Manufacturing of Formalin (37% formaldehyde aqueous solution) by partial oxidation of methanol over silver catalyst

Group 6

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25 January, 2022

Dedicated To

Our

Beloved Parents,

Respected Teachers,

&

All Those Who Devoted Their Yesterday for Our Bright Today

Preface

This document serves as the final year project thesis for BS Chemical Engineering batch (2018-2022). The aim of this thesis is to get the students familiar with all the steps involved in a chemical plant design in detail.

The students were required to perform all the literature review and engineering calculations for the design of the plant. The report states the complete procedure for the erection of a formalin manufacturing plant.

Doing this thesis, have certainly helped us get familiar with our understandings of the curriculm and apply our knowledge of engineering.

Acknowledgement

The research project titled "Manufacturing of Formalin (37% of formaldehyde aqueous solution) by partial oxidation of methanol over silver catalyst" was successfully completed in the Institute of Chemical and Environmental Engineering of the Khwaja Fareed University of Engineering and Information Technology under the Pakistan Engineering Council (PEC) Annual Award of Final Year Design Projects (FYDPs) for the year 2022-2023. The Project was supervised by Engr. Dr. Umair Azhar.

Table of Contents

List of Figures

List of Tables

List of Symbols

A	Area (m^{2})
D,d	Diameter (m)
L	Length (m)
m	Mass (Kg)
Nu	Nusselt number
n	Number of tubes
P	Pressure (atm)
Pr	Prandtl number
Re	Reynolds number
V	Volume (m^3)
T	Temperature (K)
U	Overall heat transfer (W/ m^2 .K)

Manufacturing of Formalin (37% formaldehyde aqueous solution) by partial oxidation of methanol over silver catalyst

Abstract

The present work's goal product is an aqueous solution (37%) of formaldehyde. It is a hydrocarbon molecule that represents the most basic configuration of aldehydes. Many additional chemical products, such as phenol formaldehyde, urea formaldehyde, melamine resin, paints, and glues, use it as a synthesis baseline. It's also utilised in medicine as a disinfectant and to keep cells and tissues alive. The goal of this research is to convert methanol to 98 percent utilising SilverCatalyst. This study includes detailed calculations for every plant equipment, as well as all plant building costs, taking into consideration the needed process conditions to attain our end product as per the production capacity of 70,950 tonnes per year (as formalin).

Chapter 1 – Introduction

1. Formaldehyde

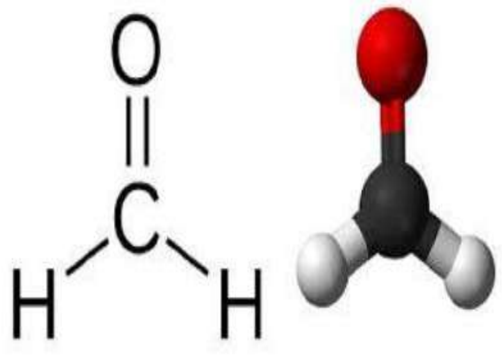

Figure 1: Formaldehyde Molecular Structure

As long as there is life on Earth, formaldehyde will be produced spontaneously in the atmosphere by photochemistry from various organic molecules. There are tiny but detectable quantities of formaldehyde in plants and animals (including humans). Even at low concentrations, it has a strong stench and is irritating to the eyes, nose, and throat. Odor detection occurs at a concentration of 0.05 and 1 ppm. Formaldehyde, on the other hand, does not produce any long-term health issues. Consequently, formaldehyde is present in combustion gases from automobiles, heating systems, gas boilers and even in cigarette smoke as a consequence of organic matter being incompletely burned and resulting in the formation of formaldehyde. Formaldehyde is a crucial chemical in many manufacturing processes and has widespread use in the consumer goods sector as well.

Incomplete combustion of carbon-containing compounds readily yields formaldehyde. Smoke from vehicles, wildfires, and cigarette smoke all include it. Methane and other hydrocarbons in the atmosphere react with sunlight and oxygen to produce formaldehyde. Most species, including humans, create small quantities of formaldehyde as a byproduct of their metabolic processes.[1]

1.1 History

Butlerov hydrolyzed methylene acetate in 1859 and recognised the distinctive odour of the resultant solution, which led to the discovery of formaldehyde. Hofmann determined in 1867 that formaldehyde had been discovered, which he made by passing methanol vapour and air through a heated platinum helix.

In 1882, Tollens developed a way to control the methanol:air vapour ratio and influence the reaction yield, making industrial manufacturing of formaldehyde practical. The platinum helical catalyst was replaced with a copper swab in 1886. In 1889, the German firm Mercklin und Losekann started commercially producing and selling formaldehyde. Hugo Blank, another German firm, received a patent in 1910 for the first practical use of a silver catalyst.[1]

1.2 Properties

At room temperature, formaldehyde is a gas; nevertheless, it may be made to dissolve in water. Formalin or formaldehyde are frequent commercial names for a 37 percent aqueous solution. Hydrate

CH2(OH)2 is formed when formaldehyde reacts with water. As a result, formalin has a low concentration of H2CO. Some methanol is frequently used in these solutions to keep polymerization under control. Most of the chemical features of aldehydes can be found in formaldehyde, however it is more reactive than aldehydes. A excellent electrolyte is formaldehyde. Electrophilic aromatic substitution reactions with aromatic compounds and electrophilic addition with alkenes may be performed using this molecule. Formaldehyde undergoes the Cannizaro reaction to produce formic acid and methanol in the presence of a basic catalyst. High pressure and low temperature are the two conditions in which formaldehyde gas defies the ideal gas law in a big way. Formic acid is formed by oxidising formaldehyde in the presence of oxygen. Protect the formaldehyde solution from the air.[1]

1.3 Physical and Thermal Properties:

Table 1: Physical and thermal properties of Formaldehyde

Physical Properties	
Boiling Point at 101.3 kPa	-19.2 ^oC
Melting Point	-118 ^oC
Density at -80 ^oC	0.9151 g/cm_3
Molecular Weight	30.03
Thermal Properties	
Heat of Formation at 25 ^oC	-115.9 + 6.3 kJ/mol
Heat of Combustion at 25 ^oC	561.5 kJ/mol
Heat of Vaporization at -19.2 ^oC	23.32 kJ/mol
Specific Heat Capacity at 25 ^oC	35.425 j/mol. K
Entropy at 25 ^oC	218.8 kJ/mol. K
Flash Point	310^{o}F (154^{o}C)
Auto Ignition Temp	932^{o}F (499^{o}C)

1.4 Reactions for formation:

Dehydrogenation of Methanol:

CH_3OH ====➔ $H_2CO + H_2$ $\Delta H = +84$ kJ/mol

Partial Oxidation of Methanol:

$CH_3OH + ½ O_2$ ======➔ $H_2CO + H_2O$ $\Delta H = -159$ kJ/mol

1.5 Uses:

Since it may be used to make so many different kinds of everyday items, the chemical industry relies on formaldehyde all the time.

Resins:

Many home items, such as cabinets, shelves, stair railing systems, and other furniture, employ glues and resins that contain formaldehyde because of its superior binding capabilities. Because formaldehyde is so readily available, these glues are not only effective but also inexpensive. Urea-formaldehyde resin, melamine resin, and phenol-formaldehyde resin are some of the most prevalent formaldehyde-based products.. Formaldehyde reacts with urea, melamine, and phenol to generate them. These glues are utilised in the carpentry industry and are quite strong. Molded from these resins, a wide range of items, including insulation, may be created. In addition to paper impregnation, melamine-formaldehyde resin is also employed in floor coverings and automotive coatings. Structural wood panels bond using phenol-formaldehyde resin. moisture-resistant formaldehydes resin may be found in face wipes, paper towels, and other items.[2]

As a Disinfectant:

The disinfecting power of formaldehyde is unmatched. There are no bacteria, fungus, yeasts or moulds that can thrive in it. Formaldehyde-containing aqueous solutions are used to treat skin infections and destroy microorganisms. Additionally, it is used in the manufacturing of vaccinations to combat specific diseases. Urethral infections may be treated with methylamine, a formaldehyde derivative. Formaldehyde derivatives are currently used in several ointments as well. They may not be suitable for prolonged usage, though. As a result of its unpleasant odour, the use of formaldehyde is confined to a small number of applications. However, a number of businesses have recently developed a non-irritating yet still efficient disinfection variant of the chemical.[1]

Textile Industry:

It is also used in the textile sector, where it is mixed with dyes and pigments to make them brighter and more vibrant. This improves the connection between the pigments and the cloth, reducing the likelihood of colour fading. Wrinkle and fold resistance are improved by using formaldehyde-based resins in the cloth.[2]

Automobile Industry:

Formaldehyde-based goods make up a large portion of automobile components. Because of its fire and high temperature resistance, phenol-formaldehyde resins are often employed in the production of automobile components like brake pads.[2]

Preserving Cells and Tissues:

To assure the safety of both people and animals, labs utilise formaldehyde solutions. For the same, a 4% solution is utilised. If you're unsure how formaldehyde maintains cells and tissues, it is by the cross-linking of major amine groups in proteins with nearby nitrogen atoms in proteins or DNA, through -CH2 binding. "[2]

Handling:

Bonding formaldehyde to just the original, completely labelled, and correctly placed container within the transport vehicle prevents any leaks or breaks. Formaldehyde should never be opened, mixed, or transferred into sample containers inside of a closed car. Those preparing with this material should have complete access to and control over MSDS (Material Safety Data Sheets). Only in ventilated settings such as outdoor tables or vertical fume hoods may formaldehyde be handled, mixed or added to containers without risk of exposure. Always keep formaldehyde out of the automobile. When using formaldehyde, the face shield should be broken if there is a chance of splashing. When handling and/or mixing this product, disposable gloves should be used to prevent skin contact. When dealing with formaldehyde, put out any open fires or cigarettes.[3]

2. Feasibility and Market Analysis

Formaldehyde is the maximum commercially significant aldehyde. Urea-, phenol-, and melamine-formaldehyde resins (UF, PF, and MF resins) account for nearly 70% of world demand for formaldehyde in 2015; other huge applications include polyacetal resins, pentaerythritol , methylene is(4-phenyl isocyanate) (MDI), 1,4-butanediol (BDO), and hexamethylenetetramine (HMTA). The demand for formaldehyde is continuously rising due to its increasing use in the production of various resins. [4]

2.1 Consumption

World consumption demand of 37% formaldehyde is estimate to raise at an average annual rate of about 5% from 2021 to 2030.Between 2010 and 2015, world capacity for 37% formaldehyde increased at an average annual rate of about 3%, slightly behind world consumption, which increased at an average annual rate of 5% through the same period.[4], [5]

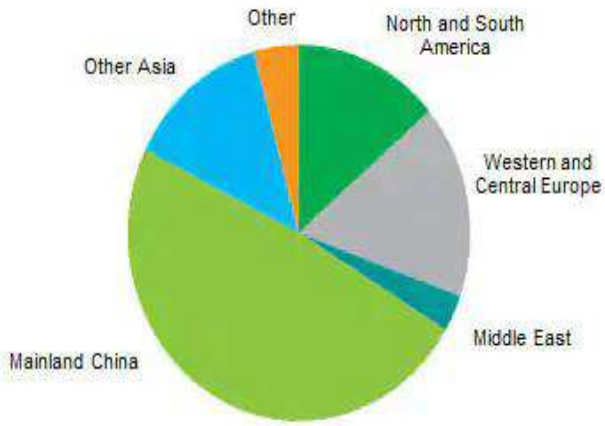

Figure 2: World Consumption

2.3 No. of companies producing Formaldehyde in world

Formaldehyde was produced by 104 companies in China, 19 companies in India, 18 companies in the USA, 15 companies each in Italy and Mexico, 14 companies in Russia, 11 companies each in Brazil and Japan, eight companies each in Canada and Germany, seven companies each in China (Province of Taiwan), Malaysia and the United Kingdom, six companies each in Argentina and Spain, five companies in Belgium, four companies each in Colombia, France, Iran, the Netherlands and Thailand, three companies each in Chile, Israel, Poland, Portugal, the Republic of Korea, Sweden, Turkey and the Ukraine, two companies each in Australia, Austria, Ecuador, Egypt, Pakistan, Peru, Romania and Serbia and Montenegro, and one company each in Algeria, Azerbaijan, Bulgaria, Denmark, Estonia, Finland, Greece, Hungary, Indonesia, Ireland, Lithuania, Norway, Saudi Arabia, Singapore, Slovakia, Slovenia, South Africa, Switzerland, Uzbekistan, and Venezuela.[6]

2.4 Leading Companies in Global Market Share

Some of the major formaldehyde manufacturers are

- Bayer AG
- Balaji Formalin Private Limited
- BASF SE
- Celanese Corporation
- Chemique Adhesives & Sealants Ltd
- Dynea Oy
- Georgia-Pacific Chemicals, LLC
- Hexion Inc.

- Huntsman Corporation
- Perstorp Holding AB.

2.5 Demand and Supply in Pakistan

Formaldehyde is a raw material for the manufacture of Urea-formaldehyde and Phenol formaldehyde. The raw material used for Formaldehyde is Methanol, which is being imported at the moment. There are six companies engaged in the manufacture of Formaldehydes in the country out of which three main players are Wah Nobel, Dynea Pakistan Ltd., and Super Chemicals Pakistan Limited. Wah Nobel is planning a 15,000 MTPY increase in capacity by June 2004. The Board of Directors of Dynea Pakistan Limited has approved the installation of a new moulding compound plant at the Gadoon Unit in July 2020 with the new plant, the total production capacity of formaldehyde would be 10,000 MTPY. The total demand for Formaldehyde is **572,000 MTPY**.[7]

Table 2: Production capacities of companies in Pakistan

Industries	Capacity	Unit
Super Chemicals, Karachi	100000	M tons / yrs.
Wah Noble Chemicals	30000	M tons / yrs.
Dynea	408000	M tons / yrs.
Total	538000	M tons / yrs.

2.6 Capacity and its Justification

In Pakistan, demand of Formaldehyde is 574,000 MTPY and our capacity of production is **538000 MTPY**. We have deficient of **36,000 MTPY.**

If we keep in mind our rate of CGAR from 2017-2026 is 5%, then our demand will be

574,000 MTPY + 28,700 MTPY (5% increment from 2017 to 2026 plans) = **602,700 MTPY**[7]

Capacity = Demand – Consumption

= 602,700 MTPY – 538,000 MTPY = 64,000 MTPY

To meet this production capacity 64,000 ton/year we have to produce 215* ton/day.

Required production capacity per year = Capacity per day * Working Day of plant

= 215 × 330 = 70,950 MTPY

Proposed production capacity of plant per year **= 70,950 MTPY** to fulfill demand with surplus.

*We have selected 215 ton per day upon statistical data of industries per day production capacity.

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Chapter 2 – Process Description

2.1 Process Selection

We've chosen the Silver Catalyst Process to make formaldehyde because it utilises a silver catalyst to partially oxidise and dehydrate methanol. As a result, only a partial oxidation occurs when an oxide catalyst is used in the production of formaldehyde. And the tail gases from the silver catalyst process can be burned, but the tail gases from the metal oxide catalyst method could not. The metal oxide catalyst method has a higher likelihood of creating by-products, while the silver catalyst technique has a far lower likelihood of doing so. The Silver Catalyst procedure was chosen because of this. Additionally, the silver method has a lower operating cost than the metal oxide process.

2.1.1 Silver Process

Silver is used as a catalyst for the oxidation and dehydrogenation of methanol in the production of formaldehyde. Oxygen has almost completed its interaction with the methanol-rich mixture in the reactor feed, which contains air, steam, and the gaseous byproduct of methanol combustion. The major processes in the silver process for converting methanol to formaldehyde are reactions 1 and 2.

Third and fourth reactions produce by-products and are secondary in nature. Formic acid, methyl formate, and methane are other byproducts.[1]

$CH_3OH \leftrightarrow CH_2O + H_2$ ΔH = +84 kJ/mol

$CH_3OH + \frac{1}{2} O_2 \rightarrow CH_2O + H_2O$ ΔH = -159 kJ/mol

$CH_2O \rightarrow CO + H_2$ ΔH = 12.5 kJ/mol

$CH_3OH + {}^{3}/_{2} O_2 \rightarrow CO_2 + 2 H_2O$ ΔH = -674 kJ/mol

2.1.2 Description

An evaporator generates a feed combination of methanol vapour and fresh air. The steam and vapour are mixed and injected into the reactor by indirect superheating. Excess methanol and steam have been introduced to the reaction mixture. Silver crystals or layers of silver gauze provide a shallow catalyst bed through which the vapour flows. Undesirable secondary reactions are repressed by the relatively low temperature of 590 - 650oC, resulting in partial conversion. Steam is generated as soon as the reaction gases exit the catalyst bed and are then indirectly cooled with water. [1] The gas is then cooled in a chiller and sent to the bottom of a formaldehyde absorption column, where the leftover reaction heat is eliminated. Most of the methanol, water, and formaldehyde are separated in the column's water-cooled segment. Countercurrent contact with process water removes all of the leftover formaldehyde and methanol from the tail gas at the column's top.

A distillation column fitted with a steam-based heat exchanger and a reflux condenser receives a 42wt percent formaldehyde solution from the bottom of the absorption column. At the top of the column, methanol is reclaimed and returned to the evaporator. The bottom of the distillation column is collected and chilled to produce a product containing up to 37% formaldehyde and less than 1% methanol.[2] In order to minimise environmental issues caused by leftover formaldehyde, the off-gas is either discharged into the atmosphere or combusted to create steam. Alternatively, the reactor may use the absorber's top-end tail gas for recycling. By combining this inert gas with steam, the reactor feed may use less methanol, resulting in a more concentrated product with reduced distillation expense. The method yields between 91 and 92 mol percent.[8]

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2.1.3 Process Flow Diagram (PFD) of Silver Process

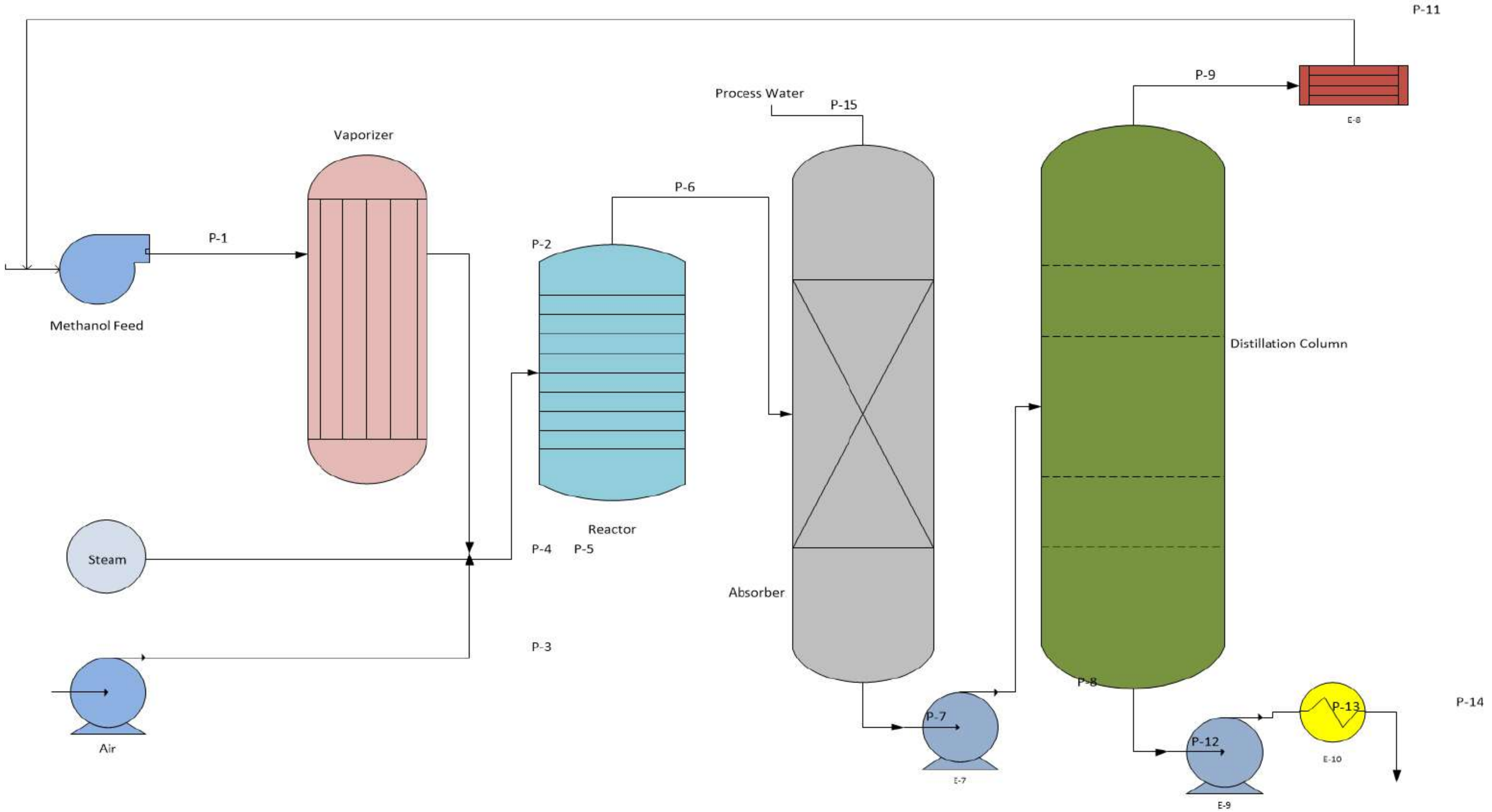

Figure 3: PFD of Silver Proces

Chapter 3 – Material Balance

3.1 Main Reactions:

CH_3OH ====➔ $CH_2O + H_2$

$CH_3OH + ½ O_2$ ====➔ $CH_2O + H_2O$

According to stoichiometric ratios

1 kmol/hr CH_3OH ====➔ 1 kmol/hr CH_2O

Capacity (According to feasibility report)

215 tons/day

=8958.333 kg/hr

Actual amount of formaldehyde = 298.611 kmol/hr

Theoretical Amount = $\frac{Actual\ Amount}{Yield}$

Overall yield of the selected process is 92%. Theoretical amount is that amount of product formed if there are no side reactions, physical or chemical losses and 100% of the reactant converts into products.

So

Theoretical Amount of Formaldehyde = 324.577 kmol/hr

So, Methanol Feed needed = 324.577 kmol/hr = 10386.464 kg/hr

Amount of O_2 needed = 149.3055 kmol/hr = 4777.776 kg/hr

Hence, the air supply rate = 710.979 kmol/hr = 20618.391 kg/hr

N_2 in the air = 504.795 kmol/hr = 14134.26 kg/hr

Steam = 216.385 kmol/hr = 3894.93 kg/hr

3.2 Material Balance at Vaporizer:

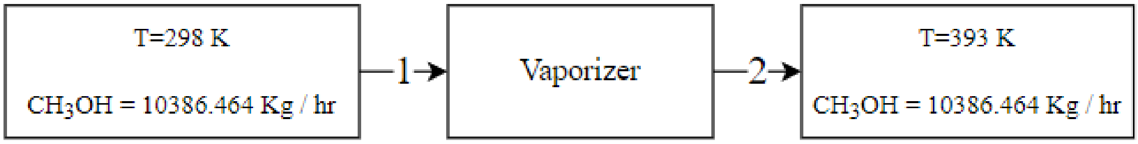

Figure 4: Mass Balance on Vaporizer

Table 3: Mass balance on Vaporiser

Components	Inlet Stream kg/hr	Outlet Stream Kg/hr
CH_3OH	10386.464	10386.464

Methanol In = Methanol Out

10386.464 kg/hr = 10386.464 kg/hr

At mixing Point:

Mixing vaporized methanol, air, and steam

= 324.577 kmol/hr + 710.979 kmol/hr + 216.385 kmol/hr

= 10386.464 kg/hr + 20618.391 kg/hr + 3894.93 kg/hr

= 34899.394 kg/hr

3.3 Mass balance At Reactor:

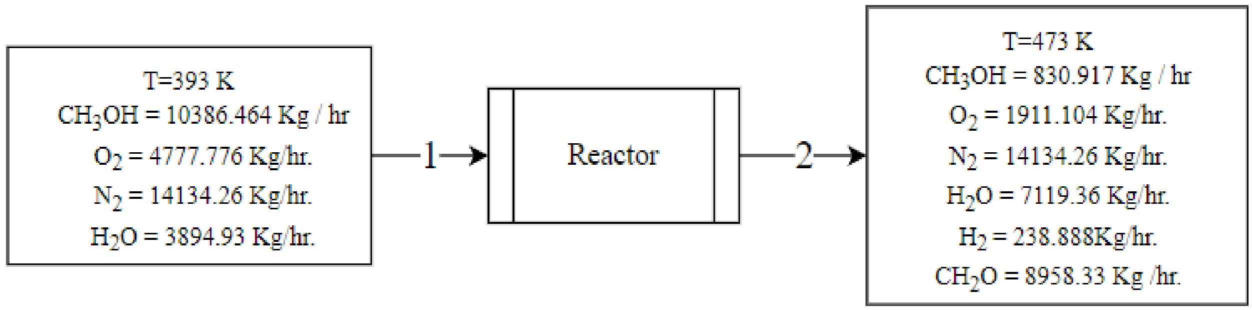

Figure 5: Mass Balance on Reactor

Table 4: Mass balance on Reactor

Components	Inlet Stream Kg/hr	Outlet Stream Kg/hr
CH_3OH	10386.464	830.9171
O_2	4777.776	1911.104
N_2	14134.26	14134.26
H_2O	3894.93	7119.936
H_2	-	238.888
CH_2O	-	8958.33
Total	33193.4	33193.4

Total Inlet Stream = 10386.46 + 4777.776 + 14134.26 + 3894.93 = 33193.4 kg/hr

For reaction 1: (Dehydrogenation) 40% of the overall yield

= 0.4 * 0.92 * 324.577 kmol/hr

Methanol Reacted = 119.4443 kmol/hr = 3822.2176 kg/hr

Formaldehyde Formed = 119.4443 kmol/hr = 3583.329 kg/hr

H_2 formed = 119.4443 kmol/hr = 238.8886 kg/hr

Methanol Remains = 205.133 kmol/ hr = 6564.256 kg/hr

Form reaction 2: (Oxidation) 60% of overall yield

= 0.6 * 0.92 * 324.577 kmol/hr

Methanol Reacted = 179.167 kmol/hr = 5733.344 kg/hr

Formaldehyde Formed = 179.167 kmol/hr = 5733.344 kg/hr

Methanol Remaining = 25.966 kmol/hr = 830.912 kg/hr

O_2 reacted = 89.5835 kmol/hr = 2866.672 kg/hr

O_2 remaining = 59.722 kmol/hr = 1911.104 kg/hr

H_2O formed = 179.167 kmol/hr = 3225.006 kg/hr

Total outlet Stream = 830.9171 + 1911.104 + 14134.26 + 7119.936 + 238.888+ 8958.33

= 33193.4 kg/hr

3.4 Mass balance at Absorber:

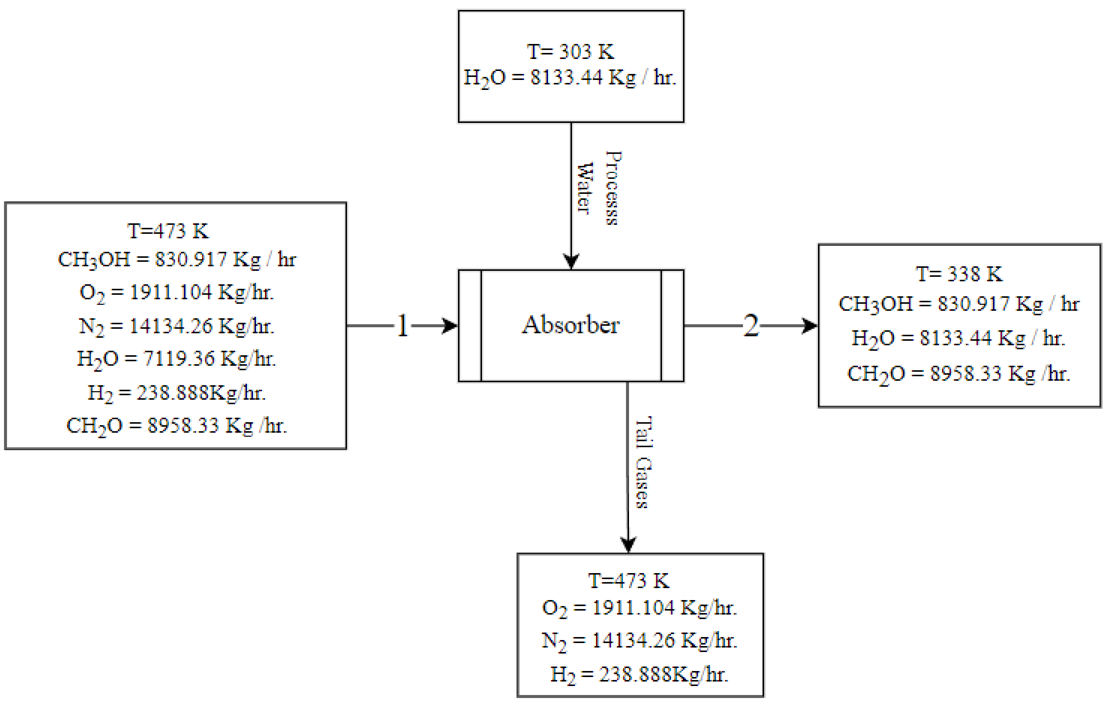

Figure 6: Mass Balance on Absorber

Table 5: Mass balance on Absorber

Components	Inlet Stream Kg/hr		Outlet Stream Kg/hr	
	1	2	1	12
CH_3OH	830.9171	-	830.917	-
O_2	1911.104	-	-	1911.104
N_2	14134.26	-	-	14134.26
H_2O	7119.936	8133.44	15252	-
H_2	238.888	-	-	238.888
CH_2O	8958.33	-	8958.33	-
Total	39843.446		39843.446	

The outlet stream from the reactor contains approximately 52% formaldehyde of methanol + water + formaldehyde mixture. Process water is being added to separate the off gases (H_2, O_2, N_2).

Inlet stream from reactor + Process Water – off gases (H_2, O_2, N_2) = Outlet Stream

33193.4 kg/hr + 8133.44 kg/hr – 1911.10 kg/hr – 14134.26 kg/hr – 238.89 kg/hr = 25042.6 kg/hr

Product from top are off gases containing H_2, unreacted O_2 and N_2.

3.5 Mass balance at Distillation Column

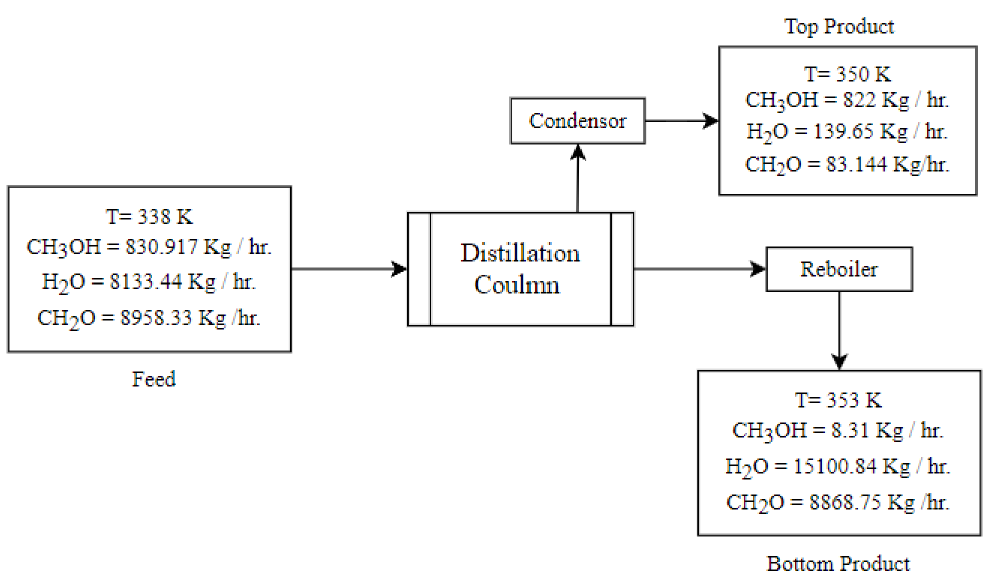

Figure 7: Mass Balance on Distillation Coulmn

Table 6: mass balance on Distillation Column

Components	Inlet Stream Kg/hr	Outlet Stream Kg/hr	
	9	12	11
CH_3OH	830.917	822.61	7.93
H_2O	15100.84	139.65	13826.14
CH_2O	8958.33	83.14	8868.75
Total	23977.9.	23977.9	

F = D + W

F.xf = Dxd + W.xw

Top Product needed: Methanol = 0.99*Unreacted = 822.61 kg/hr

Bottom Product: Formaldehyde = 0.99*Formed = 8868.75 kg/hr

Bottom Product: Water = 0.99*total water = 15100.84 kg/hr

From Bottom:

CH_3OH = 8.31/23977.9 = 0.003%

H_2O = 15100.84/23977.9 = 62.98%

CH_2O = 8868.75/23977.99 = 36.99%

Chapter 4 – Energy Balance

4.1 Energy Balance on Vaporizer

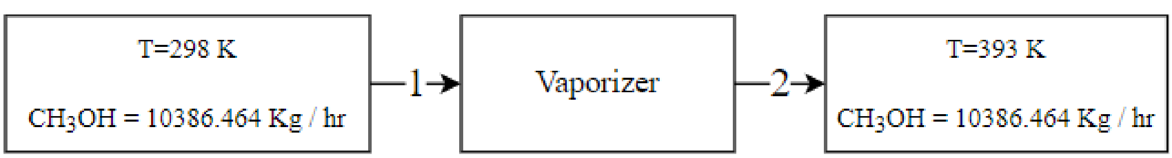

Figure 8: Streams of Vaporizer

Table 7: Energy Balance on Vaporizer

Components	Inlet Stream Kg/hr.	Outlet Stream kg/hr.	Cp at 345.5 K
	1	2	Kj/kg.K
CH_3OH	10386.464	10386.464	2.69

T_1 = 298 K, T_2 = 393 K, T_{mean} = 345.5 K, C_p at 373 K = 3.18 Kj/kg.K, C_p at 338 K = 2.83 Kj/kg.K

Q = mCpΔT

Q = m_{total}*C_{ptotal}*(338-298) + ((λ+C_p (373-338))

Q = (10386.464)*(2.69)*(338-298) + ((1100.313) + (3.18 – 2.83))

Q = 1118684.189 Kj/hr

λ: latent heat of vaporization of methanol at 338 K = 1100.313 Kj/Kg

For Steam in Vaporizer:

λ steam = 2163.22 kj/kg

Temperature = 133.54 ℃ =406.54 K

Q= m λ

m= Q/λ

Steam Flow rate:

m = 1040861.784/2163.22

m = 517.138 kg/hr.

4.2 Energy Balance at Reactor

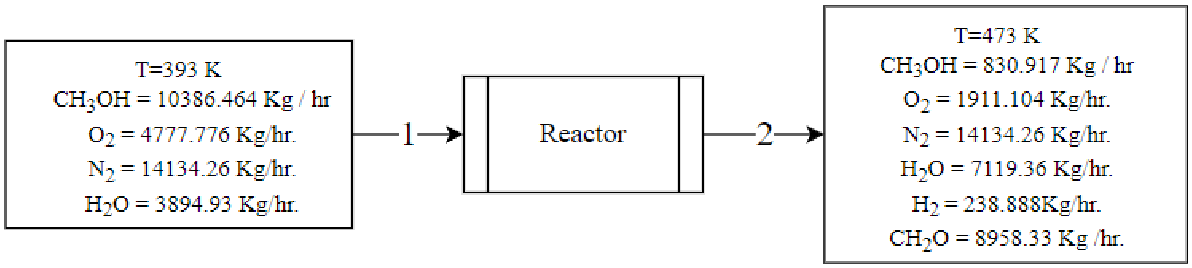

Figure 9: Streams of Reactor

Table 8: Energy balance on reactor

Components	**Inlet Stream Kg/hr.**	**Cp at 393 K**	**Outlet Stream Kg/hr**	**Cp at 473 K**
	1	**Kj/kg.k**	**2**	**Kj/kg.k**
CH_3OH	10386.46	2.63	830.917	2.8
O_2	4777.776	0.94	1911.104	0.96
N_2	14134.26	1.04	14134.26	1.05
H_2O	3894.93	1.89	7119.936	1.94
H_2	-	14.46	238.888	14.5
CH_2O	-	1.3	8958.33	1.41
Total	33193.42	-	33193.42	-

Qin - Qout + Generation - Consumption = Accumulation

T_1 = 393 K, T_2 = 473 K, T_{ref} = 298 K

Qin = mtotal*C_p*(393-298)

= 10386.46*3.4*(393-298)

= 2595057 kj/hr

Qout = mtotal*Cp*(473-393)

= 10386.46*2.8*(393-298)

= 2762798 kj/hr

Heat of Reaction:

For Reaction 1:

= 84 kj/mol

= 179.167 kmol/hr

= 84*179.167/0.001

= 15050028 kj/hr

For Reaction 2:

= -159000 kj/kmol

= 119.444 kmol/hr

= − 159000 *119.444/0.001

= − 18991596 kj/hr

Adding 1 & 2:

= − 28487553 kj/hr + 10033296 kj/hr

= −18454257 kj/hr

L.H.S:

= 3354826.57 kj/hr + (-3941568 kj/hr)

=7494388 Kj/hr

R.H.S:

=-74394388 kj/hr

Difference:

= R.H.S-L.H.S

= -2805761 Kj/hr

4.3 Energy Balance at Absorber

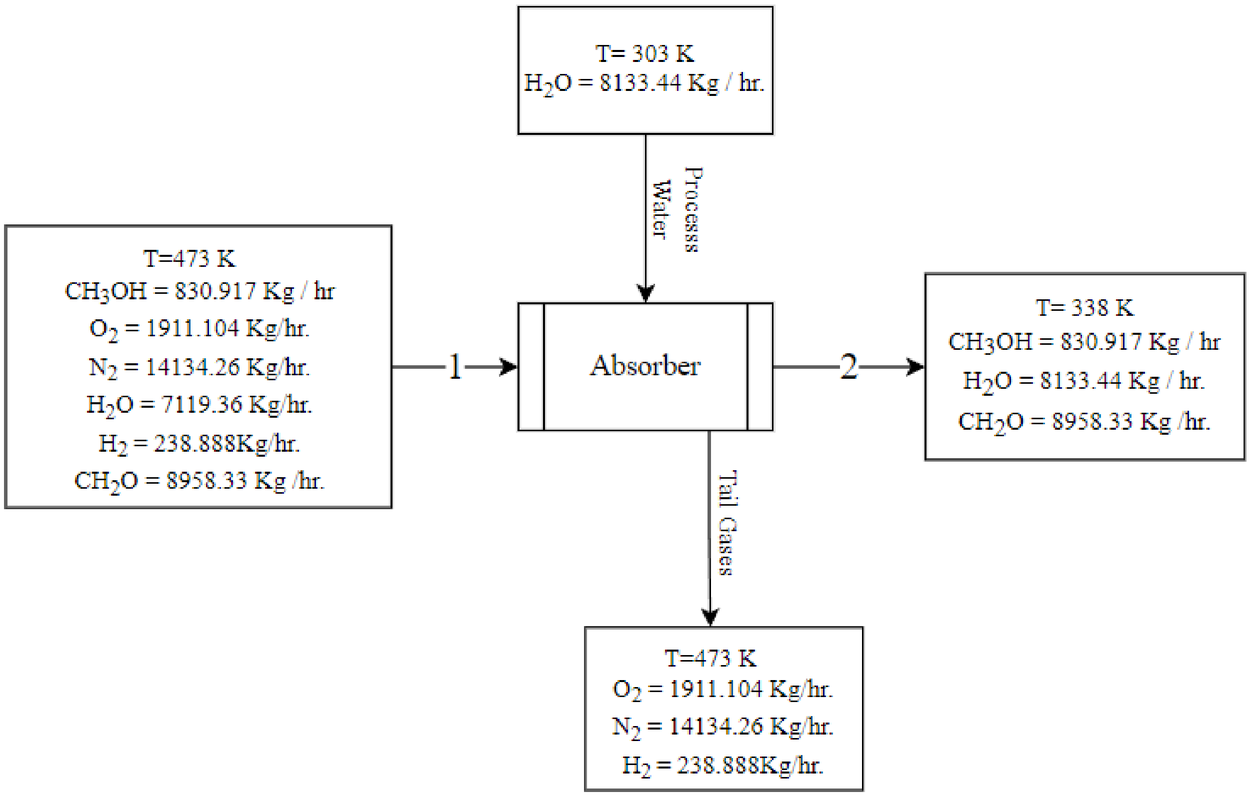

Figure 10: Streams of Absorber

Inlet Absorber

Table 9: Energy balance on Inlet of Absorber

Components	**Inlet Stream Kg/hr**	**Cp at 473 K**	**Inlet Stream Kg/hr**	**Cp at 303 K**
	1	**Kj/Kg.K**	**1**	**Kj/Kg.K**
CH_3OH	830.917	2.8	-	-
O_2	1911.104	0.963	-	-
N_2	14134.26	1.051	-	-
H_2O	7119.936	1.94	8133.44	1.86
H_2	238.888	14.5	-	-
CH_2O	8958.33	1.41	-	-
Total	33193.42	-	9107.53	-

T_1 = 473 K, T2 = 303 K, T_{ref} = 298 K

For Gas:

$\mathbf{Q_{in}} = mCp\Delta T$

= 830.917*3.4*(473-298)

$\mathbf{Q_{in}}$ = 773583.72 Kj/hr

For Water Stream:

$\mathbf{Q_{in}} = mCp\Delta T$

$\mathbf{Q_{in}}$ = 169988.89 Kj/kg

Adding both we get = 943572.61 Kj/hr

Outlet Absorber:

Table 10: Energy balance on outlet of Absorber

Components	**Outlet Stream Kg/hr**	**Cp at 465 K**	**Outlet Stream Kg/hr**	**Cp at 338 K**
	2	**Kj/kg.K**	**2**	**Kj/Kg.K**
CH_3OH	-	-	830.917	1.2
O_2	1911.10	0.919	-	-
N_2	14134.26	1.04	-	-
H_2O	-	-	8133.44	4.65
H_2	238.29	14.32	-	-
CH_2O	-	-	8958.33	1.22
Total	16283.65		17921.7	

T_1 = 338 K, T_2 = 465 K, T_{ref} = 298 K

For Product:

$\mathbf{Q_{out}} = mCp\Delta T$

= 8958.33*1.244*(338-298)

$\mathbf{Q_{out}}$ = 445766.50 Kj/hr

For Tail Gases:

For N_2

$\mathbf{Q_{out}}$ = mCpΔT

= 14134.26*1.0511* (465-298)

= 1572488.81 Kj/hr

For H_2

$\mathbf{Q_{out}}$ = mCpΔT

= 238.29*14.5065* (465-298)

= 577277.89 Kj/hr

Total Q_{out} = 943572.61 Kj/hr

4.4 Energy balance at Distillation Unit

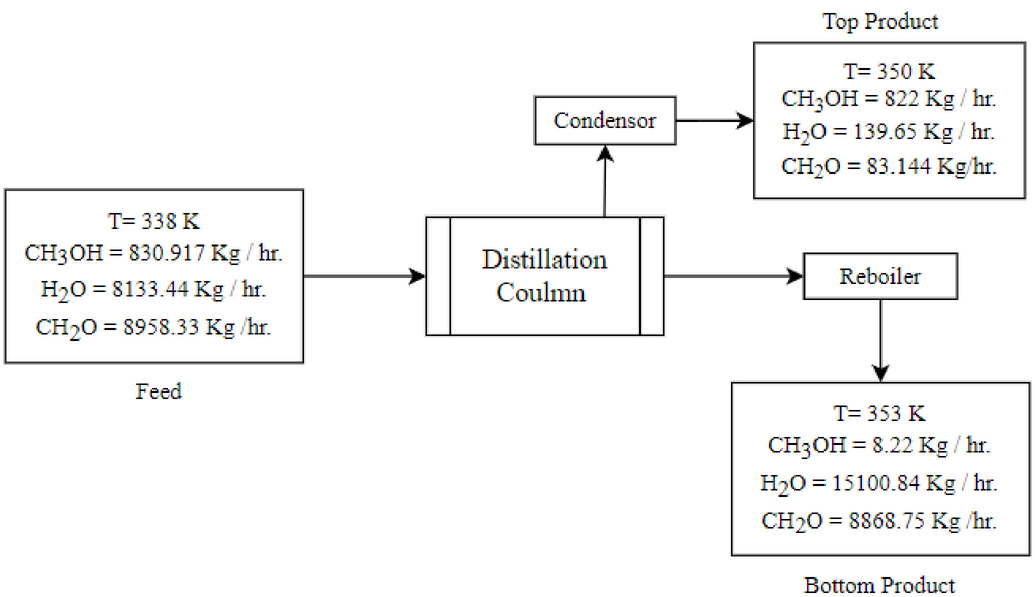

Figure 11: Streams of Distillation Coulmn

Reboiler

Table 11: Energy balance on reboiler

Component	Kg/hr	Cp at 358K, Kj/Kg.K
CH_3OH	8.22	1.78
H_2O	15100.84	1.88
CH_2O	8868.75	1.27
Total	23977.81	-

λ mixture = 1035 kJ/kg

Q total = m λ

Q = 24817033.35 Kj/hr

For Steam:

Pressure = 1atm

λ= 2250.76 Kj/Kg

m = Q/λ

m = 24817033.35 / 2250.76

=11026.06 kg/hr

Condenser:

Table 12: Energy balance on condenser/condensate

Component	Kg/hr	Cp at 350K, Kj/Kg.K
CH_3OH	822	1.7
H_2O	139.65	1.88
CH_2O	83.144	1.24
Total	1044.79	-

Latent heat λ of mixture = 1055 kJ/kg

Q = m λ

Q = 1102253.45 kJ/hr

Water Requirement:

T_1 = 298K, T_2 = 323 K, T_{mean} = 310.5

C_p = 1.865 kJ/kg.K

Q = $mC_p(\Delta T)$

m = $Q/C_p(\Delta T)$

= 23,640.82 kg/hr

4.5 Energy Balance at Exchanger

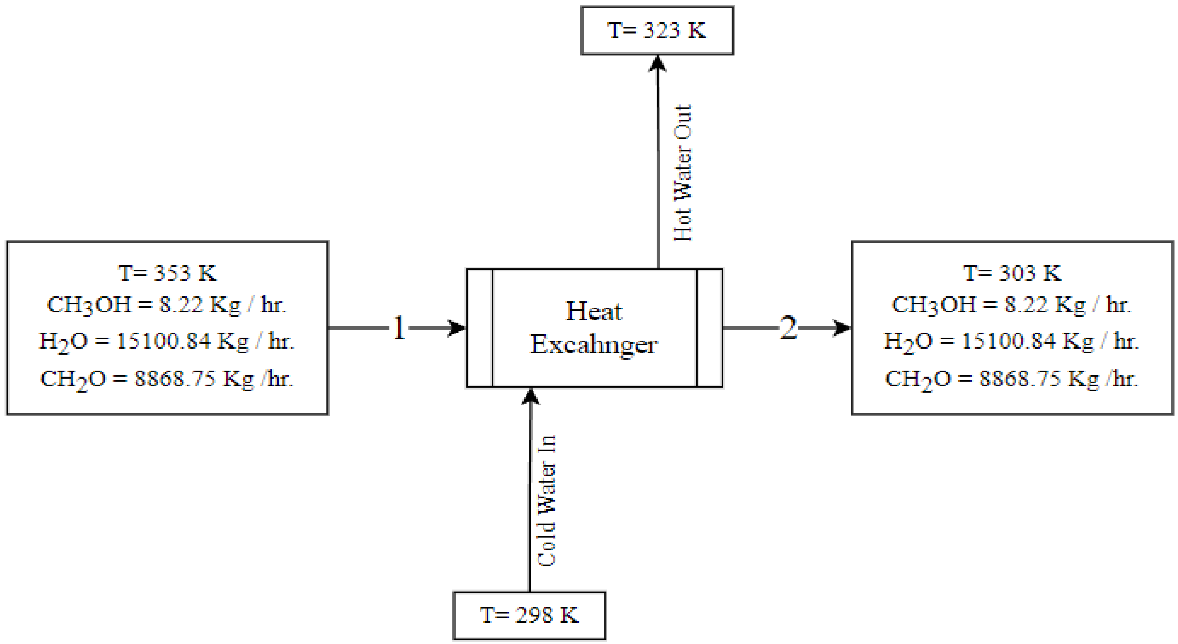

Figure 12: Streams of Excahnger

For Mixture:

T_1 = 353 K, T_2 = 303 K, T_{mean} = 328 K

C_p = 1.873 kJ/kg.K

Q = mCpΔT

= 23977.81*1.873*(50)

=2245521.9065 kJ/hr

For Cooling Water:

$Q_{mix} = Q_{Cooling\ water}$

T_1 = 298K, T_2 = 318K, T_{mean} = 308K

C_p = 4.204kJ/kg.K

$Q = mC_p\Delta T$

$m = Q/C_p\Delta T$

= 2245521.9065/4.204*(20)

= 26706.96kg/hr

Chapter 5 – Plant Design

5.1 - Design of Absorber

Total flow rate into absorber = 39843.46 Kg/hr

Pressure = 1.75 kg / cm^2

Temperature = 200 °C

Desnity = PM / RT

Table 13: Design of Absorber

	$\dot{m}$	x	M	$\dot{n}$	y
CH_3OH	830.917	0.021	32	25.97	0.019
O_2	1911.11	0.048	32	59.72	0.043
N_2	14134.26	0.355	28	504.76	0.360
H_2O	7119.93	0.179	18	395.55	0.282
H_2	238.888	0.005	2	119.44	0.085
CH_2O	8958.33	0.225	30	298.611	0.213
Total	39843.46			1405.05	

M= 23.7 Kg/mol

R= 0.0821 atm.L / mol.K

ρ = 1.031 Kg/m^3

μ_g = 0.0000125 N.s/m^2

L = solvent flow rate = 813.44 Kg/hr

P_L = 1.85 Kg cm^2

Temperature = 30 °C

ρ_l = density of water (solvent) = 1000 Kg/m^3

μ_L = viscosity of solvent = 0.00091 N.s/m^2

Flow Factor

$F_{LV} = \frac{L}{G} \sqrt{\frac{\rho_g}{\rho_L}}$

F_{LV} = 0.01

Percentage Flooding = $\sqrt{\frac{K_4}{k_4 \; at \; flooding}}$

K_4 value from the graph is (Coulson Richardson Vol 6)

K_4 at flooding = 60

K_4 w.r.t F_{LV} = 20

Percentage Flooding = 0.577 = 57 %

Packing Material = Pall Rings (Metal)

Packing Factor = F_p = 66 m^{-1}

Using K_4 relation

$$K_4 = \frac{13.1\ (V_W^*)^2\ F_p \left(\frac{\mu_L}{\rho_L}\right)^{0.1}}{\rho_g\ (\rho_L - \rho_g)}$$

$$V^* = \frac{K_4\ \rho_g\ (\rho_L - \rho_g)}{13.1 \times F_p \left(\frac{\mu_L}{\rho_L}\right)^{0.1}}$$

V* = 3.0521 $Kg/m^2.S$

Coulmn Area

G = Gas Flow Rate

Coulmn area = 3.626 m^2

Diameter = $\sqrt{\frac{4}{\pi} \times 3.626}$

D = 2.148 m^2

Calculation of Height of Transfer Unit

Using Ondas Method

$$a_w / a = 1 - \exp\left(-1.45 \left(\frac{\varsigma_c}{\varsigma_c}\right)^{0.75} \left(\frac{L_w}{a\mu_l}\right)^{0.1} \left(\frac{L_w^2 a}{\rho_L^2 g}\right)^{-0.05} \left(\frac{L_w^2}{\rho_L \varsigma_c^a}\right)\right) [3]$$

A= surface area ferom the table = 102 m^2

Packing Size = 55 mm or 2 in

L_w = Liquid mass velocity = Liquid flow rate / area of column

L_w = 0.623 Kg/m^2 .S

ςL = surface tension of water = 0.072 N/m

ςC = surface tension of packing = 0.0075 N/m

μ_c = viscocity of water = 0.00091 N.s / m^2

g = 9.81 m/s^2

By putting all values

a_w = 0.08 × 102 8.16 m^2 / m^3

Liquid Film Mass Transfer Cooefficent

$$K_L \left(\frac{\rho_L}{\mu L\ g}\right)^{1/3} = 0.0051 \left(\frac{L_w}{a_w \mu_L}\right)\text{^}1/3 \left(\frac{\mu_L}{\rho_L D_L}\right)^{1/3} (o.d)^{0.4}\ [3]$$

D_p = 51 mm

Di = Kinematics Viscosity of Water = 2.82 × 10^{-5} m^2 / s

Diffusivity = 2.82 × 10^{-5} m^2 /s

By putting all values , we get

K_L (48.21) = 0.3327

K_L = 0.0069 m/s

For Gas film co efficient

$$K_G \left(\frac{R\ T_g}{a\ D_g}\right) = K_5 \left(\frac{V_w}{a\ \mu_g}\right)^{0.7} \left(\frac{\mu_g}{\rho_g\ D_g}\right)^{1/3} (a\ d_p)^{-2}\ [3]$$

Value of K_5 = 5.23

V_w = 3.0521 Kg / m^2 .s

P_g = 1.031 Kg / m^3

H_g = 0.0000125 N.s / m^2

D_g = H_g / ρ_g = 1.212 × 10^{-5} m^2/s

R = 0.08314 $\frac{bar\ .m^3}{kmol\ .K}$

By putting all values we get

K_G = 0.000302 Kmol / m^2 . S. bar

Height of gas transfer film co effeicent

$H_G = \frac{G_m}{K_G\, a_w\, \rho}$ [3]

G_m = 0.12878 kmol/ s.m^2

ρ_G = 1.75 Kg/cm^2

K_G = 0.000302 Kmol / m^2 .S . bar

By putting all values

H_G = 7.629 m

Height of liquid film transfer unit

L_m = 0.0346 kmol / m^2 . S

$C_t = \rho_t$ / M = 1000/18 = 55.55 Kmol/m^3

H_L = 0.011 m

Height of Transfer Unit

$H_{oG} = H_G + mG_m / L_m \times H_c$

H_{oG} = 7.64 m

Number of transfer units

Y_1 = 0.232

Y_2 = 0.0232

Y_1 / Y_2 = 10

mG_m / L_m = 0.75

N_{oG} = 5

Height of tower = Z = $N_{oG} \times H_{oG}$ [3]

= 3.82 m

Total Height = 38.2 m + 2m

= 40.2 m

From these all values , we can calculate pressure drop

Pressure Drop = ΔP = 0.2 atm

Table 14: Specification sheet of Absorber

Specification Sheet	
Identification **Item:** Absorber (A-100) **Type:** Packed Column **Packing:** Metal Pall Rings	
Function: To Absorb CH_3OH & CH_2O Gas From Product Stream	
Operating Pressure	1.69 atm
Operating Temperature	303 K
Dia of Absorber	2.148 m
Column Height	40.2 m
Area	3.626 m2
Height of Transfer Unit	7.64 m
No. of Transfer Unit	5
Pressure Drop (ΔP)	0.2 atm

5.2 - Design of Reactor

Table 15: Design of Reactor

	Kg/hr	Kg/s	Kmol/hr	Kmol/s	ρ_i
CH_3OH	10386.464	2.89	324.57	0.09	15.9
O_2	4771.776	1.38	149.305	0.04	0.6
N_2	14134.26	3.93	504.795	0.14	1.30
H_2O	3894.23	1.08	216.385	0.06	1.14
Total		9.23			4.73

Volumertric flow rate of inlet stream = $V_o = \dot{m} / \rho$ = 1.951 m^3 / s

.$C_{ao} = \frac{F_{ao}}{V_o}$ [3]

C_{ao} = 0.09 / 1.9513 = 0.046 kgmol / m^3

Design Equation

$W = F_{AO} \int_0^{X_A} \frac{dX_A}{-r_A^1}$

$-r = \frac{K_1\, C_{AO}\, (1-x)RT}{1+K_2 C_{AO}(1-x)RT}$

Weight of catalyst

By simpson two point rule

$\Delta X = 0.49$

$W = \frac{\Delta X}{2}\left(\frac{F_{AO}}{-r_A^1\,(X=0\,)} + \frac{F_{AO}}{-r_A^1\,(X=0.98\,)}\right)$ [3]

F_{AO} = 0.09 kmol/s (for methanol)

W = 0.49 (1797.96 + 89896.40)

W = 44930.23 Kg

Density of catalyst

ρ = 10490 kg / m^3

Volume of catalyst = m / ρ

= 4.28 m^3

Reactor Volume = Volume of catalyst / 1- ϴ

Let ϴ = 0.6

V_r = 4.28 / 1- 0.6

V_r = 10.7 m^3

Resdience Time = Volume of reacor / Volumetric Flow Rate

St = $\frac{10.7}{1.95137}$

St = 5.5 sec

For Packed bed reactor

L / D =3

L= 3D

Diameter of reactor

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

V = $\frac{\pi}{4} \times D^2$ (3D)

D = 1.656 m

Then L = 3 (1.656)

L = 4.968 m

Number of tubes

Number of tubes = Volume of catalyst / Volume of one tube

Let 1 tube of dia d = 0.3937 ft

Length of tube = 16 ft

Volume of catalyst = No. of tubes / Vol. of one tube

= 151.03 ft^3 or 4.27 m^3

Number of tubes = Volume of catalyst / Volume of one tube

By putting values we get , N_t

No. of tubes = 77

Pressure Drop

Using Ergun's Equation

$$\Delta P / L = \left(\frac{150\,\overline{V_o}\,\mu\,(1-\varepsilon)^2}{\varphi_s^2\,D_p^2\,\varepsilon^3}\right) + \left(\frac{1.75\,\rho\,\overline{V_o}^2\,(1-\varepsilon)}{\varphi_s\,D_p\,\varepsilon^3}\right) \text{ [3]}$$

Cross-sectional area = 2.1538 m^2

Volumetric flow rate V_o = 1.95137 m^3/s

Superficied velocity = V_o / A = 0.906 m/s

Average viscosity = 0.00047035 Kg/m.s

Average desnity = 4.7382 Kg/m^3

Dp = 0.004 m

L = 4.96 m

ε = 0.6

By putting all these values in Ergun's equations

ΔP / L = 13594

ΔP = 0.6 atm

Table 16: Specification sheet of Reactor

Specification Sheet	
Identification: **Item:** Reactor (R-100) **Type:** Packed Bed Catalytic Reactor	
Function: To Produce CH_2O From CH_3OH using Silver Catalyst	
Operating Pressure	2 atm
Operating Temperature	473 K
Space Time	5.5 s
Volume of Reactor (Vr)	10.7 m^3
Volume of Catalyst (Vc)	4.27 m^3
Weight of Catalyst	44930.23 kg
Dia of Reactor (D)	1.656 m
Length of Reactor (L)	4.968 m
No. of Tubes	77
Pressure Drop (ΔP)	0.6 atm

5.3 - Design of Heat Exchanger

Table 17: Design of Heat Exchanger

	Kg/hr	Kmol/hr
CH_3OH	8.22	0.257
H_2O	15100.84	838.93
CH_2O	8868.75	295.625

Inlet temp. of soution = T_1 = 353 K = 176 °F

Outlet temp. of soution = T_2 = 303 K = 86 °F

Inlet temp. of cooling water = t_1 = 298 K = 77 °F

Outlet temp. of cooling water= t_2 = 323 K = 122 °F

Flow rate of solution = 23977.81 Kg / hr = 52862.03 Lb / hr

C_p = 1.87 KJ/.kg.K

Heat capcity of water = 4.2 Kj / Kg . °C

Water flow rate req. = 26706.96 Kg. / hr

$T_{LM} = \frac{T_1 - \ t_2\ ) - (\ T_2 - t_1)}{\ln \frac{(\ T^1 - t+)}{T^2 - t_1}}$

Water flow rate req. = 7.523 Kg/sec

ΔT_{LM} = 13.95 K

Here , we use 1 shall and 2 tube pass

$R - \frac{T_1 - T_2}{t1 - t2}$

R = 2

$S = \frac{t2 - t1}{T_2 - T_1}$

S = 0.45

R = 0.34

F_t = 0.59

$\Delta T_m = F_{t\,.}\ \Delta\ T_{LM}$

= 8.64 °C

From graphs , assume [3]

U = 1400 W/m^2 . ℃ or W/m^2.K

Provisional area

Q = AUΔt

Put values in it

A = 51.53 m^2

Outer dia = 0.02 m

Innnerdia = 0.016 m

Allow for tube sheet

L = 4.83 min

Area of one tube

Area of one tube = 0.303 m^2

No. of tubes = Area of 1 tube / One tube A

= 51.53 / 0.303

N_t = 170

Using Triangular pitch

$d_o \left(\frac{N_t}{K_1}\right)^{1/n_1}$

Bundle diameter = 386 mm = 0.386 m

Bundle dia clearance = 68 mm

Shell Diameter = 386 +68 mm

= 454 mm = 0.454 m

Tube Side Coefficent [3]

Mean Water Side Termeporature = 310.5 K

Tube cross sectional area = $\frac{\pi}{4} \times (0.16)^2$

= 0.02011 m^2

Tube per pass = 170 / 2 = 85

Total flow area = 85 × 0.02011

$= 1.7093\ m^2$

Water mass velocity = $\frac{7.418}{1.7093}$

$= 4.35\ Kg / s . m^2$

Desnity of water = 995 Kg / m^3

Water linear velocity = $\frac{4.35}{995}$ = 0.0044 m/s

$h_i = \frac{4200\ (\ 1.35+0.02t)\ u_t^{0.8}}{d_i^{0.2}}$

h_i = 262.667 W/m^2.K

Shell Side Coefficent [3]

D_s = 454 mm

Baffle spacing = $\frac{Ds}{5} = \frac{454}{5}$ = 91 mm

Tube pitch = 1.25 × 20 = 25 mm

Cross sectional flow area = $\frac{(p_t - D_o)\ D_s}{p_t}$

$= 0.00826\ m^2$

Mass velocity = 812 Kg / m^2 . S

Eq. Dia = $\frac{1.10}{d_o}$ (p_t^2 – 0.917 d^2o) [3]

Eq. Dia = 14.4 mm

Mean shell side temp = 328 K

Desnity of solution = 1.44 kg / m^3

Viscosity = 0.002083 N.s / m^2

$Re = \frac{G_S\ d_e}{\mu}$

Re = 5600

$Pr = \frac{C_p\ \mu}{k}$

Pr = 0.06

By these all values calculated

Pressure drop ΔP = 0.41 atm

Table 18: Specification sheet of Heat Exchanger

Specification Sheet	
Identification: **Item:** Heat Exc. (HE-100) **Type:** Shell and Tube Heat Exchanger	
Function: To reduce the temperature of Product Formaldehyde	
Heat Duty = 1506475.8 btu/hr	
Shell Side	**Tube Side**
Fluid Handled = Mixture of feed	Utility = Cooling Water
Flow rate = 52862.03 lb/hr	Flow rate = 47985.5 lb/hr
Baffle Spacing = 3.5 in	No. of Tubes = 124
Passes = 1	Passes = 2
Shell Dia = 454 mm	OD = 0.02 in
Inlet = 350 K, Oulet = 303 K	Intet = 307 K, Outlet =320 K
Pressure Drop (ΔP) = 0.41 atm	Pressure Drop (ΔP) = 0.22 atm

5.4 - Design of Distillation Coulmn

Table 19: Design of Distillation coulmn

	Feed	Bottom	Distillate	x_d	x_b
CH_3OH	830.917	822.607	8.30	0.774	0.0003
H_2O	15100.84	151.008	14949.8	0.142	0.627
CH_2O	8958.3	89.88	8868.74	0.084	0.372

$$K_i = P_v / P_t$$

Table 20: Relative distribution coefficents

	K_i	P_v
CH_3OH (Light Key)	0.7053	1.269
H_2O	0.3955	0.7118
CH_2O (Heavy Key)	2.0468	3.684

Ideal No. of Stages

$N_{min} +1 = \frac{\log \left(\frac{x_{lk}}{x_{hk}}\right) d \left(\frac{x_{hk}}{x_{lk}}\right) b}{\log(\sigma_{lk})}$ [5]

$N_{min} +1 = 4.69$

$N_{min} = 6$ Approx.

By using Eduljee relation [5]

$N - 6 / N +1 = 0.75 \left(1 - \left(\frac{R-Rmin}{R+1}\right)^{0.566}\right)$

By solving this relation

$N - 6 / N+1 = 0.5188$

$N - 6 = 0.1588 N + 0.1588$

$0.4812N = 6.518$

$N = 14$

Minimum and Total Reflux

$R_{min}+1 = \frac{\alpha_i \times x_d}{\alpha_i - \theta}$

α_i = 3.46

ϴ = 2.7

R_{min} = 2.5

R = 2.5 × 1.2

R = 3

Feed point location

Using Kirk bride correlation [3]

$$\text{Log}\left(\frac{N_E}{N_s}\right) = 0.206\left(\left(\frac{x_{hk}}{x_{lk}}\right)F\ \left(\frac{B}{D}\right)\left(\frac{x_{lk}}{x_{hk}}\right)_d^b\right)^2$$

Feed Plate = 10.37 ~ 11

No. of Actual Trays

Using Drickamer – Bradfor correlation [5]

μ_{avg} = 0.01 m N.s / m^2

Coulmn Efficency

E_o = 13.3 – 66.8 log (μ_{avg})

E_o = 80.1 %

No. of actual trays = $\left(\frac{N}{eff}\right) \times 10\ \%\ saftey\ factor$

N_t = 19

Volumetric flow rate = $\frac{V_m}{\rho_v}$

= 0.003 m^2 / s

Flooding velocity = $U_f = K_1\sqrt{\frac{\rho_t - \rho_v}{\rho_v}}\ \left(\frac{\sigma}{0.02}\right)$^0.2 [6]

From graph , F_{LV} = 0.66

U_f = 0.015 m/s

U_{op} = 0.75 U_f

= 0.015 m/s

Net area required = Q_v / U_{op}

$Q_v = 0.003$

So Net area will be = 0.2 m^2

Coulmn cross sectional area = $A_n = A_c - A_d$

$A_d = 0.12\ A_c$

$A_c = 0.2 / 0.88$

$A_c = 0.227$

Diameter = $D_c = \sqrt{\frac{4 \times A_c}{\pi}}$ = 0.5 m

Table 21: Specification sheet of Distillation Coulmn

Specification Sheet			
Identification **Item:** Distillation column (D-100) **Type:** Multi component Distillation column			
Function: To recover methanol from water and formaldehyde			
Operating Pressure	1.82 atm	Operating temperature	351 K
No of stages	14	Feed plate location	11 bottom
Plate Type	Sieve Plate	d_h	0.0035 m
Plate Spacing	0.45 m	ΔP	0.14 atm
Plate thickness	0.0035 m	t_r	8.09 s
Diameter of Column	0.5 m	Hole Area	0.0056 m^2
Height of column	7.61 m	No of holes	477

References

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P&ID of Formaldehyde production using Methanol and Air over Silver catalyst

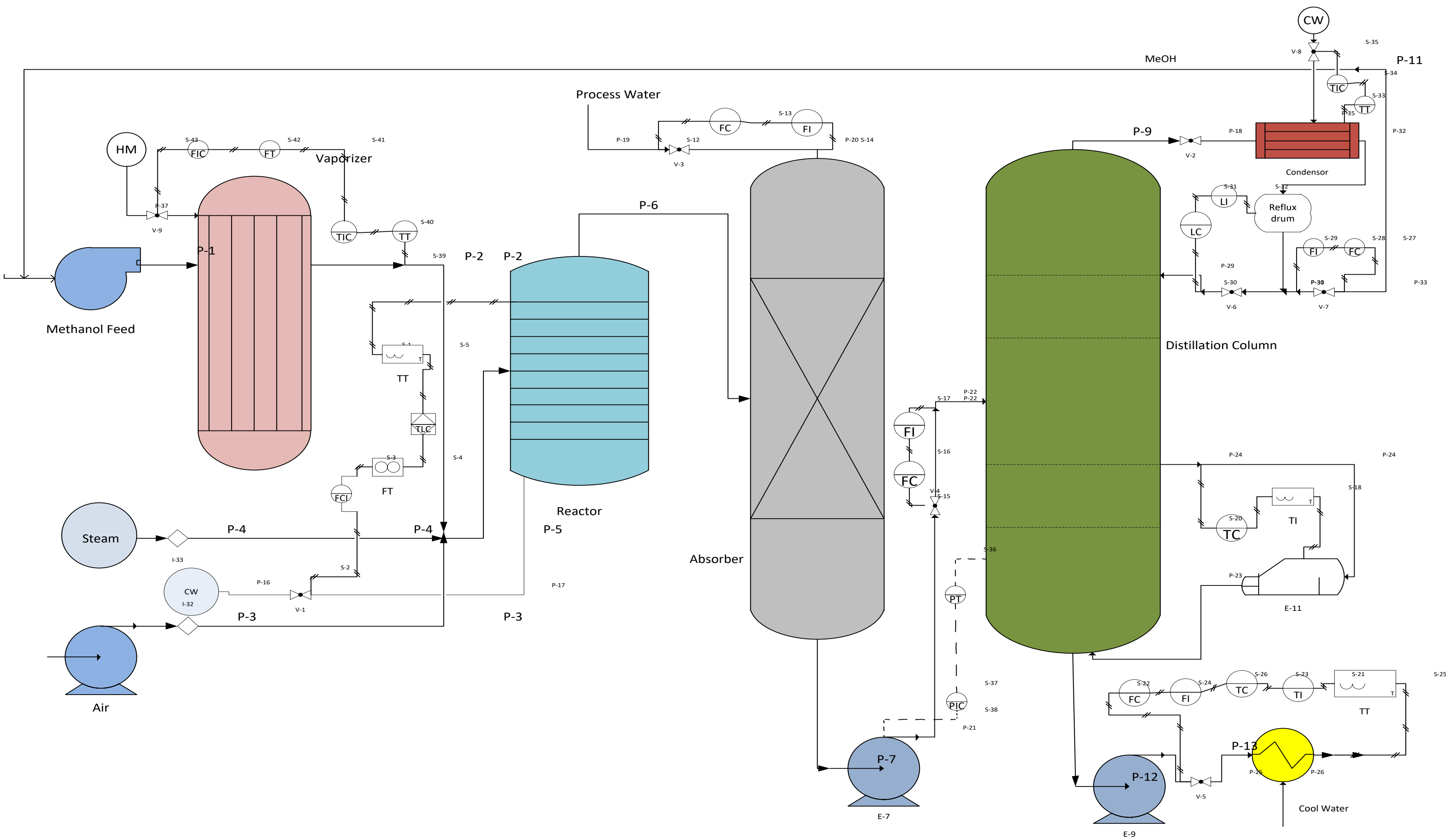

Figure 13: P&ID

Chapter 6 – Instrumentation and Control

6.1 - Introduction

Automatic, semi-automatic, or human process control all rely on measurement as a foundational element. The accuracy, repeatability, and dependability of the measuring technique influence the level of control quality that may be achieved. Employed people As a result, one of the most critical initial steps is to pick the most appropriate measuring instrument design and formulation of any process control system. When using manual controls, the process variable may be regularly read and the input can be raised by the operator on a schedule. To get the required temperature, either move it up or down. The only way to control a vehicle is by hand non-critical application in which any process condition happens slowly and in tiny amounts increments and little operator attention are needed.. While under the command of a computer, Continuous measurements and modifications are carried out automatically. Today, automation is the norm.

Because of the following advantages, control is utilized in industry.

- Improvement in the quality of the product
- Increasing the pace of production yield via the procedure
- Assert more care in protecting workers and equipment.
- Economists save money, time, and resources by reducing waste.
- Enhancement of the working environment
- In order for the procedure to succeed, manual control is not an option.

6.2 - P and I Diagrams

Process equipment, pipelines, pumps, instruments, valves and other fittings are shown in the P and I diagram. Equipment with a unique identification number should be included. Ideally, the tools would:

- The placement of the nozzles should be shown in an approximately proportional manner.
- All pipes, each with a unique line number, are listed. Size and composition of the piping used in the building should be shown For example, the content may be provided in the line identifier number.

- An identifying number is placed on each valve, whether it is a control valve or a block valve. The kind and the way it's organized
- Please provide the dimensions of your product. The valve's symbol might serve as a type indicator, or
- The valve number is a part of the hexadecimal code.
- For example, inline sight-glasses are part of the piping system and may be included in the auxiliary fittings.
- Identification number for strainers and steam traps.
- Code numbers are used to identify each pump.
- An identifying number for each and every control loop and instrument.

The utility (service) lines may be shown on the P and I diagram for basic operations. Separate schematics for the service lines should be utilized for complicated procedures, like 194 an introduction to piping and instrumentation 195. The diagram isn't cluttered with unnecessary information. The product or service The P and I diagram should, however, illustrate the connections to each unit. In some ways, the P and I diagram and the process flow-sheet will seem same. It's not clear what's going on here. The same identifier numbers should be used for each piece of equipment inside the two illustrations.

6.3 - Goals of Instrumentation and Control System

- Putting down and eliminating the disruptions that are coming from the outside.
- Maintain a consistent functioning of the process while working to improve its overall efficiency.

6.3.1 - Control Mechanism

An output signal is generated by rearranging the offer signal in the Controllers. When a controller sends out an output signal, it sends out the location of the final control element.

6.3.2 -Process Control

Regardless of the kind of chemical engineering activity, it is essential to have some sort of control. The need to maintain particular limitations on flow, pressure, temperature, composition, and other variables arises in every activity for a variety of safety and environmental reasons. It should go without saying that since manually using the device would need close attention to a variable that can be manipulated by a human operator and the operator's ability to see it with the passage of time, there will inevitably be a decline. There may be too many fluctuations in the controlled variable constantly.

6.3.3 - The Control System's components

It's important to know what makes up a typical control system.

Process:

Any action or sequence of actions that leads to the intended outcome in a procedure .

Element for Measuring:

The deciding factor is possibly the most critical of all the components of the control system. If there is a problem with the way the measurements are taken the rest of the system is likewise inoperable. In order to accurately represent the intended process conditions, the variable being measured is selected.

Controller:

When an error detection mechanism sends a signal to the controller, the controller responds. as a result of It is determined by the fault that determines the controller. The last control element is called the "final controller”, changes energy input based on a predetermined connection to the signal from the controller to the method.

6.4 -Types of Control

Many different types of controls are used in industry dependent upon requirements and particular needs. They range from very simple control to very complex system, in general they may be divided into two major classes as follows:

- Feedback control.
- Feed forward control

Feedback

It is our general behavior that we leant from practice. A feedback control, as the name suggest, is also founded on same principal. If any input to a system is changed it will change in the system called as “disturbances”. These disturbances are noted down and modified action is taken on the input to unwrap the effect that change.

Advantages

1) It does not require the ID and measurement of disturbance.

2) Effective for all disorders.

3) Insensitive to modeling errors

4) It can deliver zero steady state offset.

Disadvantages

1) It waits until the effect of disturbance has been felt by the system.

2) Poor response for slow processes or with significant dead time.

3) It may create uncertainty in the closed loop response.

6.5 - Feed-forward Control

Being ability to think ahead is something we take great pleasure in in our everyday lives. No driver of a car waits for the car to completely leave the road before turning the wheel to control the direction. To some extent, he contributed to the restricted road's impact by implementing a remedy before Controlled variables are being impacted. Using this concept in a control system creates a feedback loop. Since the manipulating variable is open-ended, feed forward is created an uncontrolled variable instead of an established one.

6.5.1 - Advantages

- It takes action before the system has had a chance to deal with the disruption.
- A sluggish system or one that has a lot of downtime might benefit from this tool.
- It does not inject any ambiguity into the control system.

6.5.1 - Disadvantages

- You need to identify all probable disruptions and measure them directly.
- It is unable to deal with unmeasured perturbations of any kind.
- Error in parameter processing might be difficult.
- It is not possible to eliminate the steady-state offset.
- A thorough understanding of the process model is required.

It is necessary to develop a control system that is both automated and resourceful in order to the ability to understand both steady-state and dynamic behaviour is commonly required in many cases. Controlled processes and control elements are the most important factors in determining how much information is gathered applied.

Instrumentation & Process Control

For Reactor:

In the figure given below, the multitubular packed reactor have been shown. The purpose of the reactor is to convert methanol into formaldehyde over silver catalyst. The overall reaction is an exothermic one. Hence, to maintain the temperature of the reactor, we aim to circulate cooling water on the shell side. The process variable to be controlled here is hence, the temperature of the reactor.

We have connected a temperature transmitter (TT) with the reactor. This sensor would sense the temperature and transmit the signal to temperature indicator controller (TIC). Here there TIC is further is connected to a flow transmitter (FT). The function of the transmitter is to sense and send the signal to flow indicator controller (FIC). Further, the FIC would interprete the signal received from the transmitter and pass it to the control valve. Control valve act as a final control element. Its function in here is to control the flowrate of cooling water (CW). As the error from the set point triggers the valve, it will open or close accordingly. The loop is a cascade loop and works on pnematic signal. The controllers used here are of PID type. The controller uses a combination of proportional, integration, and derivation and aims to maintain the output such that there is zero error or minimum error between the process variable and the setpoint. In this way, the PID controllers help maintain the desired output in a closed loop.

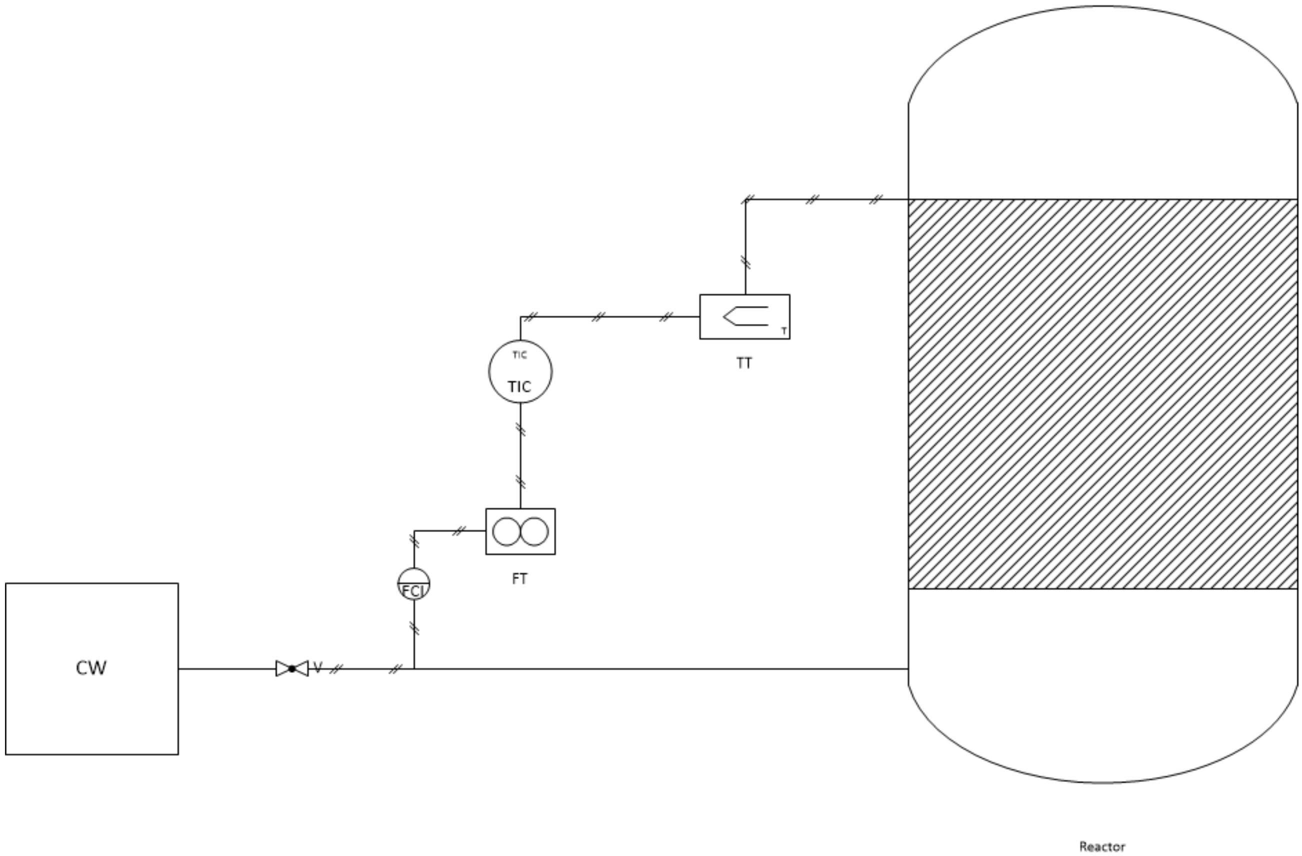

Figure 14: Instrumentation & Process Control for reactor

For Distillation Column:

The aim of distillation column is to separate the unreacted methanol from the feed mixture. The feed mixture contains methanol, formaldehyde and water coming from the absorber. Hence, in the distillation column, we need to control feed flowrate as well temperature and flowrates of distillate and bottom stream to condenser and reboiler respectively. For this purpose, a flow control loop has been set for the feed. The flow transmitter (FT) would measure and transmit the flow rate single to the flow indicator and controller (FIC). The flow indicator and controller is aimed at interpreting the signal and decide whether to open or close the control valve. In this way, the flow rate of the feed can be controlled.

Furthermore, the level control loop has been set for the reflux drum. Level transmitter (LT) is designed to sense and transmit the level of a liquid in the reboiler. The signal would be sent to level indicator controller (LIC). It is then responsible for the interpretation of the signal received from LT and decide upon the set point. In this way, it will dictate the control valve back to the distillation column.

Coming to the condenser, it is a type of heat exchanger and requires a similar kind of control system. In this system, we need to control the flow rate of cooling medium. But we also need to maintain the temperature of the fluid in the condenser. Hence, for that we connect a temperature transmitter to the condenser. It sends the signal to temperature indicator controller (TIC). Temperature indicator controller reads the signal and transmits a signal to flow transmitter. Flow transmitter (FT) reads the signal and sends it to the flow indicator controller (FIC). It decides whether the flow rate of the cooling media was appropriate or not. According to it, the control valve (the final control element) is opened or closed.

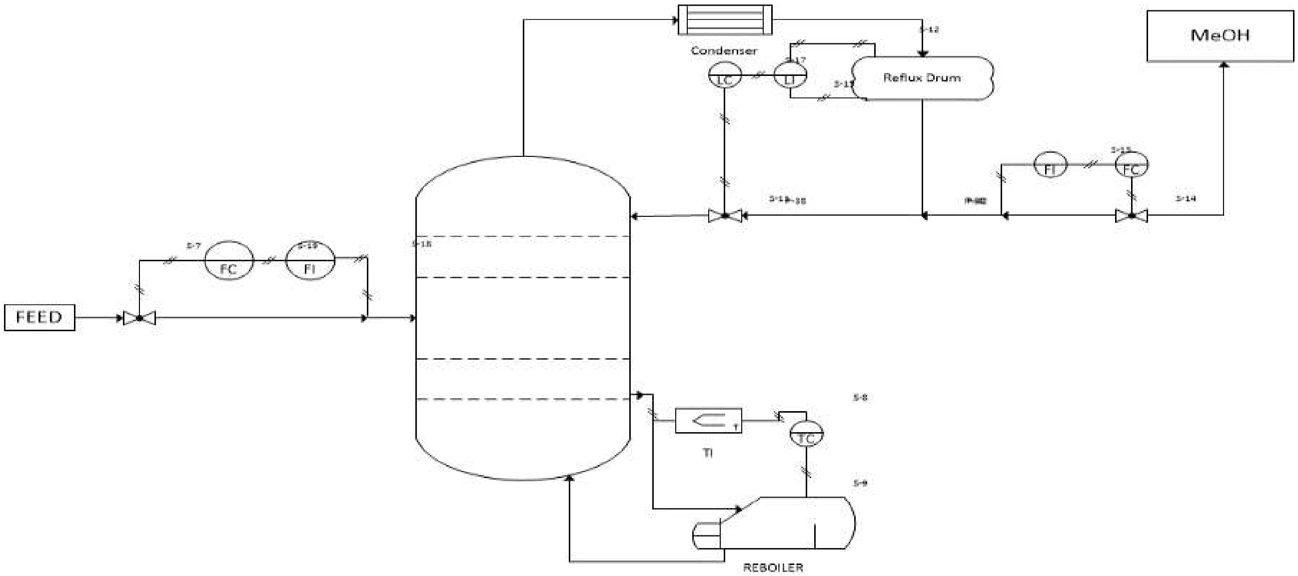

Figure 15: P&ID for Distillation Column

For Heat Exchanger:

In the heat exchanger, we need to control the cooling process of the process liquid. For this purpose we shell use some cooling medium. In our case, we are using cooling water since it is easiliy available and economical. Hence, to keep the process running smooth and without error, we need to maintain the flow rate of cooling water with reference to the temperature of the process fluid at the outlet. As we have already discussed, the temperature transmitter (TT) is used to convey a temperature signal fto temperature indicator controller (TIC). It will send a signal to the flow transmitter and hence, the signal is finally sent to flow indicator controller (FIC) for interpretation. This will dictate the final control element i.e., the valve. The control valve will keep increasing or decreasing the flow rate of the cooling water.

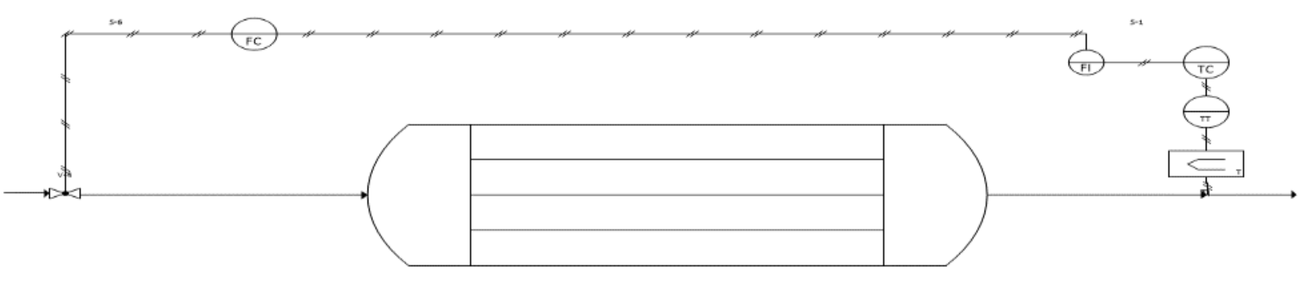

Figure 16: P&ID for Heat Exchanger

Further, the control systems for the vaporizer, condenser, and absorber are similar to that of heat exchanger and distillation column.

6.6 - Instrumentation for measuring and controlling pressure

Pressure, like temperature, is a determinant of the state and composition of a material. Industrial materials' principal calculation devices are really these two measures taken together. Pressure measurements are critical in the reactor. Compressors, pumps, and other pressure-related equipment for industrial processes Pressure is used to alter the process material Instruments for gathering data and analyzing results. As a result, pressure readings serve as a gauge of energy levels. Elastic elements devices are most often used in industrial pressure measurement for usage on-site at a single show type. The most often utilized pressure element in industrial settings is diaphragm bellows or a bourdon tube.

6.6.1 - The Process Variable

The control of process variables is critical to the success of a process. In the context of the manufacturing process, they are characterized as situations in which the temperature, pressure, or other variables are altered. A dozen or so less often encountered variables follow flow and liquid level as the primary variables, Chemicals, viscosity, density, moisture content and so on are examples of such factors forth. Process control cannot be achieved without measurement, which is a necessary precondition semi-automatically or manually. The level of control that can be achieved also has a bearing the measuring technique's precision, repeatability, and dependability chosen an important initial step in design is to pick the most effective technique of measuring. Modeling of any control system for any process measuring with precision is made possible by an automated control and refines the four primary categories of process variation.

- A thermometer is used to take temperature readings.
- Detection of pressure
- Flow meter readings

6.6.2 - Measurement and Control of Temperature

Exhaust and intake temperatures may be controlled by measuring temperature. Flows in heat exchangers, reactors, and other industrial equipment are often used to detect temperatures using to aid in the integration of measurement for local measurements, thermocouples it's common for the device to employ bimetallic or filled system thermometers to a lesser degree. Resistance thermometers with excellent measurement accuracy are utilized. Every single one of these meters has been fitted with when they are utilized locally, thermo-walls. This protects you against the effects of the weather and other natural factors.

6.6.3 - Control and Measurement of Flow

Nearly every industrial process relies on flow measurement, and a wide variety of methods have been developed to do so. As a general rule, flow measurement is based on the same principles. As a means of measuring pressure i.e., a sensor and a DP cell. Other flow meters may be used for more advanced applications, such as in a process when there is no external pressure. Magnetic flow meters need a disruption in the fluid flow. Indicator of flow – controls all manually set streams need a flow meter to indicate the quantity of liquid being dispensed is a simple method for taking a random sample. The majority of industrial flow measurements are unpredictable Headgear. A small amount of variables is employed, as well as the various sorts of variables. Situations requiring the use of measurement methods emerge.

6.7 - Measuring Devices

Temperature

- Thermocouples, resistance
- Thermometer, thermistors
- Thermometer bimetallic
- Thermometers
- Radiation
- Pyrometers

Pressure

- Manometers
- Bourdon tube elements
- Bellow elements
- Strain gauges
- Capsule gauges
- Thermal conductivity gauge
- McLeod gauge

Flow Rate

- Orifice plate
- Venture flow nozzle
- Dell flow tube
- Pitot tube
- Dennison flow nozzle
- Turbine flow meter
- Hot wire anemometer
- Positive displacement and
- Mass flow meter

Liquid Level

- Float actuated devices
- Displacer devices
- Liquid head pressure
- Devices Dielectric
- Measurement

6.8 - Process Control System Hardware

According to Stephanopoulos (1984), the hardware elements that can be established in control configuration include:

i. Chemical Process:

It indicates the material equipment together with the physical or chemical operations that occur there.

ii. Sensor:

These type of measuring instruments are usually used for the measurement of the disturbances, the controlled output variables, or secondary output variables. It represents the behavior of the process. For instance, thermocouple, venture meter and gas chromatographs.

iii. Transducer:

It used to convert measurement to physical quantities (such as electrical voltage or pneumatic signal) which can be transmitted easily

iv. Transmission line:

The line is used to carry the measurement signal from the measuring device to the controller. Sometimes it is equipped with amplifier due to weak signal coming from a far measuring device.

v. Controller:

It is usually a hardware element of an instrument which has "intelligence" features. It accepts the facts and decides what action should be taken.

vi. Final Control Element:

It implements in real life the decision taken by the controller. For example control valve.

vii. Recording Elements:

They are used to provide a visual demonstration of how a chemical process behaves.

6.8 - Selection of a Valve

Chemical plant valves may be categorized into two types based on the purpose they serve:

Shut off Valve: The primary function of shut off valves is to stop the flow of fluid.

Control Valves: Two types of control valves are available: automatic and manual, control the rate of the liquid.

Control Valves:

A significant consideration is the choice of control valves. Good flow management is essential achieved in order to keep the pressure decrease to a minimum. There have been instances when control valves have failed to open. When there is a power outage. A diaphragm valve is often used in this situation.

The illustration below shows an example of a valve:

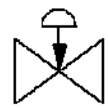

Figure 17: Control valve

Flanged Valves:

Drainage may be accomplished using flanged valves. A typical flanged valve is seen in the illustration below. Most of the time, they are locked and only used when a facility or individual unit has to be serviced.

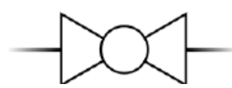

Figure 18: Ball valve

No Return Valves:

The purpose of this valve is to prevent fluid from flowing backwards in the process. When installing non-return valves, be careful to do it in the right direction to ensure that they function properly. In the graphic below, you can see an example of this valve in action:

Figure 19: NRV

Gate Valve:

Shutting down a system via a gate valve is a common practice. Choosing a valve that provides a strong seal when closed and little resistance to flow when open is critical for this application . Gate valves come in a variety of sizes and may be operated manually or automatically using a motor. A minor pressure drop occurs when the gate valves are completely open. Attention must be made while manipulating gate valves to ensure that they are not partly open. As a consequence, the valve won't seal correctly. This is due to the fact that the valve seal may distort. An example of a gate valve, which is commonly seen in pipe and instrumentation diagrams, is shown in the image below

Figure 20: Gate valve

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Chapter 7 – Cost Estimation

7.1 - Equipment's Cost

The cost has been calculated using CAPCOST, has been adjusted for inflation depending on the value of currency over time:

Equipment	Cost ($)
Vaporizer	31,049
Reactor	27,135
Absorber	711,000
Distillation Column	36,800
Heat Exchanger (Cooler)	39,100
Pump 1	9644
Pump 2	10,356
Blower	158342
Total	1023426

7.2 - Direct Cost

Direct Cost = 3.6* (Purchased Equipment Cost)

Direct Cost = 3.68 Million

7.3 - Indirect Cost

Indirect Cost = 1.44* (Equipment's Cost)

Indirect Cost = 1.47 Million

7.4 - Fixed Capital Investment (FCI)

FCI = Direct Cost + Indirect Cost

FCI = 5.15 Million

7.5 - Working Capital Investment

Working Capital Investment = 0.15 * (Fixed Capital Investment)

Working Capital Investment = 0.77 Million

7.6 - Total Capital Investment

Total Capital Investment = Working Capital Investment + Fixed Capital Investment

Total Capital Investment = 5.92 Million $

7.7 - Raw Materials

7.7.1 - Methanol

Cost = $ 430/ton [3]

Flow Rate = 10.3 ton/hr

Total Cost = 3.69 Million/yr

7.7.2 - Catalyst

Weight of Catalyst = 50 ton

Cost per ton = 100000/ton [3]

Total Cost = 5 Million/ year

7.8 - Operating Labor

Minimum Wage = 0.41 $/hr

Capacity = 218 ton / day

Operating Labour = 40 h/day

Processing Step = 7

From Appendix F

Operating Labour = 40 * 7= 280 h/day

Operating Cost of Labour = 280*330*0.21 = $ 19404

7.9 - Total Production Cost

From Appendix

Variable Cost = Raw Materials + Utilities + Miscellaneous Materials

Variable Cost = 11.05 million $/yr

Fixed cost

Fixed Cost = $ 0.50 million

Direct production cost

Direct Production Cost = Variable Cost + Fixed Cost = 11.55 million $/yr

Overhead Cost:

Overhead Cost = 30% (Direct Production Cost)

= 3.46 million $/yr

Manufacturing cost

Manufacturing Cost = Overhead Cost + Direct Production Cost

= 15.01 million $/yr [4]

General Expenses

1.35 million $/yr

Total Production Cost = Manufacturing Cost + General Expenses= 16.36 million $/yr

Total Production Cost/Capacity (ton/year) = 16360958.96 /70950

= 247.89 $/ton [5]

7.10 - Gross earning

Capacity = 70950 ton /yr

Selling Price = 300 $/ton

Total Income = 19.80 million $/yr

Taxes = 40% Gross Income

Taxes = 1.33 million $/yr

Net Income = Gross Income – Taxes

= 1.99 million $/yr

7.11 - Rate of return

ROR $= \frac{Net\ Income}{Capital\ Investment} \times 100$

ROR = 72.56 %

7.12 - Payback period

$= \frac{1}{ROR} \times 100$

= 1.37 yr

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[1] R. M. a. R. W. R. Felder, Elementary Principles of Chemical Processes, New York: Wiley, 2005.

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[15] D. Q. K. Kern, Process Heat Transfer, First Edition..

Conclusion

To conclude with, we state that formalin is a multipurpose compound. It is one of the most used compunds in industries all over the world. Keeping that in mind, we have designed a formalin manufacturing plant. The plant capacity and design have been completed via a thorough review of literature. Material and energy balances have been done accordingly. Moreover, overall plant cost and payback period, alongwith relevant parameters have been calculated. We believe our report can act as a guiding material for anyone who wants to invest in the valuable field.

Future Prospect

Formalin manufacturing plant is a sustainable one. Moreover, its demand is projected to be increasing in the coming years with an annual increase rate of 4%. Hence, with the increasing demand, the plant can be upscaled.

To innovate the plant, via research and development, hydrogen capturing techniques can also be used. In this way, the gases coming out of absorber can be stripped off of hydrogen in them. This can help in the field of renewable energy production, since hydrogen is considered a clean fuel.

Appendix

Appendix A

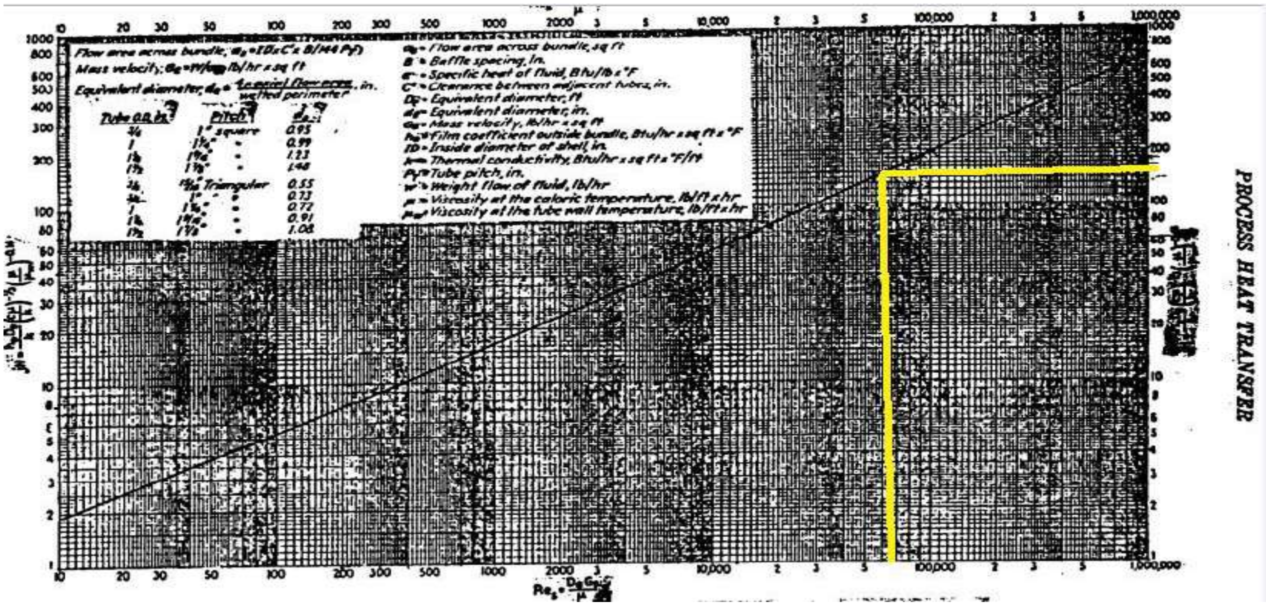


Figure : JH Factor

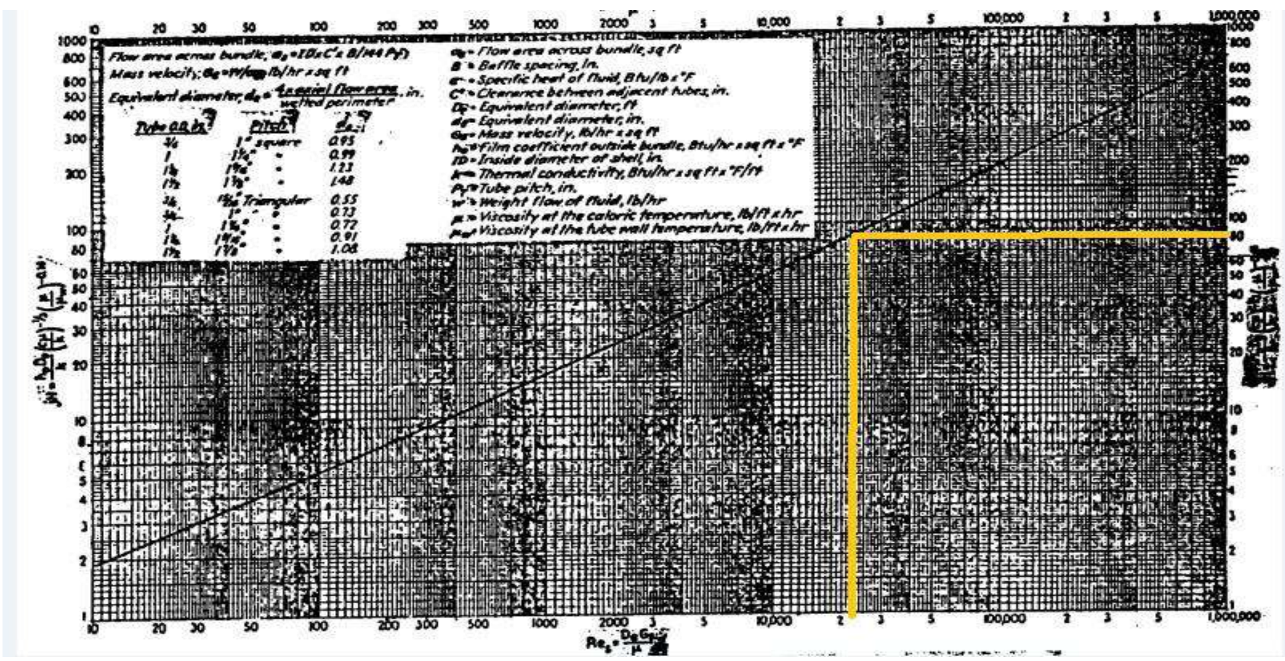


Figure : JH Factor

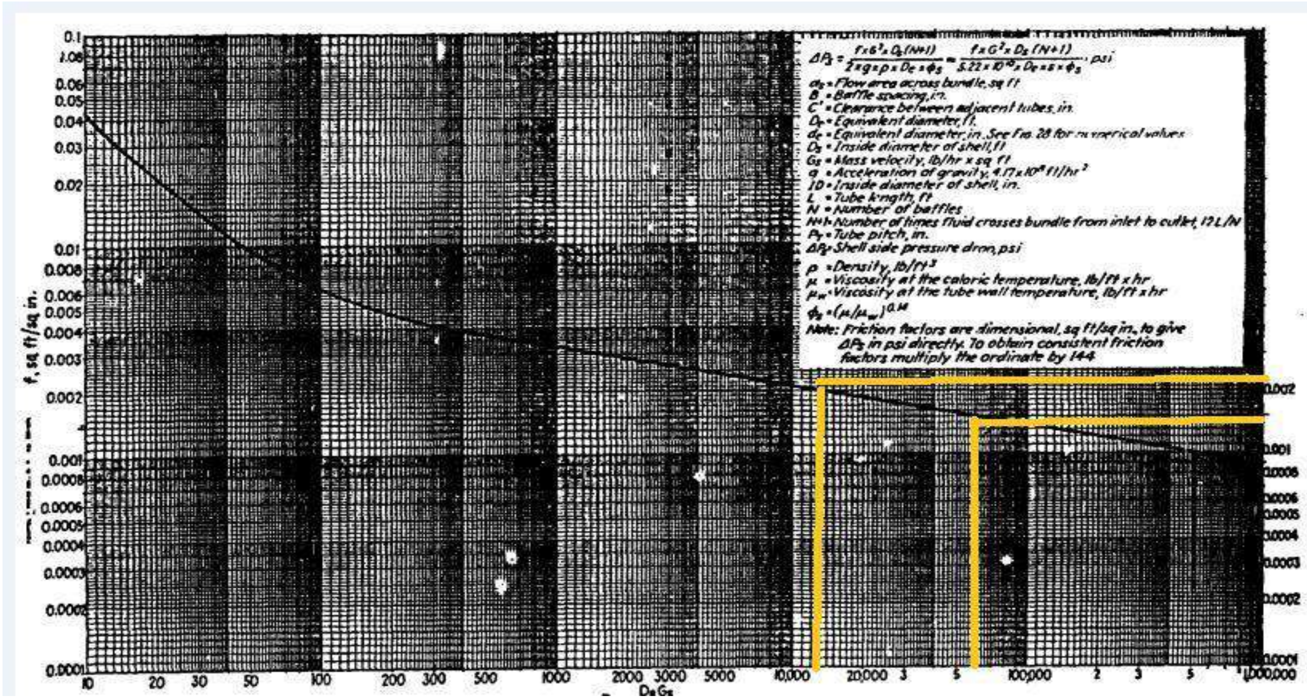


Figure : Reynolds Number

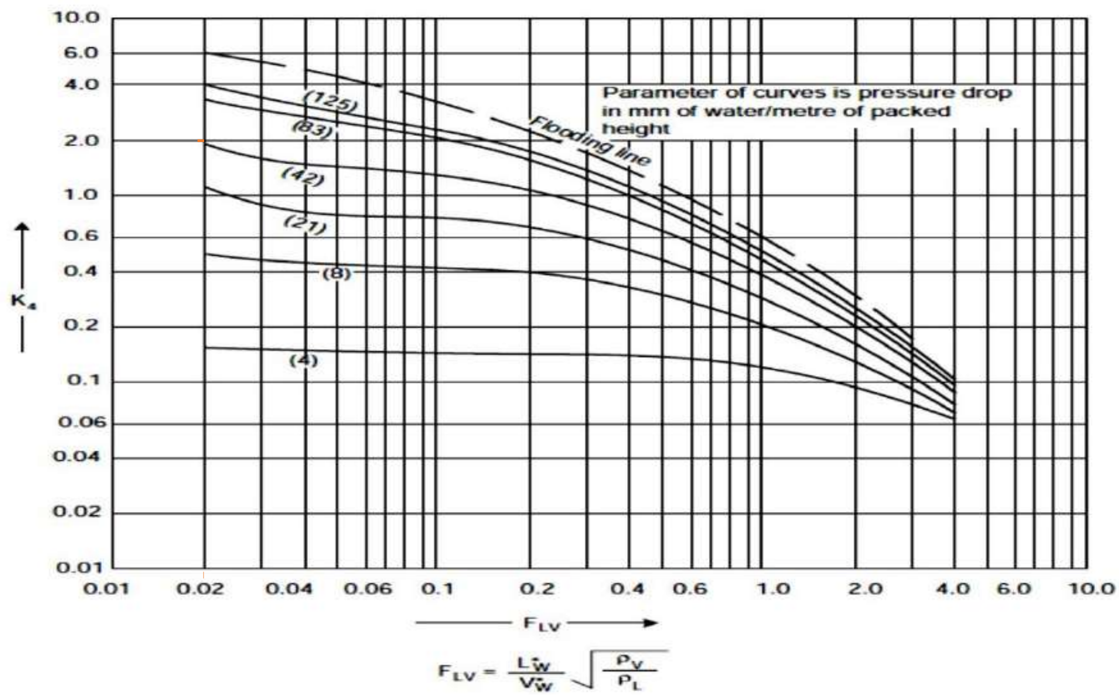
Table: Design Coefficient

Hot fluid	Cold fluid	Overall U_D
Steam	Water	200–700§
Steam	Methanol	200–700§
Steam	Ammonia	200–700§
Steam	Aqueous solutions:	
Steam	Less than 2.0 cp	200–700
Steam	More than 2.0 cp	100–500§
Steam	Light organics	100–200
Steam	Medium organics	50–100
Steam	Heavy organics	6–60
Steam	Gases	5–50¶

1¼ in. OD tubes on 1$^{9}/_{16}$-in. triangular pitch					
10	20	18	14		
12	32	30	26	22	20
13¼	38	36	32	28	26
15¼	54	51	45	42	38
17¼	69	66	62	58	54
19¼	95	91	86	78	69
21¼	117	112	105	101	95
23¼	140	136	130	123	117
25	170	164	155	150	140
27	202	196	185	179	170
29	235	228	217	212	202
31	275	270	255	245	235
33	315	305	297	288	275
35	357	348	335	327	315
37	407	390	380	374	357
39	449	436	425	419	407

1	8	0.165	0.670	0.355	0.2618	0.1754	1.61
	9	0.148	0.704	0.389		0.1843	1.47
	10	0.134	0.732	0.421		0.1916	1.36
	11	0.120	0.760	0.455		0.1990	1.23
	12	0.109	0.782	0.479		0.2048	1.14
	13	0.095	0.810	0.515		0.2121	1.00
	14	0.083	0.834	0.546		0.2183	0.890
	15	0.072	0.856	0.576		0.2241	0.781
	16	0.065	0.870	0.594		0.2277	0.710
	17	0.058	0.884	0.613		0.2314	0.639
	18	0.049	0.902	0.639		0.2361	0.545
1¼	8	0.165	0.920	0.665	0.3271	0.2409	2.09
	9	0.148	0.954	0.714		0.2498	1.91
	10	0.134	0.982	0.757		0.2572	1.75
	11	0.120	1.01	0.800		0.2644	1.58
	12	0.109	1.03	0.836		0.2701	1.45
	13	0.095	1.06	0.884		0.2775	1.28
	14	0.083	1.08	0.923		0.2839	1.13
	15	0.072	1.11	0.960		0.2896	0.991
	16	0.065	1.12	0.985		0.2932	0.900
	17	0.058	1.13	1.01		0.2969	0.808
	18	0.049	1.15	1.04		0.3015	0.688
1½	8	0.165	1.17	1.075	0.3925	0.3063	2.57
	9	0.148	1.20	1.14		0.3152	2.34
	10	0.134	1.23	1.19		0.3225	2.14
	11	0.120	1.26	1.25		0.3299	1.98
	12	0.109	1.28	1.29		0.3356	1.77
	13	0.095	1.31	1.35		0.3430	1.56
	14	0.083	1.33	1.42		0.3492	1.37
	15	[illegible]	[illegible]	[illegible]		[illegible]	[illegible]

Appendix B:



$$F_{LV} = \frac{L_W^*}{V_W^*}\sqrt{\frac{\rho_V}{\rho_L}}$$

Figure : Generalized Pressure Drop correlation

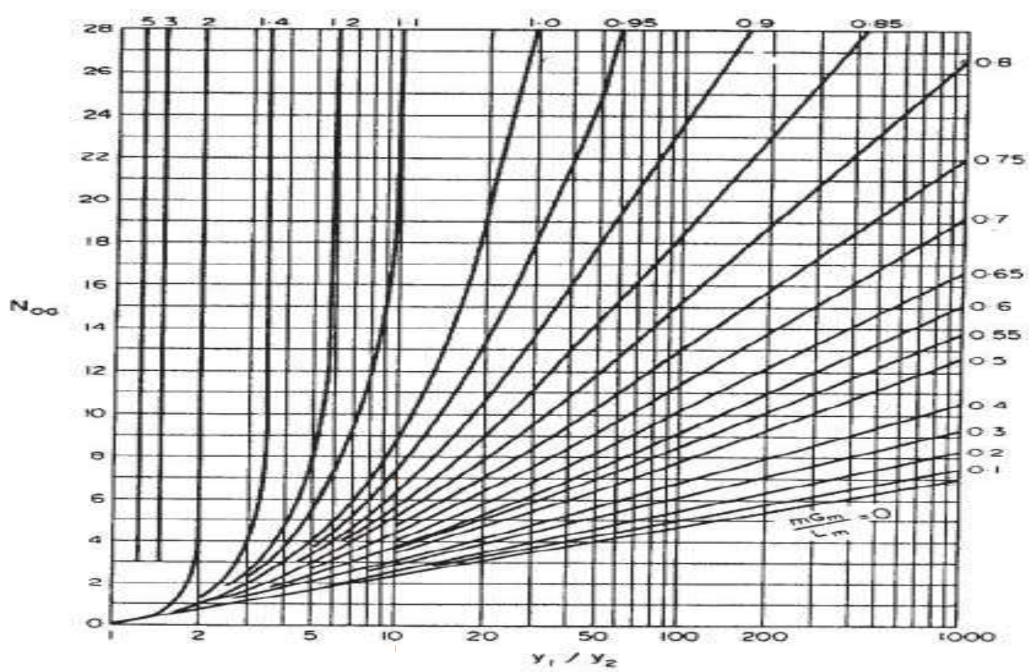


Figure : Number of transfer units NOG as a function of Y1/Y2 with mGm/Lm as parameter

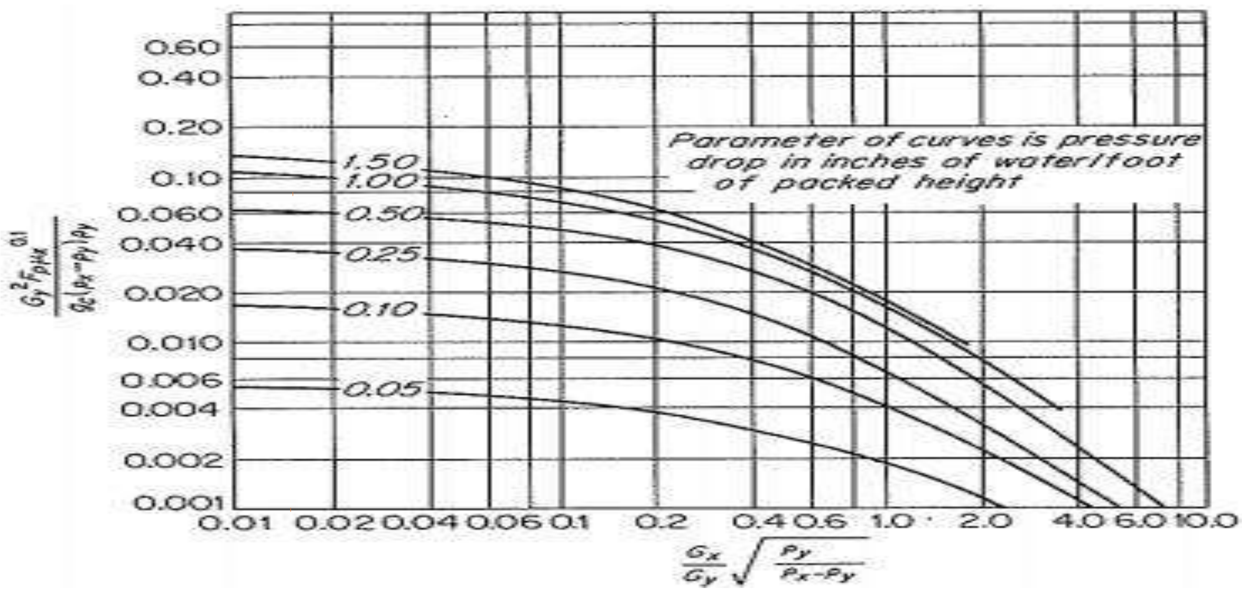


Figure : Generalized correlation for pressure drop

Tables:

Table B-1: Design data for various packing's

	Size		Bulk density (kg/m^3)	Surface area a (m^2/m^3)	Packing factor F_pm^{-1}
	in.	mm			
Raschig rings	0.50	13	881	368	2100
ceramic	1.0	25	673	190	525
	1.5	38	689	128	310
	2.0	51	651	95	210
	3.0	76	561	69	120
Metal	0.5	13	1201	417	980
(density for carbon steel)	1.0	25	625	207	375
	1.5	38	785	141	270
	2.0	51	593	102	190
	3.0	76	400	72	105
Pall rings	0.625	16	593	341	230
metal	1.0	25	481	210	160
(density for carbon steel)	1.25	32	385	128	92
	2.0	51	353	102	66
	3.5	76	273	66	52
Plastics	0.625	16	112	341	320
(density for polypropylene)	1.0	25	88	207	170
	1.5	38	76	128	130
	2.0	51	68	102	82
	3.5	89	64	85	52
Intalox saddles	0.5	13	737	480	660
ceramic	1.0	25	673	253	300
	1.5	38	625	194	170
	2.0	51	609	108	130
	3.0	76	577		72

Appendix C:

Figure C-1: Flow Factor

Figure C-2: (A_d/A_c)*100 vs. l_w / D_c

Figure C-3: K_2

Figure C-4: Orifice Coefficient C_o

Figures:

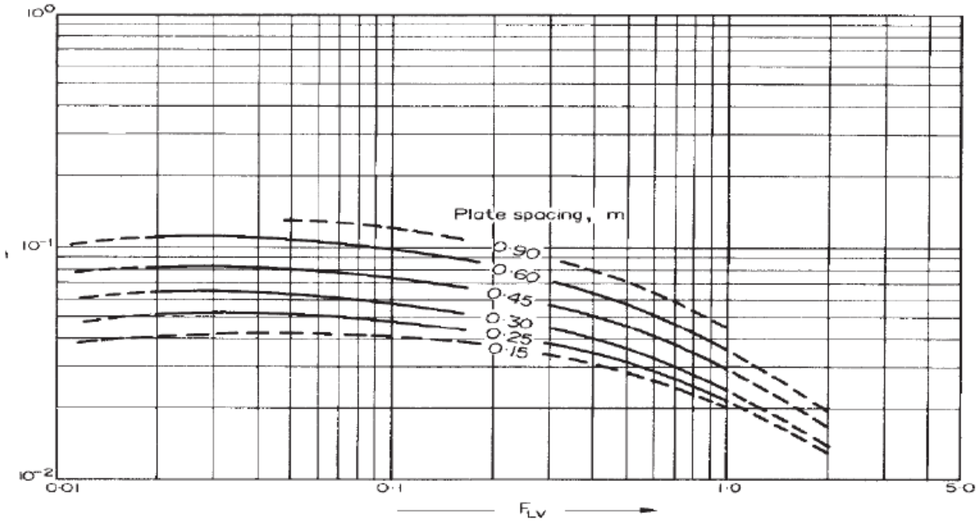


Figure : Flow Factor

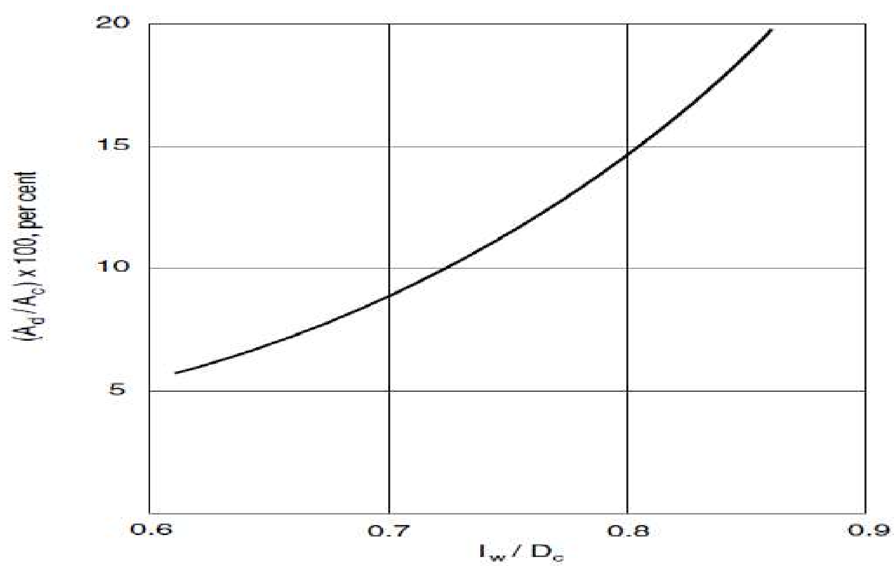


Figure : $(A_d/A_c)*100$ vs. l_w / D_c

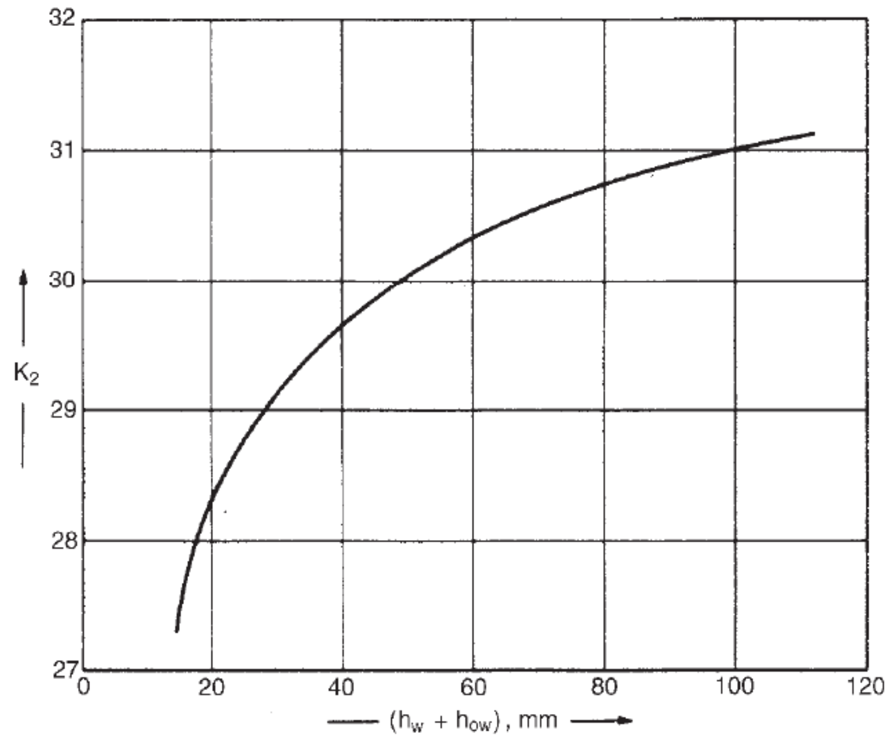


Figure : K_2

Appendix D:

Figure D-1: Shell side heat-transfer Curve

Figure D-2 Tube Side heat-transfer Curve

Figure D-3 Friction Factor

Figure D-4 Friction Factor

Table D-1: Design Coefficient

Table D-2: Tube-Sheet Layout Square Pitch

Table D-3: Heat Exchanger Tube Data

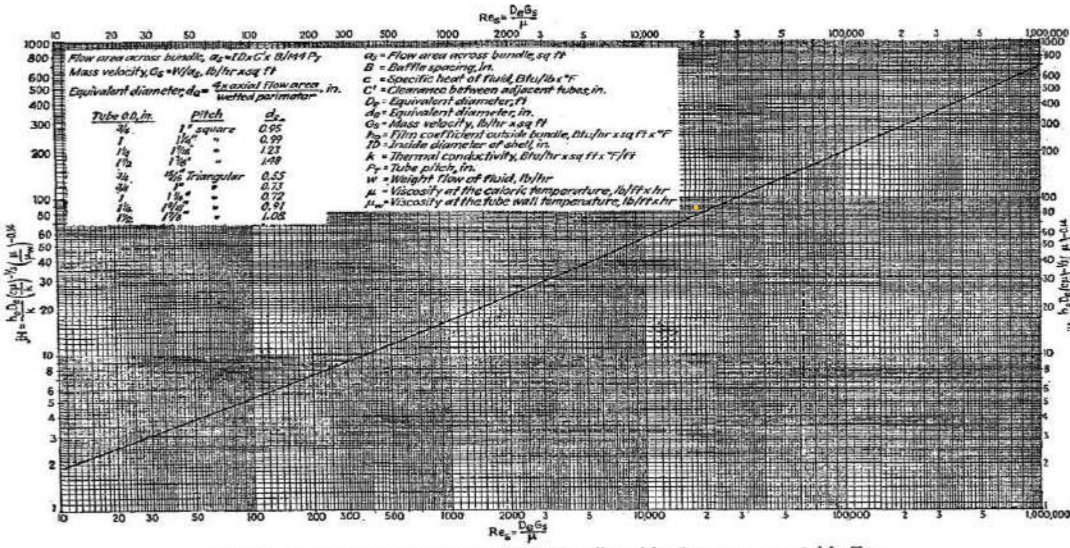


FIG. 28. Shell-side heat-transfer curve for bundles with 25% cut segmental baffles.

Figure : Shell side heat-transfer Curve

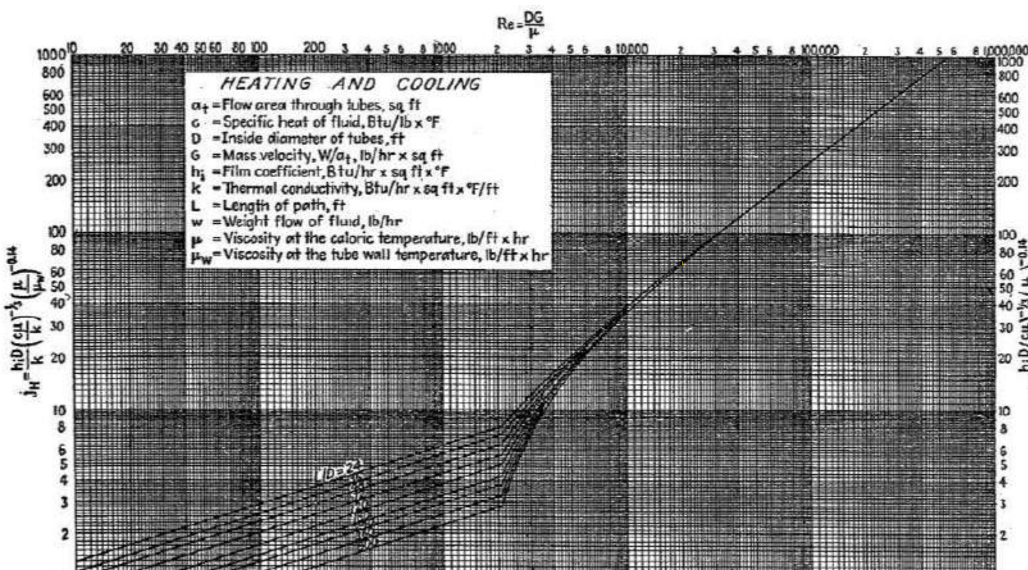


Figure : Tube Side heat-transfer Curve

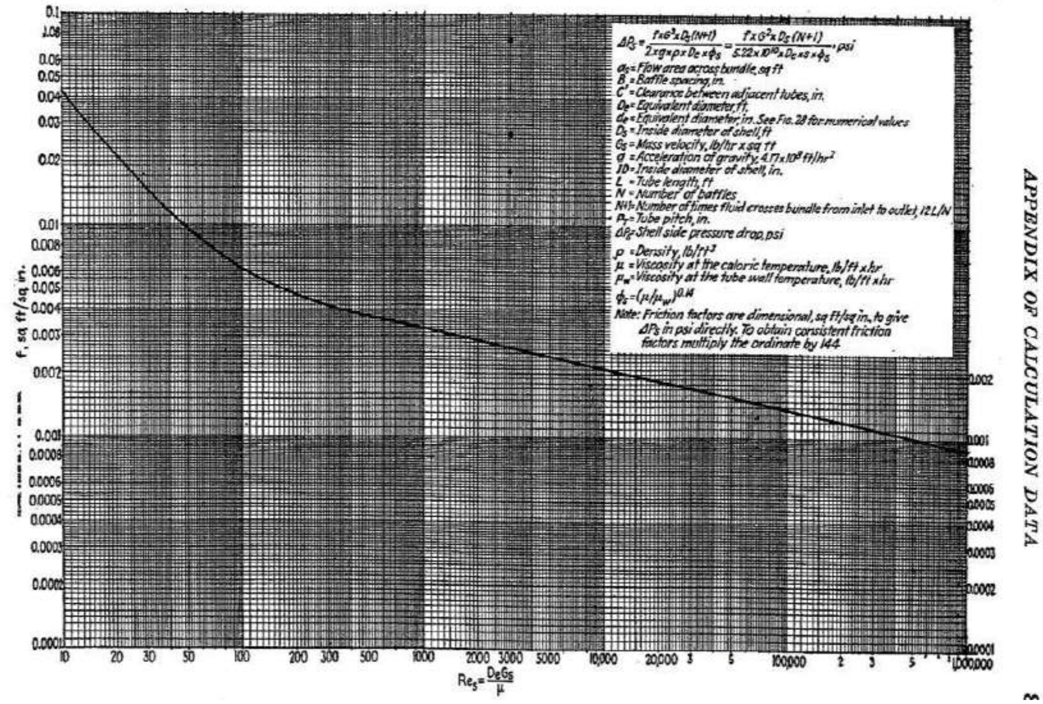


Figure : Friction Factor

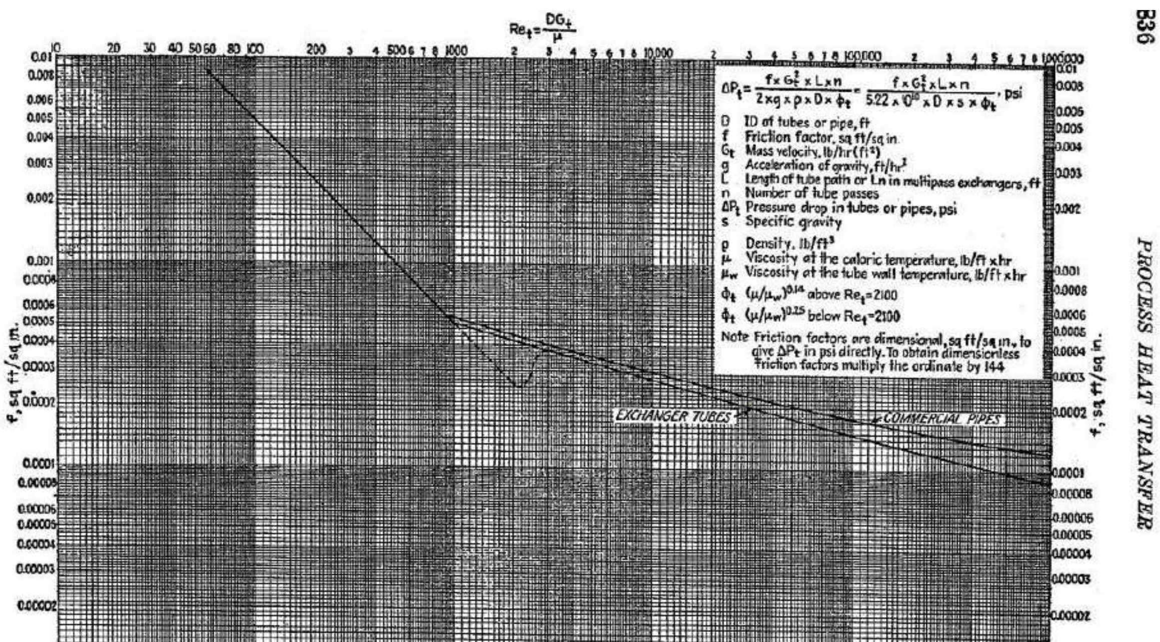


Figure : Friction Factor

Tables:

Table : Design Coefficient

Hot fluid	Cold fluid	Overall U_D
Water	Water	250–500§
Methanol	Water	250–500§
Ammonia	Water	250–500§
Aqueous solutions	Water	250–500§
Light organics*	Water	75–150
Medium organics†	Water	50–125
Heavy organics‡	Water	5–75‖
Gases	Water	2–50¶
Water	Brine	100–200
Light organics	Brine	40–100

Table : Tube-Sheet Layout Square Pitch

¾ in. OD tubes on 1-in. square pitch						1 in. OD tubes on 1¼-in. square pitch					
Shell ID, in.	1-P	2-P	4-P	6-P	8-P	Shell ID, in.	1-P	2-P	4-P	6-P	8-P
8	32	26	20	20		8	21	16	14		
10	52	52	40	36		10	32	32	26	24	
12	81	76	68	68	60	12	48	45	40	38	36
13¼	97	90	82	76	70	13¼	61	56	52	48	44
15¼	137	124	116	108	108	15¼	81	76	68	68	64
17¼	177	166	158	150	142	17¼	112	112	96	90	82
19¼	224	220	204	192	188	19¼	138	132	128	122	116
21¼	277	270	246	240	234	21¼	177	166	158	152	148
23¼	341	324	308	302	292	23¼	213	208	192	184	184
25	413	394	370	356	346	25	260	252	238	226	222
27	481	460	432	420	408	27	300	288	278	268	260
29	553	526	480	468	456	29	341	326	300	294	286
31	657	640	600	580	560	31	406	398	380	368	358
33	749	718	688	676	648	33	465	460	432	420	414
35	845	824	780	766	748	35	522	518	488	484	472
37	934	914	886	866	838	37	596	574	562	544	532
39	1049	1024	982	968	948	39	665	644	624	612	600

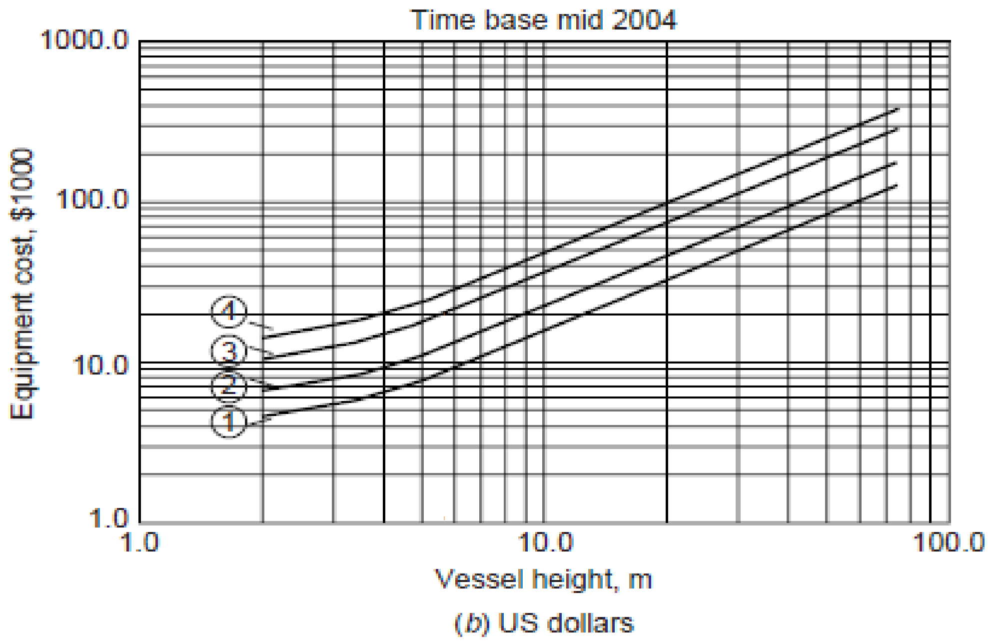
Table Heat Exchanger Tube Data

Tube OD, in.	BWG	Wall thick-ness, in.	ID, in.	Flow area per tube, in.^{2}	Surface per lin ft, ft^2		Weight per lin ft, lb steel
					Outside	Inside	
½	12	0.109	0.282	0.0625	0.1309	0.0748	0.493
	14	0.083	0.334	0.0876		0.0874	0.403
	16	0.065	0.370	0.1076		0.0969	0.329
	18	0.049	0.402	0.127		0.1052	0.258
	20	0.035	0.430	0.145		0.1125	0.190
¾	10	0.134	0.482	0.182	0.1963	0.1263	0.965
	11	0.120	0.510	0.204		0.1335	0.884
	12	0.109	0.532	0.223		0.1393	0.817
	13	0.095	0.560	0.247		0.1466	0.727
	14	0.083	0.584	0.268		0.1529	0.647
	15	0.072	0.606	0.289		0.1587	0.571
	16	0.065	0.620	0.302		0.1623	0.520
	17	0.058	0.634	0.314		0.1660	0.469
	18	0.049	0.652	0.334		0.1707	0.401

Appendix F:

Figures:

Tables:



Diameter, m	
①—0.5	③—2.0
②—1.0	④—3.0

Material factors	
C.S.	× 1.0
S.S.	× 2.0
Monel	× 3.4
S.S. clad	× 1.5
Monel clad	× 2.1

Pressure factors	
1–5 bar	× 1.0
5–10	× 1.1
10–20	× 1.2
20–30	× 1.4
30–40	× 1.6
40–50	× 1.8
50–60	× 2.2

Figure F-2: Reactor Cost

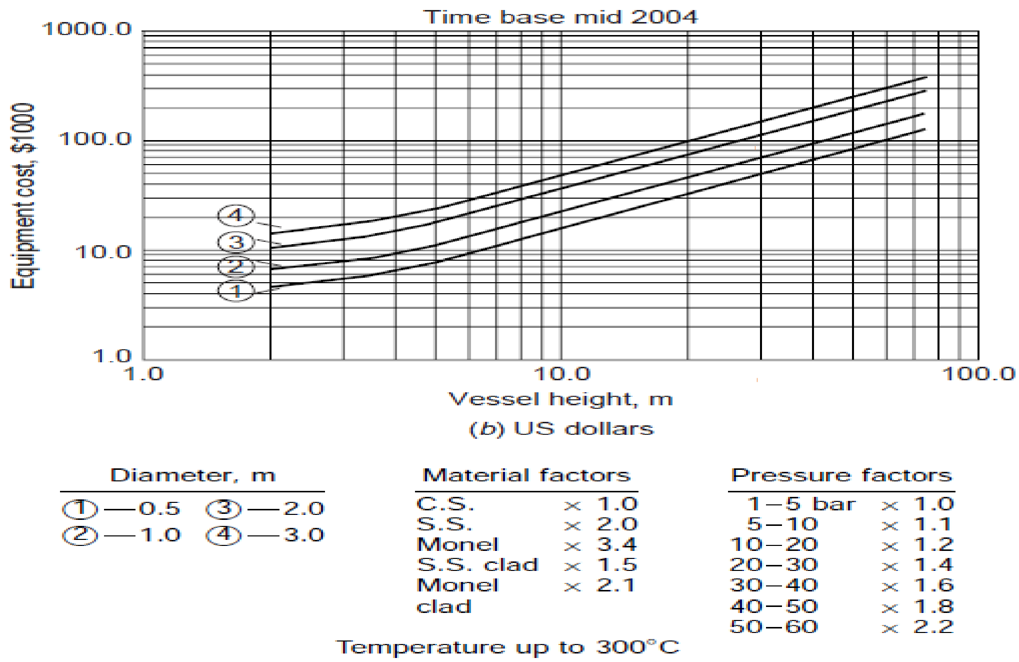


Figure : Absorber Cost

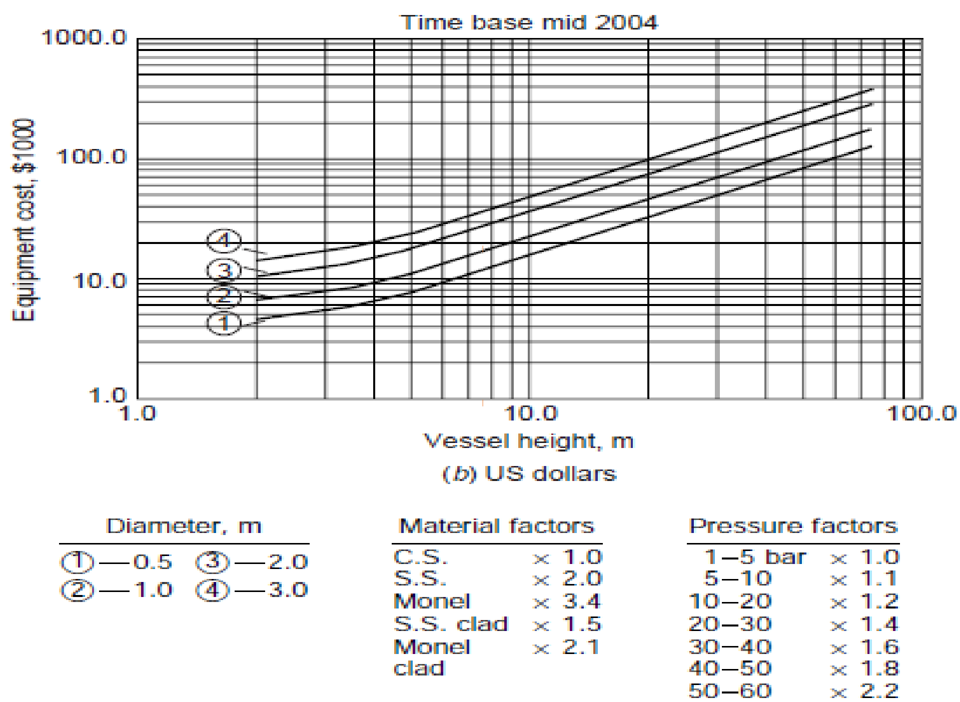
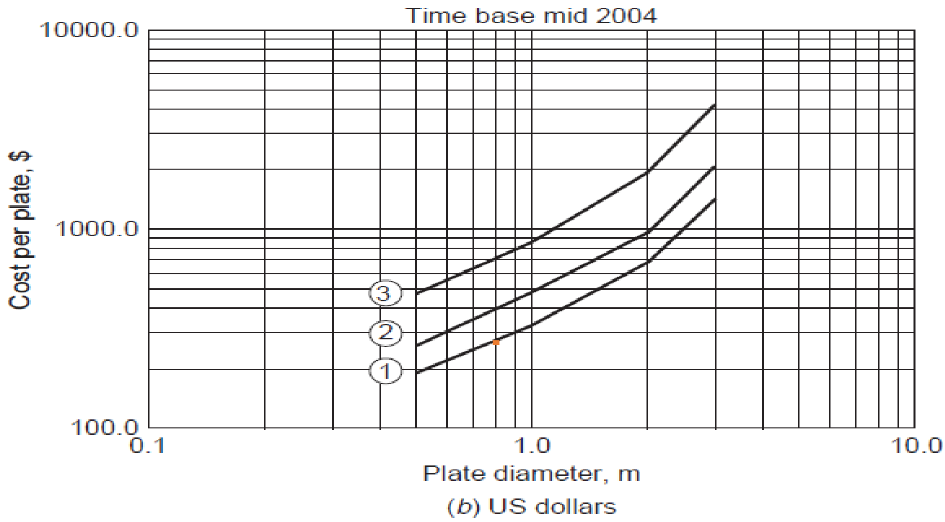
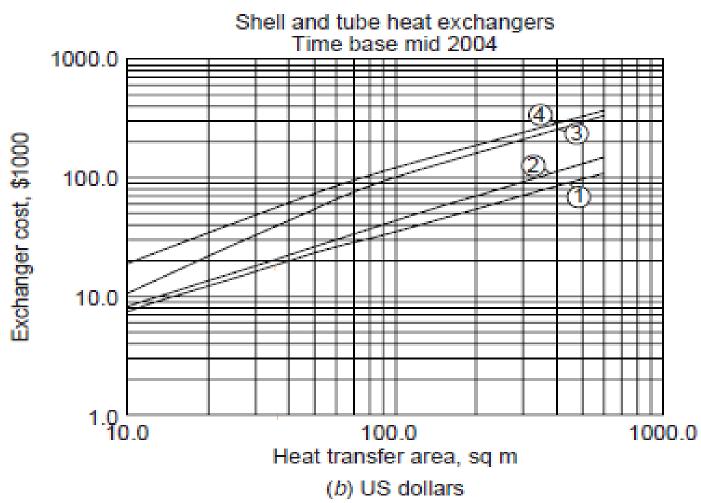


Figure : Distillation Cost



Type	Material factors
① Sieve	C.S. × 1.0
② Valve	S.S. × 1.7
③ Bubble cap	

Figure : Distillation Plate Cost



Materials: Shell	Materials: Tubes	Pressure factors		Type factors	
① Carbon steel	Carbon steel	1–10 bar	× 1.0	Floating head	× 1.0
② C.S.	Brass	10–20	× 1.1	Fixed tube sheet	× 0.8
③ C.S.	Stainless steel	20–30	× 1.25	U tube	× 0.85
④ S.S.	S.S.	30–50	× 1.3	Kettle	× 1.3
		50–70	× 1.5		

Figure : Heat Exchanger Cost

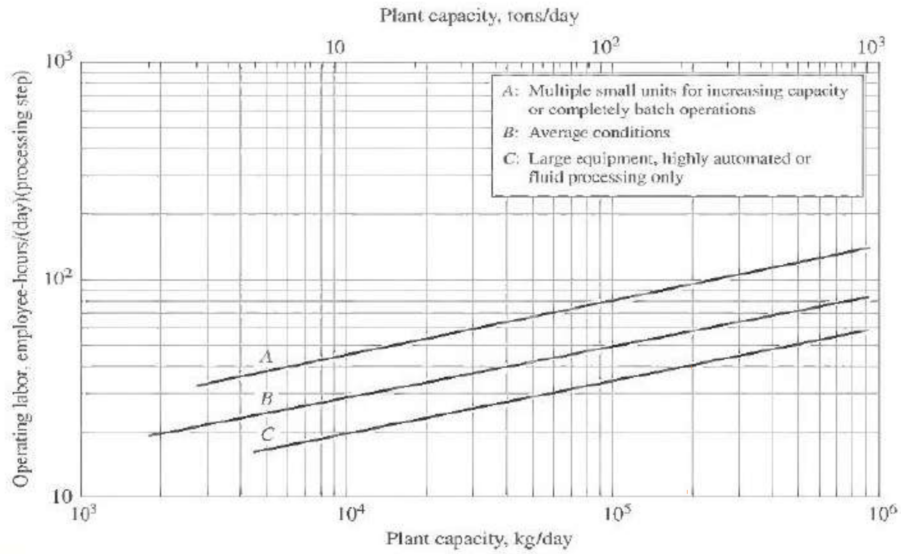


Figure : Operating Labor (h/day)

Table : Variable & Fixed Cost

Variable costs	*Typical values*
1. Raw materials	from flow-sheets
2. Miscellaneous materials	10 per cent of item (5)
3. Utilities	from flow-sheet
4. Shipping and packaging	usually negligible
Sub-total A	. . . .
Fixed costs	
5. Maintenance	5−10 per cent of fixed capital
6. Operating labour	from manning estimates
7. Laboratory costs	20−23 per cent of 6
8. Supervision	20 per cent of item (6)
9. Plant overheads	50 per cent of item (6)
10. Capital charges	10 per cent of the fixed capital
11. Insurance	1 per cent of the fixed capital
12. Local taxes	2 per cent of the fixed capital
13. Royalties	1 per cent of the fixed capital

Table : Absorber Packing Cost

Table 6.3. Cost of column packing. Cost basis mid 2004

	Cost £/m^3 (\$/m^3)		
Size, mm	25	38	50
Saddles, stoneware	840 (1400)	620 (1020)	580 (960)
Pall rings, polypropylene	650 (1080)	400 (650)	250 (400)
Pall rings, stainless steel	1500 (2500)	1500 (2500)	830 (1360)

Table : Direct & Indirect Cost

	Percent of delivered-equipment cost for: Solid processing plant[a]	Solid-fluid processing plant[a]	Fluid processing plant[a]
Direct costs			
Purchased equipment delivered (including fabricated equipment, process machinery, pumps, and compressors)	100	100	100
Purchased-equipment installation	45	39	47
Instrumentation and controls (installed)	18	26	36
Piping (installed)	16	31	68
Electrical systems (installed)	10	10	11
Buildings (including services)	25	29	18
Yard improvements	15	12	10
Service facilities (installed)	40	55	70
Total direct plant cost	269	302	360
Indirect costs			
Engineering and supervision	33	32	33
Construction expenses	39	34	41
Legal expenses	4	4	4
Contractor's fee	17	19	22
Contingency	35	37	44
Total indirect plant cost	128	126	144
Fixed-capital investment	397	428	504
Working capital (15% of total capital investment)	70	75	89
Total capital investment	467	503	593