COOLING TOWER DEBOTTLENECKING WITH RESPECT TO NEW TECHNOLOGIES

By

Shanza Afzal

Muhammad Muneeb Ur Rahman

Usama Rais Bin Ilyas

School of Chemical and Materials Engineering

National University of Sciences and Technology

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By

Leader - 00000191133 Shanza Afzal

Member 1 - 00000194490 Muhammad Muneeb Ur Rahman

Member 2 - 00000130049 Usama Rais Bin Ilyas

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CERTIFICATE

This is to certify that work in this thesis has been completed by Ms. Shanza Afzal, Mr. Muhammad Muneeb Ur Rahman and Mr. Usama Rais Bin Ilyas under the supervision of Dr. M. Bilal Khan Niazi at School of Chemical and Materials Engineering (SCME), National University of Sciences and Technology, H-12, Islamabad, Pakistan.

Advisor:

Dr. M. Bilal Khan Niazi
Department of Chemical Engineering
School of Chemical and Materials Engineering
National University of Sciences and Technology

Submitted Through:

HOD -------------------------------------
Dr. M. Bilal Khan Niazi
Department of Chemical Engineering
School of Chemical and Materials Engineering
National University of Sciences and Technology

Principal/Dean -------------------------------------
Dr. Zakir Hussain
School of Chemical and Materials Engineering
National University of Sciences and Technology

DEDICATION
TO

OUR PARENTS

Without whom none of this would have been possible and for their support throughout our lives.

AND TEACHERS

For inspiring us and supporting us throughout the entirety of this project.

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First of all, we bow before Allah Almighty to thank for His countless blessings and rewards who gave us the strength and ability to complete the thesis.

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ABSTRACT

Cooling tower is a fundamental piece of equipment in any processing plant. As water is used as a cooling medium in a cooling tower, there is a tendency of biocides formation. Chloride ions are used in the form of NaOCl + NaBr to remove the biocides so that they don't corrode any equipment that uses cooling water. The problem doesn't end here, the chloride ions reach the limit where make-up water is added in order to compensate for the loss of chlorinated water and the use of makeup water is not cheap. Our project is to treat this chlorinated water by using a chemical compound that will not only do the job of removing the biocides but also to keep the chloride ions concentration under the threshold value to avoid addition of makeup water. A full-fledged chemical dosing facility is designed for this purpose.

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ΔG: Gibbs free energy

A: Area

C: Cost

^{o}C: Degree centigrade

D: Diameter

F: Flow Rate

g: Acceleration due to gravity

H: Height

J: Joule

L: Length

Mol: Mole

P: Pressure

Q: Energy Flow rate

t: time

V: Volume

W: Width

C_P: Specific Heat Capacity at Constant Pressure

T: Temperature

V: Volumetric Flow Rate

CHAPTER 1

INTRODUCTION

1.1 About Engro Polymer and Chemicals

Engro Polymer and Chemicals Limited (EPCL) has the honor of being the only fully confederated Chlor-Vinyl chemical manufacturing facility in Pakistan. It is a subsidiary of the Engro Corporation which manufactures, sells and distributes quality products associated with Chlor-Vinyl and PVC under the 'SABZ' brand name.

The company was established in 1997 and came into operation in 1999. It started off with the name Engro Asahi Polymer and Chemical Ltd. At the time of its foundation, it was a joint venture between Engro Chemical which had 50% shares, Asahi Glass Company which had 30% shares and Mitsubishi Corporation which had 20% of the shares. Initially the plant was designed to operate at a 100,000 ton capacity. The plant was to be built at Port Qasim.

In the year of 2006 Asahi Glass sold their part of the shares to Engro Chemical and later its name was changed to Engro Polymer and Chemicals Limited.

In the year of 2007, Company decided to expand and increase the capacity of PVC to 150,000 ton and also to set up Chlor-alkali and EDC-Vcal plants.

Figure 1 EPCL Karachi Plant

1.2 Products Manufactured

Apart from being the only manufacturer of PVC resin in Pakistan, EPCL also manufactures Caustic Soda, EDC, VCM and Sodium Hypochlorite.

1.3 Problem Statement

In EPCL plant, there are a number of process streams which require cooling and the process of cooling is done by cooling water which is obtained by cooling tower. We have to increase the current efficiency of the cooling tower and sort out the water losses issues that are being faced in an economical way that is beneficial for the company.

1.4 Background

There is a specific threshold value for the amount of chloride ions in the industrial water and that is 390 ppm, if this threshold value exceeds then we have to use excessive blowdown water which is around $60m^3/hr$. This excessive water means the use of excessive makeup water to cope up for the loss of water.

1.5 Issue

We cannot let chloride rich water to pass through different equipment as the water will corrode the equipment. In order to make the water safer for the equipment we add makeup fresh water to cope up the situation. The makeup water costs around Rs. $56/m^3$ which becomes a very large amount as an yearly expense.

1.6 Possible Solutions

In order to solve the issue, an alternative biocide can be used as compared to NaOCl + NaBr which will release less Chloride ions in the water streams. Most favorable chemicals that can replace the current chemicals are Ozone and Chlorine Dioxide.

1.7 Mechanical Draft Cooling Tower

A large number of industries are using mechanical draft cooling towers. Mechanical draft cooling towers are famous due to their compactness and brilliant performance in transferring heat. Mechanical draft is famous due to their high effectiveness, light weight and reasonable price.

Although they are used by industries for many years, this technology and its manufacturing is limited to few companies in some developed nations.

Mechanical draft towers use fans, driven by electric motors to produce the flow of air. The tower is called an induced draft if a fan is installed in the air exit at the top of the tower. The tower is called force draft if a fan is installed in the air entry at the bottom of the tower. The flow is counter flow hot water enters from the top and air from the bottom in between there is a packing where there is a direct contact between two fluids and they exchange heat. Cold water leaves from the bottom and hot air from the top.

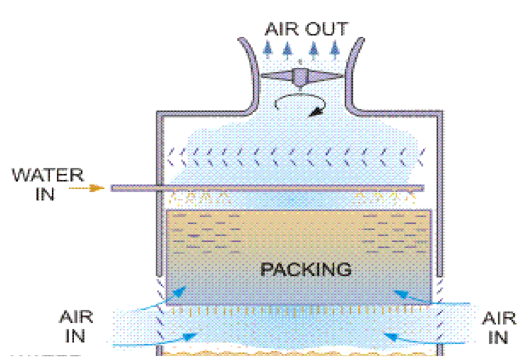


Figure 2 Mechanical Draft Cooling Tower

1.7.1 Why Mechanical draft Tower

- For the same capacity the mechanical draft cooling towers are much smaller in size than natural draft cooling towers because of an increase in cooling capacity due to increase in volume of air being forced out by the fan.
- Capacity control is possible by regulating the speed of fans which control the volume of air which in turn control capacity.
- Natural draft cooling towers are only suitable for outside areas whereas mechanical draft cooling towers can be located even inside the building.

1.7.2 How things work

The working principle of cooling towers is very similar to evaporative type condensers, in which hot water is cooled by evaporation. Water evaporates when warm water comes in contact with cold air. The evaporating water also absorbs the latent heat form water surrounding it. By losing latent heat, the water is cooled down.

1.8 Types of Mechanical Draft Cooling Tower

Following are the types of mechanical draft cooling tower

- Induced draft
- Forced draft

1.8.1 Induced Draft

In an induced type cooling tower, the fan is located at the top of the tower where it creates low pressure inside the tower. Axial fan is used for this type of tower. The advantage of using induced draft is that it uses 50% less energy as compared to forced draft. It is easy to install and maintain. Low noise level is another advantage of cooling towers.

1.8.2 Forced Draft

In this system the fan is located at the bottom of the tower which causes over pressure, both axial and centrifugal fans can be used. The advantages of using forced draft is that it has low absorbed capacity, dry air stream drive and easy maintenance.

CHAPTER 2

LITERATURE REVIEW

2.1 Process Description:

Initially, the chemical compound that was used for the removal of biocides was reaching the threshold value of 390ppm of chloride ions. This resulted in an excessive blowdown of 60m^3/h which was compensated by adding fresh makeup water at the cost of Rs. 56/m^3 which resulted in a huge amount on a yearly basis. To save or even reduce this amount, a new chemical compound has to be used which would not release much chloride ions in the water and in the end extra fresh water would not be added to compensate for the loss of chlorinated water. The new Chemical compound that will be used as an alternative for NaOCl + NaBr and that compound is ClO_2. Chlorine Dioxide is economically more favorable than any other chemical compound at increased system contamination. Chlorine dioxide will be produced on site where it will be injected into the outlet stream of the cooling tower. Chloride ions concentration in the cooling water will be continuously monitored and depending upon the concentration, the dosing amount of Chlorine Dioxide will be increased or reduced. Chlorine Dioxide will be produced by the reaction of Sodium Chlorate ($NaClO_3$) and Sulfuric Acid (H_2SO_4). As a result, less chloride ions will be present in the cooling water and thus there will be less blowdown and less usage of fresh makeup water which will directly reduce the operating cost.

2.2 Cooling Tower:

Cooling tower is one of the major components of many industries, its basic purpose is to reject waste heat to the atmosphere with the help of air to decrease the temperate of the water to the required value. Water that has been heated in by any industrial process is then sent to the cooling tower via pipes. Water is sprayed on to the banks called “fill”, it slows the water flow in the cooling tower, which helps in the increased air-water contact time. In the cooling tower, water is then subjected to incoming air, which is being entered in to the tower with the help of fans.

Basic principle

Cooling tower utilizes both mass and heat transfer to cool down the water. Cooling of water is due to the evaporation of a small amount of water. Heat transfer process includes the latent heat transfer from water to air and a sensible heat transfer for the evaporation of water.

About 80% of this heat transfer per kg of air flowing inside the cooling tower relies upon the temperature and dampness substance of air. Wet bulb temperature of air demonstrates the water content of air in short wet bulb temperature of air is the most minimal temperature to which the water can be cooled. Essentially, the water temperature approaches the wet bulb temperature, however practically it will not reach the wet bulb temperature of air in a cooling tower, as it is difficult to contact all the water with outside air as the water drops through the wetted fill surface to the basin.

Factors affecting the operation of cooling tower

- Dry-bulb and wet-bulb temperature of air
- Temperature of hot water entering the tower
- Contact time between air and water
- Uniformity of distribution of the air and water inside the tower
- Air pressure drop
- Required temperature of cooled water

2.3 Types of Cooling Tower:

Cooling towers are manufactured in many types based on the requirement, having various sizes and shapes.

2.3.1 Atmospheric Cooling Towers:

Atmospheric cooling tower doesn't require any mechanical fan for the air to enter the tower, air flows into the tower naturally. Although these types of cooling tower are very inexpensive, they are mostly used on a small scale, and can only be used in areas where wind flow is high.

2.3.2 Hyperbolic Natural Draft:

In hyperbolic natural draft cooling towers air is transferred due to the density difference between the hot air inside and the cold air outside. Hyperbolic natural draft is divided into the following types.

2.3.3 Counterflow Natural Draft:

Counter flow towers are designed in a way that air flows upward vertically, and the water falls from top to bottom, as the name suggests, air and water are flowing in opposite directions to each other. Counter flow towers use pressurized spray type systems which sprays water on the top of the fill.

2.3.4 Cross Flow Natural Draft:

In cross flow natural draft, the water flows horizontally while air flows vertically in the chamber. Air doesn't pass through the distribution chamber in cross flow towers.

2.3.5 Mechanical Draft Cooling Towers:

Mechanical draft cooling towers consist of either a single fan or multiple fans which are used to suck in the air that is required for the heat exchange. Efficiency of mechanical draft cooling towers is much higher, and mechanical draft cooling towers can be used anywhere. They are not affected by the outside atmosphere. Mechanical draft cooling towers are further divided into two types based on the position of the fan in the tower.

2.3.6 Forced Draft:

A forced draft cooling tower fan is placed at the bottom of the tower from where air enters the tower.

Advantages:

- A part of the velocity head of air thrown by the blower is converted to pressure head on entering into the tower. It makes energy efficient than induced drafts.

- As Fans are installed near the ground it leads to less vibrations in Cooling Tower.

Disadvantages:

- Air flow through packing may not be uniform.
- Recirculation rate decreases if the wind velocity becomes high.

2.3.7 Induced Draft:

In induced draft cooling tower fan is placed at the top of the cooling tower where air exists the tower, in induced draft cooling tower pressure difference is created which results in better performance as compared to forced draft cooling tower.

Advantages:

- More contact of dry air at the bottom of the tower with the coldest water.
- As more humid air is in contact with the warm water is leads to maximum average driving force for both mass and heat transfer

Disadvantages:

- Power consumption is high.
- Power consumption of cross flow induced tower is lower than counter current flow induced draft tower.

2.4 Important Terms:

Wet Bulb Temperature: The temperature of the entering air that enters into the cooling tower is measured by a wet bulb thermometer.

Factors affecting the wet bulb temperature:

- Dry bulb temperature of air
- Humidity of air
- Velocity of air

Dry Bulb temperature: The temperature of the entering air that enters into the cooling tower is measured by dry bulb thermometer.

Approach: The difference between the wet bulb temperature of the ambient air and the water leaving the cooling tower is known as the tower's approach. The approach is a function of cooling tower capability to cool down the water. For example, a large cooling tower will produce a closer approach for a given heat load, flow rate and entering conditions of the air.
Approach depends on tower design and the following factors affect approach:

- Air to water contact time
- Amount of fill surface
- Size of water droplets

Blowdown: Water that is discharged from the system to control the concentrations of impurities and salts from the system. The loss of water through blowdown is termed as Blowdown losses

Drift losses: Lost water during the circulation when water droplets are being carried by the air stream into the atmosphere.

Relative Humidity: Relative Humidity is the ratio of water vapors partial pressure to the equilibrium pressure of water at any temperature. It depends upon pressure and the temperature of the system. At low temperatures, it requires less water vapor to achieve high value of relative humidity; more water vapor is required to achieve high relative humidity in warm or hot air.

Range: Difference between the hot water temperate and the cold-water temperature is called range

$$R = HW - CW$$

2.5 The Psychrometric chart construction and its use

Some thermodynamics properties of air like dry-bulb temperature, wet-bulb temperature, relative humidity, absolute humidity, dew point, enthalpy and specific volume are all inter-related. The psychrometric chart shows how these interdependencies are related. It also helps to calculate them for example if value of any two of these properties are known other 5 properties can be easily obtained through a psychrometric chart.

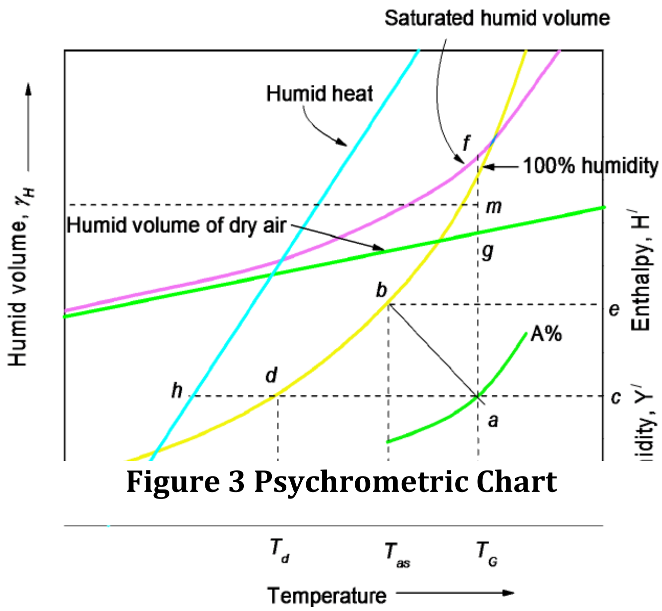


Figure 3 Psychrometric Chart

2.6 Why is water used for Cooling?

These factors make the water an excellent cooling medium:

- Its cost and availability.
- Easy handling
- Amount of heat per unit volume carried by water is high
- Insignificant compression and expansion with normal temperature ranges.
- It does not decompose

CHAPTER 3

PROCESS DESIGN METHODOLOGY

Designing is an action meant at giving a complete explanation of a manufacturing system or part of a system. For successive engineering and utilization these explanations characterize an explicit specification of size, performance and other characteristics are important.

3.1 Process Flow Diagram

The process flow diagram for the production of Chlorine Dioxide is developed so that the material and energy balances on the equipment can be applied.

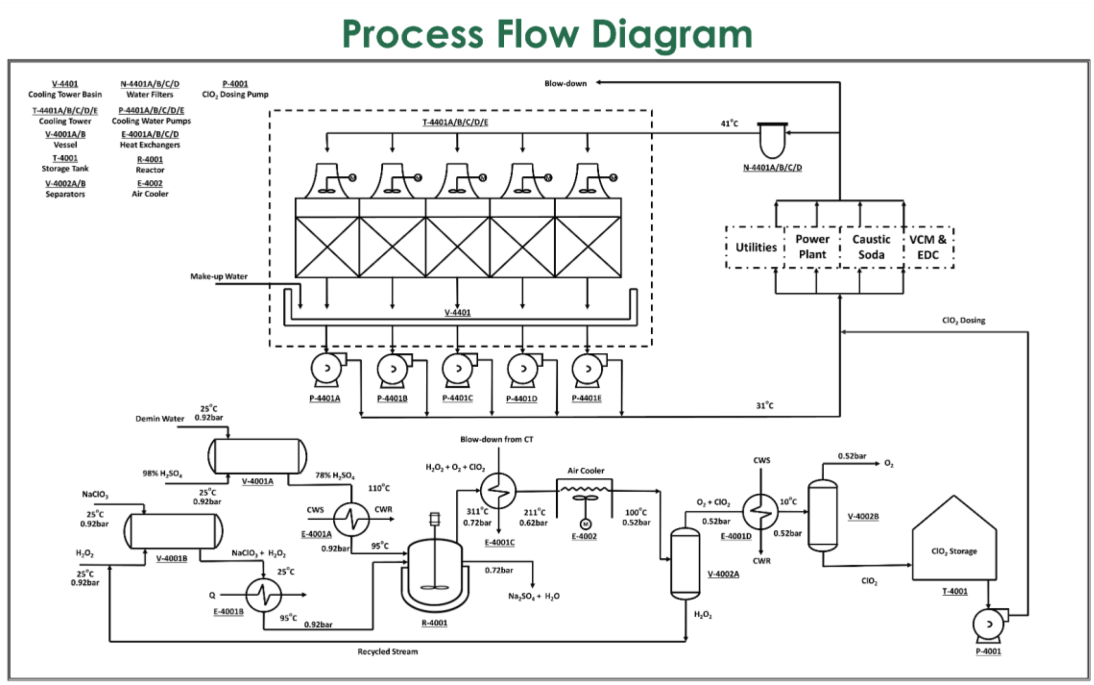


Figure 4 Process Flow Diagram

3.2 Material Balance and Energy Balance

Material and Energy balance is applied on every equipment of the whole unit to calculate the flow rates and other parameters for every stream. Following are the assumptions we have taken for our material balance:

1. Steady State System
2. Basis 1h
3. In= out

3.2.1 Mixing Vessel (V-4001A):

In this vessel Sulphuric acid is being diluted by addition of water up to 78%. By addition of water temperature of acid raised up to 110°C.

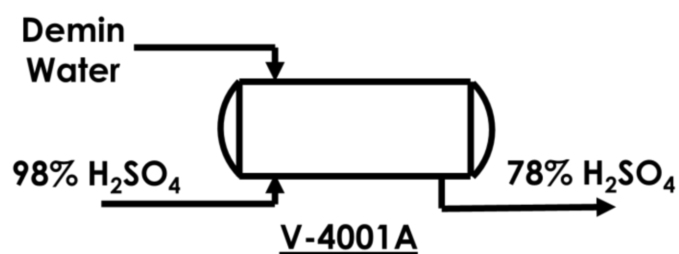


Figure 5 V-4001A

H_2SO_4 In= 0.0214kgmol

H_2O In = 0.00547kgmol

Mixer Outlet=0.0269kgmol

H_2SO_4 78%

H_2O 22%

3.2.2 Heat Exchanger (E-4001A):

Temperature of Sulphuric acid is reduced by exchanging heat with cooling water.

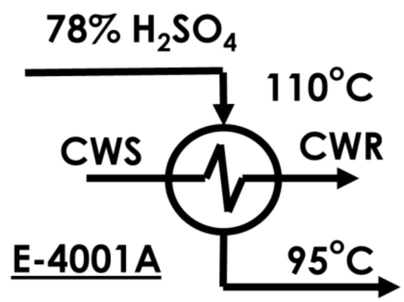


Figure 6 E-4001A

$\Delta H = n c_p \Delta T$

n=0.0269kgmoles

c_p of H_2SO_4=131.32kJ/moles.°C

c_p of H_2O= 12.25kJ/moles.°C

ΔH=41.41KJ

Mass of water =1.01kg/h

3.2.3 Mixing Vessel (V-4001B):

It is preferable to mix hydrogen peroxide with sodium chlorate because it has ability to deteriorate the reactor. So, in this vessel hydrogen peroxide is mixed with solid sodium chlorate.

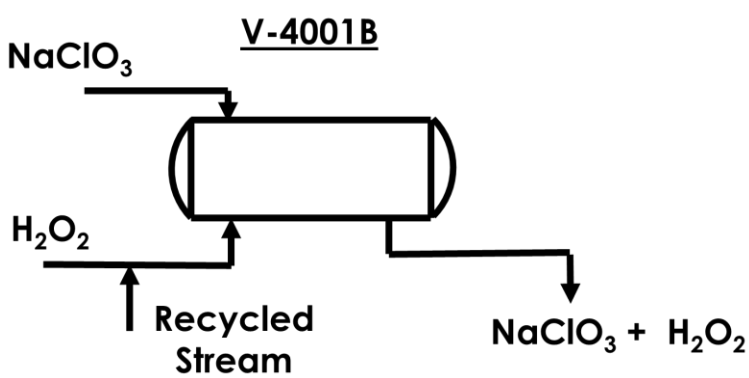


Figure 7 V-4001B

$NaClO_3$ in=0.04125 kgmol

H_2O_2 $_{FRESH}$= 0.021 kgmol

H_2O_2 $_{recycled=}$ 0.0021 kgmol

H_2O_2 $_{total}$=0.023 kgmol

Mixer Outlet= 0.06435 kgmol

$NaClO_3$=64%

H_2O_2=36%

3.2.4 Heat Exchanger (E-4001B):

The temperature required for reaction is 95°C. So, mixture of hydrogen peroxide and sodium chlorate is heated with steam.

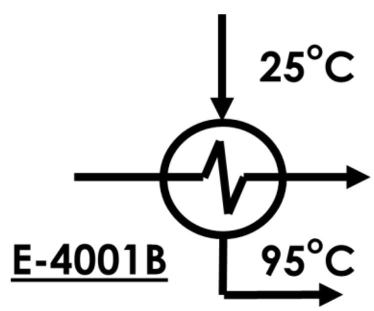


Figure 8 V-4001B

$\Delta H = nc_p\Delta T$

c_p of $NaClO_3$ = 104.6 kJ/moles.°C

c_p of H_2O_2 = 36.619kJ/moles.°C

ΔH = 0.06435(80.126) (95-25)

ΔH = 360.93kJ/h

Mass of air required= 0.5kg/h

3.2.5 Reactor:

The reactor is continuous stirred tank reactor. Reaction conditions are temperature 95°C and 0.92 bar pressure. Reaction conversion is 80% with respect to sodium chlorate. And hydrogen peroxide is added in 10% excess otherwise there are chances of mixing impure chlorine dioxide with chlorine. Its autocatalyzed reaction, the chloride ion produced are used to speed up the reaction. Chlorine Dioxide, oxygen and hydrogen peroxide are taken from the top. Water and sodium sulphate are removed from the bottom.

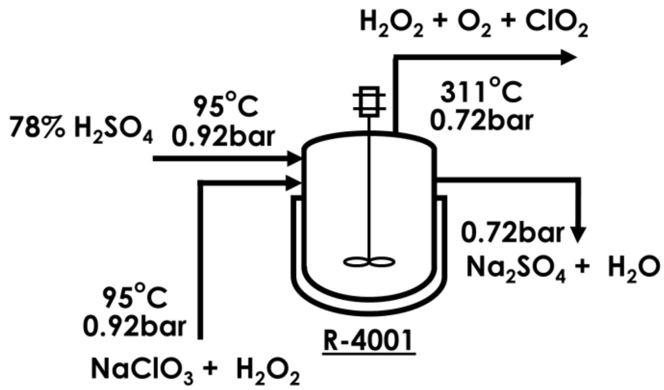


Figure 9 R-4001

Material Balance		
Equipments	R-4001	
Flow	In	Out
Components	Molar Flows in kgmol/hr	
H_2SO_4	0.021	0
H_2O_2	0.0231	0.0021
$NaClO_3$	0.04125	0.00825
O_2	0	0.021
ClO_2	0	0.033
Na_2SO_4	0	0.021
H_2O	0	0.04125
Total	0.08535	0.1266
Temperature (°C)	95	311
Pressure (bar)	0.91	0.072

Table 1 Material Balance on Reactor

$$2NaClO_3 + H_2O_2 + H_2SO_4 \rightarrow 2ClO_2 + O_2 + Na_2SO_4 + 2H_2O$$

In-Out= Accumulation

Conversion w.r.t $NaClO_3$=80%

Energy Balance

$\Delta H = \Delta H_{reaction} + \Delta H_{products} - \Delta H_{reactants}$

$\Delta H_{products}$= 1924.75 kJ/h

$\Delta H_{reactants}$= 554.53 kJ/h

$\Delta H_{reaction}$= -263.74 kJ/h

ΔH= 1115.94 kJ/h

Components	ΔH^o_f (kJ/mol)
H_2O_2	-190.75
$NaClO_3$	-365.4
H_2SO_4	1295
O_2	0
H_2O	-285.53
ClO_2	104.6

Table 2 Energy Balance on Reactor

3.2.6 Heat Exchanger (E-4001C):

The top products of the reactor are cooled with blow-down from cooling tower. The purpose of using blow-down is to save cost of cooling water.

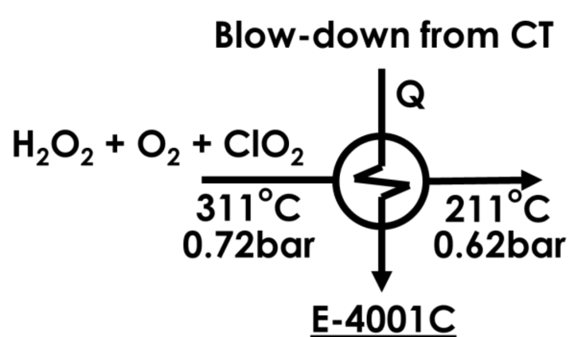


Figure 10 E-4001C

c_p ClO_2 = 42 kJ/kmol.°C

c_p O_2 = 31.91 kJ/kmol.°C

c_p H_2O_2 = 36.619 kJ/kmol.°C

c_p avg = 36.94 kJ/kmol.°C

$\Delta H = \eta c_p \Delta T$ = (0.0561) (100) (31.94) = 207.23 kJ/h

$Q = \Delta H = mc_p\Delta T$

207.23= m (4.184) (10)

Mass of Water = 4.95 kg/h

3.2.7 Heat Exchanger (E-4002):

Temperature of the mixture of hydrogen peroxide, oxygen and chlorine dioxide is further reduced in air cooler. The reason for reduction in temperature is to purify chlorine dioxide.

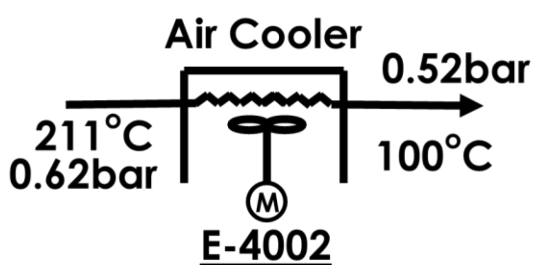


Figure 11 E-4002

c_p average = 36.94 kJ/mol.°C

ΔT = 111°C

$Q = nc_p\Delta T$

Q = 230.02 kJ/h

$\Delta H = mc_p\Delta T$

Mass of Air Required = 15.33 kg/h

3.2.8 Separating Vessel (V-4002A):

In this separator chlorine dioxide and oxygen is separated from hydrogen peroxide on the basis of density difference.

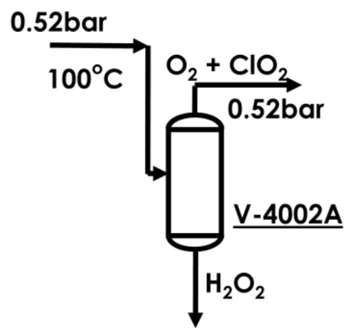


Figure 12 V-4002A

Feed = 0.0681 kgmol/h

Tops = 0.066 kgmol/h

Bottoms = 0.0021 kgmol/h

Recovery 99%

3.2.9 Heat Exchanger(E-4001D):

Temperature is reduced by exchanging heat with cooling water from 100^{o}C to 10 ^{o}C.

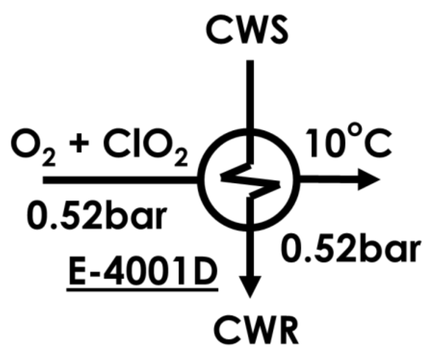


Figure 13 E-4001D

$Q=\Delta H = \eta c_p \Delta T$

cp avg = (0.6) (41.97) + 0.4(29.82) = 37.11 kJ/kmol.^{o}C

Q= 0.054(37.11) (90)

Q = 180.3546 kJ/h

$\Delta H = mc_p \Delta T$

Mass of water = 4.31 kg/h

3.2.10 Separating Vessel (V-4002B):

The cold mixture is separated in this tank based on density mixture. Oxygen is removed from the top in gaseous form and chlorine dioxide is taken from the bottom and stored in a storage tank.

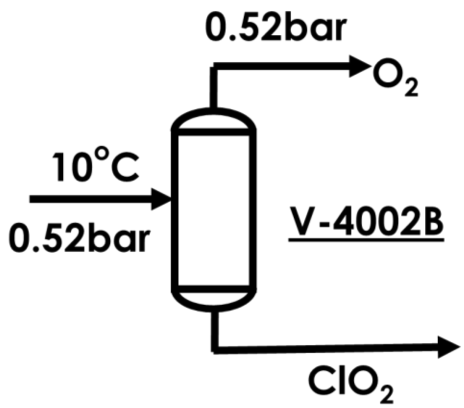


Figure 14 V-4002B

Feed = 0.054 kgmol/h

Top = 0.021 kgmol/h

Bottom = 0.033 kgmol/h

Recovery 99%

3.2.11 Pump(P-4001):

Pump is required for the dosing of liquid chlorine dioxide. It is a positive displacement pump.

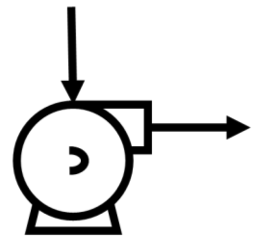


Figure 15 P-4001

Ws(isentropic) = $(\Delta H)s$

η=75%

H_1= 104 kJ/kgmol

H_2= 107 kJ/kgmol

H_2-H_1= 3kJ/kgmol

Ws= H_2-H_1= 3kJ/kgmol x 0.033 = 0.099 kJ/h

Ws(actual)= 0.099/0.75 = 0.132 kJ/h

Power= 0.036W

Equipment	Mixer 1 Outlet	Mixer 2 Outlet	Reactor Inlet	Reactor Outlet	Separator 1 Tops	Separator 1 Bottoms	Separator 2 Tops	Separator 2 Bottoms
Components	Molar Flows in kgmol/h							
H_2SO_4	0.0214	0	0.0214	0	0	0	0	0
H_2O_2	0	0.023	0.023	0.0021	0	0.0021	0	0
$NaClO_3$	0	0.04125	0.04125	0.00825	0	0	0	0
O_2	0	0	0	0.021	0.021	0	0.021	0
ClO_2	0	0	0	0.033	0.033	0	0	0.033
Na_2SO_4	0	0	0	0.021	0	0	0	0
H_2O	0.00547	0	0.00547	0.04125	0	0	0	0
Total	0.02687	0.06425	0.09112	0.1266	0.054	0.0021	0.021	0.033
Temperature (^oC)	110	25	95	311	100	100	10	10
Pressure (bar)	0.92	0.92	0.92	0.72	0.52	0.52	0.52	0.52

Table 3 Overall Material Balance

Equipment	Inlet Temperature	Outlet Temperature	ΔH
E-4001A	110 °C	95 °C	41.41 kJ/h
E-4001B	25 °C	95 °C	360.93 kJ/h
E-4001C	311 °C	211 °C	207.23 kJ/h
E-4001D	100 °C	10 °C	180.35 kJ/h
E-4002	211 °C	100 °C	230.02 kJ/h
R-4001	95 °C	311 °C	1115.94 kJ/h

Table 4 Overall Energy Balance

3.2.12 Cooling Tower:

Material Balance:

The material balance around cooling tower helps in computing the evaporation losses, blowdown losses and drift losses. The addition of these losses gives the makeup water required.

Flow rate of water = 22500 m^3/h

Since we are considering no leakage therefore

$$\text{Make up Water} = \text{Evaporation} + \text{Blowdown} + \text{Drift}$$

The evaporation losses are calculated from following formula

$$\text{Evaporation losses} = 0.00085 * R * 1.8 * \text{inlet flow}$$

R = Range=10°C

Evaporation losses = 180 m^3/h

The calculation of blow down losses depend on the solids balance present in water therefore

$$\text{Blowdown losses} = \text{Evaporation losses}/(\text{COC} - 1)$$

The COC is cycle of concentration and it is calculated with the help of chloride balance on entrance and exit of water from cooling tower.

COC = 4

Blowdown losses = 60m^3/h

Drift losses is usually 0.0005% of the total flow of water from cooling tower

$$\text{Drift losses} = 0.0005\% * \text{inlet flow}$$

Drift losses = 0.1125m^3 /h

Therefore, after every hour the amount of makeup water is fed:

Makeup = 240.11m^3/h

Energy Balance:

The energy balance around cooling tower is complex because of simultaneously heat and mass transfer and due to this some assumption are made before applying energy balance.

- The rate of vaporization of water is less than the rate of water input to the tower i.e. 1% of the total input flow rate.
- Adiabatic and evaporative cooling of water occur in tower.

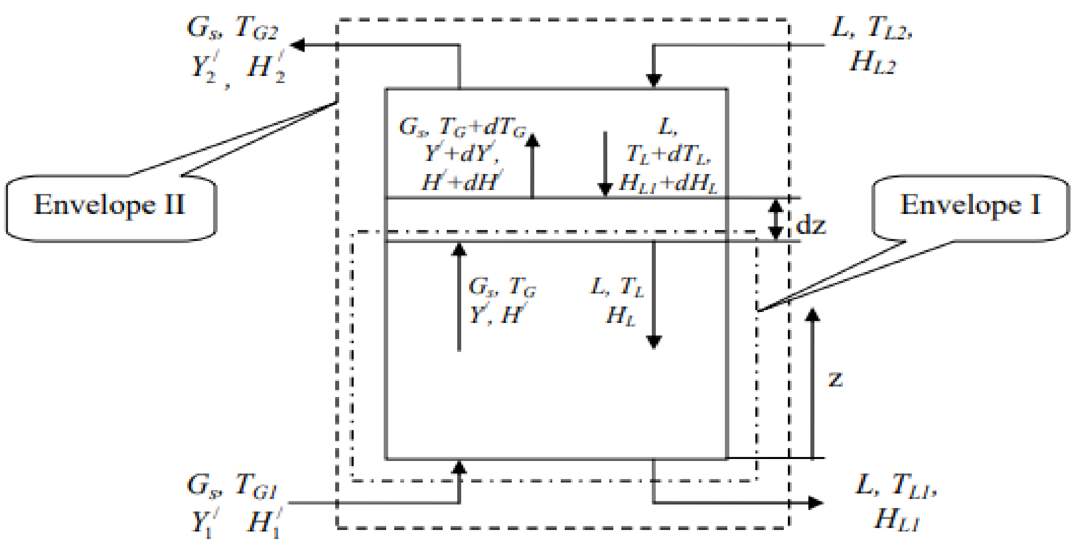


Figure 16 Enthalpy balance diagram of cooling tower

Let L is the water flow rate and Gs is the air flow rate both in m^3/hr. Across the differential thickness dZ the temperature of water is decreases by dTl and enthalpy of air is increased by dH`.

Hence the change in enthalpy of water is

$$L * Cwl * dTl$$

And change in enthalpy of air is

$$Gs * dH`$$

Number of transfer unit is

$$N_{tG} = \int_{H1`}^{H2`} dH`/(Hi` - H`)$$

Height of transfer unit is

$$H_{tG} = \frac{Gs}{(k\gamma * a)}$$

Hence the height of cooling tower packing section is the product of number of transfer unit and height of transfer unit.

$$` = L * Cwl * dTl$$

$$\int_{Tli}^{Tlo} dTl/(Hi` - H`) = k\gamma` \frac{a}{L * Cwl} * Z$$

This equation is called Markel Equation.

Thermodynamic Properties of Air:

The thermodynamic properties of air are found by the assistance of psychometric graph. Psychometric diagram is a graphical portrayal of property of air which incorporates physical and thermodynamic properties, for example, dry bulb temperature, wet bulb temperature, humidity, enthalpy and density of air.

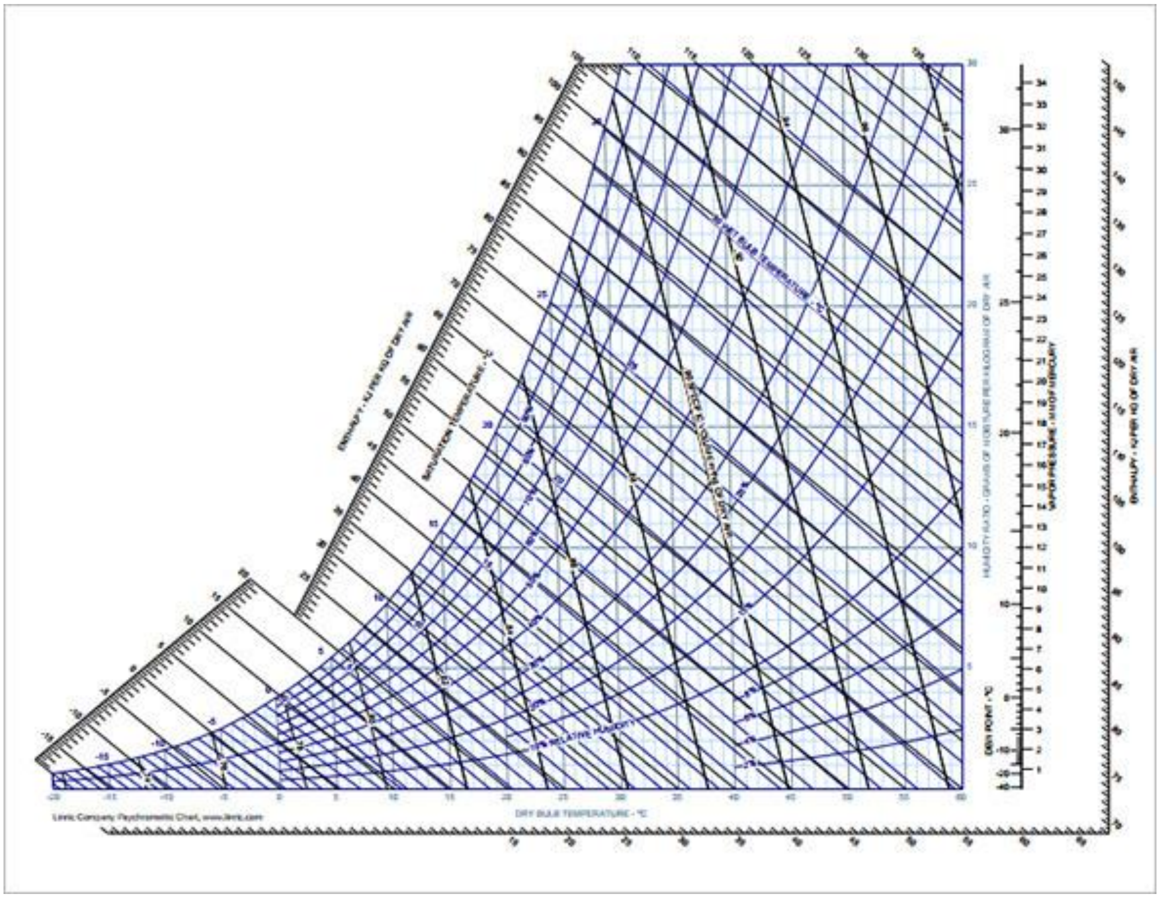


Figure 17 Psychrometric Chart

Energy balance calculations

Merkel equation is used to calculate the tower characteristic

$$\int_{Tli}^{Tlo} dTl/(Hi` - H`) \ = k\gamma` \frac{a}{L * Cwl} * Z$$

The tower characteristic is normally determined used the Chebyshev rule

$$kaV/L \ = ((Ti - To)/4) * (1/\Delta\, h1) + (1/\Delta\, h2) + (1/\Delta\, h3) + (1/\Delta\, h4))$$

$$\Delta h1 = \text{value of hw} - \text{ha} \ \text{ at } (T2 + 0.1(T2 - T1))$$

$$\Delta h2 = \text{value of } hw - ha \text{ at } (T2 + 0.4(T2 - T1))$$

$$\Delta h3 = \text{value of } hw - ha \text{ at } (T1 - 0.4(T2 - T1))$$

$$\Delta h4 = \text{value of } hw - ha \text{ at } (T1 - 0.1(T2 - T1))$$

$T_i = 41^0C$

$T_o = 31^0C$

Δh_1

T = 32 ^{0}C

h_w = 135.02 kJ/kg

ha = 104 kJ/kg

Δh_1=31.02 kj/kg

Δh_2

T = 35 ^{0}C

h_w = 150.82 kJ/kg

ha = 113 kJ/kg

Δh_2 =37.82 kj/kg

Δh_3

T = 37 ^{0}C

h_w = 160.36 kJ/kg

h_a = 115 kJ/kg

Δh_3=45.37 kJ/kg

Δh_4

T = 40 ^{0}C

$h_w = 164.36$ kJ/kg

$h_a = 118$ kJ/kg

$\Delta h_4 = 46.37$ kJ/kg

$$\frac{kVa}{L} = 0.256$$

Height of transfer unit = 5.48m

Height of packing = 2.01m

Range of cooling tower is the difference between hot water temperature and cold-water temperature of cooling tower.

Hot water temperature = 41 ^oC

Cold water temperature = 31 ^oC

Range of cooling tower = 10 ^oC

The approach of cooling tower is the difference between cold water temperature and wet bulb temperature of air

Wet bulb temperature = 27 ^oC

Approach = 4 ^oC

The heat lost by water is equal to the heat gain by air

Heat lost by water = $m * cp * \Delta T$

m = $2.25*10^7$ kg/h

cp water = 4.18 kJ/kg

Delta T = 10^oC

Heat lost = $9.414*10^8$ kJ/h

This amount of heat is absorbed by air and from there we can calculate the mass of air required

Inlet wet bulb temperature of air = 27^{o}C

Enthalpy of air at inlet temperature = 72.11 kJ/kg

Outlet wet bulb temperature of air = 31 ^{o}C

Enthalpy of air at outlet temperature = 118.62 kJ/kg

Specific volume of air at inlet temperature = 0.845 m3/kg

Mass of air required = 2.35*10^{8} kg/h

CHAPTER 4

DESIGN CALCULATIONS

4.1 Reactor Design (CSTR):

A reactor is device in which a chemical reaction takes place along with heat and mass transfer. Almost every chemical process involves reactor. Designing of reactor helps to find out the economics of overall process. Basically, its vessel that is specially designed according to reaction conditions. Vessels are of two types:

1. Tank type
2. Pipe type

4.1.1 Types of Reactors:

There are three main types of reactor

1. Batch Reactor
2. Continuous Stirred Tank Reactor
3. Plug Flow Reactor

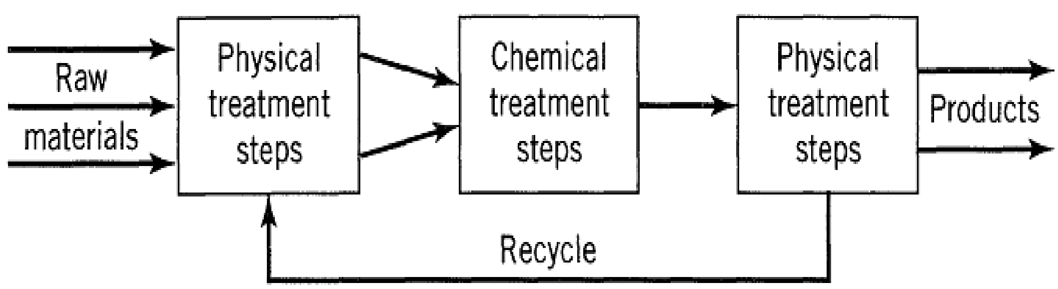


Figure 18 Description of a Chemcial Process

Batch Reactor:

Batch reactor is used for small scale operations in which product is removed after a certain time. It is usually used in a steady state process where large amount of product is required. It requires equipment for support. It provides good quality control of product. It is widely used in oil industry.

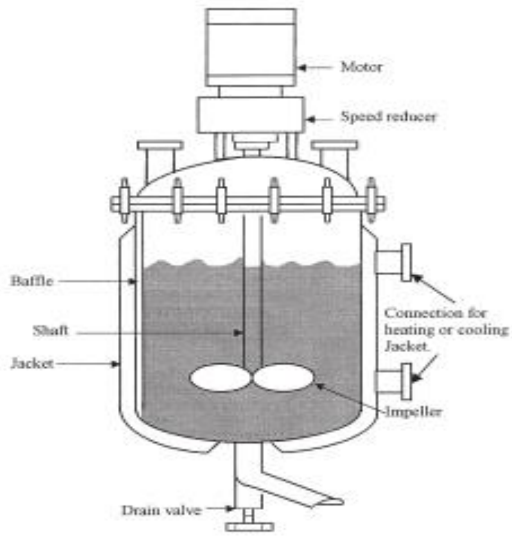


Figure 19 Diagram of a batch reactor

Continuous Stirred Tank Reactor (CSTR):

One or more reactant is introduced in the tank and mixture is well mixed with agitator to disperse the reagent thoroughly into reaction mixture just after entering in reactor. Concentration is constant throughout the reactor and product is removed continuously.

Key features of CSTR:

- It has a tank that is equipped with impeller and cooling jackets.
- More than one reactant can be introduced in this reactor.
- Mass flow rate is same at entrance and exit because it is steady state reactor.
- The assumption of all calculations is perfect mixing means no concentration gradient.
- The reaction continues with final concentration in rate equation.
- It can be operating in series and parallel from economical point of view.
- When CSTR are connected in series their efficiency is equal to PFR.

Space time $= \tau = \frac{V}{v_0}$

τ = space time

V = volume of reactor

V_0 = Volumetric flow rate

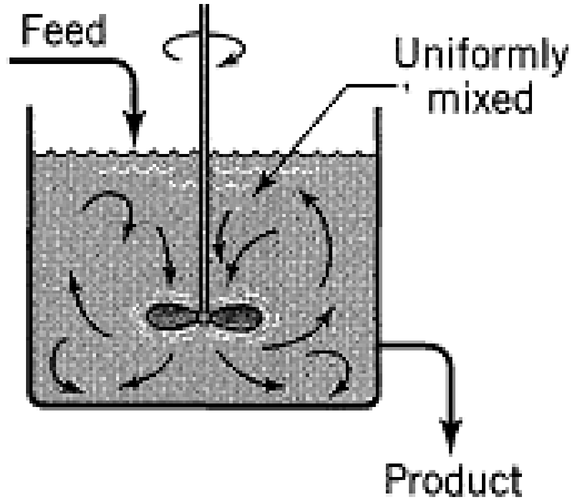


Figure 20 Diagram of a CSTR

PFR (Plug Flow Reactors):

In plug flow reactor reactants pass through pipe and the concentration of product increases gradually as the reaction proceeds. There is no homogenous mixing in this reactor. It has efficiency higher than CSTR. Best suit for gaseous reactions.

Key features:

- Steady-state operation
- In axial direction there lies spatial changes but not in radial direction
- Best suit for fast reaction
- difficult to control temperature
- no moving parts

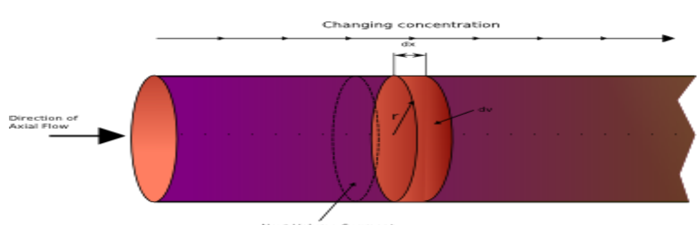


Figure 21 Diagram of a PFR

4.1.2 Reason of Choosing CSTR:

We have selected CSTR because homogenous mixing was required throughout the reaction. It also provides good heat and mass transfer. For mixing of liquid reactant this reactor was suitable.

Approach to reactor selection:

1. Identification of number of phases means homogenous or heterogenous phase.
2. To find out the stoichiometry of reaction, number of reactions taking place and energy requirement
3. To study the mechanism of reaction in detail
4. Decision of selection of reactor. For this kinetics, data for scale up and commercial design is required.

4.1.3 Reactor Design :

- Rate equation tells how homogenous reaction proceeds. It is an intensive measure and explains how fast a component disappear or generate in a given reaction as a function of reaction condition. For example, in some reactions rate equation is function of volume.
- The purpose of reactor design is to find out size and type of reactor. How reaction condition changes with respect to space and time can only be find out by proper integration of rate equation

Following are the steps of reactor design:

1. Collection of kinetics and thermodynamic of the reaction
2. Collection of physical properties for designing
3. Study of predominant rate mechanism
4. Selection of well-suited reactor
5. To achieve desired yield, selection of reactor conditions
6. Size of reactor
7. Then select material of construction

8. Final design specification of reactor

	M	Mol. wt	F_o	ρ	V
Stream 1	kg/hr	Kg/Kgmol	Kgmol/h	Kg/m^3	m^3/h
H_2O_2	0.714	34.01	0.021	1450	$4.92*10^{-4}$
$NaClO_3$	3.52	106.44	0.021	2500	0.0014
Total	4.234				
Stream 2	kg/hr	Kg/Kgmol	Kgmol/h	Kg/m^3	m^3/h
H_2SO_4	2.058	98	0.033	1830	0.00112

Table 5 Parameters for the Reactor

Volumetric flow rate = $V_o = V_1 + V_2$ = 0.001892 m^3/h

Molar Flow rate= F_o= Initial concentration

$C_{A0}(H_2SO_4) = F_{H2SO4} / V_{H2SO4}$

$C_{B0}(H_2O_2 + NaClO_3) = (F_1 + F_2) / V_o$

C_{A0} =18.75 Kgmol/m^3

C_{B0}= 28.54 Kgmol/m^3

$-r_A = kC_A C_B^{0.5}$

Conversion = X_A = 80 %

Order of reaction = n = 1.5

Rate Constant = k = 2.27 m^3/ kgmol sec

$-r_A = k C_A (1- X_A) (M- X_A)^{0.5}$

Where $M= C_{B0} / C_{A0}$

$-r_A$= 7.23 Kgmol/m^3.hr

Space time=$\tau = \frac{C_{A_0} x_A}{-\gamma_A}$

= 2.07 h

Volumetric flow rate of reaction mixture = $V_o + V_{H2SO4}$

= 0.01892+0.0112

= 0.03012 m^3/h

Volume of the reactor = V

Space time= V/Vo

V= 2.07*0.03012

=0.06m^3

By giving 20% allowance

Volume of the reactor = V = 0.06+0.012= 0.072 m^3

Volume of the reactor = 0.072 m^3

Dimensions of Reactor:

Height to diameter ratio of the cylindrical reactor is 1 to 2.

H/D = 1-2

We selected height to diameter ratio is 1.6

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

H=1.6D

Volume=V=$\frac{\pi}{4} D^2 (1.6D)$

Diameter = D = 0.38 m

So,

Height = H = 0.62 m

4.1.4 The Vessel:

A dished bottom requires less power than a flat one.

Selection criteria of impeller

The impeller selected is pitched blade turbine, 45 degree because

- The weighted of the reaction mixture is calculated to be up to 12.391cP which lies in the range of impeller
- Efficient turbulence flow impeller for blending immiscible liquids
- Especially effective for heat exchange with vessel walls and internal coils
- It can operate at reasonable speed
- Low cost
- Wide application range

Design of Impeller:

Da/Dt = 1/3	Da = 0.2 m
H/Dt = 1	H = 0.62m
J/Dt = 1/12	J = 0.052m
E/Dt = 1/3	E = 0.2m
W/Da = 1/5	W = 0.04m
L/Da = 1/4	L = 0.05m

Da = diameter of impeller

Dt = tank diameter

H = Depth of liquid in tank

J = width of Baffles

E = Height of impeller above vessel floor

W = impeller width

L = length of impeller blade

4.1.5 Baffles:

One radial baffle is required.

Impeller Reynolds Number

$R_e = (Da^2 Nr\ \rho)/\mu$

Where:

Nr = 75 rpm = 1.25

$\rho = 1371.716\ kg/m^3$

$\mu = 12.391 * 10^{-3}$ Pa. sec

4.1.6 Material selection:

For reactor

Carbon steel type 310

Its composition is

Cr	24 – 26%
Ni	19 – 22%
C	0.25%

Table 6 Composition of Reactor Material

- High strength and resistant to scaling at high temperatures.
- This allow show increased resistance to high temperature corrosion
- Jacketed high-temperature, high pressure reactors, oil refining.

For blades

Carbon steel type - 410

Its composition is

Cr	11.50-13.50 %
C	0.15%

Table 7 Composition of Impeller Blades

- Lowest cost general purpose stainless steel.
- Wide use where corrosion is not severe.
- Bubble tower parts for petroleum refining, pump rods and valves, machines parts, turbine blades.

For baffles:

Carbon steel type 405

Cr	11.50-14.5 %
C	0.08%
Al	0.1-0.3%

Table 8 Composition of Reactor Baffles

- Version of type 410 with limited hardenability but improves weldability.
- Good weld ability and cladding properties.
- Tower lining, baffles, separator towers, heat exchangers tubing.

Baffle spacing:

It is calculated from the following formula

Baffle spacing =Di /4

Baffle spacing = 3.1415 * 0.38 /4

Baffle spacing = 0.29 m

Width of baffle = Di/12

Width of baffle = 0.38/12

Width of baffle = 0.03 m

Distance from bottom = Di /2

Distance from bottom = 0.38 /2

Distance from bottom = 0.19m

4.2 Mixing Vessel Design

4.2.1 Volume Calculation

By using the mentioned below we can calculate volume of tank

$v = \tau^*R \times Q/0.8$

flow rate= $Q=0.00129\ m^3$

time of residence = $\tau^*R = 1h$

$v = 0.00161\ m^3$

Now we have:

$V = 3/4 \times D^2L$………………….. (1)

Where V is $0.00129 m^3$.

L=height or length D= internal diameter

Assume

L/D=3 put this into equation (1)

$V=\pi/4*D^2(3*D)$

D=0.0881m

L=3(0.0881)

L = 0.26 m

Pressure in gauge = 1-1=0

Pressure in the tank =1 atm

Design pressure = Pi = 0+10% = 0.1

$N/m^2 = 0.01\ N/mm^2$

Design temperature = 110 °C

Material of construction= stainless steel 18cr/8Ni

At this temperature the design stress comes out to be = f =160 (from table 13.2)

Joint factor = 1

tank diameter Di = 0.0881 m

Thickness for cylindrical shell 'e'

e= Pi *Di/2 J f-Pi

e=0.00000275 mm

Corrosion allowance = 2mm

e=2.00000275 mm

Head section thickness

Large- and low-axis ratio of 2:1 produces most standard ellipsoidal heads. To calculate the minimum thickness required, the following equation may be used for this ratio:

e= Pi*Di/2 J f-Pi

e = 0.01(0.0881) / 2(1) (160) −0.2(0.01)

e=0.00000275 m

Choice of closure:

$$e = \frac{P_i R_C Cs}{2fj + P_i(C_s - 0.2)}$$

internal pressure is between 0-15 bar so we will use tori spherical heads

where Cs = stress concentration factor for tori spherical head

$$Cs = \frac{1}{4} \times 13 + \frac{\sqrt{RC}}{\sqrt{R_k}}$$

RK = knuckle radius

RC =crown radius

(To prevent buckling, the relation between the knuckle and the crown shall not be below 0.06; and the radius of the crown shall not be greater as the diameter of the cylindrical portion. The joint factor J is taken as 1.0 for the shaped heads (no joints in the head)).

Rc =Rk (0.06) equal to diameter of vessel

RC= (0.0881) (0.06) =0.005286

Cs=0.8075

We will now put values in the main equation

e = 0.01*(0.005286)*(0.8075) / (2*(160)*(1) + 0.01*(0.005286 – 0.2))

e =1.33e^{-7}

corrosion allowance will be added =2 mm

e = 2.00000013 mm

4.2.2 Impeller Design

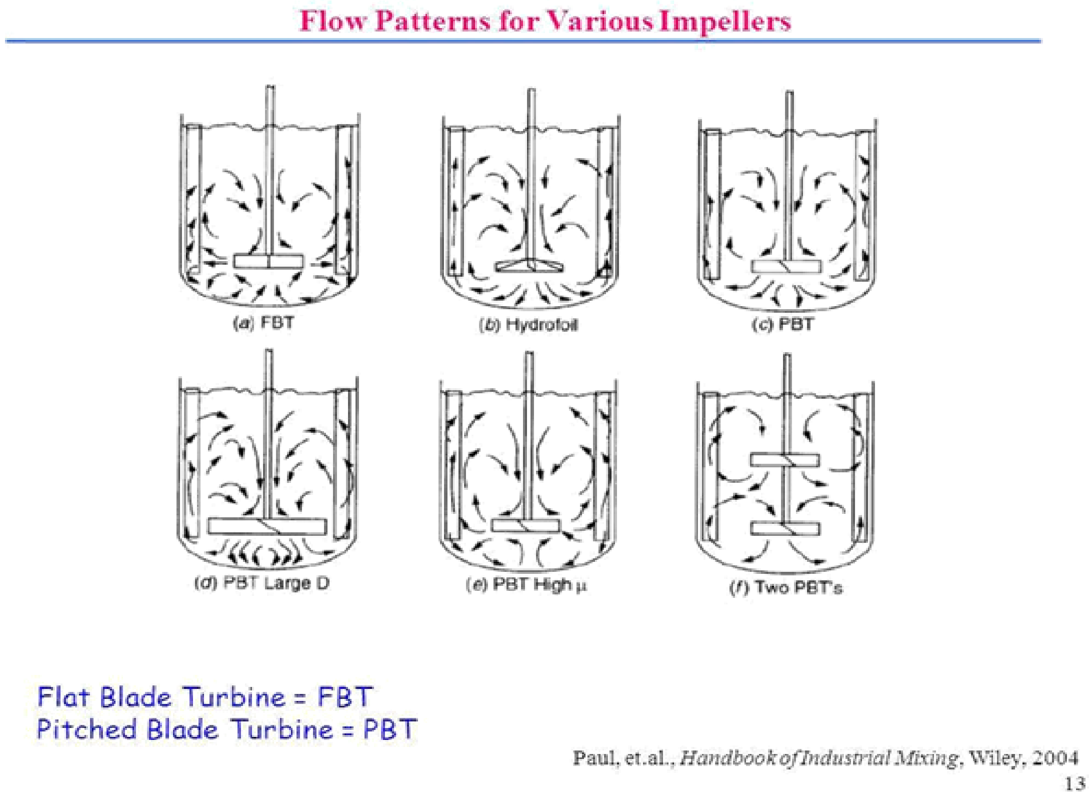


Figure 18 Flow Patterns for Impeller Types

Type: pitched-blade turbine impeller

This is used for both radial and axial blending if the fluid is low-viscous.

Standard impeller properties

Dt = tank diameter =0.0881 m

Da = impeller diameter

Impeller diameter

Da / Dt = 1/3

Da =0.0881/3

Da = 0.0293 m

Liquid Depth

$H/D_t = 1$

H=0.0881m

Impeller blade Width

w/Da=1/5

W = 0.0293/5 = 0.00586 m

Length of impeller

L/Da=1/4

L=0.0293/4 = 0.0073m

Clearance

$E/D_t=1/3$

0.0881/3 = 0.0294m

Parameter	**Value**	**Units**
Height	0.26	m
Internal diameter	0.0881	m
Volume	0.00161	m^3
Total pressure	0.9	Bar
Wall Thickness	1	mm
Operating temperature	110	°C
Impeller Type	Pitch Blade Turbine	Dimensionless
Closure	Torri Spherical	Dimensionless

Table 9 Mixing Vessel Design Description

4.3 Design of Heat Exchanger (E4001A):

4.3.1 Definition:

A heat exchanger is a heat transfer device that is used for transfer of internal thermal energy between two or more fluids available at different temperatures.

In most exchangers the fluids are separated by heat transfer surface and ideally, they don't mix. The word exchanger really applies to all types of equipment in which heat is exchange but is often used specifically to denote equipment in which heat is exchanged between two process fluids such as;

Heaters & coolers:

Exchangers in which process fluid is heated or cooled by a plant service stream are called heaters or coolers.

Vaporizer:

If the process stream is vaporized the exchanger is termed as vaporizer.

Reboiler:

If the stream is essentially completely vaporized, then the exchanger is Reboiler. It is associated with the distillation column.

Evaporator:

For the purpose of concentration of solution, the exchanger is called an evaporator.

Fixed exchanger:

It is used for exchangers heated by combustion gases, such as boilers.

Chiller:

One stream is a process fluid being condensed at sub atmospheric temperature and the other boiling refrigerant or process stream.

4.3.2 Application:

Heat exchangers are used in the process, power, petroleum, transportation, air conditioning, refrigeration, cryogenic, heat recovery, alternate fuels and other industries.

4.3.3 Classification of heat exchangers:

In general, industries heat exchanger classified according to them

- Construction
- Process transfer
- Degree of surface compactness
- Flow arrangement
- Pass arrangement
- Phase of process fluid
- Heat transfer mechanism
- Flow arrangement

Classification in accordance with construction:

In accordance with construction heat exchangers are:

- Plate heat exchanger (gas kited, spiral, plate coil)
- Tubular heat exchanger (double pipe, shell and tube, coiled tube)
- Extended surface exchangers (tube fin, plate fin)
- Regenerator

Classification according to transfer process:

- Direct contact (cooling towers)
- Indirect contact (double pipe, shell and tube, coiled tube)

Classifying in accordance with surface compactness:

A compact heat exchanger has a high-density surface that is the ratio of heat transfer area (A) to its volume (V). The heat transfer volume is the same. It's about $700m^2$ / square meter. They also have higher thermal efficiency (95% vs. 60% to 80% for STHE), which makes them useful especially for energy-intensive industries.

Classifying in accordance with flow arrangement:

The basic flow arrangements in heat exchanger are:

- Parallel flow
- Cross flow
- Counterflow

Depends on the required efficiency of the heat exchanger, fluid flow pathways and the packaging envelope, the permissible thermal stress, the temperature, etc. All these factors decide the type of flow arrangement.

Parallel flow heat exchangers:

In parallel flow heat exchangers, two fluids enter the exchanger at the same end, and travel in parallel to one another to other side.

Counter flow heat exchangers:

In counter flow heat exchangers, which are often more efficient, the fluids enter the exchanger from opposite ends. Countercurrent exchange is a mechanism used to transfer some component of fluid from one flowing current of fluid to another across a permeable barrier between them. It is extensively used in biological systems for a wide variety of purposes.

Cross flow heat exchanger:

In a crossflow heat exchanger, the fluids travel perpendicular to one another.

Classifying in accordance with pass arrangement:

A fluid is thought to have passed if it flows once in its entire length through a section of the heat exchanger. Whether a single pass or multi pass is given, the fluid is reversed in a multi pass system and flows two or more times over the flow volume. Compact shell and tube and plate exchangers are necessary for multi-pass arrangements.

Classifying in accordance with phase of fluid:

Classification is based on the fluid phase of gas + gas, liquid + fluid, gas + liquid, etc.

Classification according to heat transfer mechanism:

The basic heat transfer mechanism employed for heat transfer from one fluid to another is:

- Single phase convection, forced or free
- Two phase convection (condensation or evaporation)
- Combined convection or radiation

4.3.4 Types of heat exchangers

The principal types of heat exchangers used in chemical process and allied industries are as follows:

- Double pipe heat exchangers
- Shell & tube heat exchangers
- Plate & frame heat exchangers
- Plate fin exchangers
- Spiral heat exchangers
- Air cooled: coolers & condensers
- Direct contact: cooling & quenching
- Agitated vessels
- Fired heaters

4.3.5 Selection criteria of heat exchangers

- Cost: want to have the least expensive exchanger
- Efficiency: want a most efficient, minimally energy-loss transmission exchanger and minimum fluid pressure drop
- Space: Want to have a small exchanger
- Material: want a material-compatible exchanger that doesn't take much to build with process streams
- Sustainability: you want an exchanger that is easy to clean

- Easy to construct
- Thermal and hydraulic requirements
- Environmental, health and safety consideration and regulations

4.3.6 Double pipe heat exchangers

Main Parts:

- Two concentric pipes
- Two connector tees (these tees are fitted with dots or squeezed connections that allow annulus fluid entry and exit that crosses through the head back from leg to leg).
- The head back (the annulus fluid crosses the head through the head back from one leg to the other leg.
- Return Bend: the two internal tube lengths are connected by a return bend that is usually exposed and does not efficiently transfer heat.
- Glands: the inner tube is supported by packing glands in the outer tube.

Hair pin:

When two legs of a double pipe exchanger are arranged in U shape, the unit is a hair pin.

Two sets of concentric pipes are the key pieces, two linking teas and a head back and back turn. The inner tube is supported by packaging glands within the other tube and the fluid is pushed into the inner tube via a threaded connection situated outside the exchanger section. The tees are fastened to allow the entrance and exit of the annulus fluid from a leg to another through the rear head. The two inner pipe lengths are connected by a return curve, usually exposed and not providing an efficient surface heat transfer.

Scope & limitation of Double Pipe heat exchanger:

Simplest type has one tube inside another, inner tube may have longitudinal fins on outside

Normal size is 100 to 200 ft^2

Multiple units are often used

Built of carbon steel where possible

Advantages	**Disadvantages**
Easy to obtain counter current flow	Become expensive for large duty
Can handle high pressure	Suitable only for small capacity
Modular Construction	Small amount of heat transfer contained in single hairpin
Easy to maintain and repair	

Table 9 Merits and Demerits of Double Pipe HEX

Fluid allocation:

Locate the fluid on tube side if fluid is

- More corrosive
- Less viscous
- More fouling
- Hotter
- Higher pressure
- High flow rate

4.3.7 Steps for designing heat Exchanger

Hot fluid temperature at inlet = T_1= 110 ^oC=230^oF

Hot fluid temperature at Outlet = T_2= 95 ^oC=203 ^oF

Cold fluid temperature at inlet = t_1= 31 ^oC=88 ^oF

Cold fluid temperature at outlet = t_2= 41 ^oC=106 ^oF

Function:

To cool Sulphuric acid by using water as a Cooling medium.

Fluid allocation:

Inner pipe	Cold fluid	Water
Outer pipe (Annulus)	Hot fluid	H_2SO_4

Material of construction: stainless Steel

Selection of diameters of inner and out pipe:

Inner pipe diameter = ¼ in

Outer pipe diameter = 1 in

Design Steps:

1. Heat Balance:

Mass flow rate of water=?

Mass flow rate of Sulphuric acid=5.82lb/h

Heat capacity of Sulphuric acid=0.32Btu/lb. ^oF

Average temperature of water=t_{avg}=97 ^oF

Average temperature of Sulphuric acid=216.5 ^oF

$Q = WC_p (T_1-T_2)$ (for hot fluid)

Q=5.82*0.32(230-203)

=39.24Btu/h

$Q=wc_p (t_2-t_1)$ (for cold fluid)

39.24=w*0.162(106-88)

w=2.226lb/h

2. Log Mean Temperature Difference:

Hot fluid		Cold fluid		
230	Higher temperature	**106**	**124**	Δt_2
203	Lower temperature	**88**	**115**	Δt_1
				$\Delta t_2-\Delta t_1$

LMTD= $\frac{\Delta t_2-\Delta t_1}{2.3 log log \frac{\Delta t_2}{\Delta t_1}}$

LMTD= 119.57 ^oF

3. Caloric Temperature:

Caloric temperature in this case is same as average temperature.

Tc=216.5 ^oF

tc=97 ^oF

4. Physical properties at Tc and tc

For Inner Pipe	For Annulus
A t tc = 97 °F	A T t c =216 °F
μ = 1.694 lb/ft h	μ = 3.63 lb/ft h
K = 0.356 Btu / (h) (ft^2) (°F/ft)	K = 0.23 Btu / (h) (ft^2) (°F/ft)
C_P= 0.162 Btu /lb °F	C P = 0.32 Btu /lb °F

Table 10 Physical Properties

Hot Fluid Annulus(H_2SO_4)	Cold Fluid Inner Pipe (Water)
5. Flow Area	
D_2=1.049/12=0.087ft D_1=0.54/12=0.045ft	D=0.364/12=0.03ft
$a_0 = \frac{\pi}{4}(D_2^2 - D_1^2)$ =4.35*$10^{-3}$$ft^2$	$a_p = \pi \frac{D^2}{4}$ = 7.065*$10^{-4}$$ft^2$
Equivalent diameter=$De = (D_2^2 - D_1^2) / D_1$ **=**0.1232ft	
6. Mass velocity	

$$G_a = \frac{W}{a_0}$$ =1337.93 lb/ (h)(ft^2)	$$G_P = \frac{w}{a_P}$$ =3151.18 lb/ (h)(ft^2)
7. Reynold Number:	
$$a = \frac{DeG_a}{u}$$ **=**45.33	$$p = \frac{DG_p}{u}$$ =61.33
8. Heat Transfer Factor (from fig): $$j_H = 2.3$$ $\left(\frac{cu}{k}\right)^{1/3}$=12.74	$$j_H = 3.4$$ $$\left(\frac{cu}{k}\right)^{1/3} = 3.87$$
9. Heat transfer coefficient: $$h_0 = j_H \frac{k}{De}\left(\frac{Cu}{k}\right)^{\frac{1}{3}}\left(\frac{u}{\mu_w}\right)^{0.14}$$ =2.3(0.0248/0.1232) (4.386) =2.03Btu/h.ft^2. ^{o}F	$$h_i = j_H \frac{k}{D}\left(\frac{Cu}{k}\right)^{\frac{1}{3}}\left(\frac{u}{\mu_w}\right)^{0.14}$$ =3.4(0.356/0.115) (3.87) =768.18Btu/h.ft^2.^{o}F $h_{i^0} = h_i \times \frac{ID}{0D}$ hi$_0$=517.81 Btu/h.ft^2. ^{o}F

Now proceeding to Annulus

Clean Overall Coefficient:

$U_c = \frac{h_{i^0} h_0}{h_{i^0} + h_0}$

U_c=220.19 Btu/h.ft^2. ^{o}F

10. Design Overall Coefficient, U_D:

$\frac{1}{U_D} + \frac{1}{U_c} + R_d$

R_d=0.01

U_d=68.83 Btu/h.ft^2. ^{o}F

11. Required Surface:

Q = U_D.A.Δt

A= $\frac{Q}{UD.\Delta t}$

A=0.117ft^2

L= 1ft

Pressure Drop Calculations:

Annulus:	**Inner Pipe:**
1. Reynold Number Calculations: De′ for pressure drop differs from De for heat transfer De′=(D_2-D_1) =0.087-0.045 =0.042ft $Re = \frac{DeG_a}{u}$ Re=15.48 f= 0.0035+$\frac{0.264}{15.48\text{^}0.42}$	for Re=61.38 $f = 0.0035 + \frac{0 \cdot 264}{(R_e)^{0.42}}$ =0.0035+$\frac{0.264}{61.38\text{^}0.42}$ =0.05 s=1, ρ=1*62.4=62.4

=0.087 s=1.71, ρ=1.71*62.4=106.75	
2. $\Delta F_p = \frac{4fG_a^2L}{2g\rho^2De}$ $=1.55*10^{-6}$	$\Delta F_p = \frac{4fG_p^2L}{2g\rho^2D}$ $= 2.07*10^{-6}$
3. $v = \frac{G}{3600\rho}$ $= 3.47*10^{-3}$ $F_t = 3\frac{v^2}{2g} = 5.63 * 10^{-7}$ ΔP=2.57 psia	$\Delta P = \frac{2.07\times10^{-6}\times62\cdot4}{0\cdot144}$ $\Delta P = 0.087 psia$

Table 11 Pressure Drop Calculations

Allowable ΔP=10.0 psia

Unit	**HEAT EXCHANGER**
Type	DOUBLE PIPE HEAT EXCHANGER
Function	To cool H_2SO_4
Operation	Continuous
Heat Duty	39.24Btu/h
Heat Transfer Area	$0.117ft^2$
Overall Heat Transfer Coefficient	U_d=68.83 Btu/h.ft^2. ^{o}F

	Annulus Side	**Pipe Side**
Fluid Circulated	Hot Fluid	Cold Fluid
Flow Rates	5.87lb/hr	2.22lb/hr
Temperatures	Inlet=230^oF Outlet=203 ^oF	Inlet=88 ^oF Outlet=106 ^oF
Pressure Drop	2.57psia	0.87psia
Specifications	Diameter D=0.045ft D_e=0.1232ft J_h=2.3	Diameter D=0.03ft J_h=3.4

Table 12 Design Description for Heat Exchanger E-4001A

4.4 Design of Heat Exchanger (E-4001B):

4.4.1 Steps for designing heat Exchanger

Hot fluid temperature at inlet = T_1= 158 ^oC=316^oF

Hot fluid temperature at Outlet = T_2= 150 ^oC=302 ^oF

Cold fluid temperature at inlet = t_1= 25 ^oC=77^oF

Cold fluid temperature at outlet = t_2=95 ^oC=203 ^oF

Function:

To heat a mixture of hydrogen peroxide and sodium chlorate using steam as a heating medium.

Fluid allocation:

Inner pipe	Cold fluid	H_2O_2+$NaClO_3$
Outer pipe (Annulus)	Hot fluid	Steam

Material of construction: stainless Steel

Selection of diameters of inner and out pipe:

Inner pipe diameter = ¼ in

Outer pipe diameter = 1 in

4.4.2 Design Steps:

1. Heat Balance:

Mass flow rate of Cold Stream=6.81lb/h

Mass flow rate of steam=1.1lb/h

Heat capacity of Cold Stream=19.13Btu/lb. ^oF

Average temperature of water=t_{avg}=309 ^oF

Average temperature of sulphuric acid=140^oF

$Q = WC_p (T_1-T_2)$ (for Cold fluid)

Q=6.81*19.13(203-77)

=342.09Btu/h

$Q=wc_p (t_2-t_1)$ (for cold fluid)

w=1.1lb/h

2. Log Mean Temperature Difference:

Hot fluid		**Cold fluid**		
316	Higher temperature	**203**	**225**	Δt_2
302	Lower temperature	**77**	**113**	Δt_1
				$\Delta t_2 - \Delta t_1$

$$LMTD = \frac{\Delta t_2 - \Delta t_1}{2.3 \log(\Delta t_2/\Delta t_1)}$$

LMTD= 162 °F

3. Caloric Temperature:

Caloric temperature in this case is same as average temperature.

T_c=309°F, t_c=140 °F

4. Physical properties at T_c and t_c

For Inner Pipe	**For Annulus**
At t_c = 140°F	At T_c = 309 °F
μ = 3.01 lb/ft h	μ = 1.693 lb/ft h
K = 0.68 Btu / (h) (ft^2) (°F/ft)	K = 0.0248 Btu / (h) (ft^2) (°F/ft)
c_p = 19.13 Btu /lb °F	c_P = 0.44 Btu /lb °F

Hot Fluid Annulus (Steam)	**Cold Fluid Inner Pipe (H_2O_2+$NaClO_3$)**
5. Flow Area	
D_2=1.049/12=0.087ft D_1=0.54/12=0.045ft	D=0.364/12=0.03ft
$a_0 = \frac{\pi}{4}(D_2^2 - D_1^2)$ =4.35*10^{-3}ft^2	$a_p = \pi \frac{D^2}{4}$ = 7.065*10^{-4}ft^2
Equivalent diameter=$De = (D_2^2 - D_1^2) / D_1$ =0.1232ft	
6. Mass velocity	
$G_a = \frac{W}{a_0}$ =1565.52 lb/ (h)(ft^2)	$G_P = \frac{w}{a_P}$ =1556.9 lb/ (h)(ft^2)
7. Reynold Number:	
$a = \frac{DeG_a}{u}$ =113.78	$p = \frac{DG_p}{u}$ =15.56
8. Heat Transfer Factor (from fig): $j_H = 2.3$ $\left(\frac{cu}{k}\right)^{1/3}$=1.1	$j_H = 1.1$ $\left(\frac{cu}{k}\right)^{1/3} = 4.386$
9. Heat-transfer coefficient: $h_0 = j_H \frac{k}{De}\left(\frac{Cu}{k}\right)^{\frac{1}{3}}\left(\frac{u}{\mu_w}\right)^{0.14}$ =2.3(0.0248/0.1232) (4.386) =2.03Btu/h.ft^2. ^{o}F	$h_i = j_H \frac{k}{D}\left(\frac{Cu}{k}\right)^{\frac{1}{3}}\left(\frac{u}{\mu_w}\right)^{0.14}$ =77.54Btu/h.ft^2.^{o}F hi_0=51.32Btu/h.ft^2. ^{o}F

Table 13 Physical Properties

Now proceed to Annulus

10. Clean Overall Coefficient:

$U_c = \frac{h_{i0} h_0}{h_{i0}+h_0}$

U_c=2.64 Btu/h.ft^2. ^{o}F

11. Design Overall Coefficient, U_D:

$\frac{1}{U_D} + \frac{1}{U_c} + R_d$

R_d=0.002

U_D=2.62 Btu/h.ft^2. ^{o}F

12. Required Surface:

$Q = U_D.A.\Delta t$

A= $\frac{Q}{\text{UD}.\Delta t}$

A=0.8ft^2

L= 1ft

Annulus:	**Inner Pipe**
1. Reynold Number Calculations: De′ for pressure drop differs from De for heat transfer De′=(D_2-D_1) =0.087-0.045 =0.042ft $$Re = \frac{DeG_a}{u}$$ Re=60.48	for Re=15.569 $$f = 0.0035 + \frac{0 \cdot 264}{(R_e)^{0.42}}$$ =0.0035+$\frac{0.264}{61.38\text{^}0.42}$ =0.05 s=1, ρ=1*62.4=62.4

f= 0.0035+$\frac{0.264}{15.48\hat{}0.42}$ =0.087 s=1.71, ρ=1.71*62.4=106.75	
2. $\Delta F_p = \frac{4fG_a^2L}{2g\rho^2De}$ $=1.55*10^{-6}$	$\Delta F_p = \frac{4fG_p^2L}{2g\rho^2D}$ $= 2.07*10^{-6}$
3. $v = \frac{G}{3600\rho}$ $= 3.47*10^{-3}$ $F_t = 3\frac{v^2}{2g} = 5.63 * 10^{-7}$ ΔP=2.87 psia	$\Delta P = \frac{2.07\times10^{-6}\times62\cdot4}{0\cdot144}$ $\Delta P = 1.29psia$

Table 14 Pressure Drop Calculations

Allowable ΔP=10.0 psia

Unit	**HEAT EXCHANGER**
Type	DOUBLE PIPE HEAT EXCHANGER
Function	To heat H_2O_2+$NaClO_3$
Operation	Continuous
Heat Duty	342.09Btu/h
Heat Transfer Area	$0.8ft^2$
Overall Heat Transfer Coefficient	U_D=2.62 Btu/h.ft^2. ^oF

	Annulus Side	**Pipe Side**
Fluid Circulated	Hot Fluid	Cold Fluid
Flow Rates	1.1lb/h	6.81lb/h
Temperatures	Inlet=316 °F Outlet=302 °F	Inlet=77 °F Outlet=203 °F
Pressure Drop	2.87psia	1.29psia
Specifications	Diameter D=0.045ft D_e=0.1232ft J_h=2.3	Diameter D=0.03ft J_h=1.1

Table 15 Design Description for Heat Exchanger E-4001B

4.5 Design of Separator:

This vertical separator has efficiency of 90%.

The settling velocity is given by:

$$U_s = 0.015\left[\frac{\rho_L - \rho_g}{\rho_g}\right]^{\frac{1}{2}}$$

μ_s=0.35m/s

Now, diameter for vertical separator is calculated by using this formula:

V = 3 /4 x D^2L………………….. (1)

Where V is 2.4m^3.

D= internal diameter

L=height or length

Suppose , L=3D or L/D=3 putting values of L in (1)

$V=\pi/4*D^2(3D)$

D=1m

L=3m

Pressure Drop:

$\Delta P = 0.5\ \rho_m v^2_{m,\, in} + 0.22\ \rho_g v^2_{g,\, out}$

ΔP=0.02 bar

Nozzles:

If the vessel diameter is less than 0.5 m, the feed nozzle should be fitted with a half-open pipe inlet device, with the opening directed downwards. For vessel diameters of 0.5 m and larger and inlet nozzle sizes of 0.15 m and larger, a Schoepentoeter inlet device is recommended.

4.6 Design of Cooling Tower:

Cooling tower design calculations are used to calculate the ground area, tower height, air loading, length of water distribution pipes etc.

Ground area of cooling tower is calculated by the ratio of water flow rate to water loading

$$Ground\ area = \ water\ flow\ rate/water\ loading$$

Water loading = 2000 $kg/h*m^2$

Water flow rate = $2.25*10^7$ kg/h

Ground area = 1045.19 m^2

Air loading is the flow of air on the specific area. Air loading is very important for the transfer of heat the more the air loading the more will be the transfer of heat. Air loading depends on the fan capacity, tower area and density of air and water.

$$Air\ Loading = (Fan\ capacity/Tower\ area\ ) * density\ (air + water)$$

Fan capacity = 1000m3/h

Density of (water + air) = 1001.25 kg/m3

Air loading = 2633.13 kg/h*m^2

Velocity of water is calculated by the ratio of volume of water to the area of pipe

Volume of water = 22500 m3/h

Diameter of pipe = 0.3 m

Area of pipe = 0.07m2

Velocity of water = 89.28 m/sec

Length of the pipe required for the water distribution in cooling tower is calculated by the following formula

$$Q = 2 * 3.14 * K * L * (T2 - T1)/log(r0/ri)$$

The material used for piping is FRP

K = 40 W/m.^{o}C

r_o = 0.187 m

r_i = 0.0762 m

Log (r_o/r_i) = 0.038

Length of pipe = 6 m

Number of turns required depend upon the distance between 2 pipes

Pitch = 0.4 m

Height of tower = 2 m

Number of turns = 5

The efficiency of cooling tower is calculated by following formula

$$Efficiency = range\ /range + approach$$

Hence the efficiency is **71%**

CHAPTER 5

PROCESS MODELLING & SIMULATION

5.1 Selection of Components

The components were selected from the HYSYS library and some of them were added manually as hypothetical components using their boiling point ranges and densities.

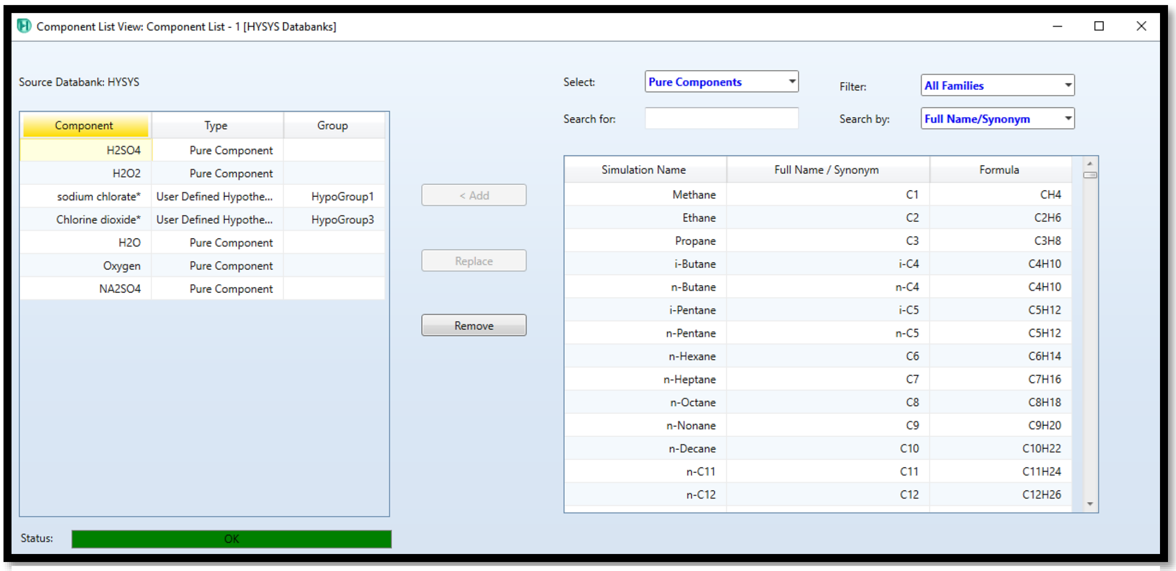


Figure 22 Selection of Components in Aspen HYSYS

5.2 Selection of Fluid Package

The fluid package was selected to be **NRTL,** on the basis of compatibility with the selection of components as well as the pressure ranges were less than 10 bar. The HYSYS method assistant was also used and the final selection was done.

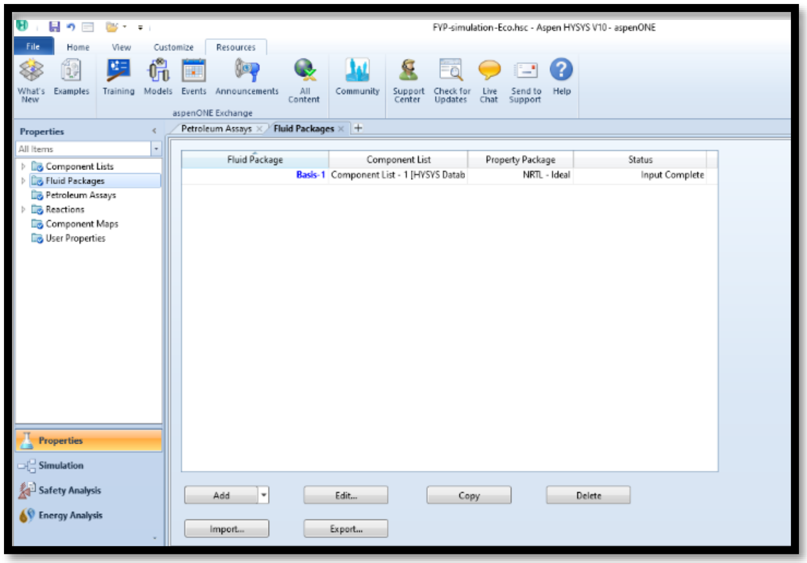


Figure 23 Selection of Fluid Package in Aspen HYSYS

5.3 Defining the Kinetic Reaction Set

A kinetic reaction set was added on the basis of the reaction data obtained from the literature.

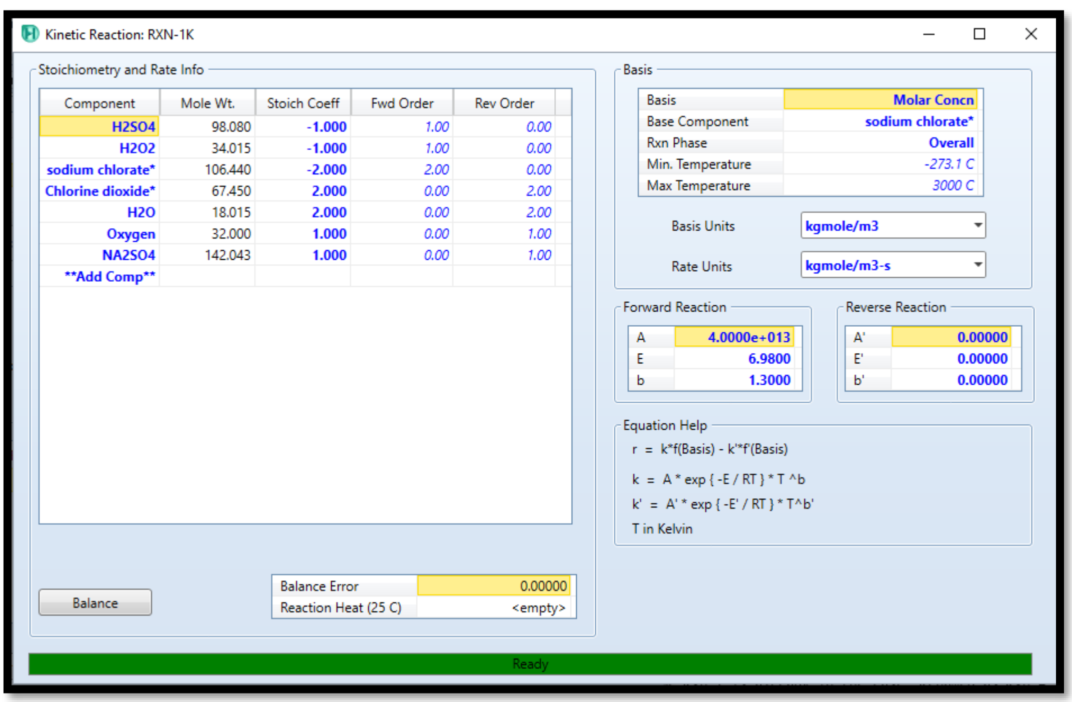


Figure 24 Defining the Kinetic Reaction Set in Aspen HYSYS

5.4 Process Flowsheet Modelling and Simulation

The process flow diagram was replicated as the flowsheet on Aspen HYSYS as shown by the snippet. The molar flows were the same as that of our manual calculations. The temperature and pressure parameters were also defined according to the requirements and then the simulation was run to obtain the final composition of the Chlorine Dioxide stream from the separator.

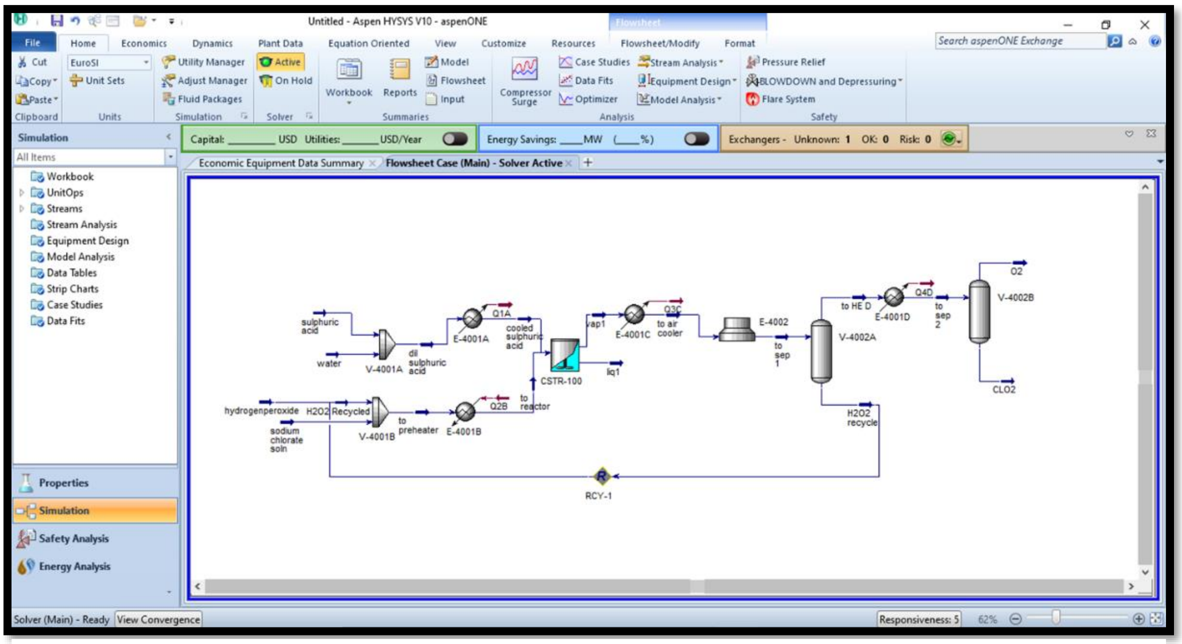
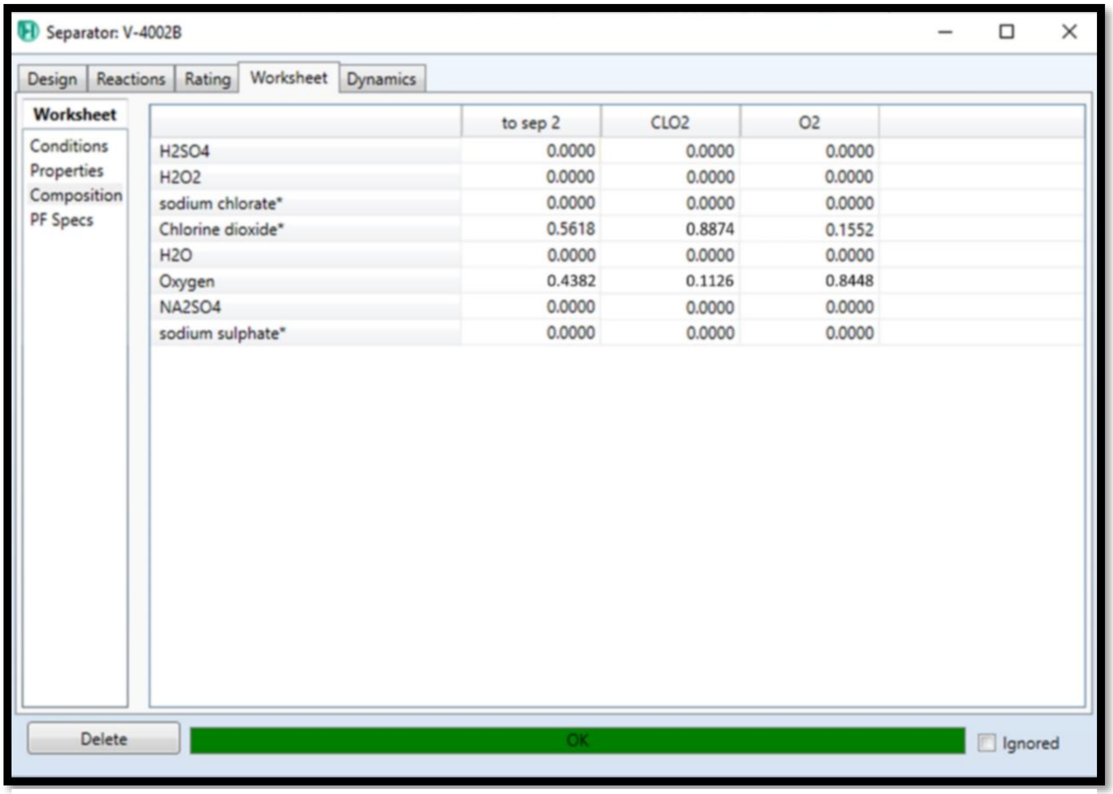


Figure 25 Process Flowsheet in Aspen HYSYS

5.5 Results

After the successful simulation of the model, the results were obtained that were close to our theoretical calculations. The final separator shows a recovery of chlorine dioxide up to a percentage mole fraction of 88.7%



	to sep 2	CLO2	O2
H2SO4	0.0000	0.0000	0.0000
H2O2	0.0000	0.0000	0.0000
sodium chlorate*	0.0000	0.0000	0.0000
Chlorine dioxide*	0.5618	0.8874	0.1552
H2O	0.0000	0.0000	0.0000
Oxygen	0.4382	0.1126	0.8448
NA2SO4	0.0000	0.0000	0.0000
sodium sulphate*	0.0000	0.0000	0.0000

Figure 26 Worksheet of the second Separator

CHAPTER 6

INSTRUMENTATION

6.1 Introduction:

Instrumentation and Process Control play a key-role in the smooth functioning of a process plant. Instrumentation utilizes the hardware components that are also known as controllers to maintain and regulate the various variables that are essential for the process. To provide control and monitoring of our process, we have included the instrumentation and process control in our project. This is done by applying controls on major equipment, including the cooling tower, reactor, mixing vessels and the heat exchangers.

6.2 Requirements of control:

Control system must meet the following requirements and objectives during operation of chemical plant:

6.2.2 Safety:

The safe operation is very crucial for the well-being of the personnel working at the processing plant. The operating factors should not breach the safety limits, i.e. the concentration, temperature and the pressure limits should not be breached.

6.2.3 Product specification:

Some appropriate instrumentation is being used to achieve desired product quality and quantity. This is essential to have a work system that adds stability to the process .

6.2.4 Environmental Regulation:

There are standards for the safe limits for factors like concentration, pressure and temperature of the exhaust and purge releases from a typical industrial plant.

The conditions for the work also need to lie within the less cost and more benefit to the society limit. These standards are consistently maintained by the plants and the law and regulatory authorities keep a regular check and balance on the industrial plants for it. These standards are met to fulfil the objectives of an organization related to the achievement of their operational and development goals.

For the most part, a control framework fulfills the accompanying:

- Reducing the effect of external deviations
- Keeping the plant in a stable working environment
- Optimization of a chemical process

6.3 Control Parameters

There are variables that play a key role in controlling and regulating a process, these are defined as;

6.3.1 Manipulated variables:

The inputs given to the controller to control the desired part of the process are known as the manipulated variables. For example, in changing the opening of a valve to control the flow through a pipe, the valve opening is the manipulated variable.

6.3.2 Uncontrolled variables:

Some the variables are unable to be controlled by using the controllers and these variables are known as uncontrolled variables.

6.3.3 Controlled Variables:

These are the process conditions that the user decides to regulate using the controllers. For example; in the example of regulating the flow through a pipe by changing the valve opening, flow is the controlled variable.

6.4 Summary of the Defined Controllers

The controllers were defined on the basis of Proportional-Integral type, on the major equipment to monitor and control the fluid flows effectively. A number of level and flow controllers are required to be installed to maintain the liquid level in important equipment like the mixing vessels and the reactor.

The table below represents the summary of the controllers defined throughout our process flow diagram.

Equipment	Name of Controller	Type of Controller	Manipulated Variable	Controlled Variable
Mixing Vessels	LC	PI	Flowrate	Liquid Level
Heat Exchangers	TC	PI	Steam/CW Flowrate	Temperature
Reactor	FC	PI	Valve opening	Product Output
	LC	PI	Flowrate	Product Level
Separators	FC	PI	Valve opening	Product Flowrate
	LC	PI	Flowrate	Product Level
Cooling Tower	LC	PI	Flow of Make-up Water	Level of CW in Basin
	PC	PI	Flowrate	Pressure
	TC	PI	Flowrate of Return Header	Temperature of Water
	TC	PI	Flowrate of Supply Header	Temperature of Water
	FC	PI	Valve opening	Make-up line flowrate
	FC	PI	Valve opening	Blow-down line flowrate

Table 16 Instrumentation Summary

CHAPTER 7

COST ESTIMATION AND ANALYSIS

7.1 Mixing Vessels

The cost for the agitated mixing vessel made up stainless-steel with a volume of 2.5 m^3 is calculated by using Coulson and Richardson volume 6, and is then adjusted for inflation in 2020.

$2900 x $(2.5)^{0.6}$ = $5025

For two identical vessels;

Cost = $5025 x 2 = $10050

7.2 Heat Exchangers

The heat exchangers designed have a very small heat transfer surface that is relatively very less when compared to the standards available in the market. Thus, for one custom ordered concentric double pipe heat exchanger made up of stainless steel, the market price is estimated to be $550.

For four customized ordered Heat Exchangers;

Cost = $550 x 4 = $2200

7.3 Vertical Separators

The cost for the vertical separator made up of stainless-steel with a volume of 2.4 m^3 is calculated by using Coulson and Richardson volume 6, and is then adjusted for inflation in 2020.

$2400 x (2.4)0.6 = $4056

For two vertical separators;

Cost = $4056 x 2 = $8112

7.4 Continuous Stirred Tank Reactor

The cost is calculated by using Coulson and Richardson volume 6, and is then adjusted for inflation in 2020.

Cost = $15000 x (4.2)0.4 = $26625

7.5 Other Equipment

7.5.1 Air Cooler

The air cooler is also custom ordered from the market according to the required specifications, the cost is estimated by taking quotations available on the internet.

Cost = $2100

7.5.2 Storage Tank

The cost for the storage tank made up of stainless-steel having a capacity of 50 m^3 is calculated by using Coulson and Richardson volume 6, and is then adjusted for inflation in 2020.

Cost = $2300 x (50)0.55 = $19780

7.5.3 ClO_2 Dosing Pump

For a pump with a flowrate of 3.52 gpm, the cost is calculated by using Coulson and Richardson volume 6, and is then adjusted for inflation in 2020.

Cost = $2100

7.6 Raw Materials

The cost for the raw materials to be used is calculated by multiplying the mass flow required with price of the materials per metric tonne available in the market. The price estimates have been taken from the internet. The costs for each material and the total cost are shown by the table. The total cost of raw materials per annum is estimated to be $12810.

Table 17 Calculation of the Raw Materials Costs

Materials	Mass Flow$_{kg/h}$	Price$_{per\ MT}$	Cost$_{per\ annum}$
Sodium Chlorate	2.567	$700	$11243
Demineralized Water	0.098	$5.0	$5.0
98% Sulphuric Acid	2.065	$40.3	$729
Hydrogen Peroxide	0.785	$121.1	$833

∑ = $12810

7.7 Summary of the Expenses

The cost of the equipment totals up to a value of $70667, that is the fixed capital for the project, the raw material cost is added to this value and the total investment is $83500. As the project is a retrofit, the additional costing factors are omitted. The table below represents the cost breakdown.

Equipment	Cost
Mixing Vessels	$10,050
Heat Exchangers	$2,200
Air Cooler	$2100
Reactor	$26,625
Separators	$8,112
Pump	$1,800
Storage Tank	$19,780
Fixed Capital	$70,667
Working Capital	$12,810
Total Investment	**$83,500**

Table 18 Summary of the expenses

7.8 Payout Period

By the addition of Chlorine Dioxide, the Cycle of Concentration increases by 0.5,

$B = E / (COC-1)$

Where, E = Evaporative Loss = 180 m^3/h & COC = 4.5

Blow-down with ClO_2 = 51.42 m^3/h

The blow-down is reduced by 8.58 m^3/h & this cost is saved;

Price of Make-up water = $0.36/$m^3$

Cost of Make-up Water Saved Annually;

Cost Saved = $0.3632/$m^3$ x 8.58 m^3/h x 24 h x 365 days = $27300

Total Investment = $83500

Thus,

Payout Period = $83500/$27300/year

Payout Period = 3.06 years

CHAPTER 8

HAZOP ANALYSIS

HAZOP is a risk management method that is used to foresee the potential threats and operational hazards that might be present in the system, to eliminate these threats and ensure the proper safety of working personnel present on the plant and the surroundings. Just like in every industry involving processes and safety concerns, we performed HAZOP analysis on a few of our key important equipment.

This type of analysis is basically performed in a typical two types of methods and these are Qualitative and Quantitative risk analysis. Qualitative is basically a prerequisite type of analysis whereas most industries usually adopt the Quantitative approach of analysis for better and thorough analysis of any situation. Both of these methods of analysis require different methods and require special types of people that are suited for this job to perform such tasks because it is a very risky analysis. There are a bunch of guide words for the type of deviations that can happen and as well as what are the causes, the direct consequences of the deviation and finally what action to take if a particular deviation occurs

HAZOP basically is finding out how a certain equipment or a process might deviate from what it was originally designed for, what are the possible scenarios, how to identify the problem even before there is a problem. It is basically finding out that everything is going just fine and probably identify certain issues that might cause some major problems in the future if the problem is not addressed at the right time.
HAZOP can be summarized and understood by the following points:

- Try to identify possible issues in equipment/processes.
- Identify operation and design from an ideal working map.
- See how the problem can be prevented in order ro reduce any type of risk that might involve it.
- Make the process more optimized to further

8.1 HAZOP on the CT

Intention: for the cooling of water for industry process requirements.

Guide Word	Deviation	Causes	Consequences	Action
More	More Chlorides > 300ppm	High cycles of concentration	Corrosive to most metals	Open CBD@100 m3/h or more if possible
	More pH>8.5	Evaporation of water	Scale formation	Shock dose extra 40 kg Bulab7041 (Polymer).
	More suspended solids > 20ppm	Water evaporates leaving behind dissolved or suspended solids	Blockage or corrosion to the cooling water system	Shock dose extra 40 kg bio-dispersant Bulab8006.
Less	Less pH b/w 5.0-6.0	High acid concentration	Corrosive to most metals	Stop acid dosing and isolate leaked exchanger. Maintain Molybdate b/w 4-5 ppm and zinc b/w 2-3 ppm for three days.

Table 19 HAZOP on the Cooling Tower

8.2 HAZOP on the Reactor

Intention: Main reaction occurs

Guide Word	Deviation	Causes	Consequences	Actions
More	Temperature of inlet increases	Cooler have not done proper cooling	Will affect vessel temperature and ultimately the reaction	Find rise in temperature and then using control module. Try to lower flow rate of stream through cooler
Less	Temperature of the reaction vessel has decreased	Flow of the stream has decreased from a certain point	Reaction not taking place as desired	Use flow control valve to fix the flow rate of stream
Less	Flow rate of inlet stream decreased	Formation of dirt in the pipes	Not proper reaction taking place	Clean the pipe after some time
Part of	Reaction conversion not achieved as desired	Agitation might not be good	Less product formation	Uses controller to fix the revolving speed of agitator

Table 20 HAZOP on the Reactor

8.3 HAZOP on the Heat Exchangers

Intention: To bring about the required change in temperature for the respective process

Guide Word	Deviation	Causes	Consequences	Action
None	No cooling water flow	Failure of inlet cooling water valve to open	Process fluid temperature is not lowered accordingly	Install Temperature indicator before and after the process fluid
More	More cooling water flow	Failure of inlet cooling water valve to close	Output of Process fluid temperature too low	Install Temperature indicator before and after the process fluid line.
Less	Less cooling water flow	Pipe leakage	Process fluid temperature too low	Installation of flow meter
More of	More pressure on tube side	Failure of process fluid valve	Bursting of tube	Install high pressure alarm
Reverse	Reverse process fluid flow	Failure of process fluid inlet valve	Product off set	Install check valve
Contamination	Process flow contamination	Contamination in cooling water	Outlet temperature too low	Proper maintenance and operator alert
Corrosion	Corrosion of Pipe	Hardness of cooling water	Less cooling and crack of Pipe	Proper maintenance

Table 21 HAZOP on the Heat Exchangers

CONCLUSION

After the completion of the project, we were able to achieve our desired objectives. Following points briefly conclude our project.

- ✓ Design of a Chlorine Dioxide Production & Dosing Facility
- ✓ Simulation of the Process on Aspen HYSYS
- ✓ Reduction in Cooling Tower Blow-down by 8.58 m^3/h
- ✓ Cost Saving per Annum up to $27300
- ✓ Controlled limit of the Chloride ions in Cooling Water
- ✓ Water Saved per Annum up to 75000 m^3

Our project is in line with the sustainable development goals by the United Nations which are:

- Climate Action
- Work Growth & Decent Economics
- Innovation, Industry & Infrastructure
- Responsible Production & Consumption

We were not only blessed enough to meet the desired needs of the plant but also enough to save water which will have a direct impact on the environment in a positive way.

REFERENCES

[1] Perry, R. H. (n.d.). Perry's Chemical Engineers' Handbook. McGraw-Hill Company.

[2] Z. Mingxin, H. Hui, D. Xian, S. Lina and X. Yanhua, "Kinetics and Mechanism Study on Chlorine Dioxide Generation with Hydrogen Peroxide," 2011 International Conference on Computer Distributed Control and Intelligent Environmental Monitoring, Changsha, 2011, pp. 2457-2461, doi: 10.1109/CDCIEM.2011.425.

[3] RK Sinnott, Chemical Engineering Design, Richardson and Coulson, Volume 6

[4] McCabe, Smith. Unit Operations of Chemical Engineering.

[5] McGraw Hill. Process heat transfer.

[6] Coulson, Richardson's. Chemical Engineering Design 2005.

[7] Branan, Carl. Rules of Thumb for Chemical Engineers: A Manual of Quick.

[8] David Mautner Himmelblau. Basic Principles and Calculations in Chemical Engineering.

[9] Herbert W. Stanford. HVAC Water Chillers and Cooling Towers.

[10] G. B. Hill, E. J. Pring and Peter D. Osborn. Cooling Towers. Principles and Practice.

[11] Kevin M. Dunn. Caveman Chemistry.

[12] James R. Couper, James R. Fair, and W. Roy Penney. Chemical Process Equipment: Selection and Design

[13] NPTEL "Introduction to Mass transfer operation- Module 1-6".

[14] Roland Stull University of British Columbia, Vancouver, British Columbia, Canada. Journal "Wet-Bulb Temperature from Relative Humidity and Air Temperature".