_{out}$$

$$In : \Delta H_{O2, N2, SO2} = m \int_{410}^{25} a + bT + cT + cT \, dT$$

$$Out : \Delta H_{O2, N2, SO3} = m \int_{25}^{1100} a + bT + cT + cT \, dT$$

	A	B	C	D	E	F	G	H	I	J	K	L	M	N
1	Comp.	M.wt	a	b	c	d	T1	T2	No.Stream	m (mole)	m (Kg)	ΔH	ΔH r	Q lost
2	SO2	64	38.91	0.0039	-0.00003104	0.0000000861	410	25	3 *	4.174	267.136	-4060985		
3	O2	32	29.1	0.01158	-0.00000607	0.0000000013	410	25	3 *	3.339	106.848	-1286773		
4	N2	32	29	0.002199	0.00000572	-0.0000000029	410	601	3 *	28.263	904.416	5390724		
5												42966	-303.619	12787585.1
6	SO2	64	38.91	0.0039	-0.00003104	0.0000000861	25	601	4	1.085	69.44	1644085		
7	O2	32	29.1	0.01158	-0.00000607	0.0000000013	25	601	4	1.799	57.568	1062296		
8	SO3	80	48.5	0.0988	-0.0000854	0.0000000324	25	601	4	3.0887	247.096	10038541		
9												12744923		

Heat Exchanger 1 :

$$In : \Delta H_{O2, N2, SO2} = m \int_{25}^{601} a + bT + cT + cT \, dT$$
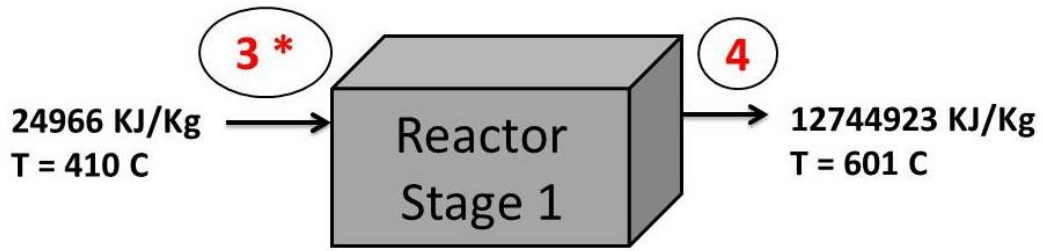
Out : $\Delta H_{O2,N2,SO3} = m \int_{25}^{438} a + bT + cT + cT \, dT$

$\Delta H_{H2O} = m \int_{25}^{65} a + bT + cT + cT \, dT$

	A	B	C	D	E	F	G	H	I	J	K	L	M
1	Comp.	M.wt	a	b	c	d	T1	T2	No.Stream	m (mole)	m (Kg)	ΔH	Q lost
2	SO2	64	38.91	0.0039	-0.00003104	0.0000000861	25	601.8	4	1.085	69.44	1646793.314	
3	O2	32	29.1	0.01158	-0.00000607	0.0000000013	25	601.8	4	1.799	57.568	1063869.371	
4	N2	28	29	0.002199	0.00000572	-0.0000000029	25	601.8	4	28.233	790.524	13791559.01	
5	SO3	80	48.5	0.0988	-0.0000854	0.0000000324	25	601.8	4	3.0887	247.096	10055161.35	
6												26557383.05	-8168105
7	SO2	64	38.91	0.0039	-0.00003104	0.0000000861	25	438	4 *	1.085	69.44	1136406.06	
8	O2	32	29.1	0.01158	-0.00000607	0.0000000013	25	438	4 *	1.799	57.568	746515.1157	
9	N2	28	29	0.002199	0.00000572	-0.0000000029	25	438	4 *	28.233	790.524	9740055.993	
10	SO3	80	48.5	0.0988	-0.0000854	0.0000000324	25	438	4 *	3.0887	247.096	6766300.406	
11	H2O	18	18.296	0.47212	-0.0013388	0.0000013142	298	338	.		48816.2	18389277.58	

Amount of service water = 48816 Kg / hr

Reactor Stage 2
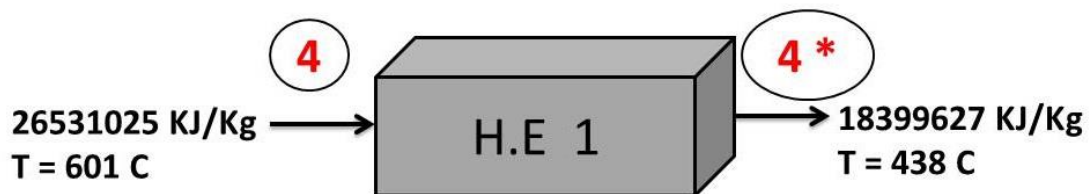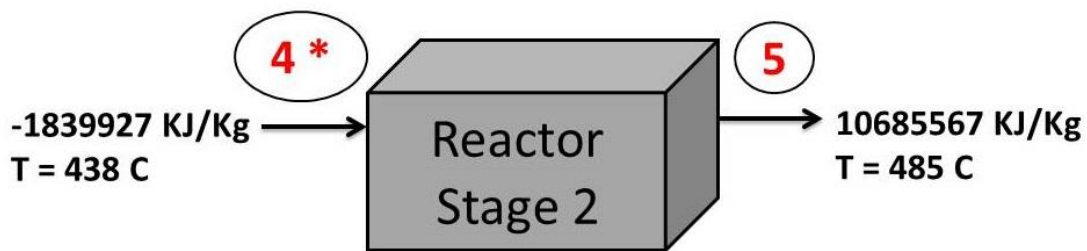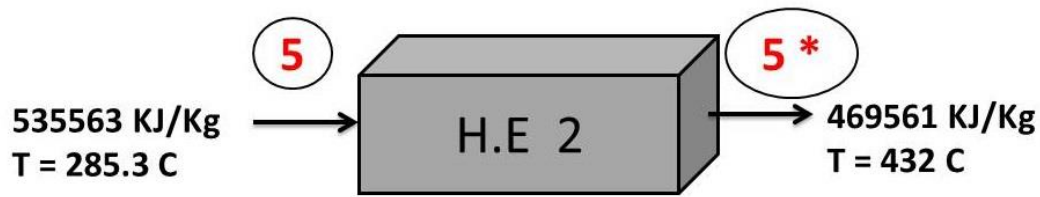

$\Delta H_{in} + \Delta H_r = \Delta H_{out}$

In : $\Delta H_{O2,N2,SO2} = m \int_{438}^{25} a + bT + cT + cT \, dT$

Out : $\Delta H_{O2,N2,SO3} = m \int_{25}^{485} a + bT + cT + cT \, dT$

	A	B	C	D	E	F	G	H	I	J	K	L	M	N
1	Comp.	M.wt	a	b	c	d	T1	T2	No.Stream	m (mole)	m (Kg)	ΔH	ΔH r	Q lost
2	SO2	64	38.91	0.0039	-0.00003104	0.0000000861	438	25	4 *	1.085	69.44	-1136406.06		
3	SO3	80	48.5	0.0988	-0.0000854	0.0000000324	438	25	4 *	3.0887	247.096	-6766300.41		
4	O2	32	29.1	0.01158	-0.00000607	0.0000000013	438	25	4 *	1.799	57.568	-746515.116		
5	N2	28	29	0.002199	0.00000572	-0.0000000029	438	25	4 *	28.263	791.364	-9750405.64		
6												-18399627.2	-75484.6	-7789544
7	SO2	64	38.91	0.0039	-0.00003104	0.0000000861	25	485	5	0.371	23.744	436088.8342		
8	SO3	80	48.5	0.0988	-0.0000854	0.0000000324	25	485	5	3.856	308.48	9593810.165		
9	O2	32	29.1	0.01158	-0.00000607	0.0000000013	25	485	5	1.41	45.12	655668.9479		
10												10685567.95		

Heat Exchanger 2 :

In : $\Delta H_{O2,N2,SO2} = m \int_{25}^{485} a + bT + cT + cT \, dT$

Out : $\Delta H_{O2,N2,SO3} = m \int_{25}^{432} a + bT + cT + cT \, dT$

$\Delta H_{H2O} = m \int_{25}^{65} a + bT + cT + cT \, dT$

	A	B	C	D	E	F	G	H	I	J	K	L	M
1	Comp.	M.wt	a	b	c	d	T1	T2	No.Stream	m (mole)	m (Kg)	ΔH	Q lost
2	SO2	64	38.91	0.0039	-0.00003104	0.0000000861	25	485.3	5	0.3172	20.3008	5829.90509	
3	O2	32	29.1	0.01158	-0.00000607	0.0000000013	25	485.3	5	1.41	45.12	20503.79933	
4	N2	28	29	0.002199	0.00000572	-0.0000000029	25	485.3	5	28.233	790.524	389193.1897	
5	SO3	80	48.5	0.0988	-0.0000854	0.0000000324	25	485.3	5	3.8567	308.536	120036.995	
6												535563.8891	-66002.4
7	SO2	64	38.91	0.0039	-0.00003104	0.0000000861	25	432	5 *	0.3172	20.3008	5111.485261	
8	O2	32	29.1	0.01158	-0.00000607	0.0000000013	25	432	5 *	1.41	45.12	18004.22858	
9	N2	28	29	0.002199	0.00000572	-0.0000000029	25	432	5 *	28.233	790.524	342641.2408	
10	SO3	80	48.5	0.0988	-0.0000854	0.0000000324	25	432	5 *	3.8567	308.536	103804.5303	
11	H2O	18	18.2964	0.47212	-0.0013388	0.0000013142	298	338	.		394.4592	469561.4849	

Amount of service water = 394.4 Kg / hr

Reactor Stage 3 :
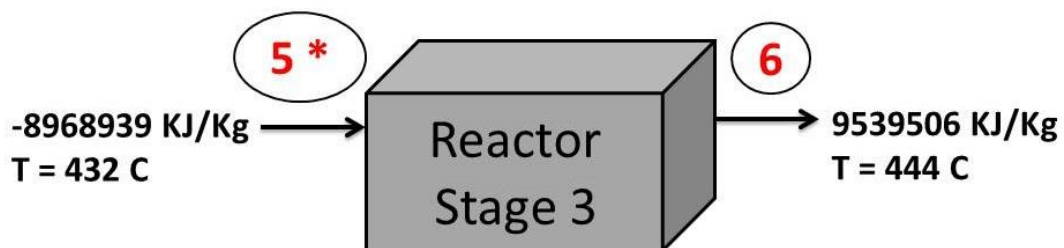
$\Delta H_{in} + \Delta H_r = \Delta H_{out}$

In : $\Delta H_{O2,N2,SO2} = m \int_{432}^{25} a + bT + cT + cT \, dT$

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Out : $\Delta H_{O2,N2,SO3} = m \int_{25}^{444} a + bT + cT + cT \, dT$

	A	B	C	D	E	F	G	H	I	J	K	L	M	N
1	Comp.	M.wt	a	b	c	d	T1	T2	No. Stream	m (mole)	m (Kg)	ΔH	ΔH r	Q lost
2	SO2	64	38.91	0.0039	-0.00003104	0.0000000861	432	25	5 *	0.371	23.744	-382620.1325		
3	SO3	80	48.5	0.0988	-0.0000854	0.0000000324	432	25	5 *	3.856	308.48	-8302855.163		
4	O2	32	29.1	0.01158	-0.00000607	0.0000000013	432	25	5 *	1.41	45.12	-576135.3144		
5	N2	28	29	0.002199	0.00000572	-0.0000000029	432	444	5 *	28.263	791.364	292671.3156		
6												-8968939.294	-17635	552932
7	SO2	64	38.91	0.0039	-0.00003104	0.0000000861	25	444	6	0.1377	8.8128	146443.5454		
8	SO3	80	48.5	0.0988	-0.0000854	0.0000000324	25	444	6	4.036	322.88	8993089.713		
9	O2	23	29.1	0.01158	-0.00000607	0.0000000013	25	444	6	1.3208	30.3784	399973.2027		
10												9539506.461		

Heat Exchanger 3 :

6 → 485182 KJ/Kg T = 444 C → H.E 3 → **6 *** 464203 KJ/Kg T = 427 C
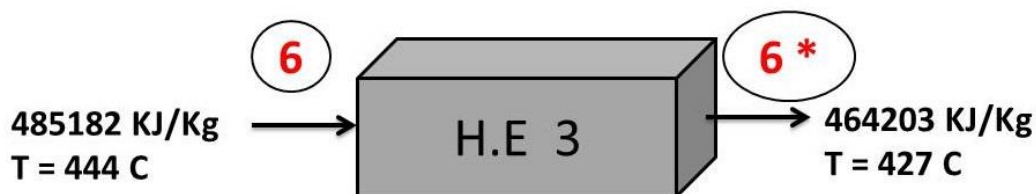
In : $\Delta H_{O2,N2,SO2} = m \int_{25}^{444} a + bT + cT + cT \, dT$
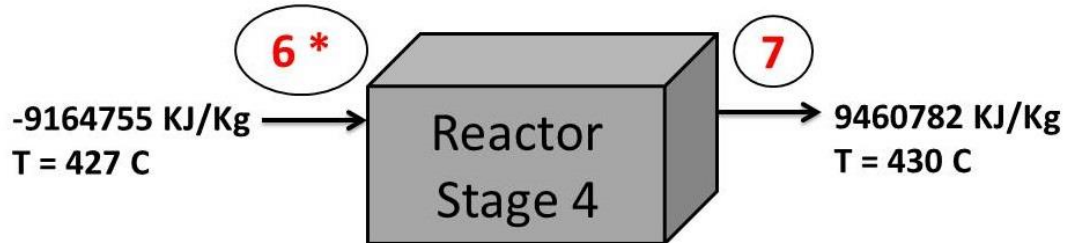
Out : $\Delta H_{O2,N2,SO3} = m \int_{25}^{427} a + bT + cT + cT \, dT$

$\Delta H_{H2O} = m \int_{25}^{65} a + bT + cT + cT \, dT$

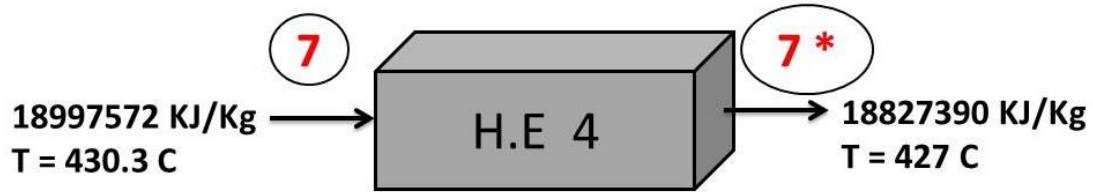|	A	B	C	D	E	F	G	H	I	J	K	L	M
1	Comp.	M.wt	a	b	c	d	T1	T2	No.Stream	m (mole)	m (Kg)	ΔH	Q lost
2	SO2	64	38.91	0.0039	-0.00003104	0.0000000861	25	444	6	0.138	8.832	2293.16554	
3	O2	32	29.1	0.01158	-0.00000607	0.0000000013	25	444	6	1.321	42.272	17392.77252	
4	N2	28	29	0.002199	0.00000572	-0.0000000029	25	444	6	28.233	790.524	353082.6928	
5	SO3	80	48.5	0.0988	-0.0000854	0.0000000324	25	444	6	4.036	322.88	112413.6214	
6												485182.2523	-20979
7	SO2	64	38.91	0.0039	-0.00003104	0.0000000861	25	427	6 *	0.138	8.832	2195.028472	
8	O2	32	29.1	0.01158	-0.00000607	0.0000000013	25	427	6 *	1.321	42.272	16649.4451	
9	N2	28	29	0.002199	0.00000572	-0.0000000029	25	427	6 *	28.233	790.524	338297.2867	
10	SO3	80	48.5	0.0988	-0.0000854	0.0000000324	25	427	6 *	4.036	322.88	107061.5066	
11	H2O	18	18.2964	0.47212	-0.0013388	0.0000013142	298	338	.		125.3796	464203.2668	

Amount of service water = 125 Kg / hr

Reactor Stage 4 :

$$\Delta H_{in} + \Delta H_r = \Delta H_{out}$$

$$In : \Delta H_{O2,N2,SO2} = m \int_{427}^{25} a + bT + cT + cT \, dT$$

$$Out : \Delta H_{O2,N2,SO3} = m \int_{25}^{430} a + bT + cT + cT \, dT$$

	A	B	C	D	E	F	G	H	I	J	K	L	M	N
1	Comp.	M.wt	a	b	c	d	T1	T2	No.Stream	m (mole)	m (Kg)	ΔH	ΔH r	Q lost
2	SO2	64	38.91	0.0039	-0.00003104	0.0000000861	427	25	6 *	0.1377	8.8128	-140176.4269		
3	SO3	80	48.5	0.0988	-0.0000854	0.0000000324	427	25	6 *	4.036	322.88	-8564920.526		
4	O2	32	29.1	0.01158	-0.00000607	0.0000000013	427	25	6 *	1.3208	42.2656	-532701.5798		
5	N2	28	29	0.002199	0.00000572	-0.0000000029	427	430	6 *	28.263	791.364	73042.85998		
6												-9164755.673	-17635	278391.6
7	SO2	64	38.91	0.0039	-0.00003104	0.0000000861	25	430	7	0.008	0.512	8207.852606		
8	SO3	80	48.5	0.0988	-0.0000854	0.0000000324	25	430	7	4.1656	333.248	8917633.249		
9	O2	32	29.1	0.01158	-0.00000607	0.0000000013	25	430	7	1.316	42.112	534941.1429		
10												9460782.244		

Heat Exchanger 4 :

In : $\Delta H_{O2, N2, SO2} = m \int_{25}^{430} a + bT + cT + cT \ dT$

Out : $\Delta H_{O2, N2, SO3} = m \int_{25}^{427} a + bT + cT + cT \ dT$

$\Delta H_{H2O} = m \int_{25}^{65} a + bT + cT + cT \ dT$

	A	B	C	D	E	F	G	H	I	J	K	L	M
1	Comp.	M.wt	a	b	c	d	T1	T2	No.Stream	m (mole)	m (Kg)	ΔH	Q lost
2	SO2	64	38.91	0.0039	-0.00003104	0.0000000861	25	430.3	7	0.0084	0.5376	8624.969616	
3	O2	32	29.1	0.01158	-0.00000607	0.0000000013	25	430.3	7	1.256	40.192	510950.3818	
4	N2	28	29	0.002199	0.00000572	-0.0000000029	25	430.3	7	28.233	790.524	9552588.048	
5	SO3	80	48.5	0.0988	-0.0000854	0.0000000324	25	430.3	7	4.1656	333.248	8925408.864	
6												18997572.26	-170182
7	SO2	64	38.91	0.0039	-0.00003104	0.0000000861	25	427	7 *	0.0084	0.5376	8551.067437	
8	O2	32	29.1	0.01158	-0.00000607	0.0000000013	25	427	7 *	1.256	40.192	506566.6143	
9	N2	28	29	0.002199	0.00000572	-0.0000000029	25	427	7 *	28.233	790.524	9472324.027	
10	SO3	80	48.5	0.0988	-0.0000854	0.0000000324	25	427	7 *	4.1656	333.248	8839948.698	
11	H2O	18	18.2964	0.47212	-0.0013388	0.0000013142	298	338	.		56.5045	18827390.41	

Amount of service water = 56 Kg / hr

Chapter Three
Equipment Design

3.1 Design of Heat Exchanger
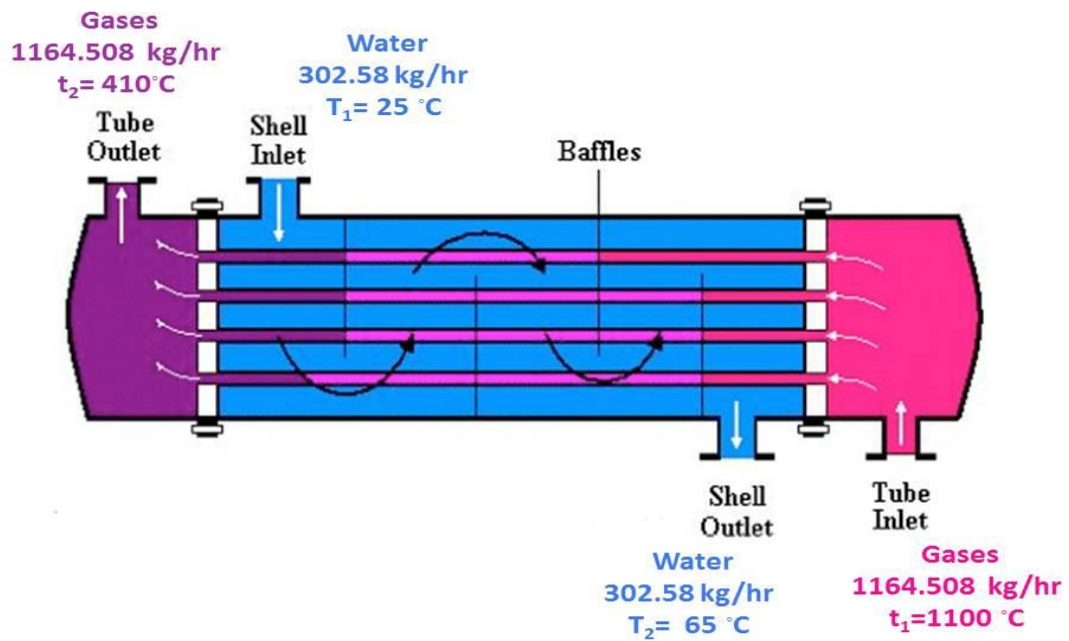
Tube Side (Gases : SO_2 & O_2 & N_2)

$t_1 = 1100 °C$

$t_2 = 410 °C$

shell Side (Water)

$T_1 = 25 °C$

$T_2 = 65 °C$

$Q = UA\ \Delta T_{lm}\ F_t$

Where

Q = heat transferred per unit time, W .

U = Overall   heat transfer Coefficient , $W/m . °C$

A = heat transfer area, m .

ΔT_{lm} = Log mean temperature difference, $°C$.

F_t = Temperature correction factor

From Energy balance $Q_{lost} = 32857827.27$ KJ/hr

$$Q == 32857827.27 * \frac{KJ}{hr} * \frac{1000J}{KJ} * \frac{h}{3600S}$$

$Q = 9127174.42$ W

$$\Delta T_{lm} = \frac{(T_1 - t_2) - (T_2 - t_1)}{ln\frac{T_1 - t_2}{T_2 - t_1}} \qquad [3]$$

$$\Delta T_{lm} = \frac{(25 - 410) - (65 - 1100)}{ln(\frac{25 - 410}{65 - 1100})}$$

$\Delta T_{lm} = 658$

Use one shell and two tube passes

$$R = \frac{T_1 - T_2}{t_2 - t_1}$$

$$R = \frac{25 - 65}{410 - 1100} = 0.057$$

$$S = \frac{t_2 - t_1}{T_1 - t_1}$$

$$S = \frac{410 - 1100}{25 - 1100} = 0.64$$

For R = 0.057 and S = 0.64   F=1   From fig.12.19   [3]

Or from equation :

$$F_t = \frac{\sqrt{(R^2+1)}\,\ln\left[\dfrac{(1-S)}{(1-RS)}\right]}{(R-1)\ln\left[\dfrac{2-S[R+1-\sqrt{(R^2+1)}]}{2-S[R+1+\sqrt{(R^2+1)}]}\right]} \qquad [3]$$

$$F_t = \frac{\sqrt{(0.0032+1)}\,\ln\left[\dfrac{(1-0.64)}{(1-0.057*0.64)}\right]}{(0.057-1)\ln\left[\dfrac{2-0.64[0.057+1-\sqrt{(0.0032+1)}}{2-0.64[0.057+1+\sqrt{(0.0032+1)}}\right]} = 0.998 \approx 1$$

From fig.12.1 the water gases system   [3]

$U = 80 - 250$

By trial and error assume $U = 90$ W/m^2.C

$$A = \frac{Q}{U\,\Delta T_{lm}\,F} = \frac{9127174.42}{90*658*1} = 156 \text{ m}^2$$

Select

Tube length   L = 1.83 m

Tube out Sid diameter d_o= 50mm   [3]

Tube thickness   = 3.2mm

$d_i = d_o - 2*3.2$

$= 50 - 2*3.2 = 43.6$ mm $= 0.0436$m

Surface area of one tube $= \text{л D L}$

$= \text{л} *0.05 * 1.83$

$= 0.287$ m^2

No. Of tube $= \dfrac{Total\ area}{area\ of\ one\ tube}$

$Nt = \dfrac{156}{0.287} = 544$

Tube Side coefficient hi

Mean tube temperater $tm = \dfrac{t_1 - t_2}{2}$

$$= \dfrac{1100 + 410}{2} = 755\ ^{\circ}C = 1023\ K$$

$\rho_v = \dfrac{PM}{RT}$

P = 10 bar = 100 kpa

T = 755 $^{\circ}$C = 1023 K

$\rho_v = \dfrac{1000 * 124}{8.314 * 1023} = 14.57928\quad Kg/m^3$

Cp = 3.077 KJ/Kg.C

K = 0. 54 w/m.c   [4]

$\mu = 0.1$ centipoise

$= 1 * 10^{-4}\ Ns/m^2$

No. of tube per pass $= \dfrac{544}{2} = 272$

Mass flow rate per tube $m = \dfrac{1164.5}{272 * 3600}$

$m = 0.00118\ Kg/s$

$M = \rho\,u\,A$

Where

M = mass flow rate kg/h

ρ = Fluid *density* kg/m²

u = Fluid velocity m/s

A_c = cross section area of tube m²

$A = \frac{\pi}{4} d^2 = \frac{\pi}{4}(0.00436)^2 = 0.149*10^{-4}$ m²

$$\mathbf{u} = \frac{\boldsymbol{m}}{\boldsymbol{\rho A}} = \frac{\mathbf{0.00118}}{\mathbf{14.57*0.149*10^{-4}}} = \mathbf{23.5\ m/s}$$

$Re = \frac{\rho u d_i}{\mu} = \frac{14.57*23.5*0.00436}{1*10^{-4}} = 3481 > 210$

$Nu = 0.021\ Re^{0.8}\ Pr^{0.33}(\frac{\mu}{\mu w})^{0.14}$ \qquad [3]

Nu = Nusselt number $= \frac{h_i\ d_i}{k}$

Pr = prondtl number $= \frac{cp\ \mu}{k}$

h_i = inside fluid film coefficient w/m².°c

d_i = inside tube diameter

k = fluid thermal conductivity w/m.°c

ρ = Fluid density kg/m³

μ = fluid viscosity kg/m.s

cp = fluid heat capacity J/kg.°c

u = fluid velocity m/s

$Re = 3481$

$Pr = \dfrac{cp\,\mu}{k} = \dfrac{3.077*10^3 *1*10^{-4}}{0.54} = 0.00064$

$(\dfrac{\mu}{\mu w})^{0.14} = 1$ [3]

$Nu = 0.021(3481)^{0.8} (0.00064)^{0.33}(1)^{0.14}$

$Nu = 0.266$

$Nu = \dfrac{h_i d_i}{k} = 0.258 = \dfrac{h_i *0.00436}{0.54}$

$h_i = 3295.6$ w/m^2.°c

Shell side coefficient h_o

Mean shell temperature $T_m = \dfrac{T_1 + T_2}{2}$

$T_m = \dfrac{25+65}{2} = 45°C$

$\rho = 990$ kg/m^3

$\mu = 0.595$ mP.s

   $= 5.95 * 10^{-4}$ Ns/m^2 [6]

$Cp = 4.18$ kJ/kg.°C

$K = 0.627$ w/m.°C

$$Nu = J_n Re\ Pr^{0.33}(\frac{\mu}{\mu w})^{0.14} \quad [3]$$

Where

$$Nu = Nusselt\ number = \frac{h_o d_e}{k}$$

$$Re = Reynolds\ number = \frac{\rho u_s d_e}{\mu}$$

$$Pr = Prandtl\ number = \frac{cp\mu}{k}$$

h_o =out side fluid film coefficient w/m^2.c

d_e = equivalent diameter m

k = fluid thermal conductivity w/m.°c

ρ = Fluid density kg/m3

μ = fluid viscosity kg/m.s

cp = fluid heat capacity J/kg.°c

u_s = fluid velocity m/s

use square tube pitch $p_t = 1.25\ d_o$

$$d_e = \frac{1.27}{d_o}\ (p_t{}^2 - 0.785\ d_o{}^2) \quad [3]$$

Where

d_o, d_e and pt in mm

$d_o = 50$mm

$P_t = 1.25(50) = 62.5$mm

$$d_e = \frac{1.27}{50}(62.5^2 - 0.785*50^2) = 49.4mm$$

$$= 0.0494m$$

$$D_b = do\left(\frac{Nt}{k_1}\right)^{1/n_1} \quad [3]$$

Where

D_b = bundle diameter   mm

Nt = total number of tube

K_1 and n_1 = constant

For squar tube pitch and two tube passes

K_1 =0.156

N_1 =2.291   Table 12.4   [3]

$$D_b = 50\left(\frac{544}{0.156}\right)^{1/2.291} = 1758 \text{ mm}$$

For bundle diameter $D_o = 551$ mm and split ring flooting head

$D_s - D_b = 60$ mm   Fig 12.10

$D_s - 551 = 60 \implies D_s = 1818$ mm = 1.818 m

$$A_s = \left(\frac{p_t - d_o}{p_t}\right)(D_s * l_B) \quad [3]$$

Where

A_s = Cross flow area m^2

l_B = baffle Spacing   m

l_B= (0.20 to l) shell diameter   [3]

$l_B = 0.5 D_s$

$l_B = 0.5 * (1.844) = 0.909$ m

$A_S = \frac{62.5-50}{62.5}(1.818 * 0.909) = 0.33$ m^2

$G_S = \frac{w_S}{A_S}$

Where

$G_S =$ mass velocity kg/m^2 .C

$W_S =$ mass flow rate kg/s

$W_S = 10909.5$ kg/h

$\quad = 3.03$ kg/s

$G_S = \frac{3.03}{0.33} = 9.16$ kg/m^2.s

$G_S = ps\ us \Longrightarrow u_S = \frac{Gs}{\rho s} = \frac{9.16}{990} = 0.0092$ m/s

$Re = \frac{G_S d_e}{\mu} = \frac{9.16*0.0494}{5.9*10^{-4}} = 1189$

For Re = 1189 and 25% baffale cut $J_n = 5*10^{-3}$ [3]

$Pr = \frac{cp\mu}{k} = \frac{4.18*10^3*5.9*10^{-4}}{0.622} = 3.93$

Nu $= 5*10^{-3}(1189)(3.39)^{0.33}$ (1)

Nu $= 75.36$

Nu $= \frac{h_o d_r}{\mu}$

$$75.36 = \frac{h_o * 0.0494}{0.627}$$

$h_o = 956.6 \ \text{w/m}^2.\text{c}$

Over all heat transfer Coefficient U

$$\frac{1}{U^\circ} = \frac{1}{h_o} + \frac{1}{h_o d} + \frac{d_o \ln d_o/d_i}{2kw} + \frac{d_o}{d_i} \cdot \frac{1}{h_{id}} + \frac{d_o}{d_i} \cdot \frac{1}{h_i} \quad [3]$$

Where

U° = over all heat transfer coefficient $\text{w/m}^{2.} \text{ c}$

h_o = out side fluid film coefficient $\text{w/ m}^2. \text{ c}$

h_{od} = out side dirt coefficient $\text{w/m}^2.\text{c}.$

d_o = tube out side diameter m.

Kw = thermarl conductivity of tube wall material w/m.c

$h_{id} = 3000$

$h_{od} = 5000$ ⎦ Table 12.2 [3]

Thermal conductivity of stainless steel

Kw = 16 w/m.c   Table 12.6 [3]

$$\frac{1}{U^\circ} = \frac{1}{1439} + \frac{1}{4000} + \frac{0.05 \ln 0.05/0.0436}{2*16} + \frac{0.05}{0.0436} \cdot \frac{1}{3000} + \frac{0.05}{0.0436} \cdot \frac{1}{3000}$$

$U^\circ = 87 \text{w/m}^2.\text{c}$

$U^\circ_{ass} = 90 \text{w/m}^2\text{c}$

Assume $U = 87 \ \text{W/m}^2.^\circ\text{c}$

$$A = \frac{9127174.42}{87*288.9*1} = 161.5 \text{ m}^2$$

$$Nt = \frac{161.5}{0.287} = 562$$

No. of tube per pass $= \frac{562}{2} = 281$

Mass flow rate per tube $= \frac{1164.5}{281*3600}$

$$m = 0.00115 \, kg/s$$

$$u = \frac{0.00115}{14.57*0.149*10^{-4}} = 22.7 \text{ m/s}$$

$$Re = \frac{3.39*22.7*0.00436}{1*10^{-4}} = 3365$$

$Nu = 0.021 \, (3365)^{0.8}(0.0064)^{0.33}(1)$

$Nu = 0.258$

$0.258 = \frac{h_i*0.00436}{0.54} \implies h_i = 3207 \text{ w/m. } ^{\circ}\text{c}$

Shell side coefficient h_o

$D_b = 50(\frac{562}{0.156})^{1/2.291} = 1784 \text{ mm}$

For $D_b = 511$ mm and split rong floating head type

$D_s - D_b = 58 \implies D_s = 1844 \text{ mm}$ [3]

$= 1.844 \text{ m}$

$l_b = 0.5(1.884) = 0.992 \ m^2$

$A_s = (\dfrac{62.5 - 50}{62.5})(1.884 * 0.922) = 0.34 \ m^2$

$G_s = \dfrac{7.374}{0.0324} = 8.9 \ kg/m^2.s$

$Re = \dfrac{990 * 22.7 * 0.0494}{5.9 * 10^{-3}} = 2387$

For Re = 2387 and 25% baffle cut

$Jn = 5 * 10^{-3}$ Fig 12.29   [3]

$Nu = 5 * 10^{-3}(1508)(3.03)^{0.33}(1)$

$Nu = 132.51$

$132.51 = \dfrac{h_o * 0.0494}{0.627} \implies h_0 = 992.6 \ w/m^2. \ ^\circ C$

$\dfrac{1}{U^\circ} = \dfrac{1}{992.6} + \dfrac{1}{5000} + \dfrac{0.05 \ln 0.05/0.00436}{2 * 16} + \dfrac{0.05}{0.00436}.\dfrac{1}{4000} + \dfrac{0.05}{0.00436}.\dfrac{1}{3207}$

$U^\circ = 86 \ w/m^{2.} \ ^\circ c$

$U_{ass} = 87 \ w/m^2. \ ^\circ c$

Error $= \dfrac{87 - 86}{87} * 100 \ \% = 1\%$

Tube side pressure drop

$$\Delta p_t = N_P [8\, j_f (\frac{l}{d_i})(\frac{\mu}{\mu_W})^{-0.14}+2.5][\frac{\rho u_t^2}{2}] \qquad [3]$$

Where

Δp_t = tube side pressure drop N/m^2

N_P = no. of tube passese

j_f = friction factor

u_t = tube side velocity m/s .

for Re = 1508

$j_f = 2.9*10^{-3}$ fig 12.24

$$\Delta p_t = 2[8 *2.9*10^{-3} (\frac{1.84}{0.00436})\,(1)^{-0.14}+2.5][\frac{3.39*22.7^2}{2}] \qquad [3]$$

= 6068 N/m^2

= 6.068 kpa

= 0.88 psi < 10psia ok

Shell side pressure drop

$$\Delta p_t = 8\, j_f (\frac{D_s}{d_e})\,(\frac{l}{l_B})(\frac{\mu}{\mu_W})^{-0.14}\,[\frac{\rho u_t^2}{2}] \qquad [3]$$

Where

Δp_s = shell side pressure drop N/m^2

u_s = shell side velocity m/s .

for Re = 15686 and 25% baffle cut

$j_f = 4.5 * 10^{-2}$ fig 12.30

$$\Delta P_s = 8*4.5*10^{-2}(\frac{1.84}{0.0494})(\frac{1.83}{0.992})(\frac{990*22.7^2}{2})(1)^{-0.14}$$

$$= 987 \text{ N/m}^2$$

$$= 0.98 \text{ kpa} = 0.14 \text{ psi} < 10 \text{ psia Ok}$$

Pipe sizing

$d = 260 \text{ } G^{0.52}p^{-0.37}$ [3]

Where

d = optimum pipe diameter mm

G = fluid mass flow rate kg/m^3

ρ = fluid density kg/m^3

Inlet and out let Gases

G = 1164.5 kg/h = 0.32 kg/s

ρ = 3.39 kg/m^3

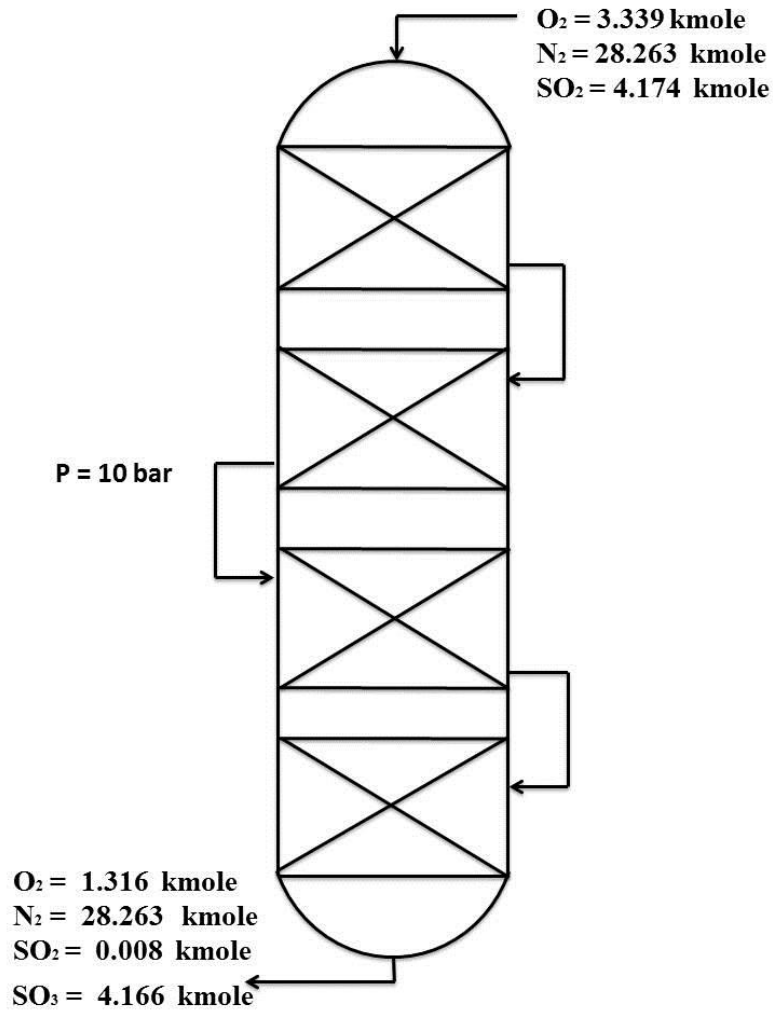$D = 260(0.32)^{0.52} (3.39)^{-0.37} = 91.5 \text{ mm} \approx 3.5 \text{ inch}$

Inlet and outlet water

G = 10909.5 kg/h = 3.03 kg/s

ρ = 990 kg/m^3

$d = 260(3.03)^{0.52}(990)^{-0.37} = 36 \text{ mm} \approx 1.5 \text{ inch}$

3.2 Design Reactor

O₂ = 3.339 kmole
N₂ = 28.263 kmole
SO₂ = 4.174 kmole

P = 10 bar

O₂ = 1.316 kmole
N₂ = 28.263 kmole
SO₂ = 0.008 kmole
SO₃ = 4.166 kmole

Catalyst :

The catalyst, vanadium(V) oxide on silica, is generally in the form of small pellets

The Vanadium pentoxide catalyst

Properties:

1-partical size =0.015 in

2-Bulk density =4.339 g/cm^3

3-partical density =1.1729g/cm^3

The volume can be evaluated using method as SIMPSONS one –third Rule :

$$V = \int_0^{X} \frac{FA^{\circ}}{-rA} dx = h/3 \{f(x)_0 + 4f(x)_1 + f(x)_2\}$$

$H = X_2 - X_0$

$-rA = Kca$

$K_1 = k_1^{\circ} \exp - E/RT$

$K_1^{\circ} = 5.78954*10^{-6} \ kmol/m^3.hr$

$K_2 = K_2^{\circ} \exp - E/RT$

$K_2^{\circ} = 2.5714*10^{2} \ Kmol/m^3.hr$

$E_1 = 20,800 \ Kcal \ /Kgmol$

$E_2 = 47,400 \ kcal/kgmol$

$K_1 = 5.78959*10^{-3} \exp - 20000/8.314*683$

$= 0.02934 \ Kmol/m^3.h$

$K_2 = 2.5714*10^{2} \exp - 47000/8.314*683$

$= 0. \ 547 \ Kmol/m^3.h$

$$y_A^{\circ} = \frac{4.174}{35.746} = 0.12$$

$\varepsilon_A = yA^{\circ}\acute{6}$

$$\epsilon_A = \left(\frac{-1}{1}\right)(0.12) = -0.12$$

$CA^{\circ} = yA*^{\circ}p/RT^{\circ}$

$CA^{\circ} = 1.12 \ atm/8.314*673$

$$= 0.0207 \ Kmol/m^3$$

$FA^\circ = 4.174 \ Kmol/h$

Simpsons rule:

X	$(1-x)/(1+\varepsilon x)$	$(1+x)/(1-x)=f(x)$
0	1	1
0.196	0.82336	1.487
0.329	0.638012	2.28
0.588	0.4432	3.584
0.784	0.2384	8.2592
0.98	0.02266	99

$H = 0.196$

$F(x) = 0.196/3 \ \{1+4*1.487+2*2.28+4*3.584+2*8.2592+99\}$

$= 8.4817$

$V = 4.147 \ / \ (0. \ 547*0.0207) \ * \ 8.4817$

$V = 43.46 \ m^3$

$V = \frac{\pi}{4} *D^2*L$

$43.46 = \frac{\pi}{4}*D^2*(4D)$

$D = 2.399 \ m$

Hence length $(L) = 4*2.399$

$$= 9.596 \ m$$

Catalyst is divided in 4 beds in ratio

Volume of catalyst in 1st bed = 43.46/4

$$= 10.8$$

Volume of catalyst in 2nd bed = 10.8

Bulk density of catalyst = 4339 Kg/m^3

Weight of catalyst in bed = 10.8*4339

$$= 46861 \ kg$$

NOW giving allowance for space for gas movement

Upward and downward and insulation be 0.5 m

Hence diameter of reactor becomes = 2.399-0.5

$$= 1.899 \ m$$

Pressure at which reactor works = 103 Kg/m^2

Let factor of safety = 20%

Design pressure = 1.2*103

$$= 123.6 \ Kg/m^2$$

We use stainless steel

Allowable stress = 66,000 psi   {hesse and Ruston}

$$= 4\ 494 \ Kgf/cm^2$$

NOW allowable stress = $p_D(1/k_2-1)$ from (Hesse)

Where p_D = design pressure

$4494 = 240 \ (1/k_2 - 1)$

K = 1.0337

D° = K Di

D° = 1.0337*2.339

D° = 2.478m

Thickness of shell = (2.478-2.339)/2

= 69 mm

Operating pressure : 103 Kg/m^2

Design pressure : 123.6 Kg/m^2

Temperature : 683-874 k°

Allowable stress : 4494 Kgf/cm^2

Diameter inside of converter : 2.339 m

Bulk density of catalyst : 4339 Kg/m^3

Volume : 43.46 m^3

Thickness of shell : 69mm

Volume of 1st catalyst bed : 10. 4 m^3

3.3 Design of Absorber

$SO_3 = 0$

G

Y2

$H_2SO_4 = 204.134$ kmole
L $H_2O = 4.166$ kmole

X2

T = 30 C
P = 10 bar

$SO_3 = 4.166$
G
Y1

$H_2SO_4 = 204.134$ kmole
$H_2SO_4 = 4.166$ kmole
L

X1
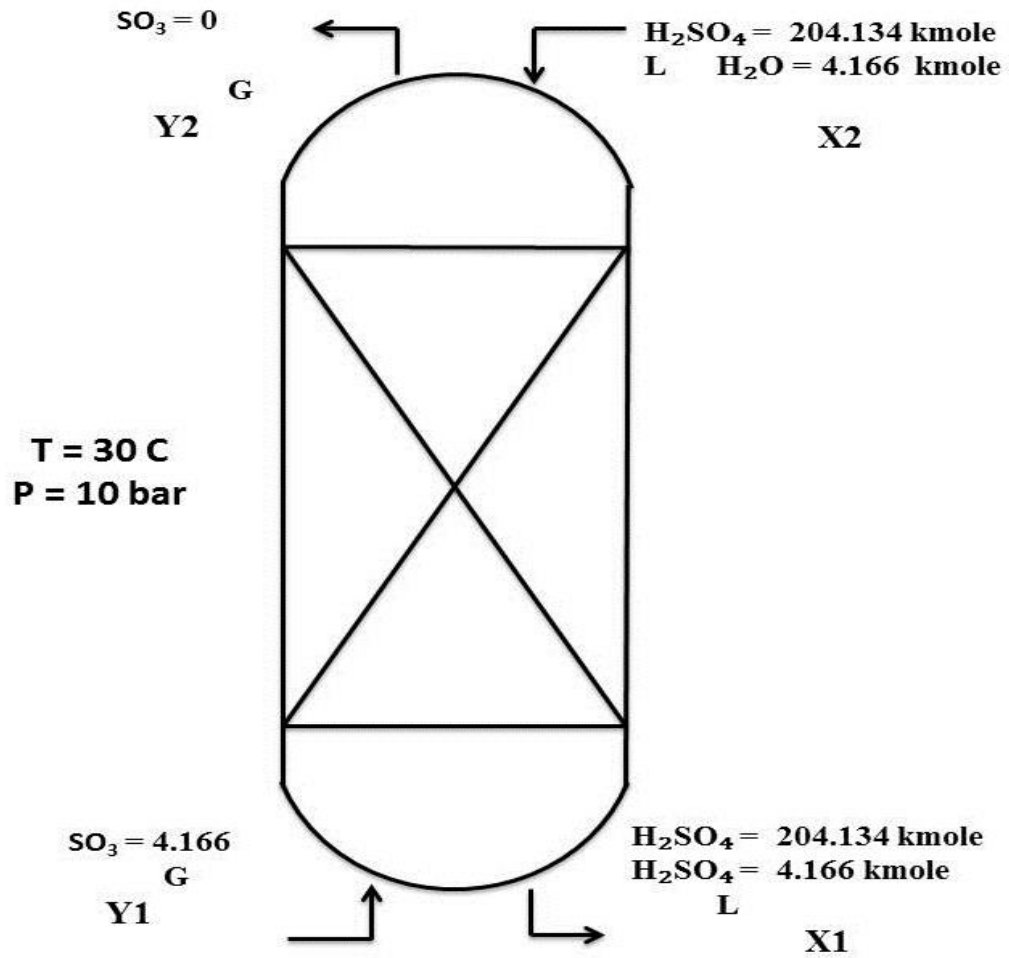
Inlet gas

Component	Kg/hr	M . wt	Kmol /hr	Mol% y
SO3	333.28	80	4.166	100

Column diameter

$$F_{L.V} = (\frac{L}{G})(\frac{\rho_V}{\rho_L})^{0.5}$$

Where :

$F_{L.V}$ = liquid vapor flow factor .

L = liquid mass flow rate kg/s .

G = gas mass flow rate kg/s .

P_v = vapor density kg/m^3 .

ρ_L = liquid density kg/m^3 .

vapor density

$$\rho_V = \frac{PM_{av}}{RT}$$

$$M_{av} = \Sigma M_i \, y_i$$

Where :

M_{av} = average molecular weight kg/k mol.

M i = molecular weight of component i kg/kmol .

yi = mol fraction of component i .

$M_{av} = (80*1)$

    = 80 kg/kmol

P = 1 bar = 100 kpa

T = 30 °C = 303 K

$$\rho_V = \frac{100*80}{8.314*303}   = 3.17 \text{ kg/m}^3$$

<u>Liquid density :</u>

Density of H_2O at 30 °C

$\rho_L = 1000$ kg/m³

L = 74.988 kg/hr

L = 0.0208 kg/s

G = 333.28 kg/hr

G = 0.0926 kg/s

$F_{L.V} = (\frac{0.0208}{0.0926})(\frac{3.17}{1000})^{0.5} = 0.012$

$V_W^* = [\frac{K_4 \rho_V (\rho_L - \rho_V)}{13.1 F_P (\frac{\mu_L}{\rho_L})^{0.1}}]^{0.5}$

Where:

V_W^* = gas mass flow rate per unit cross – sectional area kg/m².s

K_4 = constant

μ_L = liquid viscosity kg/m.s

F_p = packing factor .

Design pressure drop for absorber from from15 to50 mmH₂O /m packing

Select Δp = 42 mmH₂O /Packing

For $F_{L.V}$ = 0.01 and ΔP = 42 mmH₂O /m packing

K_4 = 3 fig 11.44

K_4 at flooding = 7

$$\text{Percent flooding} = \left(\frac{K_4}{K_4 \text{ at flooding}}\right)^{0.5} * 100\%$$

$$= \left(\frac{3}{6}\right)^{0.5} * 100\% = 70\%$$

Select 1 1/2 inch in talox saddle

$F_P = 170 \ m^{-1}$ table 11.2

Viscosity of H_2O at 30 $^\circ$C

$\mu_L = 0.722 \quad CP = 0.722*10^{-3} \ kg/m.s$

$$V_W{}^* = \left[\frac{3*3.17(1000-3.17)}{13.1*170 \left(\frac{0.722*10^{-3}}{1000}\right)^{0.1}}\right]^{0.5} \quad [3]$$

$$= 4.22 \ kg/m^2.s$$

$A = \dfrac{G}{V_W^*}$

Where :

A = cross-sectional area of column m^2 .

$A = \left(\dfrac{0.0926}{4.22}\right) = 3.4 \ m^2$

$A = \dfrac{\pi}{4} D^2$

$3.4 = \dfrac{\pi}{4} D^2 \quad D = 1.7 \ m$

Height of column :

Z = HOG . NOG

Where :

Z = height of packing m.

HOG = over all height of gas phase transfer unit m.

NOG = number of transfer unit .

$$HOG = Hg + \frac{mG}{L} H_L$$

Where :

Hg = individual height of gas film transfer unit m.

H_L = individual height of of liquid film transfer unit m.

m = slop of equilibrium line .

G = gas molar flow rate kmol/hr

L = liquid molar flow rate kmol/hr

Absorption with chemical reaction , vapor pressure of SO3 over the solution can be negligible .

$$P_A^{\circ} = 0$$

$$P_A^* = P_A^{\circ} X_A$$

$$\frac{P_A^*}{P_T} = \frac{P_A^{\circ}}{P_T} X_A$$

$$y^*_A = m \, x_A \qquad m = (\frac{P_A^{\circ}}{P_T}) = 0$$

$$m = \rho_V \, u \, A$$

$$u = \frac{m}{A \rho_V}$$

$$u = \frac{0.0926}{0.022*3.17}$$

$$= 13.5 \ m/s$$

For u = 13.5 m/s , 1.5 inch intalox saddle 1 bar and 30 $^\circ$C

Hg = 2 m

HOG = Hg = 0. 5 Table 11.3

$$NOG = \int_{y_2}^{y_1} \frac{dy}{y - y^*}$$

For absorption with chemical reaction y*= 0

$$NOG = \int_{y_2}^{y_1} \frac{dy}{y} = Ln\frac{y_1}{y_2}$$

$y_1 = 0.01$

$y_2 = 0.0005$

$$NOG = Ln\frac{0.01}{0.0005} = 2.99$$

Z = (0. 5) (2.99)

= 4.8 m

Type	Packed
Length packed	4.8 m
Diameter	1.7 m
Volume = $\frac{\pi}{4}D^2L$	0.0471
Temp. $^\circ$C	30 $^\circ$C
Pressure bar	1bar
Material of count	Carbon steel
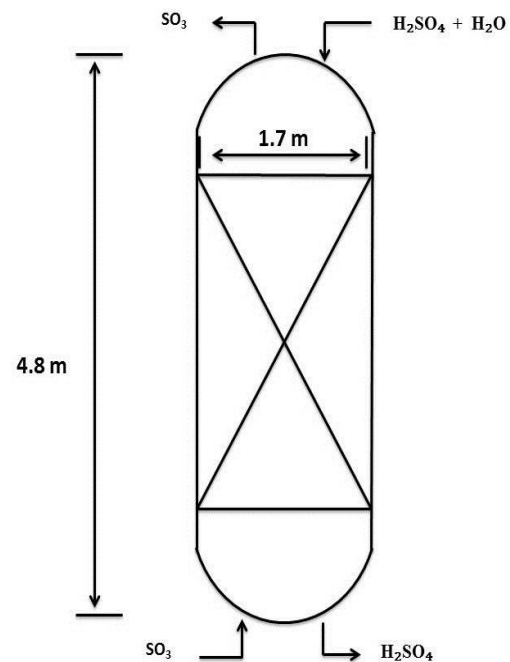
Chapter Four

Process Control

4.1 Introduction

The equipment is used in the control and measurement have a significant role in the control of the process as well as to minimize losses and to prevent damage and reduce risk. There are no industrial process devoid of control and measurement, because these are very important services in each process even if it was simple. Typically in each unit in the lab, there is a room called the control room that contains the hardware control associated with the equipment and machines for the process of production and the panel representing each unit, the index for each device and the lamps and measuring devices can be of this room control of each device and can stop the process in case there index to a significant error such as an explosion or fire.

4.2 The most important devices of control are :

1- devices to control the temperature.

2- control devices on the pressure.

3- control devices on the flow rate.

In general control device to reduce the error due to an abnormality of the process works is a mistake (error) is the difference between reading device elementary TR (reading, which is intended to occur) and read between the reading device (measuring.TM)

Error = set point – measuring give

E = TR – TM

And trying to control device to reduce the amount of error to less close to zero.

4.3 The most important control system components:

1- measuring element: it is according to the type of operating althermukmpel used to measure the temperature and albrmitr to measure pressure and venjor aoravs to measure the flow.

2- control element: a device that compares and gives instructions for a (final control) it receives a reading from the reading device and compares them with a set of reading it.

There are kinds of dominants and every kind gives frequency:

1- proportional control.

2- proportional integral.

3- proportional derivative.

4- PIB.

First the least efficient and most qualified fourth.

3- final control: a real port where it comes to him from controlling the main works this final control of the decreasing or increasing the amount depending on the amount of error.

4- process: the process is to be controlled, such as flow, pressure or temperature of the process … etc.

We can represent this circuit the following scheme:

Set point

controller → Final control → process   E R_{SP}

R_m ← Measuring element ← controlled
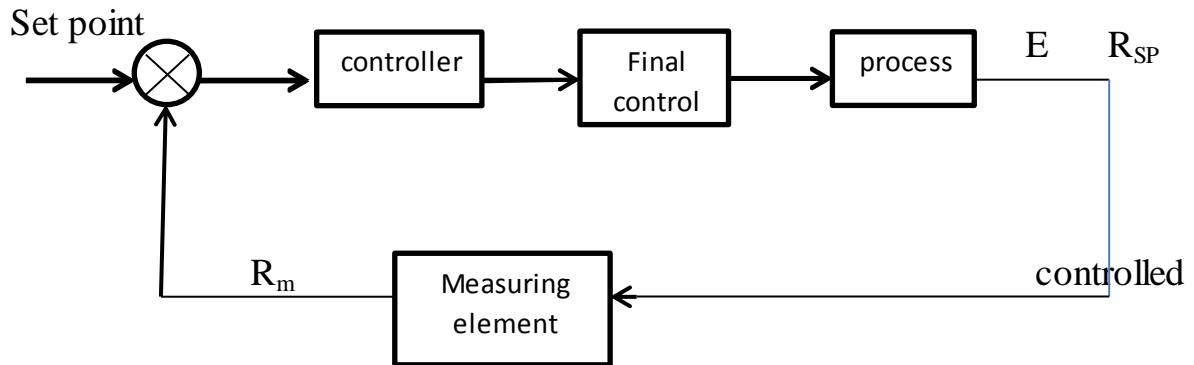
4.4 The most important symbol of control devices:

TIC = temperature control

PIC = pressure control

LIC = level control

FIC = flow control

4.3 control on reactor :

(Fc) flow controlled

(Fl) flow indicator

(Pc) pressure controlled

(Pl) pressure indicator
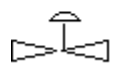
⊲⊳ control valve

Fig. (4-3) Control System of reactor

Chapter Five

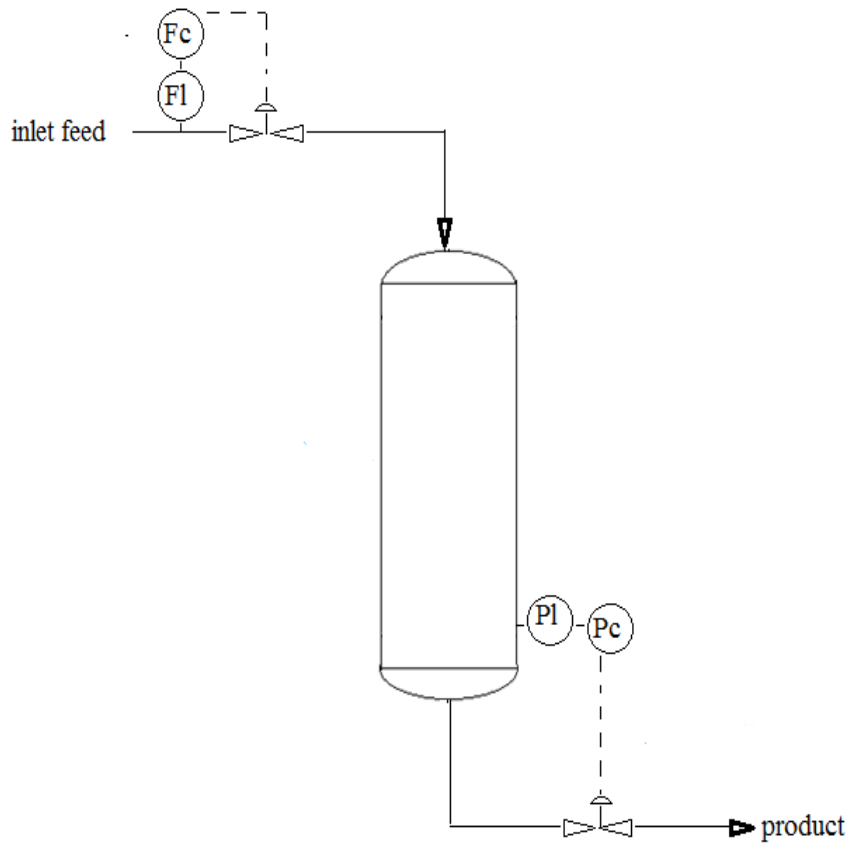# Location , Economic and Safety Consideration

5.1 Plant Location

Considerable care must be exercised in selecting the plant site, and many different factors must be considered. Primarily, the plant should be located where the minimum cost of production and distribution can be obtained, but other factors, such as room for expansion and safe living conditions for plant operation as well as the surrounding community, are also important. The following factors should be considered in selecting a plant site :

1. Raw materials availability
2. Markets
3. Energy availability
4. Climate
5. Transportation facilities
6. Water supply
7. Waste disposal
8. Labor supply
9. Taxation and legal restrictions
10. Site characteristics
11. Flood and fire protection
12. Community factors.

5.1.1: H_2SO_4 Plant Location

Based on these previous factors which are required in H_2SO_4 manufacturing plant, we select (Al-Ramadi /Al-Mohammadiat / industrial city Alkilo 70) Sulfur can be obtained from (Al-Mishraq Sulphur State Company) .
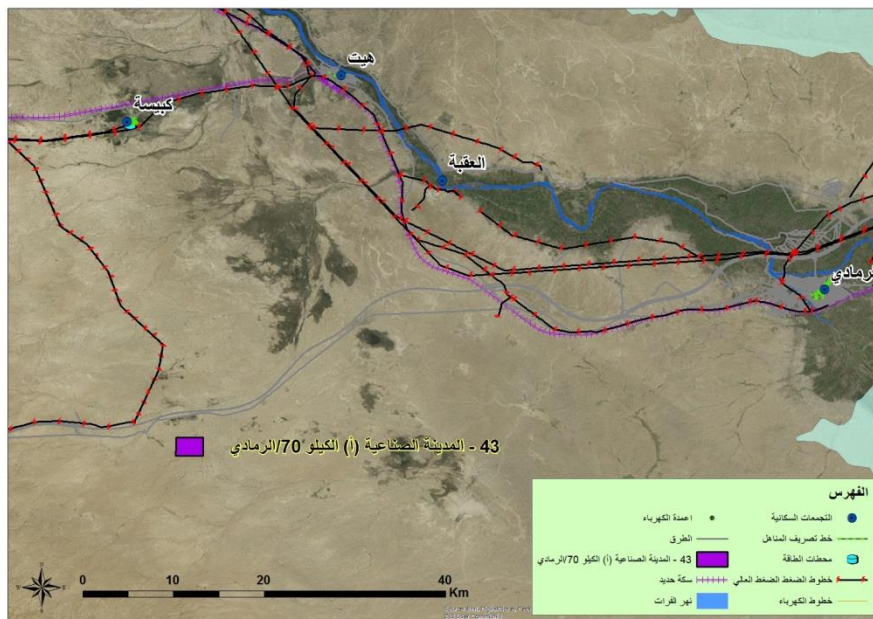
5.2 Site Considerations :

The location of the plant can have a crucial effect on the profitability of a project, and the scope for future expansion. Many factors must be considered when selecting a suitable site, the principle factors to consider are:

1- Marketing area :

For materials that are produced in bulk quantities; such as cement, mineral acids, and fertilizers, where the cost of the product per tone is relatively low and the cost of transport a significant fraction of the sales price, the plant should be located close to the primary market. This

consideration will be less important for low volume production, high-priced products; such as pharmaceuticals.

2- Raw materials

The availability and price of suitable raw materials will often determine the site location. Plants producing bulk chemicals are best located close to the source of the major raw material; where this is also close to the marketing area.

3- Transport

The transport of materials and products to and from the plant will be an overriding consideration in site selection.

4- Availability of labor

Labor will be needed for construction of the plant and its operation. Skilled tradesmen will be needed for plant maintenance.

5- Utilities (services)

Chemical processes invariably require large quantities of water for cooling and general process use, and the plant must be located near a source of water of suitable quality. Process water may be drawn from a river, from wells, or purchased from a local authority.

6- Environmental impact and effluent disposal

All industrial processes produce waste products, and full consideration must be given to the difficulties and cost of their disposal. An environmental impact assessment should be made for each new project, or major medication or addition to an existing process.

7- Land (site considerations)

Sufficient suitable land must be available for the proposed plant and for future expansion. The land should ideally be flat, well drained and have suitable load-bearing characteristics.

8- Climate

Adverse climatic conditions at a site will increase costs. Abnormally low temperatures will require the provision of additional insulation and special heating for equipment and pipe runs. Stronger structures will be needed at locations subject to high winds (cyclone/hurricane areas) or earthquakes.

5.3 Health & Safety Information :

Sulfuric acid is a strong acid and a powerful oxidizing agent . The major hazard posed by it is chemical burns , however, and the substance is not considered a carcinogen or mutagen. The standard first aid treatment for acid spills on the skin is, as for other corrosive agents, irrigation with large quantities of water. Washing is continued for at least ten to fifteen minutes to cool the tissue surrounding the acid burn and to prevent secondary damage . Contaminated clothing is removed immediately and the underlying skin washed thoroughly. Being a strong oxidizing agent, reactions of sulfuric acid with compounds such as cyanides, carbides, metallic powders can be explosive and those with many organic compounds, such as turpentine, are violent and hypergolic (i.e. self-igniting). Hence, it should be stored away from bases and organics .

5.4 Environmental Considerations :

Vigilance is required in both the design and operation of process plant to ensure that no harm is done to the environment. Consideration must be given to:

1. All emissions to land, air, water.

2. The visual impact.

3. Noise.

4. Smells.

5. Waste management.

6. Any other nuisances.

7. The environmental friendliness of the products.

Waste management: Waste arises mainly as byproducts or unused reactants from the process, or as off-specification product produced through mis-operation. The designer must consider all possible sources of pollution and, where practicable, select processes that will eliminate or minimize waste generation. Unused reactants can be recycled and off-specification product reprocessed. Integrated processes can be selected: the waste from one process becoming the raw material for another. When waste is produced, processes must be incorporated in the design for its treatment and safe disposal. The following techniques can be considered :

1. Dilution and dispersion.

2. Discharge to foul water sewer (with the agreement of the appropriate authority).

3. Physical treatments: scrubbing, settling, absorption and adsorption.

4. Chemical treatment: precipitation (for example, of heavy metals), neutralization.

5. Biological treatment: activated sludge and other processes.

6. Incineration on land, or at sea.

7. Landfill at controlled sites.

8. Sea dumping (now subject to tight international control).

Noise: Noise can cause a serious nuisance in the neighborhood of a process plant. Care needs to be taken when selecting and specifying equipment such as compressors, air-cooler fans, induced and forced draught fans for furnaces, and other noisy plant. Excessive noise can also be generated when venting through steam and other relief valves, and from flare stacks. Such equipment should be fitted with silencers.

5.5 Cost Estimation :

The choice of appropriate equipment often is influenced by considerations of price. A lower efficiency or a shorter life may be compensated for by a lower price. Funds may be low at the time of purchase and expected to be more abundant later, or the economic life of the process is expected to be limited.

5.5.1 Cost Estimation on heat exchanger

Surface area   A= 161.5 m^2

Pressure $P = 10\ bar$

Material of construction : Stainless steel

Type: floating head

Cost = 20000 \$

Pressure factor =1   Fig. 6_5b   [8]

Material factor =1

$Cost = 20000 * 1 * 1 = 20000\ \$\quad in\ (2004)$

$Cost\ in\ 2012\ =\ (cost\ in\ 2004)\dfrac{(cost\ index\ in\ 2012)}{(cost\ index\ in\ 2004)}$

$cost\ index\ in\ 2004 = 444.2$

$cost\ index\ in 2012 = 697.32$ [9]

$Cost\ in\ 2012 = (20000)\left(\dfrac{697.32}{444.2}\right)$

$= 31397\ \$$

5.5.2 Cost Estimation on reactor

Height $\qquad h = 9.596\,m$

Diameter $\qquad D = 2.399\,m$

Pressure $\qquad$ P= 10 bar

Material of construction : Stainless steel

Cost=2500 $

Pressure factor =1.1 $\qquad$ Fig. 6_5b $\qquad$ [8]

Material factor =2

$Cost = 2500 * 1.1 * 2 = 5500\,\$ \quad in\,(2004)$

$Cost\ in\ 2012 = (cost\ in\ 2004)\dfrac{(\text{cost index in}2012)}{(\text{cost index in } 2004)}$

cost index in $2004 = 444.2$

cost index in$2012 = 697.32$ $\qquad$ [9]

$Cost\ in\ 2012 = (5500)\left(\dfrac{697.32}{444.2}\right)$

$= 8600\,\$$

5.5.3 Cost estimation on absorber

Height $\qquad h = 4.8\,m$

Diameter $\qquad D = 1.7\,m$

Pressure $\quad P = 10\ bar$

Material of construction high silicon iron

Cost=5500 $

Pressure factor =1.1 $\qquad$ Fig. 6_5 b $\quad$ [8]

Material factor =1

$Cost = 5500 * 1.1 * 1\ =\ 6050\ \$\quad in\ (2004)$

$Cost\ in\ 2012\ =\ (cost\ in\ 2004)\dfrac{(\text{cost index in}2012)}{(\text{cost index in }2004)}$

cost index in $2004 = 444.2$

cost index in$2012 = 697.32$ $\qquad$ [9]

$Cost\ in\ 2012 = (6050)\left(\dfrac{697.32}{444.2}\right)$

$= 9400\ \$$

Chapter Six

Conclusion and Recommendation

6.1 Conclusions

The case study of the manufacture of sulfuric acid emphasizes the benefits of a systematic design based on the analysis of the reactor/condenser/absorber . The core of the process is the chemical reactor, and in which the reaction is take place (convert sulfur dioxide to sulfur trioxide) on a vanadium oxide V_2O_5 as a catalyst, as well as the safety and technological constraints. In this process "Accidental

pollution" there is always a risk of accidental pollution when chemicals are produced and handled. The more common a chemical, the more information is available about the different hazards and the lower the risk of accidental pollution. The highest risk for accidental pollution is during the transportation of the product . There is also a risk of pollution from the storage of sulfuric acid and different plants have different systems to collect leaks and spillages depending on guidelines for the storage of acid. Gas leaks are not normally a problem as they are handled by various monitoring and control systems, which measure the SO2 content in the air.

6.2 Recommendation

Concern about the toxicity of sulfuric acid in the workplace atmosphere is focused on its potential, as an inhaled aerosol, to exert local effects on the respiratory tract, as a consequence of low pH. Such effects can be manifested as sensory irritation of nerve endings, acute or longer term inflammation at various sites along the length of the respiratory tract epithelium, and ultimately the possibility of tumor formation in the respiratory tract, believed to be a consequence of sustained tissue inflammation and repair processes. Human carcinogenicity data and the findings of a recent 28-day inhalation study in rats suggest that the larynx is a site of particular concern, in relation to epithelial inflammation, damage and ultimately cancer.

The identification of a clear NOAEL for this range of potential respiratory tract effects is difficult, from the available data. However, the recent 28-day inhalation study in rats (using a 50% sulfuric acid aerosol) provides evidence of slight changes in the laryngeal epithelium at the lowest concentration tested, 0.3 mg/m3 Other experimental studies in a range of animal species suggest respiratory tract effects on repeated exposure to concentrations around 0.3 mg/m3, with the possibility of effects of some health significance even at concentrations down to about 0.1 mg/m3.

Taking into account the overall database, and with the concern for potential human carcinogenicity in mind, SCOEL concluded that long-term exposure should be maintained below 0.1 mg/m3 in order to provide sufficient reassurance of avoidance of possible adverse consequences for the respiratory tract epithelium. Hence SCOEL recommends an 8h TWA limit of 0.05 mg/m3 in order to satisfy this requirement. SCOEL appreciates that the reliable measurement of exposures at and around the limit value proposed is challenging. In some circumstances there might be interference from sulfate salts also present in the atmosphere. However, from the most recent evidence presented to SCOEL and from the assessment made in the Annex it appears that there are measurement techniques available that are compatible with the proposed limit.

In terms of health protection, SCOEL considered that it would be desirable to recommend a STEL of 0.1 mg/m3 to avoid short-term irritant effects. However, at present there is no available measurement method which can accommodate a short-term limit at this value (see Annex(

There is no evidence that H2SO4 can penetrate undamaged skin to cause any signs of systemic toxicity, hence there is no requirement for a 'Sk' notation.

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