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PLANT DESIGN PROJECT

INTERIM REPORT

PROJECT TITLE: PRODUCTION OF 600 TONNES ASCORBIC ACID PER ANNUM

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CHAPTER 1

INTRODUCTION

1.1 CHEMICAL PRODUCT BACKGROUND

1.1.1 INTRODUCTION OF PRODUCT

Ascorbic acid is produced from various raw materials using different methods. The raw materials used in the production of ascorbic acid include corn, wheat, molasses, d-sorbitol, and glucose powder. Sorbitol is a sugar alcohol that can be obtained from various feedstocks such as corn, cassava, and wheat. Pre-treatment is required to extract glucose from corn, molasses, and wheat for the conversion of glucose into d-sorbitol. The common raw materials used in the production of ascorbic acid in Malaysia is sorbitol that is less costly compared to others (Igbo et al., 2021). The cost of raw materials is low, and the manufacturing process is highly profitable. There are a few steps to form the raw material which is D-sorbitol feedstock from the plant.

For example, the production of sorbitol from corn involves the hydrolysis of corn starch to glucose, which is then hydrogenated to sorbitol using a nickel alloy catalyst. Both batch and continuous catalytic hydrogenation processes are employed. Corn sugar is the most common source of glucose, but hydrolyzed starch may also be used. The catalyst is nickel on diatomaceous earth. The reaction is run at 140°C and 125 atmospheres. Sorbitol solution is purified by ion-exchange resins and filtered through a bed of activated carbon. Sorbitol is sold as a 70% solution, and as a crystallized product in both powder and pellet form.

Moreover, ascorbic acid is a water-soluble vitamin that can be purchased as a dietary supplement and is present in citrus fruits and other fruits and vegetables. It is a weak sugar acid that shares structural similarities with glucose and is essential for numerous biological processes, such as the synthesis of hormones, neurotransmitters, and collagen. Ascorbic acid is a potent antioxidant and reducing agent that can quickly be resistant to several reactive oxygen species (ROS) (Yimcharoen et al., 2019). Because of its antioxidative qualities, industrially produced L-ascorbic acid is widely used as a nutritional supplement and preservative in the feed, food, and pharmaceutical industries.

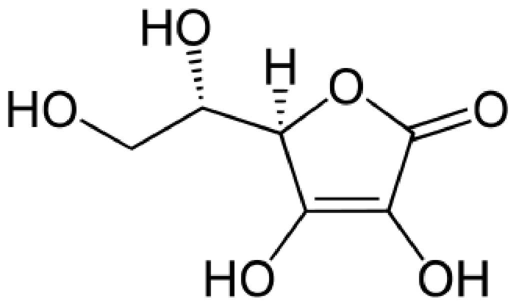


Figure 1.1 Structure of L-Ascorbic Acid (Nermin, 2018).

L-ascorbic acid is generally known as vitamin C, but it also goes by many other chemical names, including ascorbate and antiscorbutic vitamin. The asymmetric six-carbon atoms ($C_6H_8O_6$) that make up the ascorbic acid molecule share structural similarities with glucose. Ascorbic acid's molecular weight is 176 kg/kmol, its melting point (after decomposition) is between 190 to 192°C, and its density is roughly 1.65 g/cm^3. At 20°C, ascorbic acid dissolves readily in water (300 g/L), but it is difficult to dissolve in alcohol (20 g/L), and it is insoluble in benzene, ether, and chloroform. Ascorbic acid is an unstable organic acid with a weak chemical structure that is soluble in water. It is easily oxidized or destroyed by light, oxygen, high temperatures, alkali, humidity, copper, and heavy metals (Nermin, 2018). Ascorbic acid is usually found in the form of white or slightly yellowish crystalline powder. Its crystalline form is chemically stable in dryness.

1.1.2 CURRENT APPLICATION

Currently, ascorbic acid plays vital roles across various fields owing to its multifunctionality. Ascorbic acid is beneficial in food and beverage processing industry, pharmaceutical industry, cosmetic industry, agriculture industry and industry synthesis. Table 1 illustrates diverse products and their respective examples across various applications.

Table 1.1 Current application of Ascorbic acid

Application	Used of product	Example	Reference
Food and Beverage Industry	• as a preservative, antioxidant, and flavor enhancer. • helps to enhance the color, flavor, and texture of food products.	added to various products, including fruit juices, jams, jellies, and canned foods, to prevent oxidation and maintain the freshness of the product.	Bauernfeind (1982)
Pharmaceutical Industry	• as a therapeutic agent for the treatment of various health conditions. • enhance the absorption of iron in the body and to boost the immune system	Scurvy disease caused by vitamin C deficiency can be treated using ascorbic acid that is available in various forms such as tablets, capsules and powders.	Pappenberger and Hohmann (2014); Walingo (2005)
Cosmetic Industry	• as an antioxidant and skin-lightening agent • to protect the skin from oxidative damage and to	Used in various skincare products, including creams, lotions, and serums.	Ravetti et al. (2019)

	improve the skin's texture and tone		
Agriculture Industry	• as a plant growth regulator and a preservative	Used in various plant products, including fruits, vegetables, and flowers, to prevent oxidation and to prolong their shelf life, helps to enhance the color, flavor, and texture of plant product	Hancock and Viola (2005)
Industrial Synthesis	• as a reducing agent and a stabilizer to improve their properties and to prolong their shelf life	used in the industrial synthesis of various products, including plastics, resins, and adhesives	Pappenberger and Hohmann (2014); Maraveas et al. (2021)

1.1.3 PHYSICAL AND CHEMICAL PROPERTIES OF CHEMICAL PRODUCT

The physical and chemical properties data of ascorbic acid is shown in Table 2 which is obtained from Material Safety Data Sheet (MSDS) as attached in **Appendix A**.

Table 1.2 Physical and Chemical Properties of Ascorbic acid

Substance	Ascorbic acid
Physical state and appearance	crystals or powder
Odor	odourless
Taste	acidic
Molecular weight (g/mol)	176.12
Density (g/cm^3)	1.65
Colour	white to pale yellow
Boiling Point (°C)	553
Melting Point (°C)	190
Critical Temp. (°C)	509.85
Critical Pressure (MPa)	52.2
Specific gravity	1.65
Specific heat capacity (J/gmol. K)	305.4
Standard enthalpy of formation at 298K (kJ/mol)	-1164.6
Flammability	non-flammable
Solubility in organic compounds	soluble: 0.02 g/mL - methanol, propanol
Solubility in water (g/L)	3300
Toxicity	non-toxic

1.2 MARKET SURVEY

1.2.1 DEMANDS IN LOCAL AND WORLWIDE

The global market survey for ascorbic acid reveals a dynamic landscape with significant growth potential. According to a recent article, the global vitamin C market was valued at USD 2 billion in 2022, and it is projected to reach approximately USD 3.56 billion by 2032, with a compound annual growth rate (CAGR) of 6% from 2023 to 2032. The Chinese market plays a crucial role, contributing 94% of the vitamin C generated globally. The food and beverages industry holds the largest market share at 60% in 2022, with pharmaceuticals and animal feed accounting for 20% and 7.2%, respectively (*Vitamin C Market Size to Hit Around USD 3.56 Billion by 2032*, n.d.).

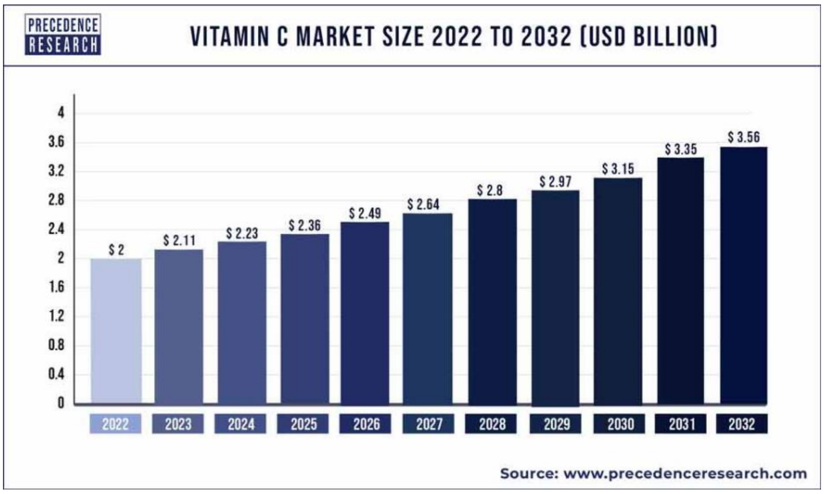


Figure 1.1 Vitamin C market size 2022 to 2023 (USD Billion) (*Vitamin C Market Size to Hit Around USD 3.56 Billion by 2032*, n.d.).

In response to the prevailing Covid-19 pandemic and an increasing awareness of health concerns, Malaysians are demonstrating a heightened sense of health consciousness, leading to a substantial surge in health supplement consumption. The local market has witnessed are markable growth, with 71% of Malaysians becoming supplement consumers in 2021. This trend has significantly impacted the health supplements market in Malaysia, experiencing a noteworthy increase of about 50% from RM 2.07 billion in 2014 to RM 3.1 billion in 2019 (*Is Health Supplement Consumption on the Rise in Malaysia?* n.d.). Shedding light on consumer habits and preferences, a comprehensive survey conducted by Vodus in August 2021, involving over 9000 Malaysians, has unearthed valuable insights.

1.2.2 CURRENT SUPPLY AND COMPETITORS

Royal DSM, CSPC Pharmaceutical Group, and Hoventa Pharma are key players in the ascorbic acid sector. Royal DSM, headquartered in the Netherlands, stands out with its impressive annual production capacity of 15,000 metric tons, making it a global leader known for its high-quality and innovative solutions across various sectors including food and beverage, nutrition, health, and sustainable living. Meanwhile, CSPC Pharmaceutical Group, a prominent Chinese pharmaceutical company, boasts a substantial production capacity of 10,000 metric tons annually for ascorbic acid, enjoying a strong reputation for quality and innovation both domestically and internationally. Hoventa Pharma, also based in China, specializes in vitamins and nutritional supplements, although with a smaller production capacity of 5,000 metric tons per year for ascorbic acid (*Ascorbic Acid API Manufacturers*, n.d.).

The future of the ascorbic acid market appears promising, driven by evolving regulatory landscapes worldwide and a growing demand for natural variants. Factors fueling this growth include an increasing preference for food-grade ascorbic acid, heightened awareness of its health benefits, and the surging consumption of packaged and processed foods. Nonetheless, challenges such as high production costs, raw material scarcity, and stringent regulatory standards remain significant hurdles for industry players to overcome. In summary, the ascorbic acid industry presents a vibrant and competitive landscape, characterized by a multitude of suppliers and manufacturers offering diverse products and solutions. While poised for growth in the coming years due to increasing demand and awareness, the sector must navigate challenges to sustain its momentum and meet evolving market dynamics.

1.2.3 MARKET PRICE OF PRODUCT

According to the DOLCHEM titled "Ascorbic Acid (Vitamin C) Market Overview Q1 2021," the current market price of ascorbic acid ranges from $7 to $8 per kilogram. This range represents a decrease from the peak price of $9.5 per kilogram observed in January 2021, although it remains higher than the price of $8 per kilogram reported in November 2020. Various factors contribute to the fluctuation in ascorbic acid prices, including the cost of raw materials, exchange rates, and overall market demand dynamics (*Ascorbic Acid (Vitamin C) Market Overview Q1 2021*, 2021).

The demand for ascorbic acid is anticipated to continue its upward trajectory, propelled by several factors. Notably, the increasing preference for food-grade ascorbic acid and the growing recognition of its health benefits are driving this trend. Consumers are increasingly seeking out products enriched with ascorbic acid, contributing to its sustained demand in various industries. However, despite the positive demand outlook, the ascorbic acid market faces significant challenges. High production costs, stemming from expenses related to labor, energy, and equipment, pose a considerable burden on manufacturers. Additionally, the limited availability of raw materials, especially during periods of heightened demand or supply chain disruptions, can impact production capabilities and consequently affect pricing dynamics.

Vitamin C stands out as one of the most extensively produced and widely sold vitamins globally, boasting a substantial production and sales scale. The epicentre of its manufacturing lies predominantly in China, characterized by low entry barriers and a multitude of manufacturers contributing to the industry. Key players in this domain include CSPC Weisheng, Luwei Pharmaceutical, DSM Jiangshan, Northeast Pharmaceutical, Tianli Pharmaceutical, Qiyuan Pharmaceutical, and Zhengzhou Tuoyang. CSPC takes the lead as the world's largest producer of vitamin C, boasting an impressive production capacity of around 40,000 tons per year. Following closely are Luwei Pharmaceutical and Northeast Pharmaceutical, with production capacities of 30,000 tons/year and 25,000 tons/year, respectively. Collectively, the top five vitamin C manufacturers on a global scale wield an aggregate production capacity of approximately 145,000 tons annually. Publicly available data reveals that the total global production capacity for vitamin C has reached 220,000 tons, underscoring China's dominant role, contributing more than 90% to the global production capacity, with a capacity exceeding 20 tons. This concentration of production capacity in China reinforces its position as the primary hub for vitamin C manufacturing, reaffirming the country's pivotal role in meeting the worldwide demand for this essential nutrient (*Extracts/Vitamins/HardCapsule*, 2020).

1.2.4 PRODUCTION CAPACITY

Vitamin C, also referred to as L-ascorbic acid, plays a vital role as an essential water-soluble vitamin, contributing to immune system enhancement and participating in the synthesis of collagen, intercellular substance, and neurotransmitters. Beyond its health benefits, vitamin C is widely utilized in the food industry as an antioxidant for food preservation, boasting additional properties such as anti-oxidation, anti-free radical capabilities, and the inhibition of tyrosinase formation, leading to skin whitening effects.

Examining the production capacity, the scale of vitamin C production in the country is on an upward trajectory, reaching an estimated 350,000 tonnes in 2021. The outbreak of the global pandemic in 2020 significantly boosted vitamin C sales, resulting in a continuous and stable growth in downstream product demand. Domestic vitamin C raw material manufacturers have capitalized on this opportunity, with notable expansions in production capacity, such as CSPC reaching 80,000 tonnes. Globally, the demand for vitamin C raw materials is projected to be around 240,000-250,000 tonnes, with expectations of reaching 300,000 tonnes after 2025, indicating a 5- 6% average annual growth (*Chemical Prices Database and Industry Market Insights - ECHEMI*, n.d.).

Integrating supply and demand data to determine the proposed production capacity of 600 tonnes per annum for ascorbic acid involves a comprehensive analysis of market size, growth rates, and current market prices. With the global ascorbic acid market valued at $1.3 billion in 2021 and projected to reach $2.2 billion by 2031, exhibiting a steady growth rate of 5.2% annually, there is a clear indication of increasing demand over the forecast period. Considering the current market price ranging between $7 to $8 per kilogram, and with a projected market valuation surge from US$ 176.8 Million in 2022 to US$ 321.5 Million in 2032, exhibiting a growth rate of 6.2%, the proposed production capacity of 600 tonnes per annum aligns with market trends and consumer needs (*Ascorbic Acid (Vitamin C) Market Overview Q1 2021*, 2021). By estimating the revenue generated from 600 tonnes of ascorbic acid at an average price of $7.5 per kilogram, the calculated annual revenue substantiates the feasibility and viability of this proposed production capacity. Then, this integration of supply and demand data facilitates the determination of a production capacity that is in sync with market dynamics and ensures adequate supply to meet growing consumer demand for this essential nutrient.

1.3 SITE ANALYSIS

1.3.1 POTENTIAL SITE ASSESSMENT

To develop a new plant, a suitable and strategic location is being examined to produce ascorbic acid to ensure the long-term viability of the plant. There are some factors that need to be considered to select the strategic plan location. The accessibility on plant sites is considered including distance to the town or market area, transportation, availability of operating labour taxes, utilities, land price and other factor are the main considerations for site location. After conducting some investigation of the plant sites, there are three proposed strategic plant location, which are Kawasan Perindustrian Tanjung Langsat, Pasir Gudang in Johor, Pulai Indah West Port, Klang in Selangor, and Kawasan Perindustrian Batu Kawan in Pulau Pinang. Table 3 shows the comparison on different potential sites from various selection criteria.

Table 1.3 Comparison on Different Potential Site on Various Selection Criteria

Location	Kawasan Perindustrian Tanjung Langsat, Pasir Gudang, Johor	Pulai Indah West Port, Klang, Selangor	Kawasan Perindustrian Batu Kawan, Pulau Pinang
Distance to town	34.5 km to Johor Bahru	58 km to Kuala Lumpur	38 km to Georgetown
Distance to port	• 5.5 km to Tanjung Langsat Port • 67 km to Port of Tanjung Pelepas	• 14.38 km to Klang Port	• 29.4 km to Butterworth Port
Distance to railway	35 km to Johor Bahru Central	13.88 km to Stesen Komuter Klang	29.6 km to Stesen Komuter Butterworth
Distance to airport	55.1 km to Senai International Airport	58 km to Kuala Lumpur International Airport (KLIA)	30.8 km to Penang International Airport

Road facilities	• Senai–Desaru Expressway • Johor Causeway 2nd Link • Johor Bahru-Kota Tinggi Highway • North-South Highway	• South Klang Valley • Pulau Indah Expressway • North-South Highway	• Penang Bridge • North-South Highway
Availability of Labor (Population)	231,832	108,8942	5537
Labour supply	• Universiti Teknologi Malaysia (UTM JB) • Politeknik Ibrahim Sultan (Pasir Gudang)	• Universiti Teknologi Mara (Shah Alam)	• Universiti Sains Malaysia • Politeknik Seberang Perai (Penang)
Utilities Availability (Electrical)	Tenaga Nasional Berhad (TNB)		
Utilities Availability (Water)	Syarikat Air Johor (SAJ) • 0-20m^3: RM0.80/m^3 • 21- 35m^3 : RM2.00/m^3 • > 35m^3 : RM3.00/ m^3	Syarikat Bekalan Air Selangor • 0-35m^3 : RM 2.07/m^3 • > 35m^3 : RM 2.28/m^3	Perbadanan Bekalan Air Penang • 0-35m^3 : RM1.50/m^3 • > 35m^3 : RM2.10/m^3
Land Price (RM/square feet)	RM 37/sf	RM55/sf	RM47/sf
Land Availability (square feet)	435600	435600	640332
Tax Incentives	Under Malaysia's Budget 2023, for new companies: • Tax exemption of up to 70% of statutory income for 5 years; or an investment tax allowance of up to 60% on qualifying expenditure incurred within 5 years and set-off against 70% of statutory income for each year of assessment		
Local community considerations	6.1 km away from the nearest residential area, Taman Kota Masai	8.4 km away from the nearest residential area, Taman Kota Pendamar	2.5km away from nearest residential area, Kampung Kebun Nyiur
Climate	Tropical		

1.3.2 POTENTIAL SITE SELECTION CRITERIA

A score and ranking analysis are conducted to evaluate the three different potential sites. This helps in comparing the different criteria and to decide the most suitable location to develop the plant for production of ascorbic acid. Table 4 illustrates the rubric for the site selection.

Table 1.4 Rubric for Site selection

Selection Criteria	3 Marks	2 Marks	1 Mark
Distance to town (km)	Nearest to the town	Near to the town	Far from the town
Distance to port (km)	Nearest to port	Near to port	Far from port
Distance to railway (km)	Nearest to railway	Near to railway	Far from railway
Distance to airport (km)	Nearest to airport	Near to airport	Far from airport
Road facilities	Numerous systematic federal road and highway nearby	Have Systematic federal road and highway nearby	Less Systematic federal road and highway nearby
Utilities Availability	Complete electric supply, lowest cost for water supply	Complete electric supply, low cost for water supply	No complete electric and water supply
Availability of Labor (Population)	Largest population	Large population	Small population
Land Price (RM/psf)	Lowest land price	Low land price	High land price
Land Availability	Largest land square feet	Large land square feet	Small land square feet
Local community consideration	Far away from the nearest residential area	Far to the nearest residential area	Near to the nearest residential area

1.3.3 POTENTIAL SITE SELECTION

According to the information and details searched on the three different potential sites, the score of each potential site is analyzed referring to the site selection rubric. The overall scores of each site are shown in Table 5 and Figure 1.2.

Table 1.5 Score Obtained by Different Sites on Selection Criteria

Location	Kawasan Perindustrian Tanjung Langsat, Pasir Gudang, Johor	Pulau Indah West Port, Klang, Selangor	Kawasan Perindustrian Batu Kawan, Pulau Pinang
Distance to town	3	1	2
Distance to port	3	2	1
Distance to railway	1	3	2
Distance to airport	2	1	3
Road Facilties	3	2	1
Utilities Availability	2	2	3
Availability of Labor	3	2	1
Land Price	3	1	2
Land Availability	2	2	3
Local community considerations	2	3	1
Total	24	19	19

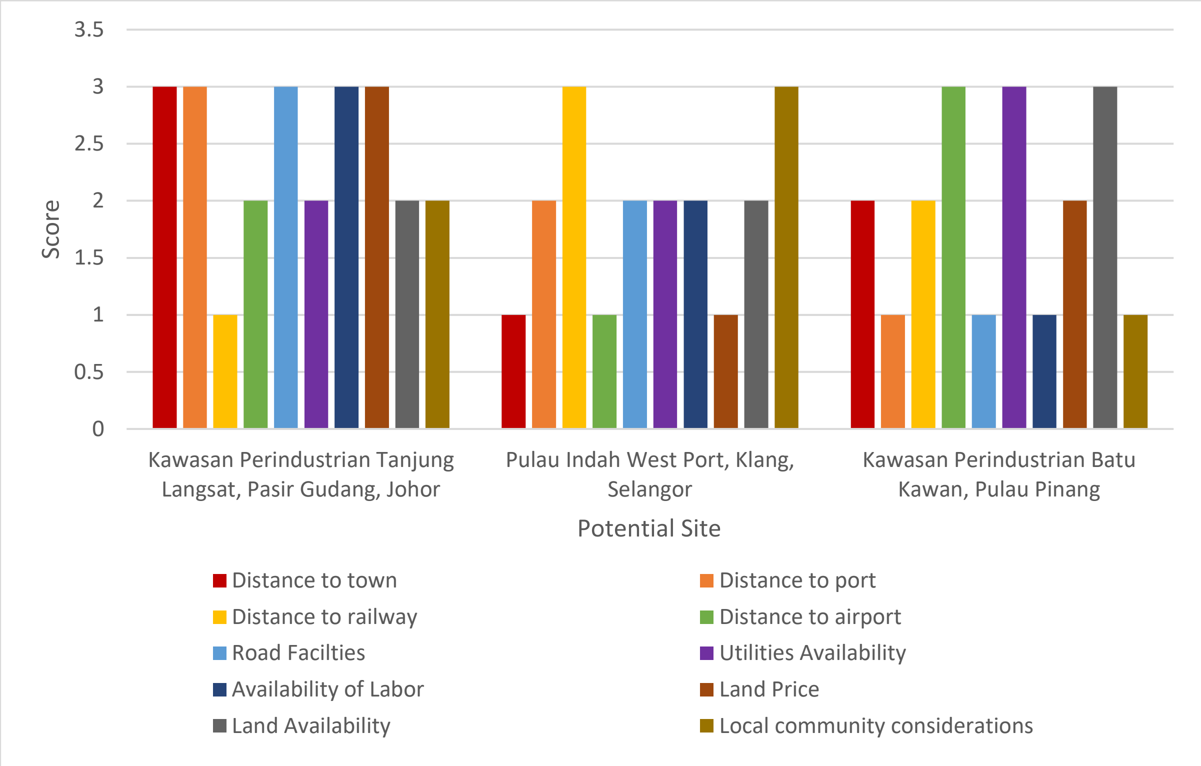


Figure 1.2 Graph of Score against Potential Site on Different Criteria

Based on Figure 1.2, it can be concluded that the total marks gained are 19 for Kawasan Perindustrian Batu Kawan, Pulau Pinang and Pulai Indah West Port, Klang, Selangor and 24 for Kawasan Perindustrian Tanjung Langsat, Pasir Gudang, Johor. Therefore, the analysis shows that Kawasan Perindustrian Tanjung Langsat, Pasir Gudang, Johor achieves the highest marks and is considered as the most suitable site location to develop the plant of ascorbic acid production.

The main factors that make it as the most strategic location include it has lowest land price, which is RM 37 per square feet. Besides, it has systematic federal road and highway, airport facilities and near to port which is it is only 5.5 km away from the Tanjung Langsat Port and 67 km to Port of Tanjung Pelepas (PTP). It has the nearest distance to the port compared with other locations. Transportation facilities, especially the ports are very important as it can ease the import of the raw materials supply to produce ascorbic acid, and thus reduce the transportation costs. The export of ascorbic acid can also be done in an easier and more convenient way to earn more profit. Other than the port, there are 4 road facilities available near to Tanjung Langsat which are Senai–Desaru Expressway, Johor Causeway 2nd Link, Johor Bahru–Kota Tinggi Highway and North-South Highway.

On the other hand, Tanjung Langsat contributes high availability of labour which is 231832, this enables the plant to hire more workers to helps in the production of ascorbic acid. Another significant factor in choosing the site is the distance to the nearest residential area. The distance of Kawasan Perindustrian Pasir Gudang is approximately 6.1 km from the nearest residential area. This indicates that the site is within a safety distance from the population and minimise risk of any kinds of spreading contamination across the community nearby. In overall, after evaluating and analyzing different criteria on the sites, Tanjung Langsat, Pasir Gudang, Johor is the most strategic site for the plant of ascorbic acid production.

CHAPTER 2

PROCESS SELECTION

2.1 COMMERCIAL PATHWAY

The production of ascorbic acid has been evolved over decades. It was originally created through Reichstein process involving microbial fermentation in 1930s (Pathy, 2018). Over the past few decades, numerous scientists have dedicated their efforts to inventing highly efficient processes for producing ascorbic acid on industrial scales. There are several biosynthesis processes manufacturing ascorbic acid naturally or chemically.

Ascorbic acid can be extracted from fruits, vegetables, algae, or plants naturally. The process involves pretreatment, extraction, and purification for natural synthesis. Some different extraction methods have been introduced including conventional solvent extraction, supercritical fluid extraction, pressurized liquid extraction and so on (Susa & Pisano, 2023). These techniques give low yield while consuming substantial amounts of energy (Susa & Pisano, 2023).

Hence, most of industries are using chemical synthesis to produce large amount of ascorbic acid. The commercial chemical synthesis of ascorbic acid involves Reichstein process and two-step fermentation process, initiating from the common sugar D-glucose by using microbes. The Reichstein process developed by Reichstein and Grüssner emerged as the industry standard for creating synthetic ascorbic acid from a widely accessible feed source until the late 1990s (Pappenberger & Hohmann, 2014). This method involving one fermentation step, several catalytic steps and purification process (Wang et al., 2018). Whereas the two-step fermentation method represents a more advanced approach, incorporating two aerobic fermentation stages, two catalytic steps, and a purification process.

2.2 ALTERNATIVE PATHWAYS

Evaluate alternatives by considering different factors from several commercial pathways to determine the most efficient approach. There are two available biochemical synthesis used to produce ascorbic acid are the Reichstein process and the two-step fermentation process. These process technologies have a similar overall yield of production, which is 75%. Additionally, natural synthesis via extraction methods is also employed for ascorbic acid production. In the nutshell, three alternative reaction pathways are introduced as below for process screening. However, ascorbic acid's natural abundance is insufficient to fulfil the demands of the world market (Wang et al., 2018). Therefore, the extraction method is eliminated, we mainly focus to compare the chemical synthesis pathways which are Reichstein process and two-step fermentation process for process screening.

<u>Alternative Reaction Path 1: Production of Ascorbic Acid through Reichstein Process</u>

According to Reichstein and Grüssner, this method has several steps that involve six chemical syntheses and one microbial transformation of the substrate using *Gluconobacter Oxydans* which is shown in Figure 2.1.

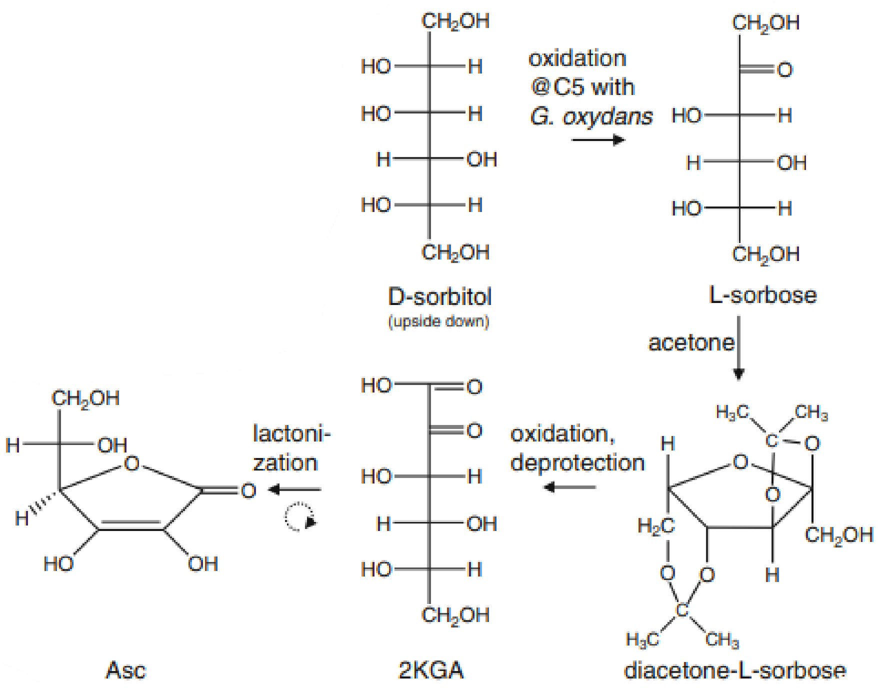


Figure 2.1 Conceptual Outline of Synthetic of Ascorbic Acid by Reichstein Process (Pappenberger & Hohmann, 2014).

The original process will transform glucose into vitamin C using 4 steps (chemical and microbial) from D-Sorbitol:

Overall chemical equation of the production of ascorbic acid from D-sorbitol:

$$C_6H_{14}O_6 + \frac{18}{2}O_2 + NaHCO_3 + 2CH_3COCH_3 \longrightarrow C_6H_8O_6 + NaOH + 9H_2O + 7CO_2$$

Step 1: Microbial oxidation or fermentation of sorbitol to L-sorbose with *Gluconobacter Oxydans* at pH 4-6 and 30 °C (production of 98% yield).

Step 2: L-sorbose will treat with acetone and sulfuric acid to obtain diacetone-sorbose with production of 80% yield.

Step 3: Direct oxidation of Diacetone-sorbose to 2-keto-L-gulonic acid (2KGA) with a platinum catalyst, avoiding the use of protective groups with production of 90% yield.

Step 4: Enolization and internal lactonization with removal of the water of 2KGA to L-ascorbic acid, which is the final product with the production of 75% yield.

Alternative Reaction Path 2: Production of Ascorbic Acid by using Two-Step Fermentation Process

The two-step fermentation process transforms the D-sorbitol into L-sorbose in the first step and further converts it to 2-KLG in the second step, then follow by Enolization and internal lactonization process which is shown at Figure 2.2. Through careful selection of microbial strains, the introduction of helper strains, and optimization of fermentation conditions, the process ultimately yields ascorbic acid. This direct production of ascorbic acid is achieved through the microbial transformations of D-sorbitol, demonstrating the efficiency and sustainability of this synthesis route (Liu et al., 2024).

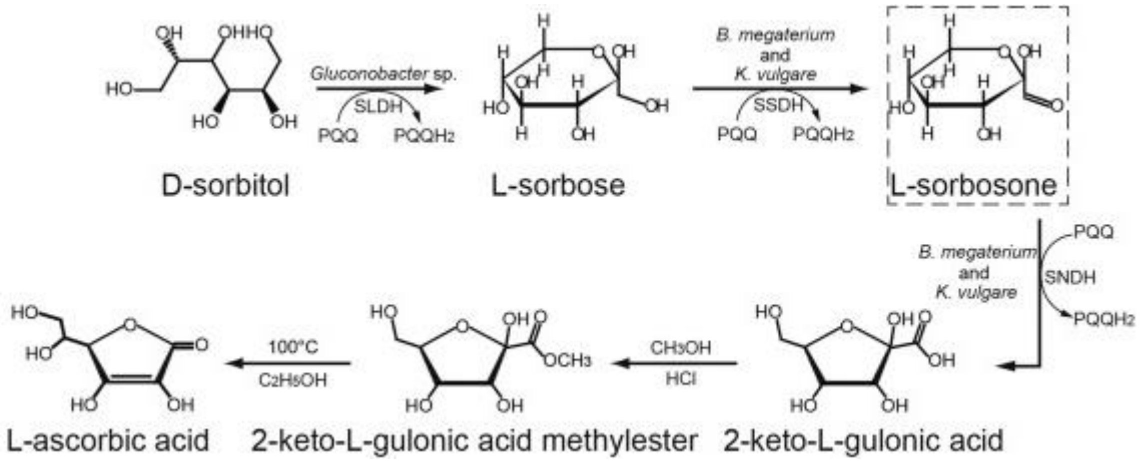


Figure 2.2 Conceptual Outline of Synthetic of Ascorbic Acid by Two-step Fermentation Process (Wang et al., 2018).

Overall Chemical equation of the production of ascorbic acid from D-sorbitol:

$$C_6H_{14}O_6 + \frac{1}{2} O_2 + \frac{1}{2} Na_2CO_3 + \frac{1}{2} NaHCO_3 \longrightarrow C_6H_8O_6 + 2NaOH + \frac{5}{2} H_2O + \frac{3}{2} CO_2$$

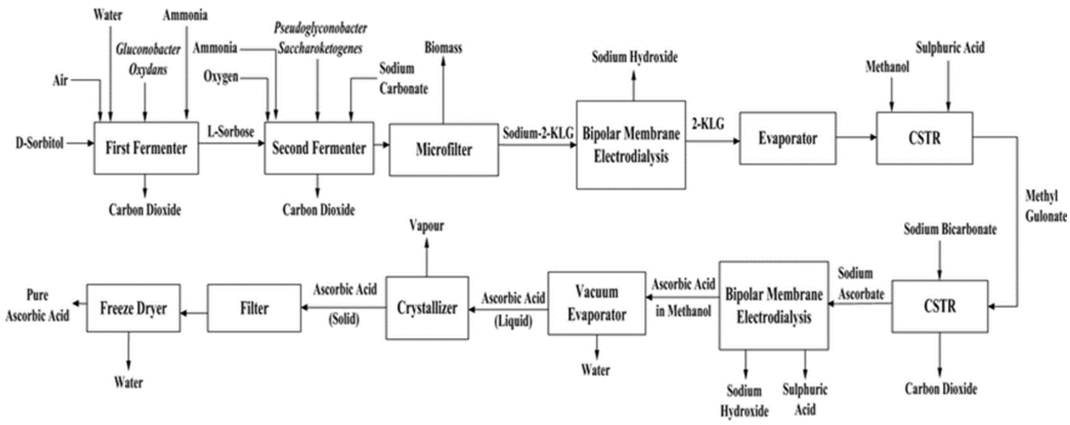


Figure 2.3 Block Diagram of Production Ascorbic Acid from D-sorbitol using Two-Step Fermentation process (Lim et al., 2020).

The two-step fermentation process for ascorbic acid production involves several key stages and steps.

Step 1: L-sorbose production from sorbitol using *G. oxydans*, which can produce highly stereospecific enzymes used by industrial producers in China. (Tucaliuc et al., 2022).

Step 2: Next step to convert L-sorbose to 2-keto-L-gluconic acid. This fermentation broth is fermented in the second fermenter by *Pseudoglyconobacter Saccharoketogenes* to produce sodium keto-gluconic acid. *Pseudoglyconobacter Saccharoketogenes* can oxidize primary alcohol, secondary alcohol, aldehydes, and polysaccharides (Lim et al., 2020). (The production yield will be 97%).

Step 3: Enolization and internal lactonization with removal of the water of 2KGA to L-ascorbic acid, which is the final product (The production of yield will be 75%).

Alternative Reaction Path 3: Production of Ascorbic Acid by using Extraction Process

The extraction method is used to derive ascorbic acid from natural sources. Raw materials that are fruits, leaves, or other plant-derived materials are often gathered, cleaned to remove unnecessary components, and then rinsed with water to be pretreated continuously by drying and milling before beginning the extraction process (Susa & Pisano, 2023).

Consequently, recover the bioactive substrates by extraction steps. The acid extraction is conducted by metaphosphoric acid as it can stabilise the isolated ascorbic acid (Susa & Pisano, 2023). After that, purification involving precipitation to remove metaphosphoric acid in the form of insoluble salts, then followed by evaporation and crystallization to remove solvents (Susa & Pisano, 2023).

2.3 MARKET PRICE OF RAW MATERIALS & PRODUCTS

Table 2.1 Assumed Cost of Chemicals Purchased or Sold in Bulk Quantities

Chemical	RM/kg*	Reference
D-sorbitol/glucitol	3.81	Guangzhou Zio Chemical Co., Ltd.
Sodium carbonate	0.86	Qingdao Hot Chemicals Co., Ltd.
Sodium bicarbonate	0.91	Gansu Kinbo Industry Co., Ltd.
Acetone	3.81	Shandong Qibo New Energy Co., Ltd.
Ascorbic acid	33.37	Xi'an International Healthcare Factory Co., Ltd.
Sodium hydroxide	1.29	Hebei Yueqian Mechanical Equipment Technology Co., Ltd.
Oxygen	0	-
Carbon dioxide	0	-
Water	0	-

**Price Source: Alibaba.com*

2.4 GROSS PROFIT/ECONOMIC POTENTIAL

2.4.1 GROSS PROFIT

To create a biochemical plant, it is crucial to examine and choose from alternative pathways of making a product. Gross profit refers to the profit after excluding equipment and operating costs, helping to eliminate pathways that are not profitable since beginning (Seider et al., 2017).

Table 2.2 Gross Profit Calculation for Alternative Reaction Path 1

	Reactant			**Product**	
Overall equation	$C_6H_{14}O_6$	$NaHCO_3$	CH_3COCH_3	$C_6H_8O_6$	$NaOH$
	sorbitol	sodium bicarbonate	acetone	ascorbic acid	sodium hydroxide
Stoichiometry	1	1	2	1	1
Molecular Weight (g/mol)	182.17	84.007	58.08	176.12	39.997
kg	182.17	84.007	116.16	176.12	39.997
kg/kg ASC	1.0344	0.4770	0.6596	1.0000	0.2271
RM/kg	3.81	0.91	3.81	33.37	1.29
Gross Profit (RM/kg ASC)	(33.37)(1) + (1.29)(0.2271) − (3.81)(1.0344) − (0.91)(0.4770) − (3.81)(0.6596) =26.77				

Table 2.3 Gross Profit Calculation for Alternative Reaction Path 2

Overall equation	**Reactant**			**Product**	
	$C_6H_{14}O_6$	Na_2CO_3	$NaHCO_3$	$C_6H_8O_6$	NaOH
	sorbitol	sodium carbonate	sodium bicarbonate	ascorbic acid	sodium hydroxide
Stoichiometry	1	0.5	0.5	1	2
Molecular Weight (g/mol)	182.17	105.9888	84.007	176.12	39.997
kg	182.17	52.9944	42.0035	176.12	79.994
kg/kg ASC	1.0344	0.3009	0.2385	1.0000	0.4542
RM/kg	3.81	0.86	0.91	33.37	1.29
Gross Profit (RM/kg ASC)	$(33.37)(1)+(1.29)(0.4542)-(3.81)(1.0344)-(0.86)(0.3009)$ $-(0.91)(0.2385)$ $=29.54$				

2.5 PROCESS SCREENING

2.5.1 PROCESS SELECTION

During this stage, selection is made based on factors including gross profit, economic potential, and the environment factors. The potential for ascorbic acid production is promising, yet its realization hinges on the future accessibility and pricing of feedstock. It is intricately linked to shifts in food demand and healthcare priorities. The price of ascorbic acid is significantly shaped by demand dynamics and the investment costs associated with raw materials and operations. The microbial fermentation process plays a crucial role in ascorbic acid production. Nevertheless, the expense of microbes is categorized as an operational cost, distinct from gross profit calculations. In this project, there are two alternative reaction pathways of manufacturing ascorbic acid to be compared which are:

Alternative Reaction Path 1: Production of ascorbic acid by Reichstein process

Alternative Reaction Path 2: Production of ascorbic acid by two-step fermentation

Table 2.4 Factor that needs to be considered in Alternative Production Path 1

Criteria	Detail	Reference
Microorganism	*Gluconobacter oxydans*	Wang et al. (2018)
Cost	Higher capital, operating and disposal cost	
Chemical catalytic steps	Complicated, consume a significant amount of energy and need plenty of organic solvents and intense reaction conditions	
Environmental Impact	Use hazardous solvent such as acetone	Tucaliuc et al. (2022b)
Conversion/yield	About 80 to 90% yield from L-sorbose to 2-keto-L-glulonic acid	

Table 2.5 Factor that need to be considered in Alternative Reaction Path 2

Criteria	Detail	Reference
Microorganism	*Gluconobacter oxydans, Pseudoglyconobacter Saccharoketogenes*	Tucaliuc et al. (2022b)
Cost	Two-third of Reichstein process cost	
Chemical catalytic steps	Require fewer steps and consume lower energy	
Environmental Impact	Less to use hazardous chemical	
Conversion/yield	Up to 92.5% yield from L-sorbose to 2-keto-L-glulonic acid	

To select the best way to produce the desired product among the alternatives, few factors we need to consider which are economic potential, environmental impact, and cost for by products, equipment, and utilities.

From the aspect of gross profit, the alternative reaction path 2 has higher gross profit compared to alternative reaction path 1. Based on Table 4 and Table 5, alternative reaction path 2 spend less cost on the process, require fewer steps with lower energy, less use of hazardous materials and higher yield whether alternative reaction path 1 spend much cost on the process including disposal cost, capital, and operating cost, require complicated steps with high energy, use hazardous material to catalyze the process and lower yield.

Overall, the alternative reaction path 2 is the best way to produce ascorbic acid from the aspect of cost and environmental impacts. For the Two-Step Fermentation method, efficiency and product quality is reported to have higher efficiency and product quality than the Reichstein process. The overall yield of production for these processes is 75%. When dealing with environmental considerations, the two-step fermentation process with a single culture is selected for its environmental friendliness, less toxicity, and lower cost compared to the Reichstein process (Lim et al., 2020).

CHAPTER 3

PROCESS SYNTHESIS

3.1 SOURCE AND SPECIFICATION OF RAW MATERIALS

The source and specification of chemical raw materials and microorganisms are listed in Table 11, Table 12, Table 13, Table 14 and Table 15.

Table 3.1 Supplier and Location of Sorbitol.

Reactant	Sorbitol
Supplier	Guangzhou Zio Chemical Co., Ltd.
Location	Guangdong, China
Specification	1) Storage type: dry, dampproof, lucifugal 2) Specification: 270kg/drum 3) Shelf Life: 24 months 4) Purity: Sorbitol 70%

Table 3.2 Supplier and Location of Sodium Carbonate

Reactant	Sordium Carbonate
Supplier	Qingdao Hot Chemicals Co., Ltd.
Location	Qingdao, China
Specification	1) Storage type: Store in a cool, dry, ventilated area 2) Specification: 25 Kg/bag 3) Shelf Life: 24 months 4) Purity: 99.2%

Table 3.3 Supplier and Location of Sodium Carbonate

Reactant	Sodium Bicarbonate
Supplier	Gansu Kinbo Industry Co., Ltd.
Location	Gansu, China
Specification	1) Storage type: Cool 2) Specification: 25 Kg/bag 3) Shelf Life: 24 months 4) Purity: 99.8%

Table 3.4 Supplier and Location of *Gluconobacter oxydans*

Reactant	Gluconobacter oxydans
Supplier	White Labs Inc
Location	San Diego, California, United States
Specification	1) Part No: WLP685 2) Fermentation Temperature: 25° - 30° C 3) Type: Vault 4) Gram stain: gram-negative rod bacterium 5) Family: *Acetobacteraceae*

Table 3.5 Supplier and Location of *Psedogluconobacter Saccharoketogenes*

Reactant	PseudoGluconobacter Saccharoketogenes
Supplier	White Labs Inc
Location	San Diego, California, United States
Specification	1) Part No: IFO 14464 2) Fermentation Temperature: 25° - 30° C

3.2 PHYSICAL AND CHEMICAL PROPERTIES OF REACTANTS AND PRODUCTS

In this chapter, the physical and chemical properties of reactants and products are determined in order to determine the feasibility and characteristics of chemical reactions. These are important in predicting the reaction outcomes, safety handling and storage, risk and hazard assessment, optimizing reaction conditions, and design synthesis routes for desired products. Table 16 shows the physical and chemical properties of the reactants and products involved in the production of ascorbic acid.

Table 3.6 Physical and Chemical Properties of the Reactants and Products

Substance	**Sorbitol**	**Water**	**Oxygen**	**Ammonia**	**Sorbose**	**Sodium Carbonate**
Physical State	Liquid	Liquid	Gas	Gas	Liquid	Liquid
Odor	Odorless	Odorless	Odorless	Pungent	Odorless	Odorless
Taste	sweet	tasteless	tasteless	tasteless	sweet	tasteless
Molecular weight (g/mol)	182.17	18.0151	31.999	17.03	180.16	105.99
Density (g/cm^3)	1.49	0.99701	1.429	0.00077	1.65	2.54
Color	White	Colorless	Colorless	Colorless	White	White
Boiling Point (°C)	295	100	−182.97	-33.3	551.7	1600
Melting Point (°C)	75	0	−218.76	-77.7	163	851
Critical Temp. (°C)	594.85	374.19	−118.39	132.39	767.86	-273.15
Specific heat capacity (J/gmol. K)	332.2	75.24	97	80	228.61	189.54
Standard enthalpy of formation at 298K (kJ/mol)	−1354.15	-285.830	0	-45.898	-1276.9	-1130.7
Solubility in organic compounds	Soluble	Soluble	Insoluble	Soluble	Insoluble	Insoluble
Solubility in water (g/L)	2350	1000	0.04	0.31	0.017	0.017

Table 16 Physical and Chemical Properties of the Reactants and Products (Con'd)

Substance	**Sodium Glucuronate**	**2-Ketogluconic acid**	**Methanol**	**Methyl 2-keto-L-glulonate**	**Sodium Bicarbonate**	**Sodium Ascorbate**
Physical state	Liquid	Liquid	Liquid	Liquid	Liquid	Liquid
Odor	Odorless	odorless	sweet pungent	odorless	odorless	odorless
Taste	Slightly bitter	Tasteless	Alcohol	Tasteless	Salty	Salty
Molecular weight (g/mol)	216.12	194.14	32.042	208.17	84.01	198.11
Density (g/cm³)	1.9	1.757	1.01	1.532	2.159	1.66
Color	White	Colorless	Colorless	Light brown	White	White
Boiling Point (°C)	673.6	550.6	337.6	495.4	851	235
Melting Point (°C)	206	159	175.6	158	50	220
Critical Temp. (°C)	509.85	509.85	239.42	509.85	-273.15	509.85
Specific heat capacity (J/gmol. K)	305.4	305.4	81.6	305.4	90	305.4
Standard enthalpy of formation at 298K (kJ/mol)	−1164.6	−1164.6	-239.1	−1164.6	-950.81	-1164.6
Solubility in organic compounds	Slightly soluble	Slightly soluble	Soluble	Slightly soluble	Insoluble	Soluble
Solubility in water (g/L)	590	49	1000	62	96	50

Table 16 Physical and Chemical Properties of the Reactants and Products (Cont'd)

Substance	**Carbon dioxide**	**Nitrogen**	**Sodium hydroxide**	**Ascorbic acid**
Physical state and appearance	Gas	Gas	Liquid	Liquid
Odor	Odorless	Odorless	Odorless	Odorless
Taste	Tasteless	Tasteless	Tasteless	Sour
Molecular weight (g/mol)	44.01	28.014	40.01	176.12
Density (g/cm^3)	1.977	0.807	2.13	1.65
Colour	Colorless	Colorless	White	White to pale yellow
Boiling Point (°C)	-78.5	-195.79	1390	190
Melting Point (°C)	-55.6	-210.01	318.4	190
Critical Temp. (°C)	31.03	-146.9	2546.85	509.85
Specific heat capacity (J/gmol. K)	209.53	88.8	87.18	305.4
Standard enthalpy of formation at 298K (kJ/mol)	-393.51	0	-111 kJ/mol	-1164.6
Solubility in organic compounds	soluble	insoluble	soluble: ethanol (12.8 g/mL), methanol (12.5 g/mL)	soluble: 0.02 g/mL - methanol, propanol
Solubility in water (g/L)	3.48	0.015	1110	3300

3.3 5 KEYS SYNTHESIS STEPS

To establish a complete process for producing ascorbic acid, five key synthesis steps are required. First step is to eliminate differences in molecular types by screening out the potential pathways from previous chapter, the alternative reaction path 2 is selected to create production process of ascorbic acid from sorbitol by two-step fermentation.

Second step, distribute the chemicals by matching source and sinks, list down the main reaction involved for manufacturing ascorbic acid shown as Figure 3.1 and Table 17. The main process is illustrated as Figure 3.2.

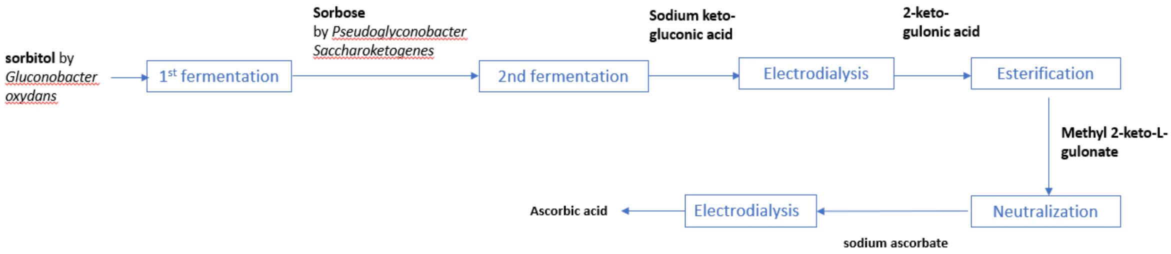


Figure 3.1 Block Diagram of Main Process of Ascorbic Acid Synthesis.

Table 3.7 List of Chemical Reactions Involved for Main Process.

Main Process	**Chemical Reaction**
First Fermentation	$C_6H_{14}O_6 + 0.5O_2 \rightarrow C_6H_{12}O_6 + H_2$
Second Fermentation	$C_6H_{12}O_6 + O_2 + Na_2CO_3 \rightarrow C_6H_9NaO_7 + 1.5H_2O + CO_2$
Electrodialysis 1	$C_6H_9NaO_7 + H_2O \rightarrow C_6H_{10}O_7 + NaOH$
Esterification	$C_6H_{10}O_7 + CH_3OH \rightarrow C_7H_{12}O_7 + H_2O$
Neutralization	$C_7H_{12}O_7 + NaHCO_3 \rightarrow C_6H_7NaO_6 + CH_3OH + H_2O + CO_2$
Electrodialysis 2	$\boldsymbol{C_6H_7NaO_6 + H_2O \rightarrow C_6H_8O_6 + NaOH}$

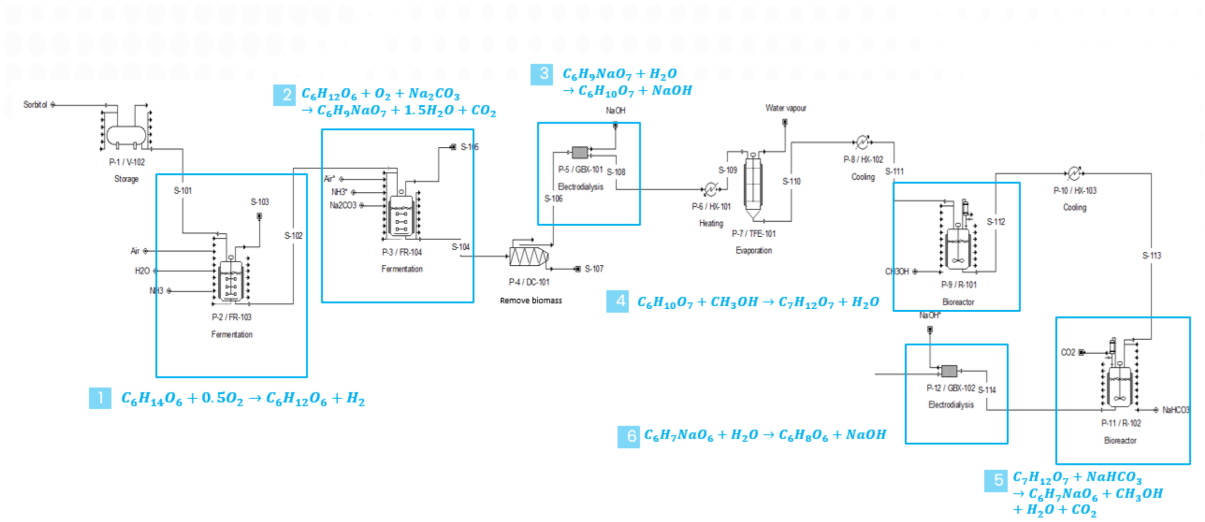


Figure 3.2 Process Flow Diagram of Main Process of Ascorbic Acid Synthesis.

The third step involve eliminating differences in composition, remove biomass, water and so on by additional of separation process including evaporation and filtration. The separation process with the main process is featured in Figure 3.3.

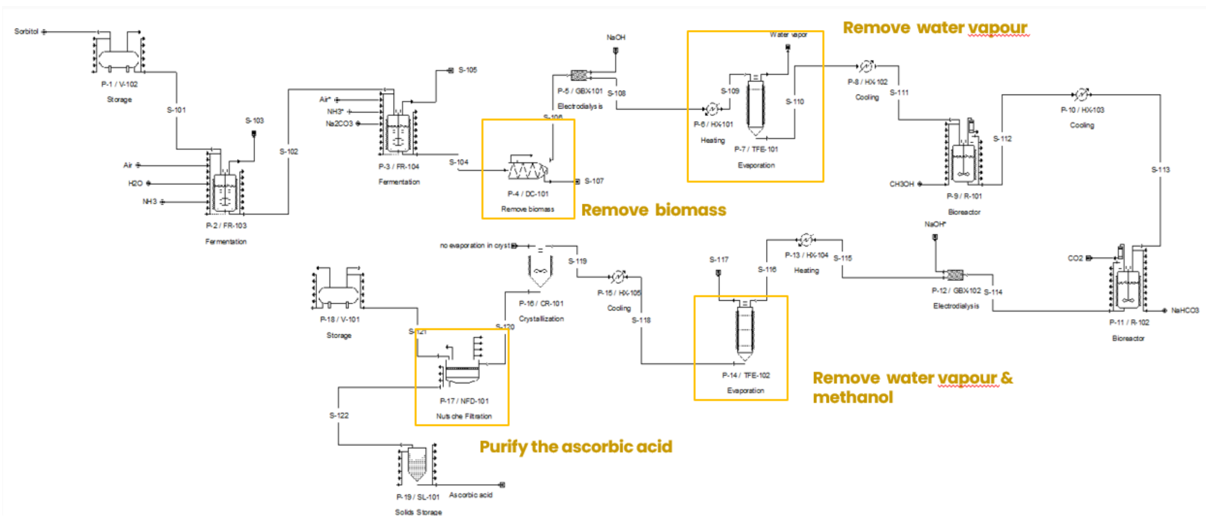


Figure 3.3 Process Flow Diagram of Main Process and Separation Process of Ascorbic Acid Synthesis.

Then, fourth step is to eliminate differences in temperature, pressure, and phase as shown in Figure 3.4, in this process of producing ascorbic acid, the pressure of whole process is controlled at 1 bar without increasing or decreasing. The desired temperature is adjusted and controlled by adding heater and cooler before or after evaporation process. The phase of material from beginning is liquid until purification process and then crystallizer is added to convert the ascorbic acid from liquid to solid.

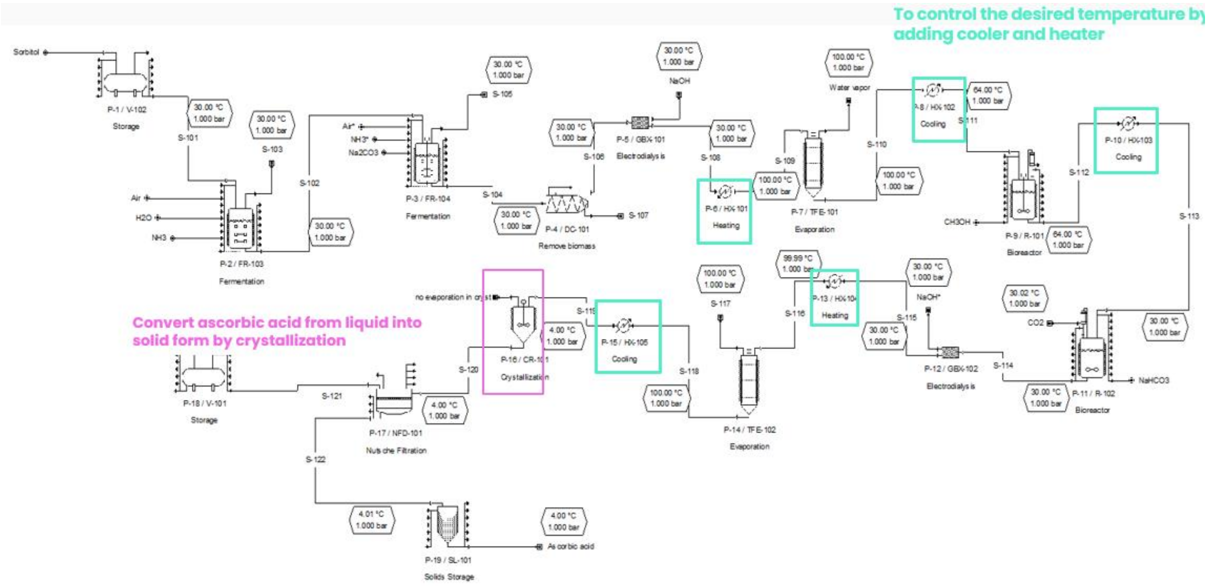


Figure 3.4 Process Flow Diagram of Main Process and Separation Process of Ascorbic Acid Synthesis with Pressure and Temperature.

Lastly, the fifth step, which is integrating task, to select the suitable equipment with the operation condition as illustrate in Chapter 3.4 and Chapter 3.5 and construct completed process flow which is shown in Chapter 3.6.

3.4 LIST OF PROCESS AND EQUIPMENT CONDITION

Table 3.8 List of Operating Condition with Relevant Process and Potential Equipment.

Process	**Operating condition**	**Justification**	**Potential Equipment**
Storage 1	Temperature: 30°C Pressure: 1 bar Phase: Liquid	To keep the sorbitol	Storage Tank
First Fermentation	Temperature: 30°C Pressure: 1 bar Phase: Liquid Duration: 14 hours pH: 6	Conversion of the sorbitol to sorbose by *Gluconobacter Oxydans* through oxidative fermentation	Airlift fermenters vs Conventional agitator-driven shaft fermenters
Second Fermentation	Temperature: 30°C Pressure: 1 bar Phase: Liquid Duration: 72 hours pH: 6	Conversion of sorbose to sodium keto-gluconic acid by *Pseudoglyconobacter Saccharoketogenes*	
Separation Biomass from main products	Temperature: 30°C Pressure: 1 bar Phase: Liquid Rotor speed: 5000rpm Relative centrifugal force (RCF): 5000g at below condition	Biomass removal from the product of fermenters	Decanter Centrifugate vs Microfilter
Electrodialysis 1	Temperature: 30°C Pressure: 1 bar Phase: Liquid	Conversion of sodium keto-gluconic acid to keto-gluconic acid through hydrolysis	Bipolar Membrane Electrodialysis 1

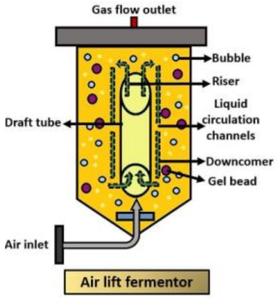
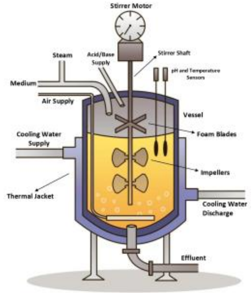
Evaporation 1	Temperature: 100°C Pressure: 1 bar Phase: Liquid and gas	Heat to remove water from 2-keto-gulonic acid before entering CSTR (R-101)	Thin Film Evaporator vs Rising Film Evaporator
Esterification	Temperature: 64°C Pressure: 1 bar Phase: Liquid	2-ketogulonic acid undergo esterification process with methanol to produce methyl gluconate	Stirred Tank Bioreactor vs Packed Bed Bioreactor
Neutralization	Temperature: 30°C Pressure: 1 bar Phase: Liquid	Reaction of methyl gluconate with sodium carbonate to form sodium ascorbate.	Stirred Tank Bioreactor vs Packed Bed Bioreactor
Electrodialysis 2	Temperature: 30°C Pressure: 1 bar Phase: Liquid	Recovery of ascorbic acid from sodium ascorbate	Bipolar Membrane Electrodialysis 2
Evaporation 2	Temperature: 100°C Pressure: 1 bar Phase: Liquid and gas	Evaporation of water and methanol produced in the reactor	Thin Film Evaporator Vs Rising Film Evaporator
Crystallization	Temperature: 4°C Pressure: 1 bar Phase: Solid and Liquid	99% of ascorbic acid crystallized in the crystallizer, other component remained in the slurry within 54 hours	Crystallizer
Filtration	Temperature: 4°C Pressure: 1 bar Phase: Solid and liquid	To purify the ascorbic acid by filtering the solid and liquid component	Nutsche Filter

Storage 2	Temperature: 4°C Pressure: 1 bar Phase: Liquid	To keep the slurry components which consist of major sorbitol & sorbose for the purpose to recycle.	Storage Tank
Solid storage	Temperature: Temperature: 4°C Pressure: 1 bar Phase: Solid and liquid	Store the ascorbic acid in low temperature for long shelve life.	Storage Tank

3.5 EQUIPMENT SELECTION

Equipment selection is a critical aspect of ensuring safety and efficiency in chemical processes. Suitable equipment needs to be selected wisely in order to achieve the desired yield of ascorbic acid production. The selection of equipment is depending on multiple criteria, including the efficiency, by-product accumulation, temperature and pressure requirement, compatibility with process requirements and others. Suitable equipment including types of fermenters, evaporator and reactor are analysed and the features of the equipment are tabulated in below.

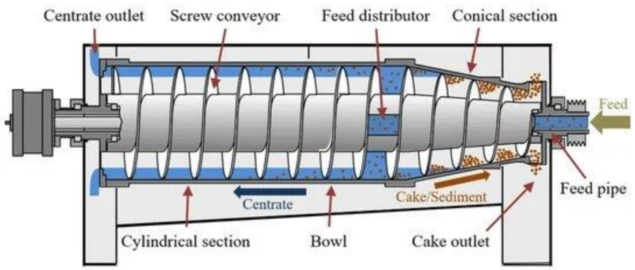
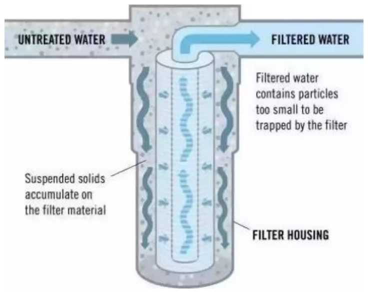
Table 3.9 Equipment Selection of Separation Processes (Adapted from Ezemba, 2022; FZE, 2023, F.Ronald, 1986)

Types of Equipment	**Airlift fermenters**	**Conventional agitator-driven shaft fermenters**
Diagram		

Working Principle	Culture broth is agitated through the introduction of gas via an airlift pump through aerobic condition	The agitator shaft in the fermenter stands vertically, causing the substrate to circulate horizontally. This creates multiple layers of decomposition zones.
Shear stress	Less shear force	High shear force
Energy consumption	low (save 70% of energy than conventional)	higher
Aeration rate	higher	low
Effort	Fewer effort to operate	More effort to operate
Cost	Cost-effective	Cost-effective
Selection	√	

Airlift fermenters are chosen in this plant because it can improve mass transfer of oxygen due to the high aeration rate, and thus improve the efficiency of the fermentation process. Besides, it has reduced power requirements, and able to provide a gentler environment for the cultivation of organism. This is because it has less shear stress compared to the conventional agitator-driven shaft fermenters. For conventional agitator-driven shaft fermenters, it has a high degree of shear which may harm the cultured cells.

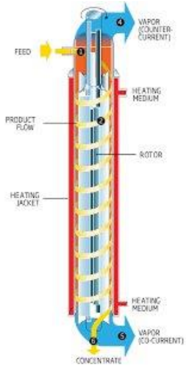
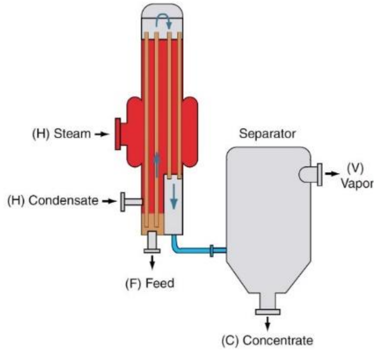
Table 3.10 Equipment Selection of Separation Processes (Adapted from Gésan-Guiziou, 2010; Leung, 2020; Ghosh et. al, 2017)

Types of Equipment	**Decanter Centrifuge**	**Microfilter**
Diagram		
Working Principle	• Separation of components with different densities (solid-liquid separation) • Rotate at high speed, denser solid particles are removed and collected in bowl wall	• Separation of components are based on different particle size exclusion. • Semi-permeable membrane, driven by transmembrane pressure
Fouling	No fouling problem	Fouling problem
Maintenance	Cleaning of centrifuge is needed, but less frequent	Frequent cleaning of membrane is required
Shear stress	Less shear stress	High shear stress to scour the membrane surface

Cost	• Higher capital and purchase cost • Reduced labor costs compared, low continuous maintenance and operator attention.	• Lower purchase cost • High cost for membrane replacement
Separation Efficiency	Unable to separate small density difference biological solids	Particles deposited onto the membrane pores, reduce filtrate flow
Total soluble sugar (TSS)	17.86 to 19.73°B in supernatant	15.13 to 17.2°B in solution
Clarity	Lower clarity, 83.6	High clarity, 93.5
Selection	√	

The main reason of choosing decanter centrifuge instead of microfilter is the total soluble sugar remained in the supernatant or the solution after filtration is higher than microfilter, which is 17.86 to 19.73°B. In the ascorbic acid production plant, sorbose produced is very important as one of the reactants. Therefore, sorbose is preferred to be remained in the plant but not discharged from the plant together with biomass. Other than that, decanter centrifuge is not suffering from fouling problem while microfilter does. Clogging problem of the microfilter may cause the frequent cleaning and maintenance required due to the deposition of particles.

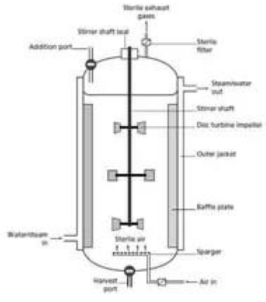
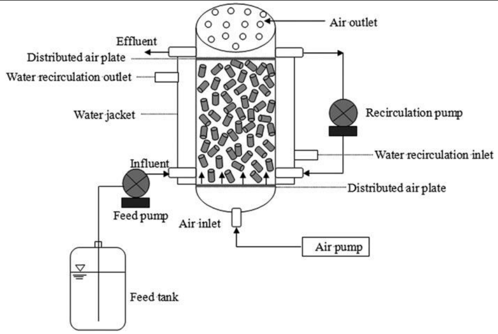
Table 3.11 Equipment Selection of Separation Processes (Adapted from Amaro et. Al., 2017; Glover 2008)

Types of Equipment	**Thin Film Evaporator (TFE)**	**Rising Film Evaporator**
Diagram		
Working Principle	Feed enters from above the heated zone and is distributed over the inner circumference of the body wall by rotor. Volatile components evaporate rapidly.	Feed enters at the bottom of the tube sheet and flows upward through the tubes, with the heating medium on the shell side. In the lower portion of the tubes, the feed is heated to its boiling point.
Efficiency	High heat-transfer coefficients due to the turbulence imparted by the rotor	High heat-transfer coefficients

Handling of Temperature-sensitive material	Suitable, especially pharmaceutical products • Short residence time, high turbulence	Not suitable • Hydrostatic head at the bottom of the tubes may increase product temperature
Cost	Higher cost	Lower cost
Pressure drop	Lower pressure drops due to following the gravitational force	Higher pressure drops
Simplicity	Complex design	More simpler structures, Reduced floor space requirements
Selection	√	

In the separation process, thin film evaporator is selected for the separation of water. The main reason is it can handle the heat-sensitive materials while the ascorbic acid is a temperature sensitive substance and need proper care. Besides, it needs shorter residence time and lower temperature time. It also has high heat transfer coefficients.

Table 3.12 Equipment Selection of Bioreactor (Adapted from Lin, 2015; Khan et. al, 2018, Wiebe et. al, 2004)

Types of Equipment	**Stirred Tank Reactor**	**Packed Bed Bioreactor**
Diagram	 Diagram of a stirred tank reactor.	
Working Principle	Medium in the reactor is mixed by using mechanical force and agitation for superior mixing	Consist of a cylindrical shell with convex heads, there are immobilized and bed of catalyst in the reactor. Fluids to flow from one end to the other, frequently used as a means of increasing contact between a liquid and gas.
Mixing Efficiency	Uniform mixing can be achieved due to the presence of impellers, forming vortex	Insufficient mixing, may cause dead zone
Mass Transfer	Higher mass transfer	Lower mass transfer

Thermal gradient	Less temperature gradient • CSTR is efficiently stirred	Undesired thermal gradients may exist • Poor temperature control
Maintenance	Easy to clean	Difficult to service and clean
Cost	Higher cost and maintenance	Low-cost maintenance and operation, unit may be difficult to service and clean
Selection	√	

The stirred tank reactor is chosen because it can carry out uniform mixing of the medium due to the presence of impellers. When the medium is efficiently mixed, the mass transfer increases. Besides, it also offers less temperature gradient in order to ensure the product quality to be maintained Packed bed reactor would exist the undesired thermal gradients sue to poor temperature control. It is also more difficult to service and clean although the cost is lower for maintenance.

3.6 PROCESS FLOW

3.6.1 PROCESS DESCRIPTION

The production involves a combination of biochemical and chemical reactions, and purification steps are crucial for obtaining high-quality ascorbic acid which is shown in Figure 3.5. Firstly, sorbitol solution with 70% purity is fed into First Fermenter which is airlift fermenter (FR-101) along with ammonia, water, and air. With oxidative fermentation in FR-101by *Gluconobacter Oxydans* at pH 6 and 30 °C for 14 hours (Tucaliuc et al., 2022a). 98% of the sorbose is converted from sorbitol. The solution continues to flow into Second Fermenter (FR-102) for second fermentation. *Pseudoglyconobacter Saccharoketogenes* ferrites for 72 hours in FR-102, producing 76% conversion of sodium keto-gluconic acid (Lim et al., 2020). Next, the biomass produced by bacteria from the fermentations is separated with high efficiency using a centrifuge (DC-101) (Zioui et al., 2023).

Recovers 2-keto-gluonic acid from sodium keto-gluconic acid by splitting water into protons and hydroxyl ions at a very fast rate remove NaOH using Bipolar Membrane Electrodialysis 1(GBX-101) (Tanaka, 2007). Consequently, the water is removed using the Thin Film Evaporator 1 (TFE-101) before it enters the Stirred Tank Bioreactor 1 (R-101). After removing large amounts of water, the compounds are cooled to 64 °C. Then, methyl gluconate is produced by the esterification of 2-keto-gulonic acid with methanol at 64 °C in R-101. Again, before entering Stirred Tank Bioreactor 2 (R-102), 2-ketogulonic acid must be cooled to 30 °C using Cooler (HX-103) which is suitable condition. Then, recovery of 2-ketogulonic acid to sodium ascorbate in R-102. Next, proceed to convert ascorbic acid from sodium ascorbate by involving ion exchanges to remove NaOH using Bipolar Membrane Electrodialysis 2 (GBX-102).

The water and methanol produced in the R-102 are evaporated in the Thin Film Evaporator 2 (TFE-102). Ascorbic acid is crystallized into solid form by Crystallizer (CR-101) at 4 °C for 54 hours. After that, the final product and slurry components are filtered by Nutsche Filter (NFD-101). The slurry components are split into Storage 2 (V-102) for recycling purpose as it major consist of sorbitol and sorbose. In the final step, solid ascorbic acid (99.5%) is being fed into solid storage (SL-101) at 4 °C.

3.6.2 PROCESS DESCRIPTION

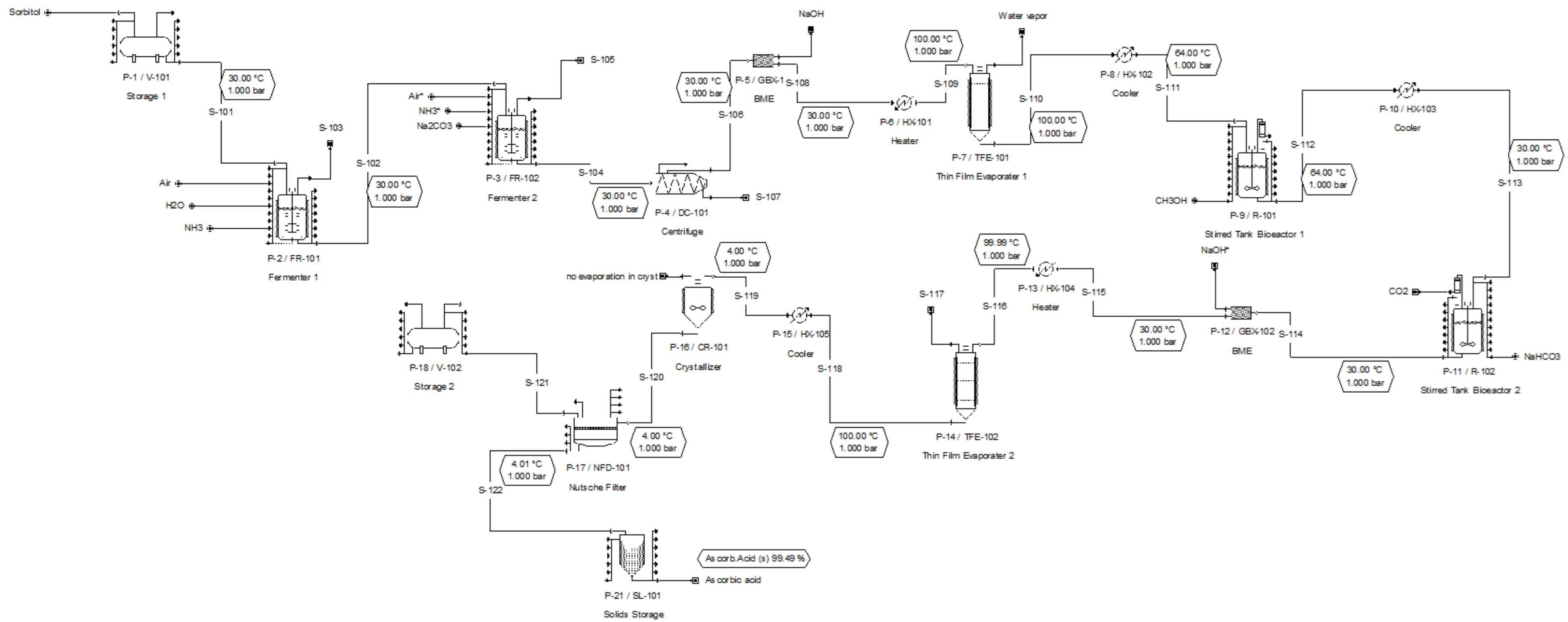


Figure 3.5 Completed Process Flow Diagram of Producing Ascorbic Acid

3.6.3 PLANT LAYOUT

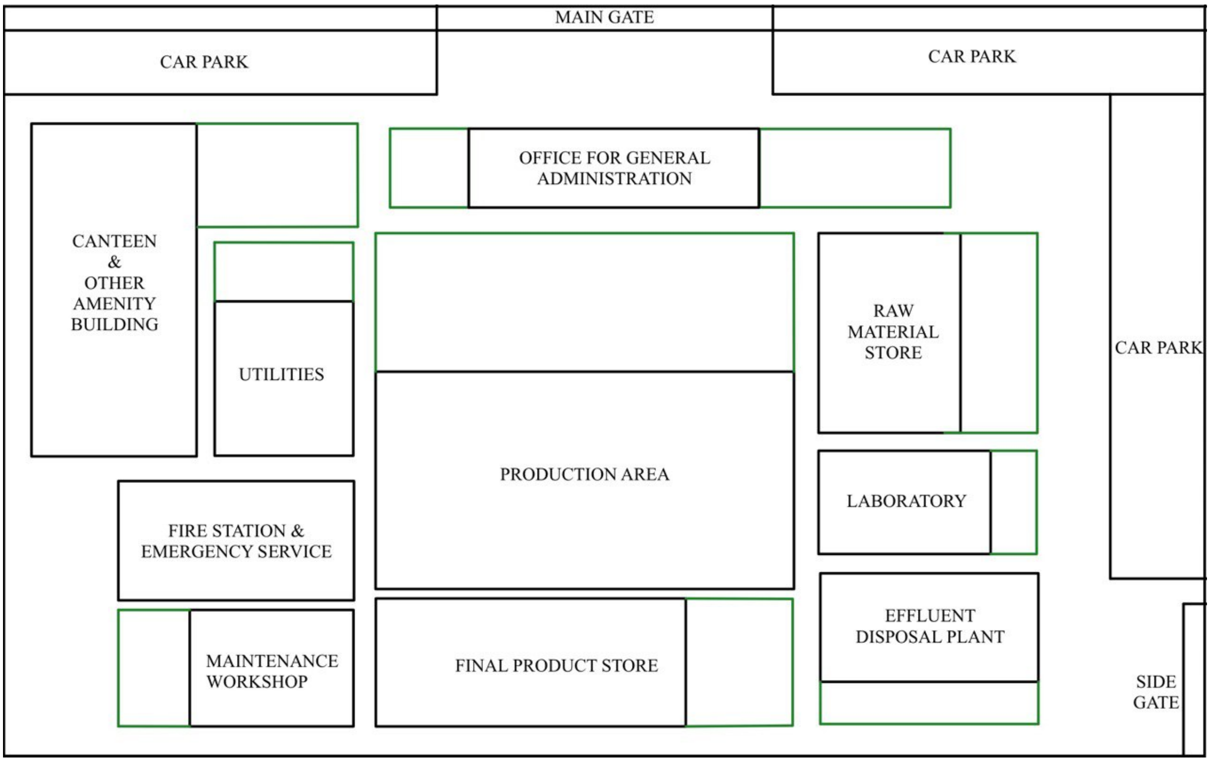


Figure 3.6 Plant Layout with Possible Expansion

Figure 3.6 illustrates the layout design of the plant, with black boxes indicating the existing layout and green boxes representing areas earmarked for potential expansion. Two gates are designated within the plant premises, serving distinct purposes. The main gate serves as the focal point for visitor registration, issuing identification tags required for access within the plant compound. Conversely, the side gate is dedicated solely to the loading and unloading of products and raw materials, streamlining logistical operations. Essential amenities are provided for workers, including an on-site canteen for convenient access to meals. Additionally, the plant encompasses various facilities such as offices, utilities areas, a fire station, and emergency services strategically positioned adjacent to the production area. A maintenance workshop and warehouse cater to operational needs, ensuring seamless workflow and efficient storage of raw materials and products. Quality control is maintained through a dedicated laboratory, while environmental sustainability is addressed with the inclusion of an effluent disposal plant. Ample parking spaces are allocated for workers, enhancing accessibility, and minimizing congestion. Overall, the plant layout is meticulously designed to optimize operations, prioritize worker welfare, and uphold safety and environmental standards.

CHAPTER 4

MASS AND ENERGY BALANCE

4.1 ASSUMPTION

This chapter will include the manual mass balance and energy balance for the overall unit operation and stream. The mass flowrate and molar flowrate of each component are tabulated in mass and energy balance tables.

For the manual material balance calculation, the equation below shows the concept.

Input + Generation – Output – Consumption = Accumulation

where
Input = Total mass enters through system boundary
Generation = Total mass produced within system
Output = Total mass leaves through system boundary
Consumption = Total mass consumed within the system
Accumulation = Total mass build up within the system

Assumptions:

1. All calculations are performed in the unit of kg/batch.
2. The system is in steady state; hence, accumulation is equal to zero.
3. All components in the system behave as ideal condition.
4. No leakage in the pipes and vessels in the system.
5. The plant operates 24 hours daily for 330 days per year, with another 35 days off for cleaning and maintenance including public holidays.
6. The total input of any substance to valves, heater and cooler is assumed equal to the total output of the substance.
7. 70% purity of sorbitol is used.

Final equation of mass balance:

$$\boldsymbol{mass\ flow\ rate}_{\boldsymbol{in}} = \boldsymbol{mass\ flow\ rate}_{\boldsymbol{out}}$$

For manual energy balance calculation, the general formula for energy balance is:

Energy Out– Energy In = Kinetic Energy + Potential Energy + Internal Energy + Shaft Work

Assumptions:

1. The system is in steady-state condition in all equipment.
2. The standard reference state for enthalpy is T_{ref} =25°C and P_{ref} =1 atm.
3. No temperature increases or decrease in the storage.
4. No pressures change for heater and cooler.
8. There is no heat loss in the piping system and the tanks, adiabatic condition.
9. Kinetics, potential energy, and shaft work are neglected in the manual calculation.

Final equation of energy balance:

Energy Out– Energy In + Heat of reaction + Heat of vapourisation = Net energy transferred to the system

$$\sum \dot{n}_{out} H_{out} - \sum \dot{n}_{in} H_{in} + \Delta H_v + \Delta H_{rec} = \Delta H$$

4.2 MASS BALANCE FOR EACH EQUIPMENT

4.2.1 STORAGE 1 (V-101)

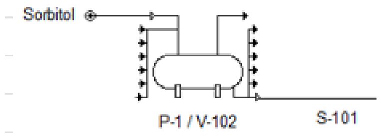


Figure 4.1 Inlet and outlet stream for V-101

Table 4.1 Summary table of mass balance for V-101

Stream		Inlet		Outlet	
		Sorbitol		S-101	
Total Mass Flow Rate (kg/batch)		45000		45000	
Temperature (°C)		30		30	
Pressure (bar)		1		1	
Component	**MW (kg/kmol)**	**Mass Flow Rate (kg/batch)**	**Molar Flow Rate (kmol/batch)**	**Mass Flow Rate (kg/batch)**	**Molar Flow Rate (kmol/batch)**
Liq/Sol Phase					
Sorbitol	182.174	31500.0000	172.9116	31500.0000	172.9116
Water	18.0151	13500.0000	749.3714	13500.0000	749.3714
Total		45000.0000	922.2830	45000.0000	922.2830

4.2.2 FERMENTER 1 (FR-101)

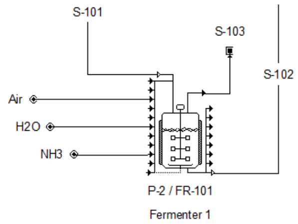


Figure 4.2 Inlet and outlet stream for FR-101

Table 4.2 Summary table of mass balance for FR-101

Stream		Inlet							
		S-101		Air		H2O		NH3	
Total Mass Flow Rate (kg/batch)		107822.0000							
Temperature (°C)		30		30		30		30	
Pressure (bar)		1		1		1		1	
Component	**MW (kg/kmol)**	**Mass Flow Rate (kg/batch)**	**Molar Flow Rate (kmol/batch)**	**Mass Flow Rate (kg/batch)**	**Molar Flow Rate (kmol/batch)**	**Mass Flow Rate (kg/batch)**	**Molar Flow Rate (kmol/batch)**	**Mass Flow Rate (kg/batch)**	**Molar Flow Rate (kmol/batch)**
Liq/Sol Phase									
Sorbitol	182.174	31500.0000	172.9116	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Water	18.0151	13500.0000	749.3714	0.0000	0.0000	50000.0000	2775.4495	0.0000	0.0000
Sorbose	180.16	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Biomass	24.63	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Vapour Phase									
Ammonia	17.03	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	22.0000	1.2918
Carbon Dioxide	44.01	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000

Oxygen	31.999	0.0000	0.0000	2980.8896	93.1557	0.0000	0.0000	0.0000	0.0000
Nitrogen	28.013	0.0000	0.0000	9819.1104	350.5198	0.0000	0.0000	0.0000	0.0000
Total		45000.0000	922.2830	12800.0000	443.6755	50000.0000	2775.4495	22.0000	1.2918

Table 24 Summary table of mass balance for FR-101 (Cont'd)

Stream		**Outlet**			
		S-102		S-103	
Total Mass Flow Rate (kg/batch)		107822.0730			
Temperature (°C)		30		30	
Pressure (bar)		1		1	
Component	**MW (kg/kmol)**	**Mass Flow Rate (kg/batch)**	**Molar Flow Rate (kmol/batch)**	**Mass Flow Rate (kg/batch)**	**Molar Flow Rate (kmol/batch)**
Liq/Sol Phase					
Sorbitol	182.174	630.0000	3.4582	0.0000	0.0000
Water	18.0151	66669.3335	3700.7473	0.0000	0.0000
Sorbose	180.16	30223.4337	167.7588	0.0000	0.0000
Biomass	24.63	152.7551	6.2020	0.0000	0.0000

Vapour Phase					
Ammonia	17.03	0.0000	0.0000	0.8760	0.0514
Carbon Dioxide	44.01	0.0000	0.0000	174.5089	3.9652
Oxygen	31.999	0.0000	0.0000	152.0555	4.7519
Nitrogen	28.013	0.0000	0.0000	9819.1104	350.5198
Total		97675.5223	3878.1664	10146.5508	359.2883

4.2.3 FERMENTER 2 (FR-102)

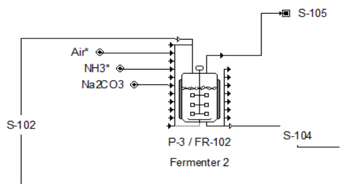


Figure 4.3 Inlet and outlet stream for FR-102

Table 4.3 Summary table of mass balance and energy balance for FR-102

Stream		**Inlet**							
		S-102		Air*		NH3*		Na2CO3	
Total Mass Flow Rate (kg/batch)		129228.5223							
Temperature (°C)		30		30		30		30	
Pressure (bar)		1		1		1		1	
Component	**MW (kg/kmol)**	**Mass Flow Rate (kg/batch)**	**Molar Flow Rate (kmol/batch)**	**Mass Flow Rate (kg/batch)**	**Molar Flow Rate (kmol/batch)**	**Mass Flow Rate (kg/batch)**	**Molar Flow Rate (kmol/batch)**	**Mass Flow Rate (kg/batch)**	**Molar Flow Rate (kmol/batch)**
Liq/Sol Phase									
Sorbitol	182.174	630.0000	3.4582	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Water	18.0151	66669.3335	3700.7473	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000

Sorbose	180.16	30223.4337	167.7588	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Biomass	24.63	152.7551	6.2020	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Sodium Carbonate	105.989	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	8532.0000	80.4989
Sodium Glucuronate	216.12	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Vapour phase									
Ammonia	17.03	0.0000	0.0000	0.0000	0.0000	21.0000	1.2331	0.0000	0.0000
Carbon Dioxide	44.01	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Oxygen	31.999	0.0000	0.0000	5356.2860	167.3892	0.0000	0.0000	0.0000	0.0000
Nitrogen	28.013	0.0000	0.0000	17643.7140	629.8402	0.0000	0.0000	0.0000	0.0000
Total		97675.5223	3878.1664	23000	797.2294	21.0000	1.2331	8532.0000	80.4989

Table 25 Summary table of mass balance and energy balance for FR-102 (Cont'd)

Stream	Outlet	
	S-104	S-105
Total Mass Flow Rate (kg/batch)	129228.4925	
Temperature (°C)	30	30
Pressure (bar)	1	1

Component	MW (kg/kmol)	Mass Flow Rate (kg/batch)	Molar Flow Rate (kmol/batch)	Mass Flow Rate (kg/batch)	Molar Flow Rate (kmol/batch)
Liq/Sol Phase					
Sorbitol	182.174	630.0000	3.4582	0.0000	0.0000
Water	18.0151	70167.5526	3894.9300	0.0000	0.0000
Sorbose	180.16	7253.6241	40.2621	0.0000	0.0000
Biomass	24.63	267.6880	10.8684	0.0000	0.0000
Sodium Carbonate	105.989	1842.9412	17.3880	0.0000	0.0000
Sodium Glucuronate	216.12	27279.0458	126.2218	0.0000	0.0000
Vapour phase					
Ammonia	17.03	0.0000	0.0000	5.8011	0.3406
Carbon Dioxide	44.01	0.0000	0.0000	2908.8102	66.0943
Oxygen	31.999	0.0000	0.0000	1229.3155	38.4173
Nitrogen	28.013	0.0000	0.0000	17643.7140	629.8402
Total		107440.8517	4093.1285	21787.6408	734.6925

4.2.4 CENTRIFUGATE (DC-101)

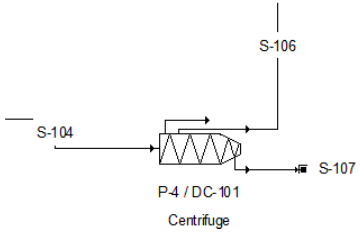


Figure 4.4 Inlet and outlet stream for DC-101

Table 4.4 Summary table of mass balance and energy balance for DC-101

Stream		Inlet		Outlet			
		S-104		S-106		S-107	
Total Mass Flow Rate (kg/batch)		107440.8517		107440.8517			
Temperature (°C)		30		30		30	
Pressure (bar)		1		1		1	
Component	**MW (kg/kmol)**	**Mass Flow Rate (kg/batch)**	**Molar Flow Rate (kmol/batch)**	**Mass Flow Rate (kg/batch)**	**Molar Flow Rate (kmol/batch)**	**Mass Flow Rate (kg/batch)**	**Molar Flow Rate (kmol/batch)**
Liq/Sol Phase							
Sorbitol	182.174	630.0000	3.4582	629.9685	3.4581	0.0315	0.0002

Water	18.0151	70167.5526	3894.9300	70164.0442	3894.7352	3.5084	0.1947
Sorbose	180.16	7253.6241	40.2621	7253.2614	40.2601	0.3627	0.0020
Biomass	24.63	267.6880	10.8684	0.0000	0.0000	267.6880	10.8684
Sodium Carbonate	105.989	1842.9412	17.3880	1842.8490	17.3872	0.0921	0.0009
Sodium Glucuronate	216.12	27279.0458	126.2218	27277.6819	126.2154	1.3640	0.0063
Total		107440.8517	4093.1285	107167.8050	4082.0560	273.0467	11.0725

4.2.5 BIPOLAR MEMBRANE ELECTRODIALYSIS 1 (GBX-101)

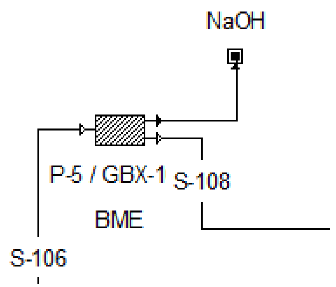


Figure 4.5 Inlet and outlet stream for GBX-101

Table 4.5 Summary table of mass balance and energy balance for GBX-101

Stream		Inlet		Outlet			
		S-106		S-108		NaOH	
Total Mass Flow Rate (kg/batch)		107167.8050		107168.0448			
Temperature (°C)		30		30		30	
Pressure (bar)		1		1		1	
Component	**MW (kg/kmol)**	**Mass Flow Rate (kg/batch)**	**Molar Flow Rate (kmol/batch)**	**Mass Flow Rate (kg/batch)**	**Molar Flow Rate (kmol/batch)**	**Mass Flow Rate (kg/batch)**	**Molar Flow Rate (kmol/batch)**
Liq/Sol Phase							
Sorbitol	182.174	629.9685	3.4581	629.9685	3.4581	0.0000	0.0000
Water	18.0151	70164.0442	3894.7352	67890.2604	3768.5198	0.0000	0.0000
Sorbose	180.16	7253.2614	40.2601	7253.2614	40.2601	0.0000	0.0000
Sodium Carbonate	105.989	1842.8490	17.3872	1842.8490	17.3872	0.0000	0.0000
Sodium Glucuronate	216.12	27277.6819	126.2154	0.0000	0.0000	0.0000	0.0000
2-ketogluconic acid	194.14	0.0000	0.0000	24503.4664	126.2154	0.0000	0.0000
Sodium Hydroxide	39.997	0.0000	0.0000	0.0000	0.0000	5048.2391	126.2154
Total		107167.8050	4082.0560	102119.8057	3955.8405	5048.2391	126.2154

4.2.6 HEATER 1 (HX-101)

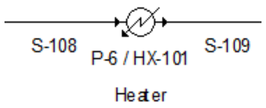


Figure 4.6 Inlet and outlet stream for HX-101

Table 4.6 Summary table of mass balance and energy balance for HX-101

Stream		Inlet		Outlet	
		S-108		S-109	
Total Mass Flow Rate (kg/batch)		102119.8057		102119.8057	
Temperature (°C)		30		90	
Pressure (bar)		1		1	
Component	**MW (kg/kmol)**	**Mass Flow Rate (kg/batch)**	**Molar Flow Rate (kmol/batch)**	**Mass Flow Rate (kg/batch)**	**Molar Flow Rate (kmol/batch)**
Liq/Sol Phase					
Sorbitol	182.174	629.9685	3.4581	629.9685	3.4581
Water	18.0151	67890.2604	3768.5198	67890.2604	3768.5198
Sorbose	180.16	7253.2614	40.2601	7253.2614	40.2601
Sodium Carbonate	105.989	1842.8490	17.3872	1842.8490	17.3872
2-ketogluconic acid	194.14	24503.4664	126.2154	24503.4664	126.2154
Sodium Hydroxide	39.997	0.0000	0.0000	0.0000	0.0000
Total		102119.8057	3955.8405	102119.8057	3955.8405

4.2.7 THIN FILM EVAPORATOR 1 (TFE-101)

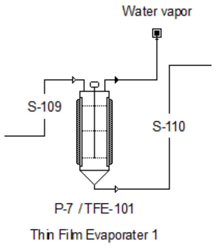


Figure 4.7 Inlet and outlet stream for TFE-101

Table 4.7 Summary table of mass balance and energy balance for TFE-101

Stream		Inlet		Outlet			
		S-109		Water vapor		S-110	
Total Mass Flow Rate (kg/batch)		102119.8057		102119.8057			
Temperature (°C)		90		90		90	
Pressure (bar)		1		1		1	
Component	**MW (kg/kmol)**	**Mass Flow Rate (kg/batch)**	**Molar Flow Rate (kmol/batch)**	**Mass Flow Rate (kg/batch)**	**Molar Flow Rate (kmol/batch)**	**Mass Flow Rate (kg/batch)**	**Molar Flow Rate (kmol/batch)**
Liq/Sol Phase							
Sorbitol	182.174	629.9685	3.4581	0.0000	0.0000	629.9685	3.4581
Water	18.0151	67890.2604	3768.5198	0.0000	0.0000	6789.0260	376.8520
Sorbose	180.16	7253.2614	40.2601	0.0000	0.0000	7253.2614	40.2601
Sodium Carbonate	105.989	1842.8490	17.3872	0.0000	0.0000	1842.8490	17.3872
2-ketogluconic acid	194.14	24503.4664	126.2154	0.0000	0.0000	24503.4664	126.2154
Vapour phase							
Water	18.0151	0.0000	0.0000	61101.2343	3391.6678	0.0000	0.0000
Total		102119.8057	3955.8405	61101.2343	3391.6678	41018.5714	564.1728

4.2.8 COOLER 1 (HX-102)

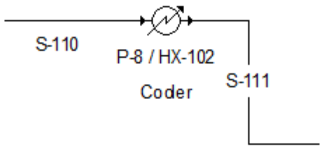


Figure 4.8 Inlet and outlet stream for HX-102

Table 4.8 Summary table of mass balance and energy balance for HX -102

Stream		Inlet		Outlet	
		S-110		S-111	
Total Mass Flow Rate (kg/batch)		41018.5714		41018.5714	
Temperature (°C)		100		64	
Pressure (bar)		1		1	
Component	**MW (kg/kmol)**	**Mass Flow Rate (kg/batch)**	**Molar Flow Rate (kmol/batch)**	**Mass Flow Rate (kg/batch)**	**Molar Flow Rate (kmol/batch)**
Liq/Sol Phase					
Sorbitol	182.174	629.9685	3.4581	629.9685	3.4581
Water	18.0151	6789.0260	376.8520	6789.0260	376.8520
Sorbose	180.16	7253.2614	40.2601	7253.2614	40.2601
Sodium Carbonate	105.989	1842.8490	17.3872	1842.8490	17.3872
2-ketogluconic acid	194.14	24503.4664	126.2154	24503.4664	126.2154
Total		41018.5714	564.1728	41018.5714	564.1728

4.2.9 STIRRED TANK BIOREACTOR 1 (R-101)

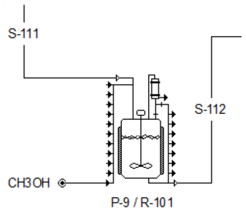


Figure 4.9 Inlet and outlet stream for R-101

Table 4.9 Summary table of mass balance and energy balance for R-101

Stream		Inlet				Outlet	
		S-111		CH3OH		S-112	
Total Mass Flow Rate (kg/batch)		46176.9127				46177.3039	
Temperature (°C)		64		30		64	
Pressure (bar)		1		1		1	
Component	**MW (kg/kmol)**	**Mass Flow Rate (kg/batch)**	**Molar Flow Rate (kmol/batch)**	**Mass Flow Rate (kg/batch)**	**Molar Flow Rate (kmol/batch)**	**Mass Flow Rate (kg/batch)**	**Molar Flow Rate (kmol/batch)**
Liq/Sol Phase							
Sorbitol	182.174	629.9685	3.4581	0.0000	0.0000	629.9685	3.4581
Water	18.0151	6789.0260	376.8520	0.0000	0.0000	9062.8099	503.0674
Sorbose	180.16	7253.2614	40.2601	0.0000	0.0000	7253.2614	40.2601
Sodium Carbonate	105.989	1842.8490	17.3872	0.0000	0.0000	1842.8490	17.3872
2-ketogluconic acid	194.14	24503.4664	126.2154	0.0000	0.0000	0.0000	0.0000
Methanol	32.042	0.0000	0.0000	5158.34128	160.9869	1114.1460	34.7714
Methyl 2-keto-L-gulonate	208.17	0.0000	0.0000	0.0000	0.0000	26274.2691	126.2154

Total		41018.5714	564.1728	5158.3413	160.9869	46177.3039	725.1596

4.2.10 COOLER 2 (HX-103)

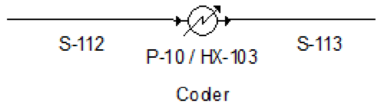


Figure 4.10 Inlet and outlet stream for HX-103

Table 4.10 Summary table of mass balance and energy balance for HX-103

Stream		Inlet		Outlet	
		S-112		S-113	
Total Mass Flow Rate (kg/batch)		46177.3039		46177.3039	
Temperature (°C)		64		30	
Pressure (bar)		1		1	
Component	**MW (kg/kmol)**	**Mass Flow Rate (kg/batch)**	**Molar Flow Rate (kmol/batch)**	**Mass Flow Rate (kg/batch)**	**Molar Flow Rate (kmol/batch)**
Liq/Sol Phase					
Sorbitol	182.174	629.9685	3.4581	629.9685	3.4581
Water	18.0151	9062.8099	503.0674	9062.8099	503.0674
Sorbose	180.16	7253.2614	40.2601	7253.2614	40.2601

Sodium Carbonate	105.989	1842.8490	17.3872	1842.8490	17.3872
2-ketogluconic acid	194.14	0.0000	0.0000	0.0000	0.0000
Methanol	32.042	1114.1460	34.7714	1114.1460	34.7714
Methyl 2-keto-L-gulonate	208.17	26274.2691	126.2154	26274.2691	126.2154
Total		46177.3039	725.1596	46177.3039	725.1596

4.2.11 STIRRED TANK BIOREACTOR 2 (R-102)

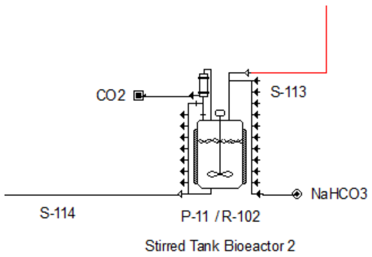


Figure 4.11 Inlet and outlet stream for R-102

Table 4.11 Summary table of mass balance and energy balance for R-102

Stream	Inlet		Outlet	
	S-113	NaHCO3	S-114	CO2
Total Mass Flow Rate (kg/batch)	59701.3279		59700.8357	
Temperature (°C)	30	30	30	30

Pressure (bar)		1		1		1		1	
Component	**MW (kg/kmol)**	**Mass Flow Rate (kg/batch)**	**Molar Flow Rate (kmol/batch)**	**Mass Flow Rate (kg/batch)**	**Molar Flow Rate (kmol/batch)**	**Mass Flow Rate (kg/batch)**	**Molar Flow Rate (kmol/batch)**	**Mass Flow Rate (kg/batch)**	**Molar Flow Rate (kmol/batch)**
Liq/Sol Phase									
Sorbitol	182.174	629.9685	3.4581	0.0000	0.0000	629.9685	3.4581	0.0000	0.0000
Water	18.0151	9062.8099	503.0674	0.0000	0.0000	11336.5937	629.2829	0.0000	0.0000
Sorbose	180.16	7253.2614	40.2601	0.0000	0.0000	7253.2614	40.2601	0.0000	0.0000
Sodium Carbonate	105.989	1842.8490	17.3872	0.0000	0.0000	1842.8490	17.3872	0.0000	0.0000
Methanol	32.042	1114.1460	34.7714	0.0000	0.0000	5158.3413	160.9869	0.0000	0.0000
Methyl 2-keto-L-gulonate	208.17	26274.2691	126.2154	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Sodium Bicarbonate	84.007	0.0000	0.0000	13524.024	160.9869	2921.0431	34.7714	0.0000	0.0000
Sodium Ascorbate	198.106	0.0000	0.0000	0.0000	0.0000	25004.0369	126.2154	0.0000	0.0000
Vapour phase									
Carbon Dioxide	44.01	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	5554.74172	126.2154
Total		46177.3039	725.1596	13524.0240	160.9869	54146.0939	1012.3619	5554.7417	126.2154

4.2.12 BIPOLAR MEMBRANE ELECTRODIALYSIS 2 (GBX-102)

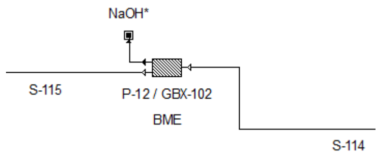


Figure 4.12 Inlet and outlet stream for GBX-102

Table 4.12 Summary table of mass balance and energy balance for GBX-102

Stream		Inlet		Outlet			
		S-114		S-115		NaOH*	
Total Mass Flow Rate (kg/batch)		54146.0939		54146.3337			
Temperature (°C)		30		30		30	
Pressure (bar)		1		1		1	
Component	**MW (kg/kmol)**	**Mass Flow Rate (kg/batch)**	**Molar Flow Rate (kmol/batch)**	**Mass Flow Rate (kg/batch)**	**Molar Flow Rate (kmol/batch)**	**Mass Flow Rate (kg/batch)**	**Molar Flow Rate (kmol/batch)**
Liq/Sol Phase							
Sorbitol	182.174	629.9685	3.4581	629.9685	3.4581	0.0000	0.0000
Water	18.0151	11336.5937	629.2829	9062.8099	503.0674	0.0000	0.0000
Sorbose	180.16	7253.2614	40.2601	7253.2614	40.2601	0.0000	0.0000
Sodium Carbonate	105.989	1842.8490	17.3872	1842.8490	17.3872	0.0000	0.0000

Sodium Hydroxide	39.997	0.0000	0.0000	0.0000	0.0000	5048.23914	126.2154
Methanol	32.042	5158.3413	160.9869	5158.3413	160.9869	0.0000	0.0000
Methyl 2-keto-L-gulonate	208.17	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Sodium Bicarbonate	84.007	2921.0431	34.7714	2921.0431	34.7714	0.0000	0.0000
Sodium Ascorbate	198.106	25004.0369	126.2154	0.0000	0.0000	0.0000	0.0000
Ascorbic Acid (l)	176.126	0.0000	0.0000	22229.8214	126.2154	0.0000	0.0000
Total		54146.0939	1012.3619	49098.0946	886.1465	5048.2391	126.2154

4.2.13 HEATER 2 (HX-104)

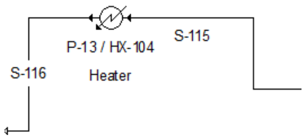


Figure 4.13 Inlet and outlet stream for HX-104

Table 4.13 Summary table of mass balance and energy balance for HX-104

Stream	Inlet	Outlet
	S-115	S-116
Total Mass Flow Rate (kg/batch)	49098.0946	49098.0946
Temperature (°C)	30	30
Pressure (bar)	1	1

Component	MW (kg/kmol)	Mass Flow Rate (kg/batch)	Molar Flow Rate (kmol/batch)	Mass Flow Rate (kg/batch)	Molar Flow Rate (kmol/batch)
Liq/Sol Phase					
Sorbitol	182.174	629.9685	3.4581	629.9685	3.4581
Water	18.0151	9062.8099	503.0674	9062.8099	503.0674
Sorbose	180.16	7253.2614	40.2601	7253.2614	40.2601
Sodium Carbonate	105.989	1842.8490	17.3872	1842.8490	17.3872
Sodium Hydroxide	39.997	0.0000	0.0000	0.0000	0.0000
Methanol	32.042	5158.3413	160.9869	5158.3413	160.9869
Methyl 2-keto-L-gulonate	208.17	0.0000	0.0000	0.0000	0.0000
Sodium Bicarbonate	84.007	2921.0431	34.7714	2921.0431	34.7714
Sodium Ascorbate	198.106	0.0000	0.0000	0.0000	0.0000
Ascorbic Acid (l)	176.126	22229.8214	126.2154	22229.8214	126.2154
Total		49098.0946	886.1465	49098.0946	886.1465

4.2.14 THIN FILM EVAPORATOR 2 (TFE-102)

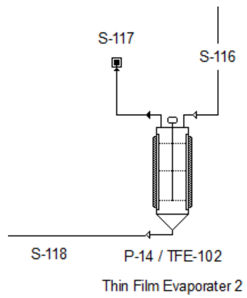


Figure 4.14 Inlet and outlet stream TFE-102

Table 4.4.14 Summary table of mass balance and energy balance for TFE-102

Stream		Inlet		Outlet			
		S-116		S-118		S-117	
Total Mass Flow Rate (kg/batch)		49098.0946		49098.0946			
Temperature (°C)		30		90		90	
Pressure (bar)		1		1		1	
Component	**MW (kg/kmol)**	**Mass Flow Rate (kg/batch)**	**Molar Flow Rate (kmol/batch)**	**Mass Flow Rate (kg/batch)**	**Molar Flow Rate (kmol/batch)**	**Mass Flow Rate (kg/batch)**	**Molar Flow Rate (kmol/batch)**
Liq/Sol Phase							
Sorbitol	182.174	629.9685	3.4581	629.9685	3.4581	0.0000	0.0000
Water	18.0151	9062.8099	503.0674	906.2810	50.3067	0.0000	0.0000
Sorbose	180.16	7253.2614	40.2601	7253.2614	40.2601	0.0000	0.0000
Sodium Carbonate	105.989	1842.8490	17.3872	1842.8490	17.3872	0.0000	0.0000
Sodium Hydroxide	39.997	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Methanol	32.042	5158.3413	160.9869	0.0000	0.0000	0.0000	0.0000
Methyl 2-keto-L-gulonate	208.17	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Sodium Bicarbonate	84.007	2921.0431	34.7714	2921.0431	34.7714	0.0000	0.0000
Sodium Ascorbate	198.106	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Ascorbic Acid (l)	176.126	22229.8214	126.2154	22229.8214	126.2154	0.0000	0.0000
Vapour phase							
Water	18.0151	0.0000	0.0000	0.0000	0.0000	8156.5289	452.7607
Methanol	32.042	0.0000	0.0000	0.0000	0.0000	5158.3413	160.9869
Total		49098.0946	886.1465	35783.2244	272.3990	13314.8702	613.7475

4.2.15 COOLER 3 (HX-105)

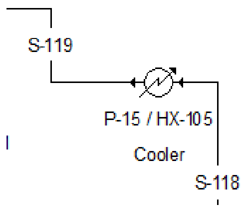


Figure 4.15 Inlet and outlet stream HX-105

Table 4.15 Summary table of mass balance and energy balance for HX-105

Stream		Inlet		Outlet	
		S-118		S-119	
Total Mass Flow Rate (kg/batch)		35783.2244		35783.2244	
Temperature (°C)		90		4	
Pressure (bar)		1		1	
Component	**MW (kg/kmol)**	**Mass Flow Rate (kg/batch)**	**Molar Flow Rate (kmol/batch)**	**Mass Flow Rate (kg/batch)**	**Molar Flow Rate (kmol/batch)**
Liq/Sol Phase					
Sorbitol	182.174	629.9685	3.4581	629.9685	3.4581
Water	18.0151	906.2810	50.3067	906.2810	50.3067
Sorbose	180.16	7253.2614	40.2601	7253.2614	40.2601
Sodium Carbonate	105.989	1842.8490	17.3872	1842.8490	17.3872
Sodium Hydroxide	39.997	0.0000	0.0000	0.0000	0.0000
Methanol	32.042	0.0000	0.0000	0.0000	0.0000

Methyl 2-keto-L-gulonate	208.17	0.0000	0.0000	0.0000	0.0000
Sodium Bicarbonate	84.007	2921.0431	34.7714	2921.0431	34.7714
Sodium Ascorbate	198.106	0.0000	0.0000	0.0000	0.0000
Ascorbic Acid (l)	176.126	22229.8214	126.2154	22229.8214	126.2154
Total		35783.2244	272.3990	35783.2244	272.3990

4.2.16 CRYSTALLIZER (CR-101)

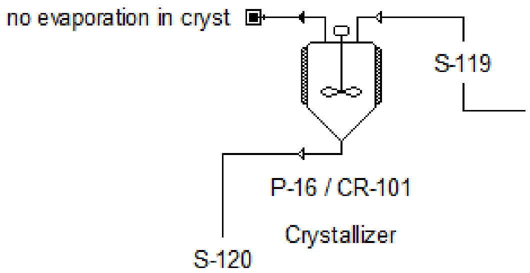


Figure 4.16 Inlet and outlet stream CR-101

Table 4.16 Summary table of mass balance and energy balance for CR-101

Stream		Inlet		Outlet	
		S-119		S-120	
Total Mass Flow Rate (kg/batch)		35783.2244		35783.2244	
Temperature (°C)		4		4	
Pressure (bar)		1		1	
Component	**MW (kg/kmol)**	**Mass Flow Rate (kg/batch)**	**Molar Flow Rate (kmol/batch)**	**Mass Flow Rate (kg/batch)**	**Molar Flow Rate (kmol/batch)**
Liq/Sol Phase					
Sorbitol	182.174	629.9685	3.4581	629.9685	3.4581
Water	18.0151	906.2810	50.3067	906.2810	50.3067
Sorbose	180.16	7253.2614	40.2601	7253.2614	40.2601
Sodium Carbonate	105.989	1842.8490	17.3872	1842.8490	17.3872
Sodium Hydroxide	39.997	0.0000	0.0000	0.0000	0.0000
Methanol	32.042	0.0000	0.0000	0.0000	0.0000
Methyl 2-keto-L-gulonate	208.17	0.0000	0.0000	0.0000	0.0000
Sodium Bicarbonate	84.007	2921.0431	34.7714	2921.0431	34.7714
Sodium Ascorbate	198.106	0.0000	0.0000	0.0000	0.0000
Ascorbic Acid (l)	176.126	22229.8214	126.2154	2222.9821	12.6215
Ascorbic Acid (s)	176.126	0.0000	0.0000	20006.8393	113.5939
Total		35783.2244	272.3990	35783.2244	272.3990

4.2.17 NUTSCHE FILTER (NFD-101)

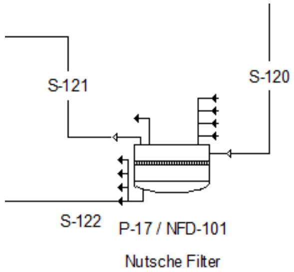


Figure 4.17 Inlet and outlet stream NFD-101

Table 4.17 Summary table of mass balance and energy balance for NFD-101

Stream		Inlet		Outlet			
		S-120		S-122		S-121	
Total Mass Flow Rate (kg/batch)		35783.2244		35783.2244			
Temperature (°C)		4		4		4	
Pressure (bar)		1		1		1	
Component	**MW (kg/kmol)**	**Mass Flow Rate (kg/batch)**	**Molar Flow Rate (kmol/batch)**	**Mass Flow Rate (kg/batch)**	**Molar Flow Rate (kmol/batch)**	**Mass Flow Rate (kg/batch)**	**Molar Flow Rate (kmol/batch)**
Liq/Sol Phase							
Sorbitol	182.174	629.9685	3.4581	0.0000	0.0000	629.9685	3.4581
Water	18.0151	906.2810	50.3067	90.6281	5.0307	815.6529	45.2761
Sorbose	180.16	7253.2614	40.2601	0.0000	0.0000	7253.2614	40.2601

Sodium Carbonate	105.989	1842.8490	17.3872	0.0000	0.0000	1842.8490	17.3872
Sodium Hydroxide	39.997	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Methanol	32.042	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Methyl 2-keto-L-gulonate	208.17	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Sodium Bicarbonate	84.007	2921.0431	34.7714	0.0000	0.0000	2921.0431	34.7714
Sodium Ascorbate	198.106	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Ascorbic Acid (l)	176.126	2222.9821	12.6215	0.0000	0.0000	2222.9821	12.6215
Ascorbic Acid (s)	176.126	20006.8393	113.5939	18006.1553	102.2345	2000.6839	11.3594
Total		35783.2244	272.3990	18096.7834	107.2652	17686.4410	165.1338

4.2.18 STORAGE 2 (V-102)

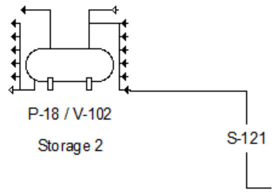


Figure 4.18 Inlet and outlet stream V-102

Table 4.18 Summary table of mass balance and energy balance for V-102

Stream		Inlet	
		S-121	
Total Mass Flow Rate (kg/batch)		17686.4410	
Temperature (°C)		4	
Pressure (bar)		1	
Component	**MW (kg/kmol)**	**Mass Flow Rate (kg/batch)**	**Molar Flow Rate (kmol/batch)**
Liq/Sol Phase			
Sorbitol	182.174	629.9685	3.4581
Water	18.0151	815.6529	45.2761
Sorbose	180.16	7253.2614	40.2601
Sodium Carbonate	105.989	1842.8490	17.3872
Sodium Hydroxide	39.997	0.0000	0.0000
Methanol	32.042	0.0000	0.0000
Methyl 2-keto-L-gulonate	208.17	0.0000	0.0000
Sodium Bicarbonate	84.007	2921.0431	34.7714
Sodium Ascorbate	198.106	0.0000	0.0000
Ascorbic Acid (l)	176.126	2222.9821	12.6215
Ascorbic Acid (s)	176.126	2000.6839	11.3594
Total		17686.4410	165.1338

4.2.19 SOLID STORAGE (V-103)

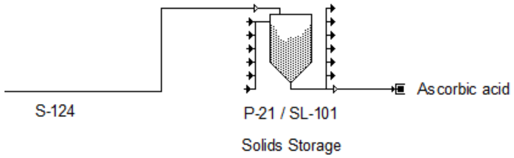


Figure 4.19 Inlet and outlet stream SL-101

Table 4.19 Summary table of mass balance and energy balance for SL-101

Stream		**Inlet**		**Outlet**	
		S-122		Ascorbic Acid	
Total Mass Flow Rate (kg/batch)		18096.7834		18096.7834	
Temperature (°C)		4		4	
Pressure (bar)		1		1	
Component	**MW (kg/kmol)**	**Mass Flow Rate (kg/batch)**	**Molar Flow Rate (kmol/batch)**	**Mass Flow Rate (kg/batch)**	**Molar Flow Rate (kmol/batch)**
Liq/Sol Phase					
Water	18.0151	90.6281	5.0307	90.6281	5.0307
Ascorbic Acid (s)	176.126	18006.1553	102.2345	18006.1553	102.2345
Vapour Phase					
Water	18.0151	0.0000	0.0000	0.0000	0.0000
Total		18096.7834	107.2652	18096.7834	107.2652

4.3 ENERGY BALANCE BY EQUIPMENT

Table 4.20 Summary of Manual Energy Balance by Streams

Equipment	Stream	Component	State	ΔHin/out + ΔHv (kJ/batch)		ΔHr (kJ/batch)	ΔH (kJ/batch)
Storage	**Sorbitol**	Sorbitol	Liquid	569119.69	569119.69	0.00	0.00
		Water	Liquid				
	S-101	Sorbitol	Liquid	569119.69	569119.69		
		Water	Liquid				
Fermenter 1	**S-101**	Sorbitol	Liquid	824844.14	824844.14	-36534465	-36571617.32
		Water	Liquid				
	Air	Air	Liquid	64819.46	64819.46		
	H2O	Water	Liquid	1044124.10	1044124.10		
	NH3	Ammonia	Gas	26510.67	26510.67		
	S-102	Sorbitol	Liquid	5744.12	1592916.05		

		Sorbose	Liquid	191756.75			
		Biomass	Solid	3194.03			
		Water	Liquid	1392221.15			
	S-103	Carbon dioxide	Gas	21546.94	74505.53		
		Oxygen	Gas	698.03			
		Nitrogen	Gas	51135.40			
		Ammonia	Gas	1125.17			
Fermenter 2	**S-102**	Sorbitol	Liquid	5744.12	1592916.05	6464489.3	6849035.22
		Sorbose	Liquid	191756.75			
		Biomass	Solid	3194.03			
		Water	Liquid	1392221.15			
	Air*	Air	Gas	116472.47	116472.47		
	NH3*	Ammonia	Gas	25305.64	25305.64		

	NaCO3	Sodium Carbonate	Liquid	76288.83	76288.83		
	S-104	Sorbitol	Liquid	5744.12	1731854.87		
		Sorbose	Liquid	46021.62			
		Biomass	Solid	5597.21			
		Sodium glucuronate	Liquid	192740.62			
		Water	Liquid	1465272.65			
		Sodium Carbonate	Liquid	16478.65			
	S-105	Carbon dioxide	Gas	359156.31	463674.05		
		Oxygen	Gas	5643.29			
		Nitrogen	Gas	91883.93			
		Ammonia	Gas	6990.52			
Centrifugate	**S-104**	Sorbitol	Liquid	5744.12	1731854.87	0.00	0.00

		Sorbose	Liquid	46021.62			
		Biomass	Solid	5597.21			
		Sodium glucuronate	Liquid	192740.62			
		Water	Liquid	1465272.65			
		Sodium Carbonate	Liquid	16478.65			
	S-106	Sorbitol	Liquid	5743.84	1726171.35		
		Sorbose	Liquid	46019.32			
		Sodium glucuronate	Liquid	192730.98			
		Water	Liquid	1465199.38			
		Sodium Carbonate	Liquid	16477.82			
	S-107	Biomass	Solid	5597.21	5683.53		

		Sodium Carbonate	Liquid	0.82			
		Sodium glucuronate	Liquid	9.64			
		Sorbitol	Liquid	0.29			
		Sorbose	Liquid	2.30			
		Water	Liquid	73.26			
Biopolar Membrane Electrodialysis 1	**S-106**	Sorbitol	Liquid	5743.84	1726171.35	-17682784	-17669522.18
		Sorbose	Liquid	46019.32			
		Sodium glucuronate	Liquid	192730.98			
		Water	Liquid	1465199.38			
		Sodium Carbonate	Liquid	16477.82			
	S-108	Sorbitol	Liquid	5743.84	1678689.10		

		Sorbose	Liquid	46019.32			
		Water	Liquid	1417717.13			
		2-ketogluconic acid	Liquid	192730.98			
		Sodium Carbonate	Liquid	16477.82			
	NaOH	Sodium hydroxide	Liquid	55017.31	55017.31		
Heating 1	**S-108**	Sorbitol	Liquid	5743.84	1678689.10	0.00	20144269.16
		Sorbose	Liquid	46019.32			
		Water	Liquid	1417717.13			
		2-ketogluconic acid	Liquid	192730.98			
		Sodium Carbonate	Liquid	16477.82			

	S-109	Sorbitol	Liquid	74669.88	21822958.26		
		Sorbose	Liquid	598251.14			
		Water	Liquid	18430322.74			
		2-ketogluconic acid	Liquid	2505502.79			
		Sodium Carbonate	Liquid	214211.70			
Thin Film Evaporator 1	**S-109**	Sorbitol	Liquid	74669.88	21822958.26	0.00	134718352.86
		Sorbose	Liquid	598251.14			
		Water	Liquid	18430322.74			
		2-ketogluconic acid	Liquid	2505502.79			
		Sodium Carbonate	Liquid	214211.70			
	S-110	Sorbitol	Liquid	74669.88	5235667.79		

		Sorbose	Liquid	598251.14			
		Water	Liquid	1843032.27			
		2-ketogluconic acid	Liquid	2505502.79			
		Sodium Carbonate	Liquid	214211.70			
	Water vapor	Water	Gas	151305643.33	151305643.33		
Cooling 1	**S-110**	Sorbitol	Liquid	74669.88	5235667.79	0.00	-2094267.11
		Sorbose	Liquid	598251.14			
		Water	Liquid	1843032.27			
		2-ketogluconic acid	Liquid	2505502.79			
		Sodium Carbonate	Liquid	214211.70			

	S-111	Sorbitol	Liquid	44801.93	3141400.67		
		Sorbose	Liquid	358950.69			
		Water	Liquid	1105819.36			
		2-ketogluconic acid	Liquid	1503301.67			
		Sodium Carbonate	Liquid	128527.02			
Stirred Tank Bioreactor 1	**S-111**	Sorbitol	Liquid	44801.93	3141400.67	-5898047.73	-5482712.23
		Sorbose	Liquid	358950.69			
		Water	Liquid	1105819.36			
		2-ketogluconic acid	Liquid	1503301.67			
		Sodium Carbonate	Liquid	128527.02			
	CH3OH	Methanol	Liquid	65682.64	65682.64		

	S-112	Sorbitol	Liquid	44801.93	3622418.81		
		Sorbose	Liquid	358950.69			
		Water	Liquid	1476180.92			
		Methyl 2-keto-L-gulonate*	Liquid	1503301.67			
		Sodium Carbonate	Liquid	128527.02			
		Methanol	Liquid	110656.58			
Cooling 2	**S-112**	Sorbitol	Liquid	44801.93	3622418.81	0.00	-3158006.14
		Sorbose	Liquid	358950.69			
		Water	Liquid	1476180.92			
		Methyl 2-keto-L-gulonate*	Liquid	1503301.67			
		Sodium Carbonate	Liquid	128527.02			

		Methanol	Liquid	110656.58			
	S-113	Sorbitol	Liquid	5743.84	464412.67		
		Sorbose	Liquid	46019.32			
		Water	Liquid	189253.96			
		Methyl 2-keto-L-gulonate*	Liquid	192730.98			
		Sodium Carbonate	Liquid	16477.82			
		Methanol	Liquid	14186.74			
Stirred Tank Bioreactor 2	**S-113**	Sorbitol	Liquid	5743.84	464412.67	4085593.94	4813629.63
		Sorbose	Liquid	46019.32			
		Water	Liquid	189253.96			
		Methyl 2-keto-L-gulonate*	Liquid	192730.98			

		Sodium Carbonate	Liquid	16477.82			
		Methanol	Liquid	14186.74			
	NaHCO3	Sodium bicarbonate	Liquid	72444.09	72444.09		
	S-114	Sorbitol	Liquid	5743.84	579037.96		
		Sorbose	Liquid	46019.32			
		Water	Liquid	236736.21			
		Sodium ascorbate	Liquid	192730.98			
		Sodium Carbonate	Liquid	16477.82			
		Methanol	Liquid	65682.64			
		Sodium bicarbonate	Liquid	15647.14			

	CO2	Carbon Dioxide	Gas	685854.49	685854.49		
Bioplar Membrane Electrodialysis 2	**S-114**	Sorbitol	Liquid	5743.84	579037.96	-17682783.79	-17675248.73
		Sorbose	Liquid	46019.32			
		Water	Liquid	236736.21			
		Sodium ascorbate	Liquid	192730.98			
		Sodium Carbonate	Liquid	16477.82			
		Methanol	Liquid	65682.64			
		Sodium bicarbonate	Liquid	15647.14			
	S-115	Ascorbic Acid (l)	Liquid	192730.98	531555.71		
		Sorbitol	Liquid	5743.84			
		Sorbose	Liquid	46019.32			

		Water	Liquid	189253.96			
		Methanol	Liquid	65682.64			
		Sodium Carbonate	Liquid	16477.82			
		Sodium bicarbonate	Liquid	15647.14			
	NaOH*	Sodium Hydroxide	Liquid	55017.31	55017.31		
Heating 2	**S-115**	Ascorbic Acid (l)	Liquid	192730.98	531555.71	0.00	12508989.14
		Sorbitol	Liquid	5743.84			
		Sorbose	Liquid	46019.32			
		Water	Liquid	189253.96			
		Methanol	Liquid	65682.64			

		Sodium Carbonate	Liquid	16477.82			
		Sodium bicarbonate	Liquid	15647.14			
	S-116	Ascorbic Acid (l)	Liquid	2505502.79	13040544.85		
		Sorbitol	Liquid	74669.88			
		Sorbose	Liquid	598251.14			
		Water	Liquid	2460301.53			
		Methanol	Gas	6984194.97			
		Sodium Carbonate	Liquid	214211.70			
		Sodium bicarbonate	Liquid	203412.84			
Thin Film Evaporator 2	**S-116**	Ascorbic Acid (l)	Liquid	2505502.79	13040544.85	0.00	19985567.19

		Sorbitol	Liquid	74669.88			
		Sorbose	Liquid	598251.14			
		Water	Liquid	2460301.53			
		Methanol	Liquid	6984194.97			
		Sodium Carbonate	Liquid	214211.70			
		Sodium bicarbonate	Liquid	203412.84			
	S-118	Ascorbic Acid (l)	Liquid	2505502.79	3842078.50		
		Sorbitol	Liquid	74669.88			
		Sorbose	Liquid	598251.14			
		Water	Liquid	246030.15			
		Sodium Carbonate	Liquid	214211.70			

		Sodium bicarbonate	Liquid	203412.84			
	S-117	Water	Gas	22199838.57	29184033.54		
		Methanol	Gas	6984194.97			
Cooling 3	**S-118**	Ascorbic Acid (l)	Liquid	2505502.79	3842078.50	0.00	-5083365.40
		Sorbitol	Liquid	74669.88			
		Sorbose	Liquid	598251.14			
		Water	Liquid	246030.15			
		Sodium Carbonate	Liquid	214211.70			
		Sodium bicarbonate	Liquid	203412.84			
	S-119	Ascorbic Acid (l)	Liquid	-809470.13	-1241286.90		

		Sorbitol	Liquid	-24124.11			
		Sorbose	Liquid	-193281.14			
		Water	Liquid	-79486.66			
		Sodium Carbonate	Liquid	-69206.86			
		Sodium bicarbonate	Liquid	-65717.99			
Crystallizer	**S-119**	Ascorbic Acid (l)	Liquid	-809470.13	-1241286.90	0.00	0.00
		Sorbitol	Liquid	-24124.11			
		Sorbose	Liquid	-193281.14			
		Water	Liquid	-79486.66			
		Sodium Carbonate	Liquid	-69206.86			

		Sodium bicarbonate	Liquid	-65717.99			
	S-120	Ascorbic Acid (l)	Liquid/Solid	-80947.01	-1241286.90		
		Sorbitol	Liquid/Solid	-24124.11			
		Sorbose	Liquid/Solid	-193281.14			
		Water	Liquid/Solid	-79486.66			
		Ascorbic Acid (s)	Solid	-728523.12			
		Sodium Carbonate	Liquid/Solid	-69206.86			
		Sodium bicarbonate	Liquid/Solid	-65717.99			
Nutsche Filter	**S-120**	Ascorbic Acid (l)	Liquid/Solid	-80947.01	-1241286.90	0.00	0.00
		Sorbitol	Liquid/Solid	-24124.11			

		Sorbose	Liquid/Solid	-193281.14			
		Water	Liquid/Solid	-79486.66			
		Ascorbic Acid (s)	Solid	-728523.12			
		Sodium Carbonate	Liquid/Solid	-69206.86			
		Sodium bicarbonate	Liquid/Solid	-65717.99			
	S-122	Ascorbic Acid (s)	Solid	-655670.81	-663619.47		
		Water	Liquid/Solid	-7948.67			
	S-121	Ascorbic Acid (s)	Liquid/Solid	-72852.31	-577667.43		
		Ascorbic Acid (l)	Solid	-80947.01			
		Sorbitol	Liquid/Solid	-24124.11			

		Sorbose	Liquid/Solid	-193281.14			
		Sodium Carbonate	Liquid/Solid	-69206.86			
		Sodium bicarbonate	Liquid/Solid	-65717.99			
		Water	Liquid/Solid	-71538.00			
Storage 2	**S-121**	Ascorbic Acid (s)	Liquid/Solid	-72852.31	-577667.43	0.00	-577667.43
		Ascorbic Acid (l)	Solid	-80947.01			
		Sorbitol	Liquid/Solid	-24124.11			
		Sorbose	Liquid/Solid	-193281.14			
		Sodium Carbonate	Liquid/Solid	-69206.86			
		Sodium bicarbonate	Liquid/Solid	-65717.99			

		Water	Liquid/Solid	-71538.00			
Solid Storage	**S-122**	Ascorbic Acid (s)	Solid	-655670.81	-663619.47	0.00	0.00
		Water	Liquid	-7948.67			
	Ascorbic acid	Ascorbic Acid (s)	Solid	-655670.81	-663619.47		
		Water	Liquid	-7948.67			

4.4 PROCESS SIMULATION

Table 4.21 Percentage error of Manual and Simulation of Material Balance for Streams

Unit operation	Stream		mass flow rate (kg/batch)		Percentage Error (%)
			Manual	Simulation	
Storage	Inlet	**Sorbitol**	45000.0000	45000.0000	0.0000
	Outlet	**S-101**	45000.0000	45000.0000	0.0000
Fermenter 1	Inlet	**S 101**	45000.0000	45000.0000	0.0000
		Air	12800.0000	12800.0000	0.0000
		H2O	50000.0000	50000.0000	0.0000
		NH3	22.0000	22.0000	0.0000
	Outlet	**S-102**	97675.5223	97675.5050	0.0000
		S-103	10146.5508	10263.0100	1.1347
Fermenter 2	Inlet	**S-102**	97675.5223	97675.5050	0.0000
		Air*	23000.0000	23000.0000	0.0000
		NH3*	21.0000	21.0000	0.0000
		Na2CO3	8532.0000	8532.0000	0.0000
	Outlet	**S-104**	107440.8517	107440.7230	0.0001
		S-105	21787.6408	21911.5270	0.5654
Centrifuge	Inlet	**S-104**	107440.8517	107440.7230	0.0001
	Outlet	**S-106**	107167.8050	107167.4740	0.0003
		S-107	273.0467	273.2490	0.0740
BME 1	Inlet	**S-106**	107167.8050	107167.4740	0.0003
	Outlet	**S-108**	102119.8057	102119.8057	0.0000
		NaOH	5048.2391	5048.2300	0.0002
Heater 1	Inlet	**S-108**	102119.8057	102119.8057	0.0000
	Outlet	**S-109**	102119.8057	102119.8057	0.0000
Evaporator	Inlet	**S-109**	102119.8057	102119.8057	0.0000
	Outlet	**S-110**	41018.5714	41018.4820	0.0002
		Water vapor	61101.2343	61101.0140	0.0004
Cooler 1	Inlet	**S-110**	41018.5714	41018.4820	0.0002
	Outlet	**S-111**	41018.5714	41018.4820	0.0002
CSTR 1	Inlet	**S-111**	41018.5714	41018.4820	0.0002
		CH3OH	5158.3413	5158.3413	0.0000
	Outlet	**S-112**	46177.3039	46177.2040	0.0002

Table 43 Percentage error of Manual and Simulation of Material Balance for Streams (Cont'd)

Unit operation	Stream		mass flow rate (kg/batch)		Percentage Error (%)
			Manual	Simulation	
Cooler 2	Inlet	**S-112**	46177.3039	46177.2040	0.0002
	Outlet	**S-113**	46177.3039	46177.2040	0.0002
CSTR 2	Inlet	**S-113**	46177.3039	46177.2040	0.0002
		NAHCO3	13524.0240	13525.0000	0.0072
	Outlet	**S-114**	54146.0939	54146.9680	0.0016
		CO2	5554.7417	5554.731	0.0002
BME 2	Inlet	**S-114**	54146.0939	54146.9680	0.0016
	Outlet	**S-115**	49098.0946	49098.991	0.0018
		NaOH*	5048.2391	5048.2300	0.0002
Heater 2	Inlet	**S-115**	49098.0946	49098.991	0.0018
	Outlet	**S-116**	49098.0946	49098.991	0.0018
Evaporator 2	Inlet	**S-116**	49098.0946	49098.991	0.0018
	Outlet	**S-117**	13314.8702	13314.8350	0.0003
		S-118	35783.2244	35784.1560	0.0026
Cooler 3	Inlet	**S-118**	35783.2244	35784.1560	0.0026
	Outlet	**S-119**	35783.2244	35784.1560	0.0026
Crystalizer	Inlet	**S-119**	35783.2244	35784.1560	0.0026
	Outlet	**S-120**	35783.2244	35784.1560	0.0026
Nutsche Filtration	Inlet	**S-120**	35783.2244	35784.1560	0.0026
	Outlet	**S-121**	17686.4410	17844.9940	0.8885
		S-122	18096.7834	17939.1620	0.8786
Storage 2	Inlet	**S-121**	17686.4410	17844.9940	0.8885
Solid storage	Inlet	**S-122**	18096.7834	17939.1620	0.8786
	Outlet	**Ascorbic acid**	18096.7834	17939.1620	0.8786

Table 4.22 Percentage error of Manual and Simulation of Energy Balance for Streams

Equipment		Enthalpy (kJ/batch)		Percentage Error (%)
		Manual	Simulation	
Storage	**P1**	0.0000	0.0000	0.0000
Fermenter 1	**P2**	-36571617.3230	-36367295.5800	0.5587
Fermenter 2	**P3**	6849035.2178	6464405.5200	5.6158
Centrifugate	**P4**	0.0000	0.0001	0.0000
Bipolar Membrane Electrodialysis 1	**P5**	-17669522.1797	-17683340.3101	0.0782
Heater 1	**P6**	20144269.16	20178214.1200	0.1685
Thin Film Evaporator 1	**P7**	134718352.8565	142989886.7770	6.1399
Cooler 1	**P8**	-2094267.1144	-2097277.4000	0.1437
Stirred Tank Bioreactor 1	**P9**	-5482712.2332	-5478264.8361	0.0811
Cooler 2	**P10**	-3158006.1396	-3158513.1200	0.0161
Stirred Tank Bioreactor 2	**P11**	4813629.6332	4098608.1900	14.8541
Bipolar Membrane Electrodialysis 2	**P12**	-17675248.7259	-17682073.5120	0.0386
Heater 2	**P13**	12508989.1393	12596899.6800	0.7028
Thin Film Evaporator 2	**P14**	19985567.1916	19087990.7960	4.4911
Cooler 3	**P15**	-5083365.4024	-5084309.0400	0.0186
Crystallizer	**P16**	0.0000	0.0000	0.0000
Nutsche Filter	**P17**	0.0000	0.0000	0.0000
Storage 2	**P18**	0.0000	0.0000	0.0000
Solid storage	**P19**	0.0000	0.0000	0.0000

There is no significant difference between the manual computed mass and energy balance and the simulated mass and energy balance, according to the results in Table 44 and 45. This has demonstrated the accuracy of the results and assumptions used in manual mass calculations.

CHAPTER 5

HEAT INTEGRATION

5.1 INTRODUCTION

In this chapter, the temperature interval method which was established by Linhoff and Flower in response to Hohmann's pioneering work is employed to calculate the minimal utility needs (Seider et al., 2017). It assesses the quantity of heating and cooling energy requires use throughout a process to transfer heat between the hot and cold streams. This method is to adjust the source and the target temperatures using minimum approach temperature (ΔT_{min}) by reducing the temperature of hot streams with ΔT_{min}. Then, analyze the energy flows between the temperature interval and determine the minimum energy requirements target by computing enthalpy cascade. After that, continue to use pinch technology to design the position of heat exchangers.

5.2 STREAM IDENTIFICATION

Identify the hot and cold streams with the initial temperature which is source temperature (Ts) and the final temperature which is target temperature (Tt). The Ts and Tt are adjusted by ΔT_{min} before conducting pinch technology. Then, list down streams data in Table below.

Table 5.1 Hot and cold streams data of the process

Stream	**Type**	**Equipment**	**Ts (℃)**	**Tt (℃)**	**Adjusted**		**Q (kJ/batch)**	**mCp (kJ/batch ℃)**
					Ts (℃)	**Tt (℃)**		
H1	Hot	HX-102	90	64	80	54	-2094267.1144	80548.73517
H2	Hot	HX-103	64	30	54	20	-3158006.1396	92882.53352
H3	Hot	HX-105	90	4	80	-6	-5083365.4024	59108.90003
C1	Cold	HX-101	30	90	30	90	20144269.1597	335737.8193
C2	Cold	HX-104	30	90	30	90	12508989.1393	106311.1421

ΔT_{min} = 10 ℃

5.3 PINCH TECHNOLOGY

The potential location of heat exchangers would be determined by using pinch technology. Involving the problem table algorithm, enthalpy cascade and grid diagram to redesign the heat exchanger network design to reduce the usage of energy.

5.3.1 PROBLEM TABLE ALGORITHM

The adjusted temperature is rearranged orderly by interval. Table 5.2 and Figure 5.1 illustrate the enthalpy differences between the enthalpy to be removed from hot streams and the energy to be taken up by cold streams in each temperature interval.

Table 5.2 Enthalpy differences for temperature intervals

Interval	T_{i-1} - T_i (℃)	H1	H2	H3	C1	C2	Stream	$\sum C_H - C_C$ (kJ/batch ℃)	ΔH (kJ/batch)
1	90-80 =10						C1, C2	-442048.9614	-4420489.614
2	80-54 =26						H1, H3, C1, C2	-302391.3262	-7862174.481
3	54-30 =24						H2, H3, C1, C2	-290057.5278	-6961380.668
4	30-20 =10						H2, H3	151991.4335	1519914.335
5	20-(-6) =26						H3	59108.90003	1536831.401

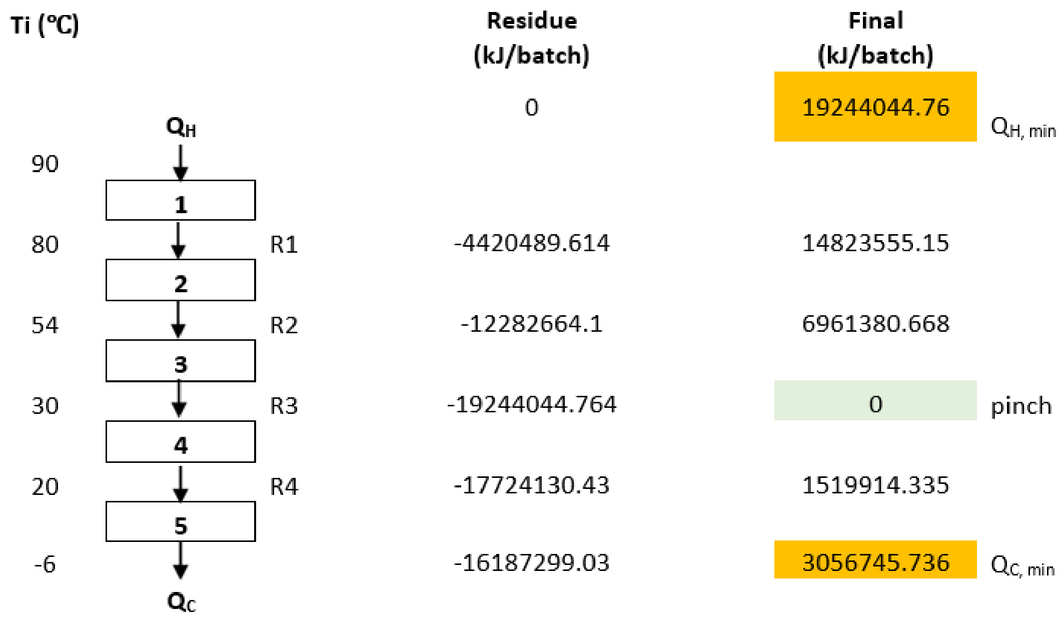


Figure 5.1 Cascade of temperature intervals with enthalpy

From Figure 5.1, the pinch temperature and minimum energy requirement are determined as show below:

Pinch temperature: 30 °C

Hot pinch temperature: 40 °C

Cold pinch temperature: 30 °C

Minimum heating requirement, $Q_{H,\,min}$ = 19244044.764 kJ/batch

Minimum cooling requirement, $Q_{C,\,min}$ = 3056745.736 kJ/batch

5.4 HEAT EXCHANGER NETWORK (HEN) DESIGN

Three unit of heat exchangers are introduced with 2 unit of heaters and 2 unit of coolers as illustrated in Figure 5.2.

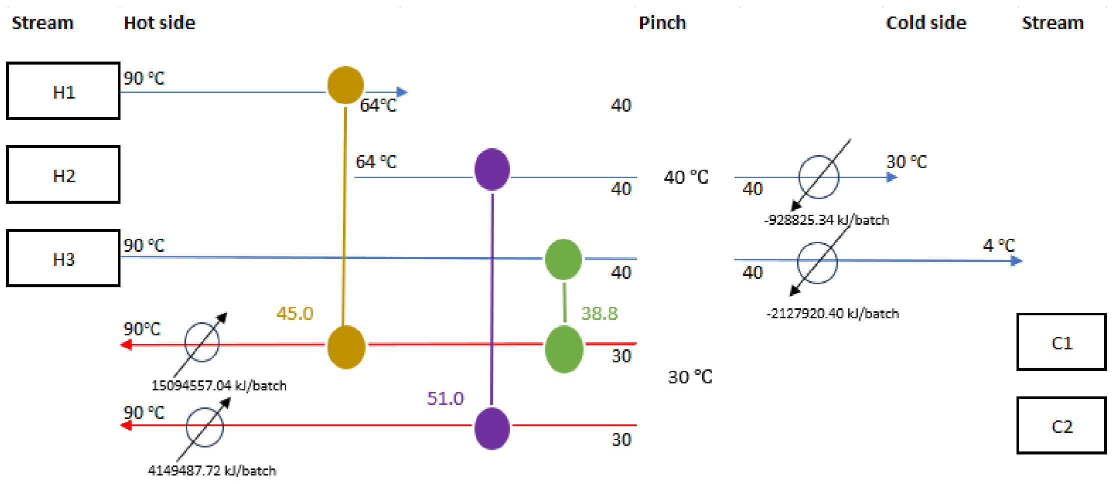


Figure 5.2 Minimum Energy Requirements Design

5.5 COMPARISON OF UTILITY CONSUMPTION

Table 5.3 shows the utility requirements before heat integration and after heat integration. Based on the results, can save 41.07% from hot utility whereas 70.43% from cold utility after energy integration. The results indicate that energy integration has increased dramatically by incorporating 3 heat exchangers. The system's performance is enhanced by decreasing the number of coolers and optimized both hot and cold utilities with minimum energy requirements.

Table 5.3 Comparison of energy integration before and after HEN

ΔH	kJ/batch			Percentage Savings (%)
	Before HEN	After HEN	Utility Savings	
Q_H	32653258.2989	19244044.764	13409213.5354	41.07
Q_C	10335638.6564	3056745.736	7278892.9202	70.43

5.6 PROCESS FLOW DIAGRAM AFTER ENERGY INTEGRATION

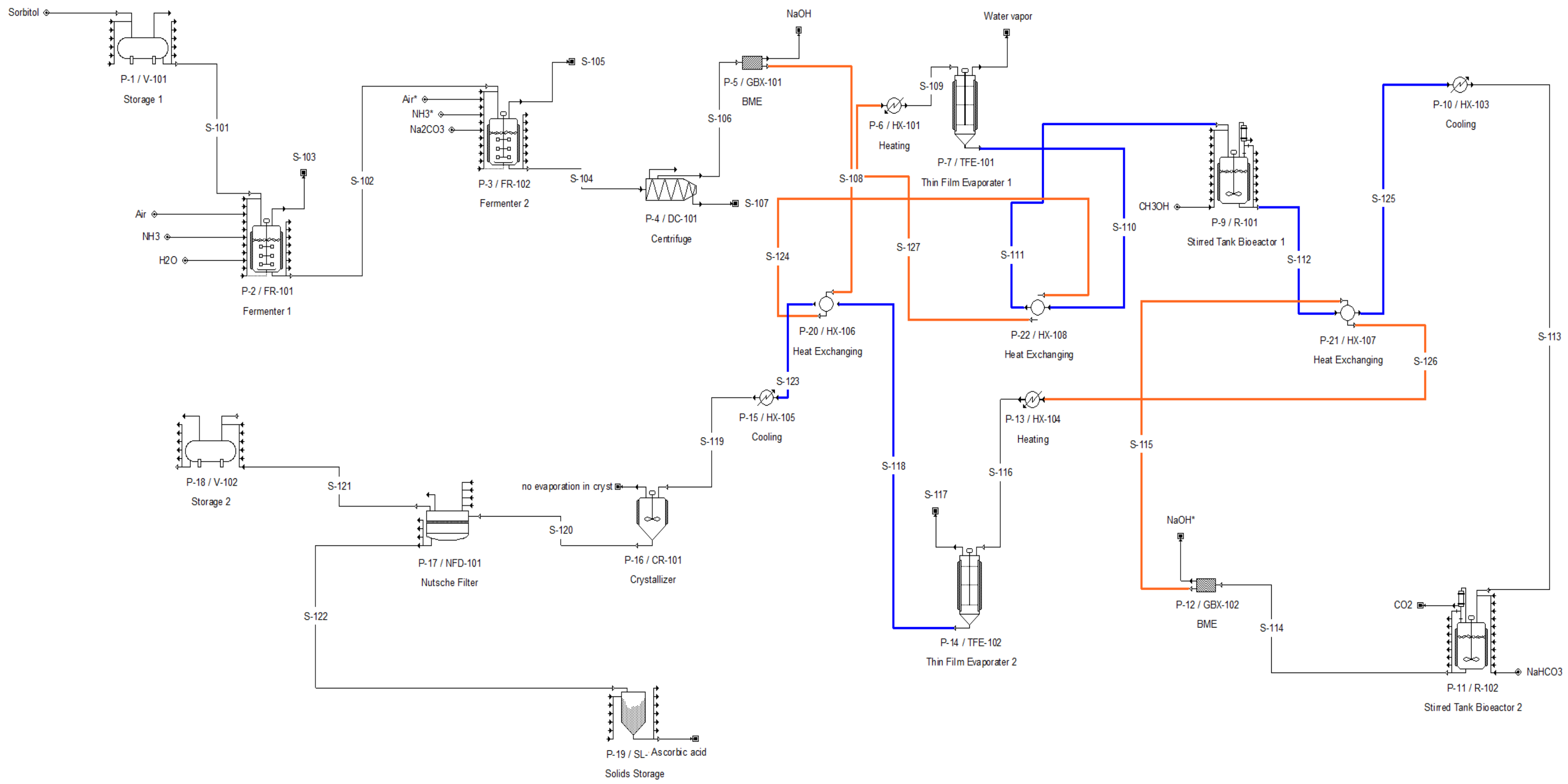


Figure 5.3 Process Flow Diagram After HEN design

CHAPTER 6

OPTIMIZATION

6.1 INTRODUCTION

Generally, the purpose of optimization is to find the best solution for equipment in order to achieve the objective function. Process optimization is one of the crucial importance applied in the designs, products or processes for maximum performance efficiency. Additionally, optimization is also important in order to maximize the product yield and profit while minimizing the operation cost and the resources. In this plant, Fermenter (FR-102) and Evaporator has been chosen for the process optimization as it is the main unit operation in this plant, hence its optimization will be a major contribution for a better performance of the plant. The purpose of the optimization is to maximize the profit of production of ascorbic acid by comparing the non-recycle stream and recycle stream.

6.1.1 OPTIMIZATION OF FERMENTER

Step 1: Define the decision variables

$X_1 = Sorbitol\ \left(\frac{kg}{batch}\right)$

$X_2 = Ascorbic\ acid\ \left(\frac{kg}{batch}\right)$

$Z = Maximum\ profit\ for\ ascorbic\ acid\ production$

Step 2: Define the objective function

$Maximum\ Z = 65X_2 - 3.81X_1$

Step 3: Define the equality and inequality constraints

$65X_2 - 3.81X_1 > 0$ (prevent -ve profit)

$X_2, X_1 \geq 0$ (Non-negativity)

$X_1 \geq 45000$ (Inlet mass flow rate of sorbitol)

$X_2 \leq 27831.1883$ (Mass flow rate of ascorbic acid production)

Step 4: Graphical Method

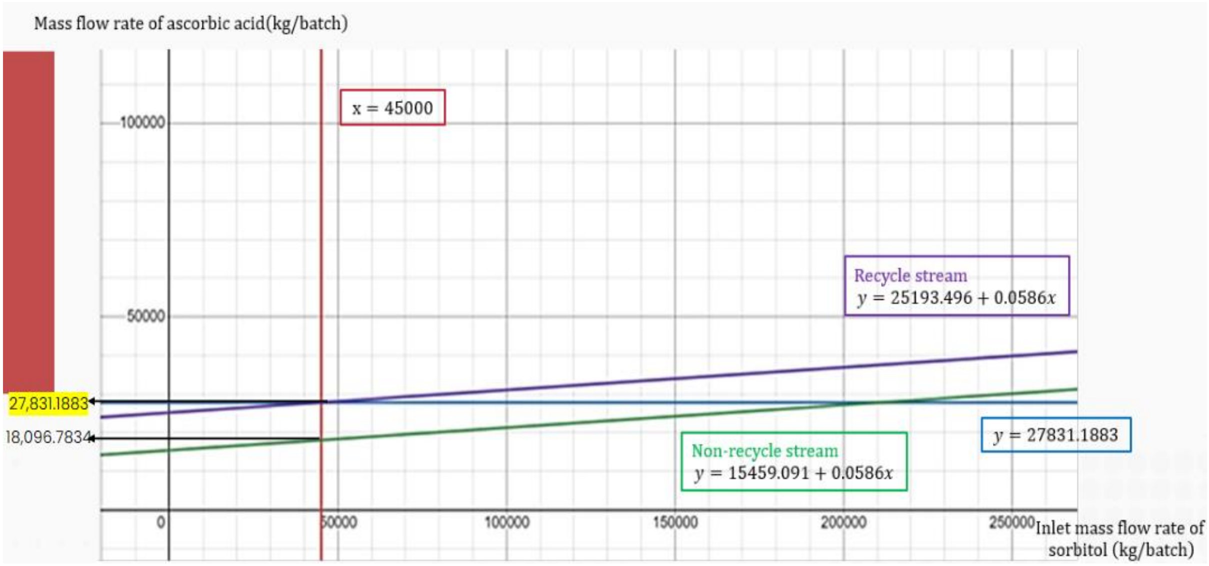


Figure 6.1 Graph intersection of recycle stream, without recycle stream, reactant, and mass flowrate of ascorbic acid

Table 6.1 Mass Flow Rate of Sorbitol (kg/batch) and Ascorbic Acid Production (kg/batch)

Parameters	Non-recycle stream	Recycle stream
X_1	45,000	45,000
X_2	18,096.78	27,831.19
z	1,004,840.92	1,637,577.24

Figure 6.1 and the tabulated shows that if feeding the same amount of reactant, which is sorbitol, into the fermenter, the recycle stream can generate more profit as compared to the non-recycle stream as larger production of ascorbic acid can be produced. For the non-recycle stream, 18,096.7834 kg/batch of ascorbic acid can be produced and is able to generate profit of RM1,004,840.92. On the other hand, the recycle stream can produce 27,831.9 kg/batch of ascorbic acid and gives a higher profit of RM1,637,577.24. Hence, the profit generated is compared by the calculation shown below, the profit improvement after introducing the recycle stream to the plant is 62.97%

Profit improvement (%) = $\frac{\text{Max Z (Recycle)} - \text{Max Z (Without Recycle)}}{\text{Max Z (Without Recycle)}}$

$$= \frac{1637577.24 - 1004840.921}{1004840.921} = 62.97\%$$

6.2 OPTIMIZATION OF THIN FILM EVAPORATOR 2 TFE-102

Thin Film Evaporator is included in the production of ascorbic acid in the plant. The purpose of this unit operation is to remove excess water and methanol by providing heated steam. The price of utilities for the production has been directly impacted by the usage of heat steam, which has raised the heat duty and energy consumption as large amount of steam is needed to be fed into the evaporator for the recovery process. Therefore, optimization of evaporator is necessary to determine the optimum temperature for obtaining the optimum operating temperature in order to minimize the required cost of thin film evaporator 2 and directly influence the operation profit. The SuperPro Designer simulation was utilized in this optimization to gather information on the operating temperature and heat transfer area for the optimization study. This information and data are used in the calculation of heat duty, steam flow rate and utility cost required. By considering these parameters, the optimized operating temperature that reflects the minimum cost can be determined.

Step 1: Define decision variable

$x_1 = Heat\ Transfer\ Area\ (m^2)$

$x_2 = Cost\ of\ Evaporator\ (RM)$

$z = Minimum\ cost\ of\ Evaporator\ (RM)$

Step 2: Define objective function

$Min\ z = Bare\ module\ cost\ of\ equipment\ (RM) + Utility\ cost$

$Min\ z = 221831.5{x_1}^{0.55} + x_2$

Step 3: Define equality and inequality constraints

$x_1, x_2 \geq 0$, to prevent negative profit earned

$x_1 \leq 0.651m^2$, which is the heat transfer area of operating condition 100℃

$x_2 \geq 415047.6901$, which is the utility cost of operating condition 100℃

Step 4: Graphical method

Table 6.2 Utility Cost and Bare Module Cost of Thin Film Evaporator 2

Temperature (ºC)	Heat duty (kJ/h)	Steam flow rate (kg/h)	Utility cost (RM/kg for 20 years)	Heat transfer area (m2)	Heat transfer area (ft2)	Bare module cost (RM)
60	142391.86	51.80	577,199.71	0.148	1.592	286,525.91
70	174078.65	63.33	580,256.69	0.203	2.184	340,912.39
80	213085.83	77.52	556,793.95	0.283	3.045	409,263.02
90	261944.14	95.29	495,782.88	0.404	4.347	497,771.14
100	354013.61	128.79	415,047.69	0.651	7.005	647,126.98

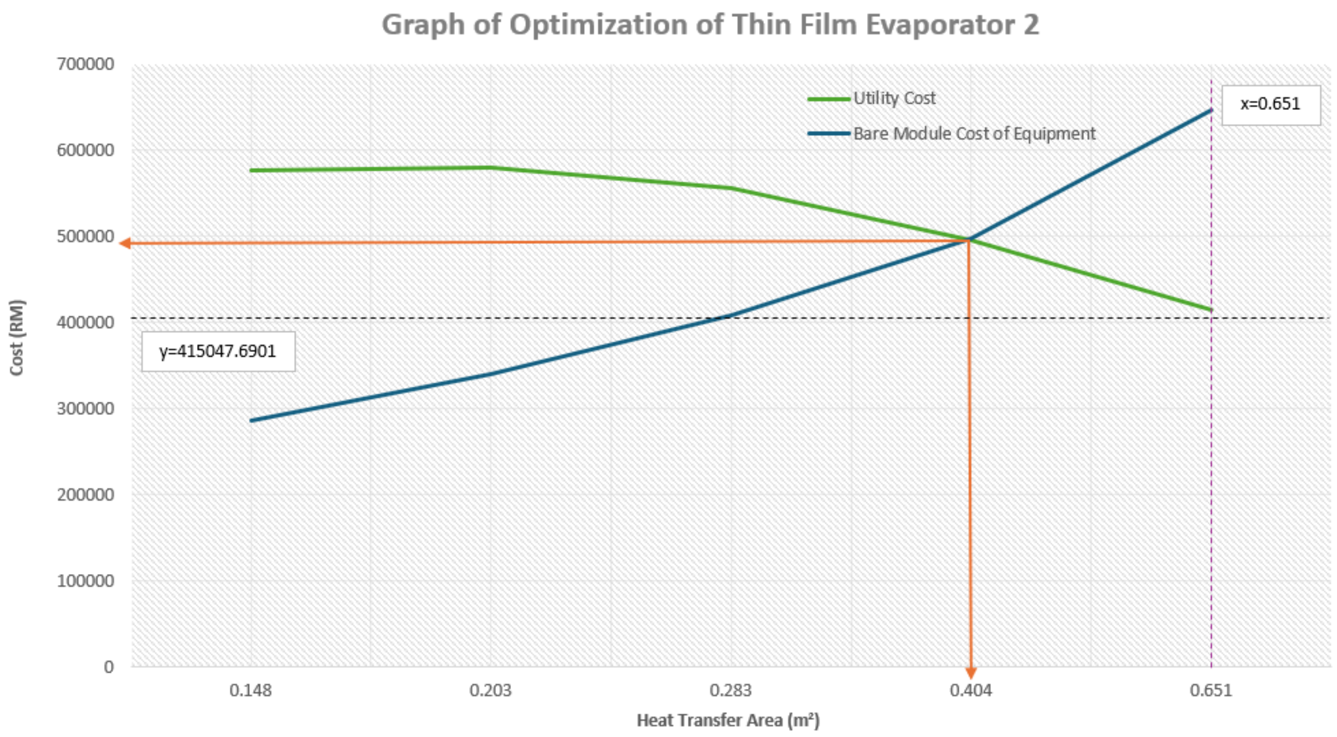


Figure 6.2 Graph of Cost of Evaporator (RM) against Heat Transfer Area (m²)

Figure 6.2 illustrates the graph of optimization of thin film evaporatore 2, TFE-102 which showing the cost of evaporator (RM) against heat transfer area (m^2) that represents each different temperature respectively. The graph shows an increasing trend of bare module cost of evaporator as the heat transfer area increases. In contrast, when the temperature is higher, the utility cost is lower due to the time consumption of the evaporating process. The higher the operating temperature, the shorter the time needed for the evaporation process. Besides, there is a feasible region which respects the designed constraints. The heat transfer area, y is equal or less than 0.651m² which is the heat transfer area of 100ºC, as the operating temperature is expected to be lower than 100 ºC. According to this figure, the optimized heat transfer area is 0.404m² which indicates the optimum temperature that can bring the minimum cost is 90ºC. At this condition, the equipment cost of 90ºC is RM 497771.15, while for 100 ºC showing the bare module cost of RM 647126.98. In overview, the z, overall cost of evaporator at 90ºC is RM 993554.02, lower when comparing to the cost at 100 ºC is RM 1062174.67. Thus, the optimized temperature, 90°C is more suitable for an evaporator.

Cost at 100°C

$$\begin{aligned} z &= 221831.5{x_1}^{0.55} + x_2 \\ &= 647126.9812 + 415047.6901 \\ &= 1062174.67 \end{aligned}$$

Cost at 90°C

$$\begin{aligned} z &= 221831.5{x_1}^{0.55} + x_2 \\ &= 497771.1416 + 495782.8799 \\ &= 993554.02 \end{aligned}$$

$$\begin{aligned} Equipment\ Cost\ reduction\ (\%) &= \frac{497771.14 - 647126.98}{647126.98} \times 100\% \\ &= 23.08\% \end{aligned}$$

$$\begin{aligned} Overall\ Cost\ reduction\ (\%) &= \frac{993554.02 - 1062174.67}{1062174.67} \times 100\% \\ &= 6.46\% \end{aligned}$$

CHAPTER 7

WASTE TREATMENT

7.1 TYPES OF WASTE GENERATED

Table 7.1 provides an extensive overview of the various waste streams generated during production processing operations that categorized by type that associated equipment, mass flowrate, concentration, and physical phase. Ascorbic acid waste, for instance, is produced in both solid and liquid forms that are processed by equipment such as the Flow Splitter FSP-101 and Centrifuge DC-101. Significant liquid waste streams include sodium carbonate (Na_2CO_3), sodium bicarbonate ($NaHCO_3$), sorbitol, sorbose, and substantial volumes of water, all displaying high concentrations.

The gaseous emissions, including ammonia, carbon dioxide, nitrogen, and oxygen, are primarily emitted from fermenters and other units. Furthermore, specific units like TFE-101 and TFE-102 emit vapors such as water vapor and methanol. Other than that, biomass waste exhibits an exceptionally high concentration, while sodium hydroxide (NaOH) from BME units stands out due to its considerable mass flowrate and concentration. This comprehensive data underscores the intricate nature of waste management in industrial batch processing, highlighting the necessity for effective waste treatment and disposal strategies to address the diverse outputs from various processing stages.

Table 7.1 Types of waste generated by each stream

Types of waste	Stream	Equipment	Mass Flowrate (kg/batch)	Concentration (mg/L)	Phase
Ammonia	S 103	Fermenter 1	9.45586	0.101842	Gas
Carbon Dioxide			252.59859	19.0338	Gas
Nitrogen			13962.62941	1081.7398	Gas
Oxygen			144.09459	19.852160	Gas
Ammonia	S105	Fermenter 2	3.56678	0.042992	Gas
Carbon Dioxide			5213.95851	203.6878	Gas
Nitrogen			27622.46729	975.441	Gas
Oxygen			987.95063	7.127685	Gas
Ascorbic acid (s)	S 107	Centrifuge DC - 101	0.14299	343.778	Solid
Ascorbic Acid			0.17080	410.650	Liquid
Biomass			427.54924	1027939.4428	Liquid
Na2CO3			0.00045	0.1084	Liquid
NaHCO3			0.00015	0.359	Liquid
S. Glucoronate			2.41037	5795.145	Liquid
Sorbitol			0.22484	0540.564	Liquid
Sorbose			0.64093	1540.956	Liquid
Water			5.38437	12945.423	Liquid
Sodium Hydroxide	NaOH	BME 1 GBX-101	9055.07552	1911170.441	Liquid
Sodium Hydroxide	NaOH	BME 2 GBX-102	9055..07552	1911170.441	Liquid
Carbon Dioxide	CO2	Stirred Tank Bioreactor 2 R-102	9963.9411	39.66	Gas

Water Vapor	Water vapor	TFE-101	94697.40667	296.647	Gas
Methanol	S117	TFE-102	35.5690	251.361	Gas
Water			64.4310	455.324	Gas

7.2 ALTERNATIVE FOR WASTE TREATMENT METHOD

There are several alternative methods for treating biomass waste produced in fermenters, each offering unique benefits and applications. Anaerobic digestion is a biological process where microorganisms break down organic matter in the absence of oxygen, producing methane-rich biogas that can be used for energy production. Pyrolysis is a thermal decomposition process that heats biomass in the absence of oxygen, generating biochar, bio-oil, and syngas, which can be utilized as soil amendments, fuels, or chemical feedstocks. Gasification involves heating biomass in a controlled amount of oxygen or steam, creating a synthesis gas (syngas) mainly composed of carbon monoxide and hydrogen, suitable for fuel or further chemical processing.

Composting is another biological process where microorganisms decompose organic matter in the presence of oxygen, resulting in nutrient-rich compost that enhances soil fertility and structure. Incineration reduces biomass volume through combustion, producing heat that can generate steam or electricity. Phytoremediation uses plants to absorb contaminants from soil, after which the biomass can undergo enzymatic hydrolysis to convert complex carbohydrates into fermentable sugars, producing biofuels or other bioproducts. Each method not only treats biomass waste but also offers potential for resource recovery and environmental benefits.

Integrating methanol into the anaerobic digestion of biomass represents a sophisticated and sustainable approach to enhancing biogas production and energy efficiency. Methanol, serving as a readily biodegradable carbon source that can significantly boost the microbial activity of methanogenic archaea, leading to increased methane yields and more efficient bioconversion. By carefully pre-treating methanol waste and mixing it with prepared biomass, the anaerobic digestion process can be optimized under controlled conditions, maintaining ideal temperature and pH levels to support microbial growth. The resulting biogas, rich in methane, can be utilized directly for heating, electricity generation or upgraded to biomethane, contributing to renewable energy solutions. This integration not only stabilizes the digestion process and improves waste management but also adds economic value by converting waste methanol into a valuable energy resource. Consequently, this method enhances the overall sustainability and economic feasibility of converting industrial post-fermentation biomass into high-quality biofuel, aligning with environmental goals and reducing greenhouse gas emissions.

Other than that, carbon dioxide can be treated by using carbon capture and storage. Adsorption is the method that uses material like activated carbon to physically or chemically adsorb carbon dioxide. Adsorption for carbon capture is a process where a solid adsorbent material selectively captures and retains CO2 from a gas stream that plays a crucial role in carbon capture and storage (CCS) to reduce greenhouse gas emissions. Key adsorbents include activated carbons, zeolites, metal-organic frameworks (MOFs) and hybrid materials, each known for their high porosity and specific structural properties that facilitate efficient CO2 capture. The process involves gas stream preparation that can make CO2 adsorption by the adsorbent bed, CO2 desorption through heating or solvent treatment, and adsorbent regeneration to restore its capacity. While adsorption offers high CO2 capture efficiency, scalability, and relatively low energy requirements, it faces challenges like high costs, energy-intensive regeneration, and adsorbent durability (*Reducing Industrial Emissions*, n.d.).

Neutralization is a preferred method for treating sodium hydroxide (NaOH) waste due to its effectiveness in reducing the substance's corrosive properties. This process involves gradually mixing NaOH waste with a dilute acid, such as hydrochloric acid (HCl) to lower its pH and neutralize its alkalinity. This approach reduces corrosiveness, ensures compliance with environmental regulations, and enhances safety by lowering the risk of exposure to highly caustic substances. Proper preparation, controlled acid addition, continuous pH monitoring, and final checks are essential steps in this process. Adhering to OSHA exposure limits and ensuring proper containment and ventilation are crucial to managing any fumes generated during neutralization.

In Malaysia, addressing ammonia waste from industries is crucial due to its significant environmental and health impacts. Various methods and technologies are employed to treat ammonia waste effectively. Biological treatment utilizes microorganisms to break down organic matter and remove ammonia from wastewater. This cost-effective method produces no harmful byproducts and is widely implemented in wastewater treatment plants to ensure high-quality treated drinking water. Constructed wetlands, artificial wetlands designed for industrial wastewater treatment, use plants like water lettuce to remove pollutants, including ammonia-nitrogen and orthophosphate, particularly from palm oil mill effluent (POME). This method has demonstrated high removal rates and effectiveness (*Industrial Wastewater Treatment : Removal of Ammonia-nitrogen and Orthophosphate in Palm Oil Mill Effluent Using Constructed Wetland - UMPSA-IR*, n.d.). Additionally, activated sludge technology employs a mixture of microorganisms and particles to break down organic matter and remove ammonia from wastewater. This technology is also commonly used in wastewater treatment plants to treat industrial effluent, contributing to the overall reduction of ammonia pollution and promoting environmental sustainability in Malaysia.

Wastewater treatment involves a series of processes designed to remove contaminants and pollutants from water, ensuring it is safe for discharge into the environment or for reuse. It typically involves three main stages: primary, secondary, and tertiary treatment. Primary treatment uses physical processes like screening and sedimentation to remove large particles and suspended solids. Secondary treatment employs biological processes, where aerobic and anaerobic microorganisms break down organic matter, converting it into carbon dioxide, water, or methane. (Kaneesamkandi et al., 2020). Tertiary treatment uses chemical and advanced physical processes, such as coagulation, oxidation, filtration, and disinfection, to remove remaining contaminants and dissolved substances.

7.3 SELECTION OF THE METHOD

Under the Environmental Quality Act 1974 and the Environmental Quality (Sewage) Regulations 2009, the acceptable conditions for sewage discharge under Standard B for new sewage treatment systems are clearly defined to ensure environmental protection and public health. The regulations stipulate that the temperature of the discharged sewage must not exceed 40°C, ensuring that thermal pollution is minimized. The pH value must be maintained within the range of 6.0 to 9.0 to prevent harmful effects on aquatic life and maintain the chemical balance of receiving waters. The biochemical oxygen demand (BOD5) at 20°C, a critical measure of organic pollution, is limited to 20 mg/L, which helps to reduce the depletion of dissolved oxygen in water bodies. The chemical oxygen demand (COD) that indicates the total quantity of oxygen required to oxidize both organic and inorganic matter is capped at 120 mg/L, controlling the overall pollutant load. Additionally, the concentration of suspended solids is restricted to 50 mg/L to prevent the accumulation of sediments that can degrade aquatic habitats. These stringent standards for new sewage treatment systems are designed to minimize the environmental impact of sewage discharge and protect water quality.

Based on the table above, the concentrations of various gases from fermenter 1 are within permissible limits for discharge into the environment according to Malaysian regulations. Specifically, the ammonia concentration in Fermenter 1 is 0.101842 mg/L, well below the 20 mg/L limit specified for industrial effluent discharge under standard B. This means it can be safely released. The CO_2 levels in fermenter 1 at 19.0338 mg/m^3 are well within the permissible limits set stated by National Institute for Occupational Safety and Health's (NIOSH) and Occupational Safety and Health Administration (OSHA) has set a Permissible Exposure Limit (PEL) for carbon dioxide of 5,000 mg/L. Additionally, nitrogen and oxygen levels are also within acceptable ranges for environmental release. These findings indicate that the gases produced from these fermenters meet regulatory standards, ensuring minimal environmental impact from their discharge.

The gas concentrations from Fermenter 2 indicate compliance with Malaysian environmental discharge regulations. Ammonia levels are measured at 0.042992 mg/L, significantly below the permissible limit of 20 mg/L for industrial effluent discharge under standard B, ensuring it can be safely released into the environment. Carbon dioxide levels are recorded at 203.6878mg/L are well within the permissible limits set by National Institute for Occupational Safety and Health's (NIOSH) and Occupational Safety and Health Administration (OSHA) has set a Permissible Exposure Limit (PEL) for carbon dioxide of 5,000 mg/L. The nitrogen and oxygen levels, at 975.441 mg/L and 7.127685 mg/L respectively, also fall within acceptable ranges for environmental discharge. These findings confirm that the gases produced from Fermenter 2 meet regulatory requirements, thereby minimizing potential environmental impacts associated with their release.

The process of autoclaving in industrial contexts involves subjecting substances to high-pressure steam to achieve sterilization. In the case of the listed substances, including ascorbic acid, biomass, various chemicals like Na2CO3 and NaHCO3, and organic compounds such as S. Glucoronate, Sorbitol, Sorbose, and Water, autoclaving serves to ensure microbial safety and purity. Once autoclaved, these materials can be safely disposed of in a landfill or through proper waste management practices without risk of environmental contamination. This method not only meets regulatory standards for disposal but also helps maintain environmental integrity by preventing the release of potentially harmful substances into ecosystems. By autoclaving before disposal, industries uphold responsible environmental stewardship while ensuring compliance with health and safety regulations. The carbon dioxide (CO_2) levels in Stirred Tank Bioreactor 2 (R-102) at 39.66 mg/L are well within the permissible limits set by the National Institute for Occupational Safety and Health (NIOSH) and the Occupational Safety and Health Administration (OSHA) so it can safely discharge to environment.

The sodium hydroxide produced from BME 1 and BME 2 equipment is noted for its high purity, making it suitable for sale in accordance with current market trends. Sodium hydroxide, commonly known as caustic soda, is a versatile chemical used extensively in various industries, including manufacturing, chemical processing, and water treatment. The total mass flowrate from both BME is as1 8110.151 kg/batch. Its high purity, as indicated by the data provided, enhances its market value and demand. By selling this product at the latest price trends, businesses can capitalize on its quality and ensure profitability. Moreover, the utilization of high-purity sodium hydroxide contributes to efficient industrial processes and product quality, underscoring its importance in both economic and operational contexts. This strategic approach not only aligns with market dynamics but also underscores the economic benefits derived from the production and sale of premium-grade chemicals like sodium hydroxide.

The water vapor released from TFE-101 at 90°C does not fall within permissible environmental discharge limits, as stipulated by regulations specifying a maximum temperature of 40°C. Careful management is necessary due to these regulatory limits. Water vapor emissions are typically regulated to prevent excessive heat release into the environment, which can impact local ecosystems and air quality. By adhering to these guidelines, industries ensure that their operations minimize environmental impact while maintaining compliance with regulatory standards. One effective method of managing this is by installing a condenser, which cools the water vapor before it is discharged, thereby aligning with responsible environmental practices. This approach supports sustainable development by safeguarding environmental quality and promoting the health of surrounding ecosystems. Through the controlled release of water vapor at reduced temperatures, industries can balance their activities with ecological stewardship, ensuring a sustainable future.

The methanol and water gases from TFE-102 present distinct considerations for handling and disposal. Methanol, a valuable chemical commodity, can have its purity enhanced through distillation, making it suitable for recycling within industrial processes. By optimizing its purity and reusing it, businesses can reduce costs and enhance sustainability. Conversely, the water gas emitted at 90°C needs careful management due to regulatory limits stipulating a maximum discharge temperature of 40°C to minimize environmental impact. Installing a condenser to cool the water vapor before discharge ensures compliance with environmental standards, preventing potential ecological harm from excessive heat release. This dual approach of recycling methanol for internal use while responsibly managing water vapor discharge underscores the balance between operational efficiency and environmental stewardship in industrial operations. Pressure-swing distillation is an effective method for separating methanol-water azeotropic mixtures. The process involves feeding the methanol-water mixture into a distillation column operating at low pressure (e.g., 1 atm), where the azeotropic composition shifts towards a higher methanol content in the vapor phase. The methanol-enriched distillate is then fed into a second column operating at higher pressure (e.g., 2-3 atm), where the azeotropic composition shifts towards a higher water content in the vapor phase, allowing further separation of methanol and water. The overhead vapor from the high-pressure column, enriched in water, is condensed and removed as the water product, while the methanol-enriched bottoms are recycled back to the low-pressure column. By operating the two columns at different pressures, the methanol-water azeotrope is effectively broken, allowing for the separation of the two components. Additionally, heat integration techniques can be applied to reduce the overall energy consumption of the pressure-swing distillation proces (Galanido et al., 2020).

CHAPTER 8

EQUIPMENT SIZING AND MECHANICAL DESIGN

8.1 INTRODUCTION

The most critical components in any production plant are the equipment that drives the process. Thus, equipment sizing and costing are essential procedures prior to establishing a plant. These steps enable the determination of various parameters, including equipment size, construction materials, plant layout, estimated capital requirements, and potential equipment bottlenecks. Equipment sizing calculations are based on producing 600 tonnes of ascorbic acid annually. Section 5.2 outlines the sizing and specifications of each piece of equipment. Detailed calculations for all equipment are provided in Appendix B. All sizing calculations are performed using various formulas as outlined in "Product and Process Design Principles: Synthesis, Analysis, and Evaluation, Fourth Edition." The final equipment sizing is defined based on the ASME standards.

8.2 INDIVIDUAL EQUIPMENT SPECIFICATION

8.2.1 SIZING FOR STORAGE TANK 1

Table 8.1 Equipment specification sheet for storage tank 1

Specification Sheet	
Identification : Storage tank Item No. : P-1/ V-101 Function : To store sorbitol	
Design Sizing	
Fabrication	Horizontal cylinder
Material Construction	Carbon steel
Number of Unit	1
Working Volume of Fermenter, V_w (m^3)	35.41

Volume of Storage tank, V (m^3)	44.27
Diameter of Storage tank, D (m)	2.63
Length of Storage tank, L (m)	7.87

8.2.2 SIZING FOR FERMENTER 1

Table 8.2 Equipment specification sheet for fermenter1

Specification Sheet	
Identification : Fermenter Item No. : P-2 / FR-101 Function : To convert sorbitol to sorbose by *Gluconobacter oxydans*	
Design Sizing	
Fabrication	Vertical cylinder
Material Construction	Stainless steel 316
Number of Unit	3
Reaction time, (hour)	14
Working Volume of each Fermenter, V_w (m^3)	40
Volume of each Fermenter, V (m^3)	50
Diameter of Fermenter, D (m)	2.59
Height of Fermenter, H (m)	7.77

8.2.3 SIZING FOR PUMP 1

Table 8.3 Equipment specification sheet for pump 1

Specification Sheet	
Identification : Centrifugal Pump Item No. : P-101 Function : To pump stream S-102	
Design Sizing	
Material Construction	Cast Iron
Inlet Pressure, P_i (bar)	1.0

Outlet Pressure, P_o (bar)	1.1
Differential Pressure, P (bar)	0.1
Differential Head Pump, H (m)	1.2397
Pump Shaft Power (W)	363.59
Brake Horsepower (hp)	0.6611

8.2.4 SIZING FOR FERMENTER 2

Table 8.4 Equipment specification sheet for fermenter 2

Specification Sheet	
Identification : Fermenter Item No. : P-3 / FR-102 Function : To convert sorbose to sodium keto-gluconic acid by *Pseudoglyconobacter Saccharoketogenes*	
Design Sizing	
Fabrication	Vertical cylinder
Material Construction	Stainless steel 316
Number of Unit	4
Reaction time, (hour)	72
Working Volume of Fermenter, V_w (m^3)	40
Volume of Fermenter, V (m^3)	50
Diameter of Fermenter, D (m)	2.59
Height of Fermenter, H (m)	7.77

8.2.5 SIZING FOR CENTRIFUGE

Table 8.5 Equipment specification sheet for centrifuge 1

Specification Sheet
Identification : Decanter centrifuge Item No. : P-4 / DC-101 Function : To remove biomass produced by bacteria in fermenters

Design Sizing	
Fabrication	Horizontal cylinder
Material Construction	Stainless steel 316
Number of Unit	1
Total reaction time, t (hours)	13
Capacity (m^3/h)	11.5
Volume of Centrifuge, V (m^3)	119.595
Diameter of Centrifuge Bowl, D (m)	0.353
Length of Centrifuge, D (m)	1.016
Max bowl rotational speed (rpm)	4000
Centrifugal force, G	3150

8.2.6 SIZING FOR PUMP 2

Table 8.6 Equipment specification sheet for pump 2

Specification Sheet	
Identification : Centrifugal Pump Item No. : P-102 Function : To pump stream S-106	
Design Sizing	
Material Construction	Cast iron
Inlet Pressure, P_i (bar)	1.0
Outlet Pressure, P_o (bar)	1.1
Differential Pressure, P (bar)	0.1
Differential Heap Pump, H (m)	1.0797
Pump Shaft Power (W)	441.86
Brake Horsepower (Hp)	0.8034

8.2.7 SIZING FOR BIPOLAR MEMBRANE ELECTRODIALYSIS 1

Table 8.7 Equipment specification sheet for BME 1

Specification Sheet	
Identification : Bipolar Membrane Electrodialysis Item No. : P-5 / GBX-101 Function : To convert sodium keto-gluconic acid to keto-gluconic acid	
Design Sizing	
Fabrication	Vertical cylinder
Material Construction	Stainless steel 316
Number of Unit	1
Flux, J (L/m²/h)	30
Membrane surface area of BME, A (m^2)	50.45
Membrane thickness, t_m (m)	2.96

8.2.8 SIZING FOR PUMP 3

Table 8.8 Equipment specification sheet for pump 3

Specification Sheet	
Identification : Centrifugal Pump Item No. : P-103 Function : To pump stream S-108	
Design Sizing	
Material Construction	Cast Iron
Inlet Pressure, P_i (bar)	1.0
Outlet Pressure, P_o (bar)	1.1
Differential Pressure, P (bar)	0.1
Differential Heap Pump, H (m)	1.0917
Pump Shaft Power (W)	5.37
Brake Horsepower (Hp)	0.0098

8.2.9 SIZING FOR HEAT EXCHANGER 1

Table 8.9 Equipment specification sheet for HEX 1

Specification Sheet	
Identification : Heat Exchanger Item No. : P-20 / HX-106 Function : To perform heat exchange between stream S-108 and S-118	
Design Sizing	
Fabrication	Shell and Tube Heat Exchanger
Material Construction	Stainless steel 316
Heat Duty, Q (kW)	13.7523
Area of Heat Exchanger, A (m^2)	6.5668

8.2.10 SIZING FOR HEAT EXCHANGER 2

Table 8.10 Equipment specification sheet for HEX 2

Specification Sheet	
Identification : Heat Exchanger Item No. : P-22 / HX-108 Function : To perform heat exchange between stream S-110 and S-124	
Design Sizing	
Fabrication	Shell and Tube Heat Exchanger
Material Construction	Stainless steel 316
Heat Duty, Q (kW)	9.6039
Area of Heat Exchanger, A (m^2)	2.1793

8.2.11 SIZING FOR HEATER 1

Table 8.11 Equipment specification sheet for heater 1

Specification Sheet
Identification : Heater Item No. : P-6 / HX-101 Function : To heat up S-127 from 49.4°C to 90°C
Design Sizing

Fabrication	Horizontal
Material Construction	Stainless steel 316 (shell-organic liquid, tube for steam)
Heating agent	Steam
Heat Duty, Q (kW)	51.2538
Area of Heater, A (m^2)	0.6359

8.2.12 SIZING FOR THIN FILM EVAPORATOR 1

Table 8.12 Equipment specification sheet for TFE 1

Specification Sheet	
Identification : Evaporator Item No. : P-9 / TFE-101 Function : To evaporate water from 2-keto-gluconic acid	
Design Sizing	
Fabrication	Vertical cylinder
Material Construction	Stainless steel 316
Number of Unit	1
Diameter of Evaporator, D (m)	0.6728
Height of Evaporator, H (m)	1.3456
Heat Transfer Area of Evaporator, A (m^2)	2.844

8.2.13 SIZING FOR STIRRED TANK BIOREACTOR 1

Table 8.13 Equipment specification sheet for stirred tank bioreactor 1

Specification Sheet
Identification : Bioreactor Item No. : P-9 / R-101 Function : To produce methyl gluconate by the esterification of 2-keto-gulonic acid with methanol
Design Sizing

Fabrication	Vertical cylinder
Material Construction	Stainless steel 316
Retention Time, τ (hr)	1
Volume of each Reactor, V (m^3)	0.9433
Diameter of each Reactor, D (m)	0.7239
Height of each Reactor, H (m)	2.1717

8.2.14 SIZING FOR PUMP 4

Table 8.14 Equipment specification sheet for pump 4

Specification Sheet	
Identification : Centrifugal Pump Item No. : P-104 Function : To pump stream S-112	
Design Sizing	
Material Construction	Cast Iron
Inlet Pressure, P_i (bar)	1.0
Outlet Pressure, P_o (bar)	1.1
Differential Pressure, P (bar)	0.1
Differential Heap Pump, H (m)	1.2441
Pump Shaft Power (W)	3.19
Brake Horsepower (Hp)	0.0058

8.2.15 SIZING FOR HEAT EXCHANGER 3

Table 8.15 Equipment specification sheet for HEX 3

Specification Sheet
Identification : Heat Exchanger Item No. : P-21 / HX-107 Function : To perform heat exchange between stream S112 and S-115
Design Sizing

Fabrication	Shell and Tube Heat Exchanger
Material Construction	Stainless steel 316
Heat Duty, Q (kW)	9.8880
Area of Heat Exchanger, A (m^2)	9.7800

8.2.16 SIZING FOR COOLER 1

Table 8.16 Equipment specification sheet for cooler 1

Specification Sheet	
Identification : Cooler Item No. : P-10 / HX-103 Function : To cool down S-125 from 40°C to 30°C	
Design Sizing	
Fabrication	Horizontal
Material Construction	Stainless steel 316-tube side/carbon steel-shell side
Cooling agent	Chilled water
Cooling Duty, Q (kW)	4.12
Area of Cooler, A (m^2)	0.6009

8.2.17 SIZING FOR STIRRED TANK BIOREACTOR 2

Table 8.17 Equipment specification sheet for stirred tank bioreactor 2

Specification Sheet	
Identification : Bioreactor Item No. : P-11 / R-102 Function : To recover 2-ketogulonic acid to sodium ascorbate	
Design Sizing	
Fabrication	Vertical cylinder
Material Construction	Stainless steel 316
Retention Time, τ (hr)	1

Volume of Reactor, V (m^3)	1.0203
Diameter of Reactor, D (m)	0.75
Height of Reactor, H (m)	2.23

8.2.18 SIZING FOR PUMP 5

Table 8.18 Equipment specification sheet for pump 5

Specification Sheet	
Identification : Centrifugal Pump Item No. : P-105 Function : To pump stream S-114	
Design Sizing	
Material Construction	Cast Iron
Inlet Pressure, P_i (bar)	1.0
Outlet Pressure, P_o (bar)	1.1
Differential Pressure, P (bar)	0.1
Differential Heap Pump, H (m)	1.0651
Pump Shaft Power (W)	3.02
Brake Horsepower (Hp)	0.0055

8.2.19 SIZING FOR BIPOLAR MEMBRANE ELECTRODIALYSIS 2

Table 8.19 Equipment specification sheet for BME 2

Specification Sheet	
Identification : Bipolar Membrane Electrodialysis Item No. : P-12 / GBX-102 Function : To recover ascorbic acid from sodium ascorbate through hydrolysis	
Design Sizing	
Fabrication	Vertical cylinder

Material Construction	Stainless steel 316
Number of Unit	1
Flux, J ($L/m^2/h$)	30
Membrane surface area of BME, A (m^2)	27.17
Membrane thickness, t_m (m)	2.96

8.2.20 SIZING FOR PUMP 6

Table 8.20 Equipment specification sheet for pump 6

Specification Sheet	
Identification : Centrifugal Pump Item No. : P-106 Function : To pump stream S-115	
Design Sizing	
Material Construction	Cast Iron
Inlet Pressure, P_i (bar)	1.0
Outlet Pressure, P_o (bar)	1.1
Differential Pressure, P (bar)	0.1
Differential Heap Pump, H (m)	0.8940
Pump Shaft Power (W)	2.29
Brake Horsepower (Hp)	0.0042

8.2.21 SIZING FOR HEATER 2

Table 8.21 Equipment specification sheet for heater 2

Specification Sheet	
Identification : Heater Item No. : P-13 / HX-104 Function : To heat up S-126 from 51.7°C to 90°C	
Design Sizing	
Fabrication	Horizontal cylinder

Material Construction	Stainless steel 316
Heating agent	Steam
Heat Duty, Q (kW)	25.1977
Area of Heater, A (m^2)	0.3516

8.2.22 SIZING FOR THIN FILM EVAPORATOR 2

Table 8.22 Equipment specification sheet for TFE 2

Specification Sheet	
Identification : Evaporator Item No. : P-14 / TFE-102 Function : To evaporate water and methanol	
Design Sizing	
Fabrication	Vertical cylinder
Material Construction	Stainless steel 316
Number of Unit	1
Diameter of Evaporator, D (m)	0.2536
Height of Evaporator, H (m)	0.5072
Area of Evaporator, A (m^2)	0.404

8.2.23 SIZING FOR PUMP 7

Table 8.23 Equipment specification sheet for pump 7

Specification Sheet	
Identification : Centrifugal Pump Item No. : P-107 Function : To pump stream S-118	
Design Sizing	
Material Construction	Cast Iron
Inlet Pressure, P_i (bar)	1.0
Outlet Pressure, P_o (bar)	1.1

Differential Pressure, P (bar)	0.1
Differential Heap Pump, H (m)	0.8263
Pump Shaft Power (W)	1.64
Brake Horsepower (Hp)	0.003

8.2.24 SIZING FOR COOLER 2

Table 8.24 Equipment specification sheet for cooler 2

Specification Sheet	
Identification : Cooler Item No. : P-15 / HX-105 Function : To cool down S-123 from 40°C to 4°C	
Design Sizing	
Fabrication	Horizontal
Material Construction	Stainless steel 316
Cooling agent	NaCl Brine
Cooling Duty, Q (kW)	10.2617
Area of Cooler, A (m^2)	2.0717

8.2.25 SIZING FOR CRYSTALLIZER

Table 8.25 Equipment specification sheet for crystallizer

Specification Sheet	
Identification : Crystallizer Item No. : P-16 / CR-101 Function : To crystallize ascorbic acid into solid form	
Design Sizing	
Fabrication	Vertical cylinder
Material Construction	Stainless steel 316
Number of Unit	1

Retention time, t (hour)	54
Volume of Crystallizer, V (m^3)	33.19
Diameter of Crystallizer, D (m)	2.42
Height of Crystallizer, H (m)	7.25

8.2.26 SIZING FOR PUMP 8

Table 8.26 Equipment specification sheet for pump 8

Specification Sheet	
Identification : Centrifugal Pump Item No. : P-108 Function : To pump stream S-120	
Design Sizing	
Material Construction	Cast Iron
Inlet Pressure, P_i (bar)	1.0
Outlet Pressure, P_o (bar)	1.1
Differential Pressure, P (bar)	0.1
Differential Heap Pump, H (m)	0.7867
Pump Shaft Power (W)	122.92
Brake Horsepower (Hp)	0.2235

8.2.27 SIZING FOR NUTSCHE FILTER

Table 8.27 Equipment specification sheet for filter

Specification Sheet
Identification : Nutsche Filter Item No. : P-17 / NFD-101 Function : To filter final products and slurry components
Design Sizing

Fabrication	Vertical cylinder
Material Construction	Stainless steel 316
Number of Unit	2
Volume of each filter, V (m^3)	25
Filter Area, A (m^2)	15
Diameter of Nutsche Filter, D (m)	4.3702
Length of Nutsche FIlter, H (m)	1.67

8.2.28 SIZING FOR STORAGE TANK 2

Table 8.28 Equipment specification sheet for storage tank 2

Specification Sheet	
Identification : Storage tank Item No. : P-18 / V-102 Function : To store slurry components	
Design Sizing	
Fabrication	Horizontal cylinder
Material Construction	Carbon steel
Number of Unit	1
Working Volume of Fermenter, V_w (m^3)	15.712
Volume of Storage tank, V (m^3)	29.64
Diameter of Storage tank, D (m)	2.0
Length of Storage tank, H (m)	6.0

8.2.29 SIZING FOR PUMP 9

Table 8.29 Equipment specification sheet for pump 9

Specification Sheet
Identification : Centrifugal Pump Item No. : P-109 Function : To pump stream S-128

Design Sizing	
Material Construction	Cast Iron
Inlet Pressure, P_i (bar)	1.0
Outlet Pressure, P_o (bar)	1.1
Differential Pressure, P (bar)	0.1
Differential Heap Pump, H (m)	0.9047
Pump Shaft Power (W)	51.43
Brake Horsepower (Hp)	0.0935

8.2.30 SIZING FOR SOLIS STORAGE

Table 8.30 Equipment specification sheet for solids storage

Specification Sheet	
Identification : Silo/Bin Item No. : P-19 / SL-101 Function : To store ascorbic acid	
Design Sizing	
Fabrication	Vertical cylinder
Material Construction	Stainless steel 316
Number of Unit	1
Temperature, T (°C)	4.03
Pressure, P (bar)	1
Volume of Solid storage, V (m^3)	21.45
Diameter of Solid storage, D (m)	1.953
Height of Solid storage, H (m)	5.859

8.3 MECHANICAL DESIGN

Mechanical drawing is a technique that involves using detailed equipment information to create three-dimensional objects on a two-dimensional drawing worksheet. All the geometric features inherent in the machine element is aimed to be precisely determined. Three equipment design that are heat exchanger, stirred tank bioreactor and pump from our plant are chosen to introduce their detailed engineering drawings with specifications.

8.3.1 MECHANICAL DESIGN OF MAIN BIOREACTOR

The detailed engineering drawing of the airlift fermenter shown in Figure 8.1 was developed by using AutoCAD design software. The dimension and specification of the equipment are shown in Figure, and all the detailed calculation is shown as below:

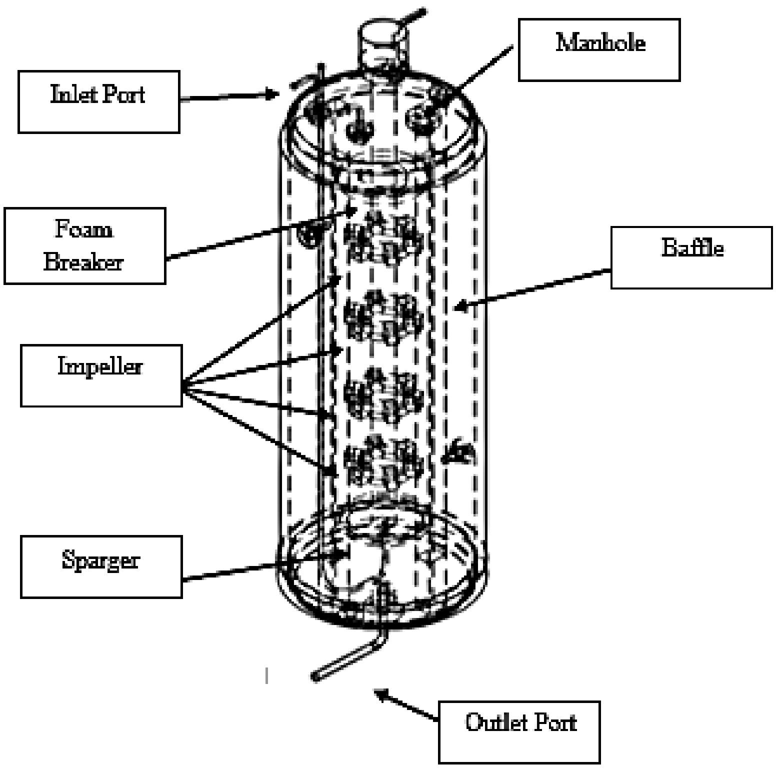
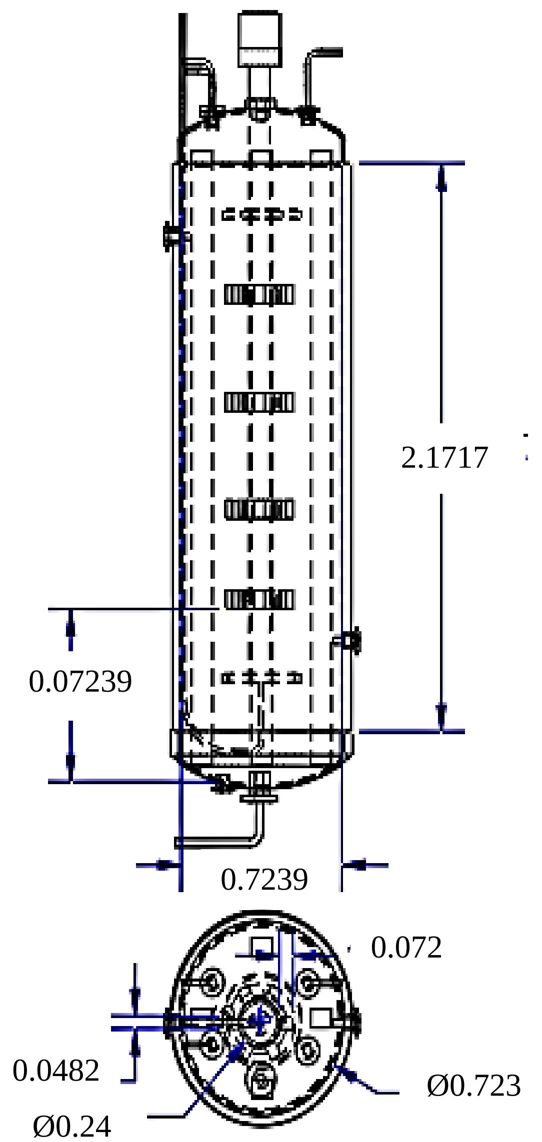


Figure 8.1 Mechanical design of main bioreactor developed by using AutoCAD® software.

Table 8.31 Dimension and Specification of Continuous Stirred Tank Bioreactor



MECHANICAL DESIGN SPECIFICATION SHEET FOR BIOREACTOR	
IDENTIFICATION	
Name	Bioreactor
Function	To produce methyl gluconate by the esterification of 2-keto-gulonic acid with methanol
Quantity	1
STIRRED TANK BIOREACTOR SPECIFICATION	
Fabrication	Vertical cylinder
Material of Construction	Stainless steel 316
Operating temperature (°C)	25
Operating pressure (bar)	1
Operation mode	Continuous batch
Retention time (hr)	1
Capacity (kg/hr)	776.54
Diameter of tank, D (m)	0.7239
Total vessel volume (m^3)	0.9433
Height to Diameter ratio	2.5:1
Vessel height (m^3)	2.1717
IMPELLERS SPECIFICATION	
Types of impellers	Rushton Impellers
Number of impellers	4
Impeller diameter, D (m)	0.2413
Number of blades	6
blade width (m)	0.04826
blade length (m)	0.060325
blade thickness (m)	0.04826
Impeller above vessel floor (m)	0.07239
BAFFLES SPECIFICATION	
Width of baffle (m)	0.07239
Height of baffle (m)	2.1717
Diameter of baffle (m)	0.36195
Length baffle between wall (m)	0.012065
Space between baffle (m)	0.14478

8.3.2 MECHANICAL DESIGN OF SHELL AND TUBE HEAT EXCHANGER

One of the heat exchangers (HX-106) is illustrated the detailed drawing from the process. Shell and tube heat exchanger is chosen for utilized in heating and cooling the fluids to reduce the energy requirements and enhance the efficiency of the process. The design is created based on the ASME (American Society of Mechanical Engineers) standards and Tubular Exchanger Manufacturers Association (TEMA) standards, all specifications and practices align with ASME and TEMA guidelines. The detailed of engineering drawing was illustrated in Figure 8.2 and Figure 8.3. The dimensions and specification of equipment are tabulated in Table 8.32. The detailed calculation is shown in Appendix -C.

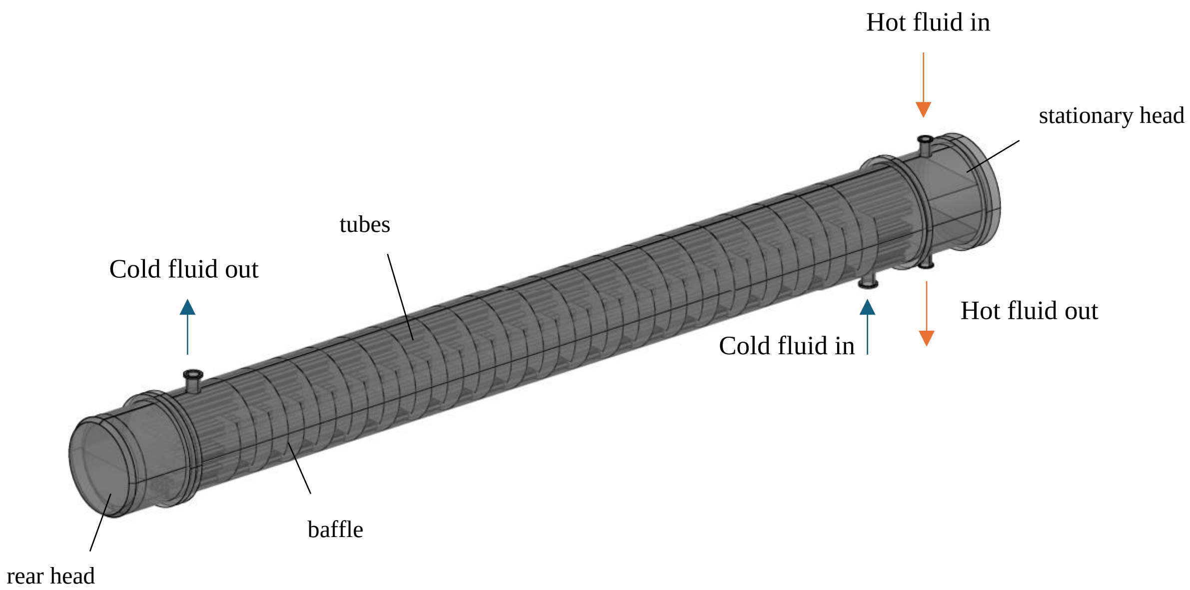


Figure 8.2 Engineering Drawing of 1-4 type of shell-and-tube heat exchanger (X-ray view) by AutoCAD software

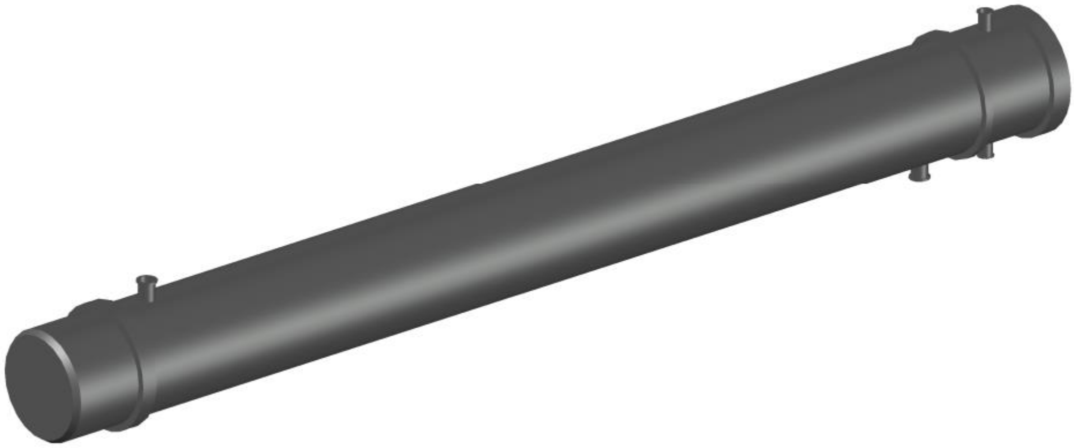
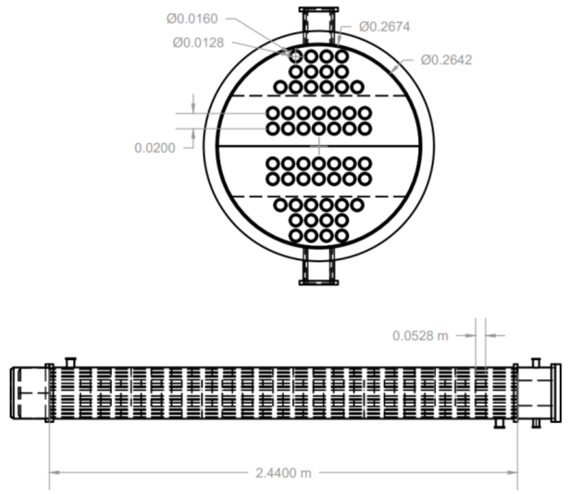


Figure 8.3 Engineering Drawing of 1-4 type of shell-and-tube heat exchanger (reality view) by AutoCAD software

Table 8.32 Dimension and specification of the shell-and-tube heat exchanger



SPECIFICATION SHEET FOR SHELL-AND-TUBE HEAT EXCHANGER			
IDENTIFICATION			
Name		Heat exchanger	
Type		1-4 type of heat exchanger	
Function		working on heat transferring between hot fluid and cold fluid	
HEAT EXCHANGER SPECIFICATION			
Flow pattern		counter flow	
Stationary head type		channel and removable cover (TEMA-A)	
Shell type		one pass shell (TEMA-E)	
Read head type		split-ring floating head (TEMA-S)	
Total heat transfer area required (m^2)		6.5668	
Overall heat transfer coefficient, U (W/m K)		100	
Tube side		**Shell side**	
Medium	hot fluid (organic solvents)	Medium	cold fluid (organic solvents)
Inlet temperature (K)	363.15	Inlet temperature (K)	303.15
Outlet temperature (K)	313.15	Outlet temperature (K)	314.15
material construction	stainless steel 316	material construction	stainless steel 316
number of passes	4	number of passes	1
Outer diameter (m)	0.016	Outer diameter (m)	0.2674
Inner diameter (m)	0.0128	Inner diameter (m)	0.2642
length (m)	2.44	baffle spacing (m)	0.0528
number of tubes	56	baffle cut	25%

8.3.3 MECHANICAL DESIGN OF CENTRIFUGAL PUMP

This section will clearly discuss the mechanical design of the centrifugal pump P-101. The specifications include the length, diameter of suction, diameter of impeller, outer diameter of inlet and impeller count. The engineering drawing Centrifugal pump is shown in Figure, while the mechanical data is shown in Table.

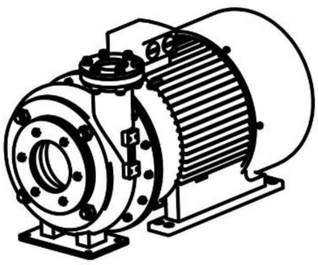
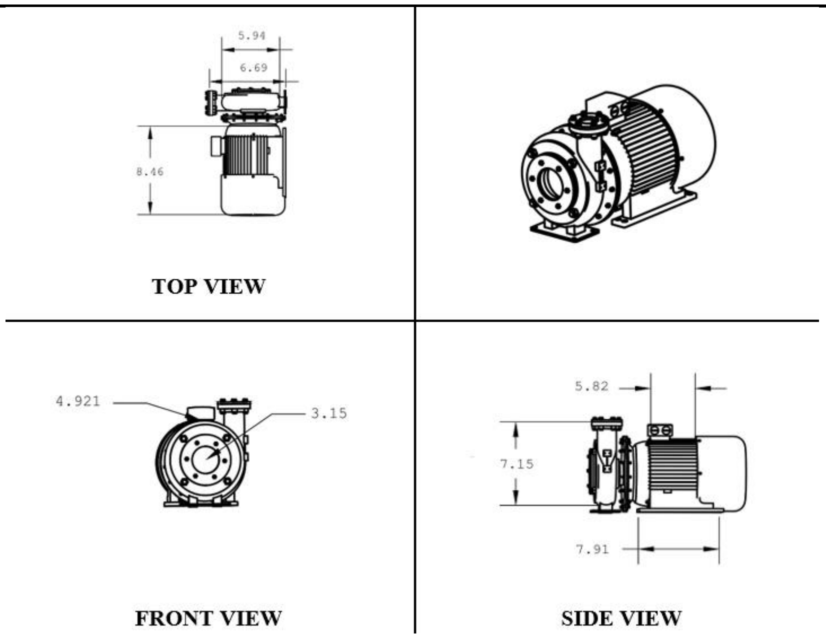


Figure 8.4 Engineering Drawing of Centrifugal Pump by AutoCAD software

Table 8.33 Dimension and Specification of Centrifugal Pump



SPECIFICATION OF CENTRIFUGAL PUMP	
IDENTIFICATION	
Name	Centrifugal Pump
Function	To pump stream S-102
CENTRIFUGAL PUMP SPECIFICATION	
Operating data	**Data**
Material Construction	Cast Iron
Working Temperature	30°C
Inlet Pressure, P_i (bar)	1
Outlet Pressure, P_o (bar)	1.1
Differential Pressure, P (bar)	0.1
Differential Head Pump, H (m)	1.2397
Pump Shaft Power (W)	363.59
Brake Horsepower (hp)	0.6611
Data Sizing	**Data**
Inlet pressure (bar)	1
Outlet pressure (bar)	1.1
Length (in)	19.82
Diameter (in)	5.94
Diameter of suction (in)	1.5
Diameter of impeller (in)	3.68
Wall thickness	0.1

CHAPTER 9

EQUIPMENT COSTING

9.1 INTRODUCTION TO EQUIPMENT COSTING

The cost of equipment plays a vital role as an early indicator of a plant's profitability and viability and affect the capital cost required. The profitability of the plant is required to be predicted based on the cost of each equipment needed for the production. The equipment cost is affected by the material selection, equipment selection, equipment sizing, facility costs, labour costs, installation cost and others, and this would decide the plant's feasibility. The calculation methods and references were mainly based on Plant Design textbook, *Product and Process Design Principles: Synthesis, Analysis and Design, Asia Edition, Seider, Seader, Lewin and Widagdo*. The detailed calculations of each equipment are demonstrated in Appendix C.

9.2 TOTAL BARE MODULE COST

Total bare module cost is determined for the ascorbic acid plant design, it includes the sum of all direct and indirect costs, such as buying, materials, and labour costs and installation costs. The factor for estimation of each purchase cost and bare module cost are refer to *Product and Process Design Principles: Synthesis, Analysis and Design, Asia Edition, Seider, Seader, Lewin and Widagdo*. The total bare-module cost, C_{TBM} of the production of 600 tons of ascorbic acid is as shown in Table 9.1, which is RM 41969839.64.

Table 9.1 Summary of Bare Module Cost, CBM of each equipment

Equipment	Identification	Unit	Purchase cost (RM)	Labor Cost (RM)	Indirect Expenses (RM)	Total of direct field materials (RM)	Bare Module Cost (RM)
Storage tank	V-101	1	312,779.30	197,050.95	296,201.99	223,324.41	2,017,739.22
Storage tank	V-102	1	179,374.19	113,005.74	169,867.36	128,073.17	1,157,142.91
Solid storage tank	SL-101	1	142,113.49	89,531.50	134,581.48	101,469.03	916,774.13
Fermenter 1	FR-101	3	399,293.74	251,555.06	378,131.17	285,095.73	5,897,967.84
Centrifugal pump	P-101	1	14,307.87	9,013.96	13,549.55	10,215.82	79,995.29
Fermenter 2	FR-102	4	257,863.31	387,613.58	292,245.08	7,748,587.82	257,863.31
Decanter Centrifuge	DC-101	1	187,591.60	118,182.71	177,649.24	133,940.40	810,583.29
Centrifugal pump	P-102	1	14,502.70	9,136.70	13,734.06	10,354.93	81,084.62
Bipolar membrane electrolysis	GBX-101	1	1,422,123.62	895,937.88	1,346,751.07	1,015,396.27	7,808,880.82
Centrifugal pump	P-103	1	14,443.11	9,099.16	13,677.62	10,312.38	80,751.40
Heat Exchanger	HX-106	1	108,514.99	68,364.44	102,763.69	77,479.70	592,600.35
Heat Exchanger	HX-108	1	146,713.36	92,429.42	138,937.55	104,753.34	801,201.65
Heater	HX-101	1	20,796.80	13,101.98	19,694.57	14,848.91	113,571.32
Thin film evaporator 1	TFE-101	1	422,733.50	266,322.11	400,328.62	301,831.72	2,004,179.52

Stirred tank bioreactor 1	R-101	1	98,504.25	62,057.68	93,283.53	70,332.04	635,450.94
Centrifugal pump	P-104	1	13,885.01	8,747.56	13149.11	9913.90	77,631.11
Heat Exchanger	HX-107	1	24,189.16	15,239.17	22,907.14	17,271.06	132,097.01
Cooler	HX-103	1	20,609.24	12,983.82	19,516.95	14,715.00	112,547.06
Stirred tank bioreactor 2	R-102	1	101,748.67	64,101.66	96,355.99	72648.55	656,380.65
Centrifugal pump	P-105	1	13,782.11	8,682.73	13,051.66	9,840.43	77,055.80
Bipolar membrane electrolysis	GBX-102	1	1,128,746.14	711,110.07	1,068,922.60	805,924.74	6,197,945.06
Centrifugal pump	P-106	1	13,635.16	8,590.15	12,912.49	9,735.50	76,234.17
Heater	HX-104	1	18,915.30	11,916.64	17,912.79	13,505.52	103,296.45
Thin film evaporator	TFE-102	1	144,514.24	91,043.97	136,854.98	103,183.16	685,141.99
Centrifugal pump	P-107	1	13,674.58	8,614.98	12,949.82	9,763.65	76,454.55
Cooler	HX-105	1	25,122.30	15,827.05	23,790.82	17,937.32	137,192.88
Crystallizer	CR-101	1	569,384.20	358,712.05	539,206.84	406,540.32	2,477,390.66
Centrifugal pump	P-108	2	13,705.63	8,634.55	12,979.23	9,785.82	121,856.76
Nutsche filter	NFD-101	3	22,765.72	14,342.40	21,559.14	16,254.72	210,605.67
Centrifugal pump	P-109	1	14,576.77	9,183.36	13,804.20	10,407.81	81,498.71
Total Bare Module Cost (RM)							41,969,839.64

9.3 TOTAL CAPITAL INVESTMENT (C_{TCI})

The total capital investment for a process plant to manufacture bioproducts is the one-time expenses for start-up of a grass root plant, design and construction to improve an existing plant. The estimation of total capital investment for the production plant for the manufacturing of 600 tons of ascorbic acid is based on the Guthrie method as demonstrated in the reference textbook, *Product and Process Design Principles: Synthesis, Analysis and Design, Asia Edition, Seider, Seader, Lewin and Widagdo*. The Total Capital Investment (CTCI) was calculated as shown in the equation below.

$C_{TCI} = C_{TPI} + C_{WC}$

$= 1.18\ (C_{TBM} + C_{SITE} + C_{BUILDINGS} + C_{OFFSITES\ FACILITIES}) + C_{WC}$

With the use of correlation of The Chemical Engineering (CE) Plant Cost Index:

$$Cost = Base\ Cost \times \frac{I_{2024}}{I_{Base\ (2013)}}$$

$I_{Base\ (2013)} = 567$

$I_{2024} = 797.3$

$$Total\ Bare\ Module\ Cost = RM\ 41{,}969{,}839.64 \times \frac{797.3}{567}$$

$$= RM\ 59{,}016{,}848.58$$

Table 9.2 Cost Required for total capital investment estimation

Type of Cost	**Cost Estimation**	**Value (RM)**
Site development cost (C_{SITE})	0.05 C_{TBM}	2,950,842.43
Building cost ($C_{BUILDINGS}$)	0.05 C_{TBM}	2,950,842.43
Offsite facilities cost ($C_{OFFSITE\ FACILITIES}$)	0.05 C_{TBM}	2,950,842.43
Total permanent investment (CTPI)	1.18 ($C_{TBM} + C_{SITE} + C_{BUILDINGS} + C_{OFFSITES\ FACILITIES}$)	80,085,863.52
Working capital (C_{WC})	0.176 C_{TPI}	14,095,111.98
Total capital investment (C_{TCI})	$C_{TPI} + C_{WC}$	94,180,975.50

Based on Table 9.2, the estimated total capital investment of the for the production of ascorbic acid is RM 94,180,975.50.

CHAPTER 10

PROCESS CONTROL AND SAFETY

10.1 PROCESS CONTROL

Process control with P&ID diagrams are essential to the efficient running of industrial processes. Process control ensures quality, safety, efficiency, and dependability, whereas P&ID diagrams offer a comprehensive visual depiction of the process, supporting design, implementation, upkeep, and instruction. In process industries, both components are essential to attaining compliance for achieving the control objectives. Therefore, Control the operating temperature, pressure and effluent to meet the environmental regulations

10.1.1 CONTROL SYSTEMS FOR INDIVIDUAL EQUIPMENT

The Tables below illustrate the control system of each individual equipment.

Table 10.1 Control system for Fermenter FR-101

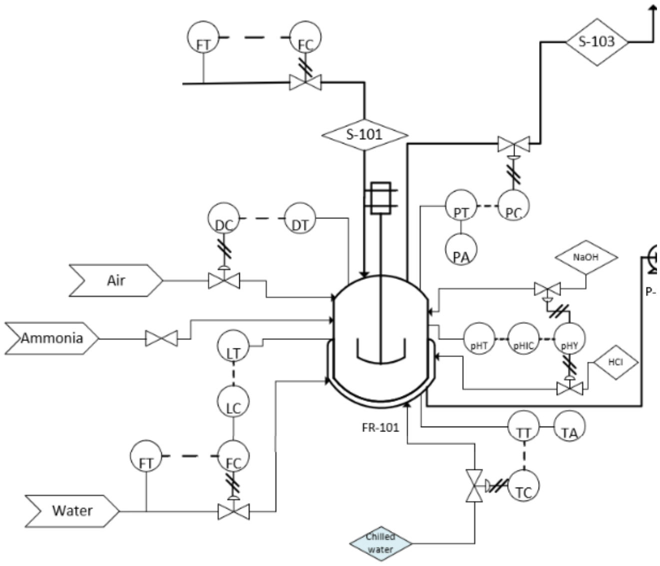
Control Objectives

1. To control the inlet flowrate of feed entering the fermenter.
2. To control the inlet flowrate of water and liquid level in fermenter.
3. To control the operating temperature of the fermenter and inlet flowrate of chilled water.
4. To control the pH in the fermenter.
5. To control the pressure in the fermenter.
6. To control the density of air in fermenter.

Control Variable	Measured variable	Manipulated Variable	Disturbance	Set Point	Configuration
The inlet flowrate of feed entering the fermenter	The inlet flowrate of feed entering the fermenter	The inlet flowrate of feed entering the fermenter	The inlet flowrate of feed entering the fermenter	Specified 45000 kg/batch of sorbitol entering fermenter	Feedforward control

Liquid level in fermenter (primary loop)	Liquid level in fermenter	Liquid level in fermenter	The liquid pressure in fermenter	Specified the liquid level range in fermenter	Cascade control
Inlet flowrate of water entering to fermenter (secondary loop)	Inlet flowrate of water entering to fermenter		The liquid pressure in fermenter	Specified the liquid level range in fermenter	
The temperature in fermenter (primary loop)	The temperature in fermenter	The flowrate of chilled water into fermenter	The liquid pressure in fermenter	30°C of liquid temperature in the fermenter	Cascade control
The inlet flowrate of chilled water (secondary loop)	The inlet flowrate of chilled water		The liquid pressure in fermenter	30°C of liquid temperature in the fermenter	
The liquid pH in fermenter	The liquid pH in fermenter	The flowrate of NaOH and HCl into fermenter	The flowrate of other inlet streams into fermenter	pH 6.0 of liquid pH in the fermenter	Feedback control
The liquid pressure in fermenter	The liquid pressure in fermenter	The flowrate of the gas venting stream (S-103) out from fermenter	The flowrate of inlet streams	1 bar of pressure in the fermenter	Feedback control
The density of air in fermenter.	The concentration of air in fermenter	The inlet flowrate of air into fermenter	The rate of foaming in fermenter	Specified level of air in the fermenter	Feedback control

Diagram



Where,

LT: Level Transmitter	pHT: pH Transmitter
LC: Level Controller	pHIC: pH Indicator Controller
TT: Temperature Transmitter	pHY: pH Calculation
TC: Temperature Controller	PT: Pressure Transmitter
TA: Temperature Alarm	PC: Pressure Controller
FT: Flow Transmitter	DT: Density Transmitter
FC: Flow Controller	DC: Density Controller

Table 10.2 Control system for Fermenter FR-102

Control Objectives

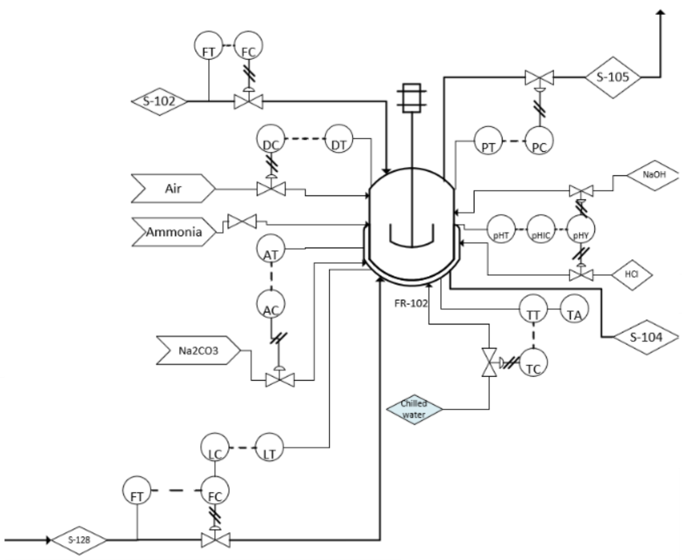
1. To control the inlet flowrate of stream from previous unit operation to enter the fermenter and liquid level in fermenter.
2. To control the inlet flowrate of sodium carbonate.
3. To control the operating temperature of the fermenter and inlet flowrate of chilled water.
4. To control the pH in the fermenter.
5. To control the pressure in the fermenter.
6. To control the density of air in fermenter.
7. Inlet flowrate from recycle stream.

Control Variable	Measured variable	Manipulated Variable	Disturbance	Set Point	Configuration

The liquid level in fermenter (primary loop)	The liquid level in fermenter	The flowrate of streams inlet (S-102) into fermenter	The flowrate of recycle streams into and out from fermenter	Specified level in the fermenter to avoid flooding	Cascade control
The inlet flowrate of stream to enter the fermenter from previous unit operation (secondary loop)	The inlet flowrate of stream from previous unit operation		The flowrate of recycle streams into and out from fermenter	Specified level in the fermenter to avoid flooding	
The inlet flowrate of sodium carbonate	The inlet flowrate of sodium carbonate	The inlet flowrate of sodium carbonate	The liquid pressure in fermenter	The inlet flowrate is specified correlated with other streams.	Feedback control
The temperature in fermenter (primary loop)	The temperature in fermenter	The flowrate of chilled water into fermenter	The inlet temperature of chilled water	30°C of liquid temperature in the fermenter	Cascade control
The inlet flowrate of chilled water entering fermenter (secondary loop)	The inlet flowrate of chilled water entering fermenter			30°C of liquid temperature in the fermenter	
The liquid pH in fermenter	The liquid pH in fermenter	The flowrate of NaOH and HCl into fermenter	The flowrate of other inlet streams into fermenter	Specified liquid pH in the fermenter	Feedback control

The liquid pressure in fermenter	The liquid pressure in fermenter	The flowrate of the gas venting stream (S-105) out from fermenter	The flowrate of inlet streams	1 bar of pressure in the fermenter	Feedback control
The density of air in fermenter.	The density of air in fermenter.	The inlet flowrate of air into fermenter	The rate of foaming in fermenter	Specified level of air in the fermenter	Feedback control
The inlet flowrate of recycle stream from storage 2	The inlet flowrate of recycle stream from storage 2	The inlet flowrate of recycle stream from storage 2	The inlet flowrate of recycle stream from storage 2	Specified the inlet flowrate of recycle stream about 80% from storage 2	Feedforward control

Diagram



Where,

LT: Level Transmitter
LC: Level Controller
TT: Temperature Transmitter
TC: Temperature Controller

pHT: pH Transmitter
pHIC: pH Indicator Controller
pHY: pH Calculation
PT: Pressure Transmitter

TA: Temperature Alarm	PC: Pressure Controller
FT: Flow Transmitter	DT: Density Transmitter
FC: Flow Controller	DC: Density Controller

Table 10.3 Control system for decanter centrifuge DC-101

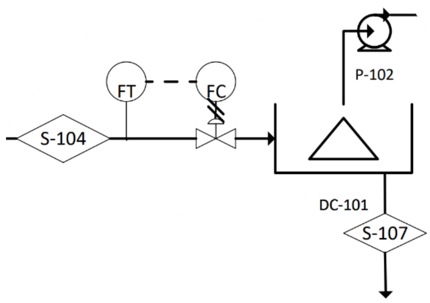
<table>
<tr><td colspan="6">Control Objective
To maintain the flow into the decanter centrifuge</td></tr>
<tr><th>Control Variable</th><th>Measured Variable</th><th>Manipulated Variable</th><th>Disturbance</th><th>Set Point</th><th>Configuration</th></tr>
<tr><td>The flowrate of the inlet stream (S-104)</td><td>The flowrate of the inlet stream (S-104)</td><td>The flowrate of the inlet stream (S-104)</td><td>The pressure of the inlet stream (S-104)</td><td>The inlet flow rate of the stream (sorbitol) is 124205 kg/batch</td><td>Feedback control</td></tr>
<tr><td colspan="6">Diagram

Where,
FT: Flow Transmitter
FC: Flow Controller</td></tr>
</table>

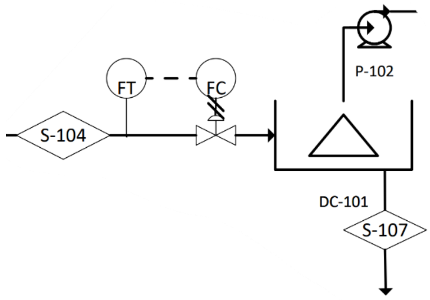
Table 10.4 Control system for decanter centrifuge DC-101

Control Objective

To control inlet flowrate of stream from previous unit operation to enter the centrifuge

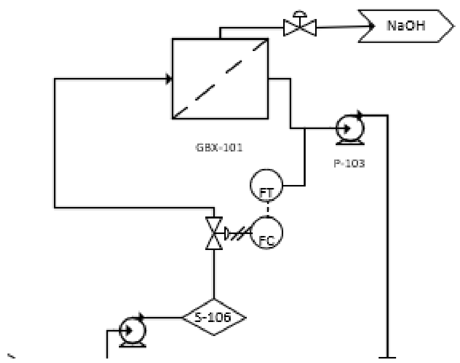
Control Variable	Measured Variable	Manipulated Variable	Disturbance	Set Point	Configuration
The flowrate of the inlet stream (S-104)	The flowrate of the inlet stream (S-104)	The flowrate of the inlet stream (S-104)	The pressure of the inlet stream (S-104)	The outlet flowrate of stream from fermenter 2	Feedback control

Diagram



Where,
FT: Flow Transmitter
FC: Flow Controller

Table 10.5 Control system for bipolar membrane electrodialysis GBX-101

<table>
<tr><td colspan="6">Control Objective
To control the liquid level in the Bipolar membrane electrodialysis (BME)</td></tr>
<tr><th>Control Variable</th><th>Measured Variable</th><th>Manipulated Variable</th><th>Disturbance</th><th>Set Point</th><th>Configuratio n</th></tr>
<tr><td>The liquid level in centrifuge</td><td>The liquid level in centrifuge</td><td>The flowrate of the inlet stream (S-106)</td><td>The pressure of the inlet stream (S-106)</td><td>Specified level in BME</td><td>Feedback control system</td></tr>
<tr><td colspan="6">Diagram


Where,
FT: Flow Transmitter
FC: Flow Controller
LT: Level Transmitter
LC: Level Controller</td></tr>
</table>

Table 10.6 Control system for Heater 1 (HX-101)

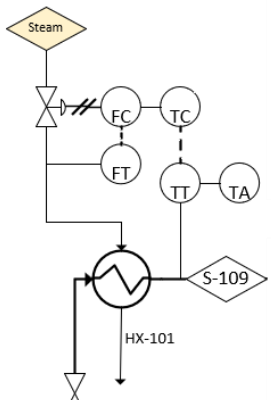
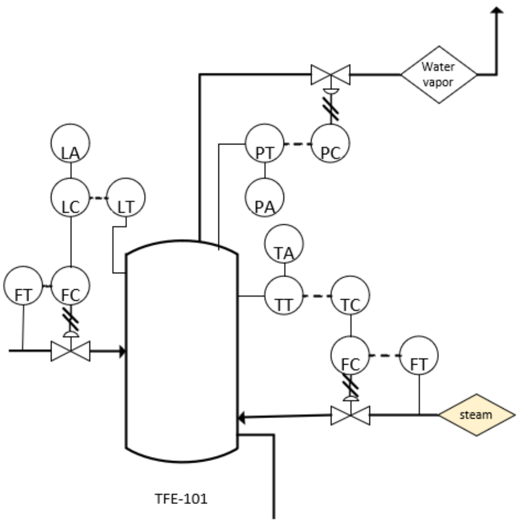
<table>
<tr><td colspan="6">Control Objective
1. To control the outlet temperature of the heated fluid at S-109 and inlet flowrate of sream</td></tr>
<tr><td>Control Variable</td><td>Measured Variable</td><td>Manipulated Variable</td><td>Disturbance</td><td>Set Point</td><td>Configuration</td></tr>
<tr><td>The outlet temperature at stream (S-109) of the fluid from Heater 1 (HX-101)</td><td>The outlet temperature at stream (S-109) of the fluid from Heater 1.</td><td rowspan="2">The inlet flowrate of steam entering HX-101</td><td rowspan="2">Temperature of inlet flowrate of stream, S-127</td><td rowspan="2">Set point is 90°C is the desired outlet temperature of the fluid</td><td rowspan="2">Cascade control</td></tr>
<tr><td>The inlet flowrate of steam entering HX-101</td><td>The inlet flowrate of steam entering HX-101</td></tr>
<tr><td colspan="6">Diagram

</td></tr>
<tr><td colspan="6">Symbols
Where,
TT: Temperature Transmitter
TC: Temperature Controller
TA: Temperature Alarm
FT: Flow Transmitter
FC: Flow Controller</td></tr>
</table>

Table 10.7 Control system for Thin Film Evaporator (TFE-101)

Control Objectives					
1. To control the inlet flowrate of stream from previous unit operation to enter evaporator and liquid level in the evaporator 2. To control the liquid pressure in the evaporator 3. To control the temperature of liquid in the evaporator and inlet flowrate of steam entering the evaporator					
Control Variable	**Measured variable**	**Manipulated Variable**	**Disturbance**	**Set Point**	**Configuration**
Liquid level in the evaporator	Liquid level inside the evaporator	The inlet flowrate of stream from previous unit operation	The liquid pressure in the evaporator	The specified liquid level in the evaporator	Cascade control
The inlet flowrate of stream from previous unit operation to enter the evaporator	The inlet flowrate of stream from previous unit operation		The liquid pressure in the evaporator	The specified liquid level in the evaporator	
The liquid pressure in the evaporator	Pressure of the liquid in the evaporator	The outlet of gaseous venting out from the evaporator	The inlet flowrate from the previous unit operation	Set the pressure along the stream is at 1 bar	Feedback control
Temperature of liquid in evaporator	The temperature of liquid in the evaporator	The inlet flow rate of the steam into evaporator	Feed flow into the evaporator	Desired temperature in evaporator at 90 ℃	Cascade control
The inlet flow rate of the steam	The inlet flow rate of the steam		Feed flow into the evaporator	Desired temperature	

into evaporator	into evaporator			in evaporator at 90 °C	

Diagram



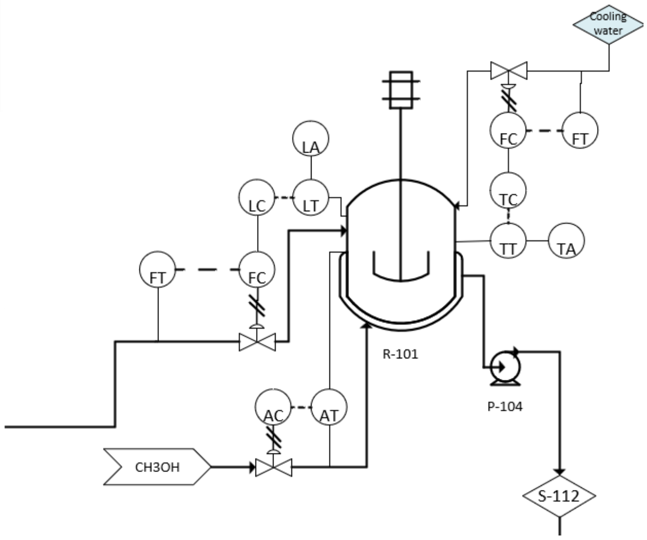
Where,
LT: Level Transmitter
LC: Level Controller
LA: Level Alarm
FT: Flow Transmitter
FC: Flow Control
TT: Temperature Transmitter
TC: Temperature Control
TA: Temperature Alarm
PT: Pressure Transmitter
PC: Pressure Controller
PA: Pressure Alarm

Table 10.8 Control system for R-101

Control Objectives

1. To control the operating temperature of the stirring tank reactor and the inlet flowrate of cooling water.
2. To control the inlet flowrate of methanol.

<table>
<tr><td colspan="6">3. To control the inlet flowrate of stream from previous unit operation enter the reactor and liquid level in the stirred tank reactor.</td></tr>
<tr><th>Control Variable</th><th>Measured variable</th><th>Manipulated Variable</th><th>Disturbance</th><th>Set Point</th><th>Configuration</th></tr>
<tr><td>Temperature of the liquid in the stirred tank reactor</td><td>Operating temperature of the stirred tank reactor</td><td rowspan="2">Operating temperature of the stirred tank reactor</td><td>The inlet flowrate from previous unit operation</td><td>Optimum temperature of stirred tank bioreactor 1 is 64°C</td><td rowspan="2">Cascade control</td></tr>
<tr><td>Inlet flowrate of the steam entering the stirred tank reactor</td><td>Inlet flowrate of the steam entering the stirred tank reactor</td><td>The inlet flowrate from previous unit operation</td><td>Optimum temperature of stirred tank bioreactor 1 is 64°C</td></tr>
<tr><td>The inlet flowrate of methanol</td><td>The inlet flowrate of methanol</td><td>The inlet flowrate of methanol</td><td>The inlet flowrate from previous unit operation</td><td>The desired inlet flowrate from previous unit operation</td><td>Feedback control</td></tr>
<tr><td>The liquid level in the stirred tank reactor.</td><td>The liquid level in the stirred tank reactor.</td><td rowspan="2">The inlet flowrate of stream from previous unit operation</td><td>The temperature of liquid in the tank</td><td>Specified liquid level in the tank</td><td rowspan="2">Cascade control</td></tr>
<tr><td>The inlet flowrate of stream from previous unit operation to enter the reactor</td><td>The inlet flowrate of stream from previous unit operation</td><td>The temperature of liquid in the tank</td><td>Specified liquid level in the tank</td></tr>
<tr><th colspan="6">Diagram</th></tr>
</table>



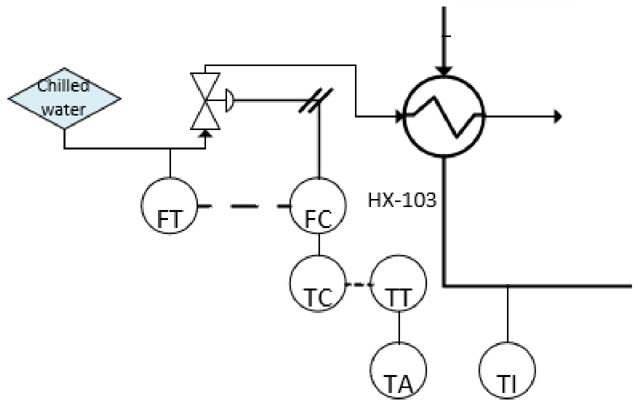
Symbols
Where,
LT: Level Transmitter
LC: Level Controller
LA: Level Alarm
FT: Flow Transmitter
FC: Flow Control
TT: Temperature Transmitter
TC: Temperature Control
TA: Temperature Alarm
AC: Analytical Controller
AT: Analytical Transmitter

Table 10.9 Control system for Cooler HX-103

Control Objective 1. To control the temperature of outlet stream of the HX-103					
Control Variable	**Measured Variable**	**Manipulated Variable**	**Disturbance**	**Set Point**	**Configuration**
The temperature of the outlet fluid from HX-103	The temperature of the outlet fluid	The inlet flowrate of chilled water	The inlet flowrate of stream, S-125	Desired temperature of outlet stream at 30°C.	Cascade control

The inlet flowrate of chilled water entering the cooler	The inlet flowrate of chilled water entering the cooler	entering the cooler	The inlet flowrate of stream, S-125	Desired temperature of outlet stream at 30°C.	

Diagram



Symbols

Where,
TT: Level Transmitter
TC: Level Controller
TA: Level Alarm
TI: Temperature Indicator
FC: Flow Controller
FT: Flow Transmitter

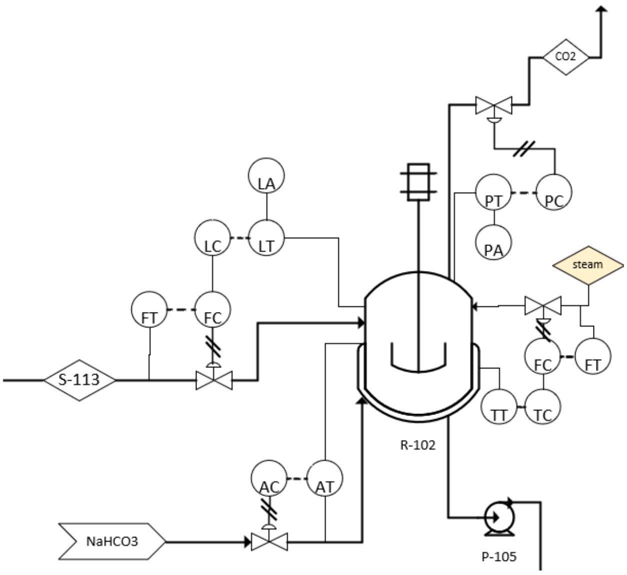
Table 10.10 Control system for R-102

Control Objective

1. To control the temperature of liquid in stirred tank reactor 2 and the inlet flowrate of steam.
2. To control the inlet flowrate from previous unit operation and liquid level in stirred tank reactor 2
3. To control the inlet flowrate of sodium bicarbonate
4. To control the pressure of liquid in the stirred tank reactor 2

Control Variable	**Measured variable**	**Manipulated Variable**	**Disturbance**	**Set Point**	**Configuration**

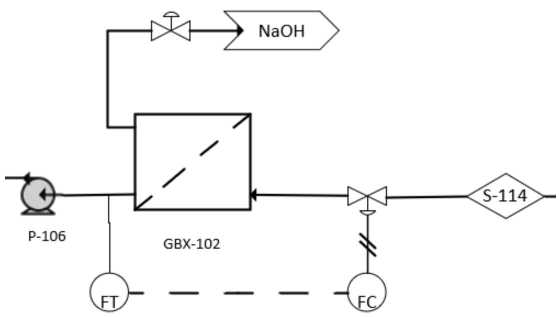
The temperature in the stirred tank reactor 2	The temperature in the stirred tank reactor 2	The inlet flowrate of steam entering the stirred tank reactor 2	The inlet flowrate from the previous unit operation	The desired temperature is 30°C	Cascade control
The inlet flowrate of steam	The inlet flowrate of steam		The inlet flowrate from the previous unit operation	The desired temperature is 30°C	
The liquid level in the stirred tank reactor 2	The actual liquid level in the stirred tank reactor 2	The inlet flowrate od stream from previous unit operation	The inlet flowrate of steam entering the stirred tank reactor 2	The desired liquid level in bioreactor to prevent overflow or underflow	Cascade control
The inlet flowrate of stream from previous unit operation to enter the reactor	The inlet flowrate of stream from previous unit operation			The desired liquid level in bioreactor to prevent overflow or underflow	
The inlet flowrate of sodium bicarbonate	The inlet flowrate of sodium bicarbonate	The inlet flowrate of sodium bicarbonate	The liquid pressure in stirred tank reactor 2	The inlet flowrate from previous unit operation	Feedback
The pressure of liquid in the stirred tank reactor 2	The pressure of liquid in the stirred tank reactor 2	The outlet of gaseous venting out from the reactor	The inlet flowrate from previous unit operation	The desired pressure level is 1 bar	Feedback control
Diagram					



Where,
LT: Level Transmitter
LC: Level Controller
LA: Level Alarm
FT: Flow Transmitter
FC: Flow Control
TT: Temperature Transmitter
TC: Temperature Control
TA: Temperature Alarm
PT: Pressure Transmitter
PC: Pressure Control
PA: Pressure Alarm
AC: Analytical Controller
AT: Analytical Transmitter

Table 10.11 Control system for GBX-102

<table>
<tr><td colspan="6">Control Objective
1. To control the inlet flowrate of stream from previous unit operation to enter the bipolar membrane electrodialysis</td></tr>
<tr><td>Control Variable</td><td>Measured variable</td><td>Manipulated Variable</td><td>Disturbance</td><td>Set Point</td><td>Configuration</td></tr>
<tr><td>The inlet flowrate of stream from previous unit operation to enter the bipolar membrane electrodialysis</td><td>The inlet flowrate of liquid from previous unit operation</td><td>The inlet flowrate of liquid from previous unit operation</td><td>The pressure of the liquid in the bipolar membrane electrodialysis, GBX-102</td><td>The outlet flowrate of stream from the R-102</td><td>Feedback control</td></tr>
<tr><td colspan="6">Diagram



</td></tr>
<tr><td colspan="6">Symbols
Where,
LT: Level Transmitter
LC: Level Controller
FT : Flow Transmitter
FC: Flow Control</td></tr>
</table>

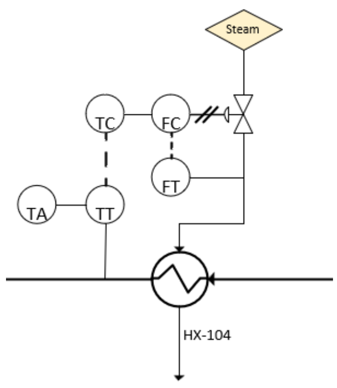
Table 10.12 Control system for Heater (HX-104)

Control Objective

1. To control the outlet temperature of the stream and the inlet flowrate of steam

Control Variable	**Measured Variable**	**Manipulated Variable**	**Disturbance**	**Set Point**	**Configuration**
The temperature of stream at S-126	The temperature of stream at S-126	The inlet flowrate of steam entering the heater	The inlet flowrate of stream from previous unit operation	The set point is the desired outlet temperature of the fluid, which is 90°C.	Cascade control
The inlet flowrate of steam entering the heater	The inlet flowrate of steam entering the heater		The inlet flowrate of stream from previous unit operation	The set point is the desired outlet temperature of the fluid, which is 90°C.	

Diagram



Symbols

Where,
TT: Temperature Transmitter
TC: Temperature Controller
TA: Temperature Alarm
FT: Flow Transmitter
FC: Flow Controller

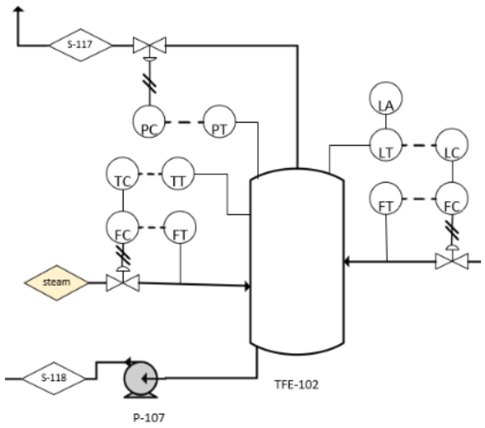
Table 10.13 Control system for TFE-102

Control Objective

1. To control the inlet flowrate of stream from previous unit operation enter the evaporator and the liquid level in the evaporator
2. To control temperature of liquid in the evaporator and the inlet flowrate of steam
3. To control the pressure in the evaporator

Control Variable	**Measured Variable**	**Manipulated Variable**	**Disturbance**	**Set Point**	**Configuration**
Liquid level in the evaporator	Liquid level inside the evaporator	The inlet flowrate of stream from previous unit operation	The liquid pressure in the evaporator	The specified liquid level in the evaporator	Cascade control
The inlet flowrate of stream from previous unit operation to enter the evaporator	The inlet flowrate of stream from previous unit operation		The liquid pressure in the evaporator	The specified liquid level in the evaporator	
The liquid pressure in the evaporator	Pressure of the liquid in the evaporator	The outlet of gaseous venting out from the evaporator	The inlet flowrate from the previous unit operation	Set the pressure along the stream is at 1 bar	Feedback control
Temperature of liquid in evaporator	The temperature of liquid in the evaporator	The inlet flow rate of the steam into evaporator	Feed flow into the evaporator	Desired temperature in evaporator at 90 °C	Cascade control
The inlet flow rate of the steam into evaporator	The inlet flow rate of the steam into evaporator		Feed flow into the evaporator	Desired temperature in evaporator at 90 °C	

Diagram



Symbols

Where,

LT: Level Transmitter

LC: Level Controller

LA: Level Alarm

FT: Flow Transmitter

FC: Flow Control

TT: Temperature Transmitter

TC: Temperature Control

TA: Temperature Alarm

PT: Pressure Transmitter

PC: Pressure Control

PA: Pressure Alarm

Table 10.14 Control system for Cooler HX-105

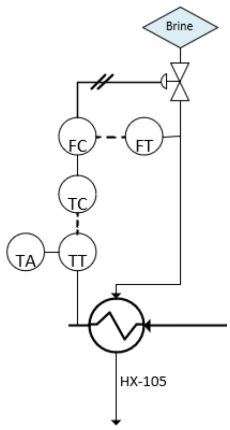
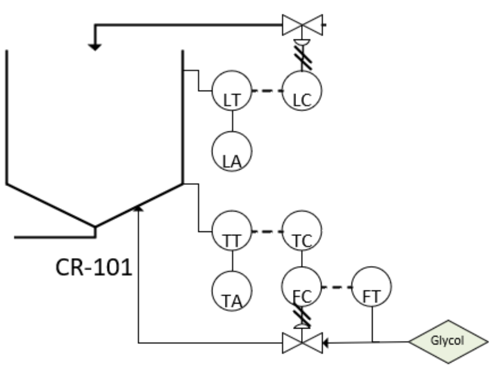
<table>
<tr><td colspan="6">Control Objective
To control the desired outlet temperature of the stream and inlet flowrate of steam</td></tr>
<tr><th>Control Variable</th><th>Measured Variable</th><th>Manipulated Variable</th><th>Disturbance</th><th>Set Point</th><th>Configuration</th></tr>
<tr><td>The temperature of outlet stream at S-113</td><td>The temperature of outlet stream at S-113</td><td rowspan="2">The inlet flowrate of steam entering evaporator</td><td>The inlet flowrate of stream which is S-123</td><td>Temperature of outlet at 4°C.</td><td rowspan="2">Cascade control</td></tr>
<tr><td>The inlet flowrate of steam entering evaporator</td><td>The inlet flowrate of steam entering evaporator</td><td>The inlet flowrate of stream which is S-123</td><td>Temperature of outlet at 4°C.</td></tr>
<tr><td colspan="6">Diagram

</td></tr>
<tr><td colspan="6">Symbols
Where,
TT: Temperature Transmitter
TC: Temperature Controller
TA: Temperature Alarm
FT: Flow Transmitter
FC: Flow Controller</td></tr>
</table>

Table 10.15 Control system for Crystallizer CR-101

Control Objective					
1. To control the liquid level in the crystallizer 2. To control the temperature of stream and inlet flowrate of glycol entering the crystallizer					
Control Variable	**Measured variable**	**Manipulated Variable**	**Disturbance**	**Set Point**	**Configuration**
The level of ascorbic acid in the crystallizer	The level of ascorbic acid in the crystallizer	The flow rate of the feed stream into crystallizer (S-119)	Fouling effect in the crystallizer, Temperature and pressure change in the crystallizer	The desired liquid level in the crystallizer	Feedback control
The temperature of stream in the crystallizer	The temperature of steam in the crystallizer	The inlet flowrate of glycol into the crystallizer	Pressure changes in the crystallizer	Temperature in the crystallizer is 4°C	Cascade control
The inlet flowrate of glycol into the crystallizer	The inlet flowrate of glycol into the crystallizer		Pressure changes in the crystallizer	Temperature in the crystallizer is 4°C	
Diagram					

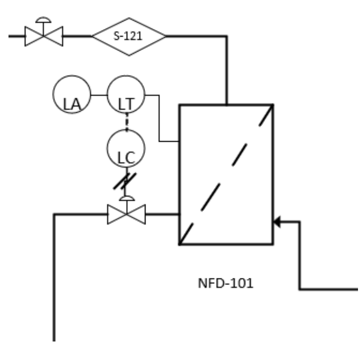


Where, LT: Level Transmitter LC: Level Controller LA: Level Alarm TT: Temperature Transmitter TC: Temperature Controller TA: Temperature Alarm FT: Flow Transmitter FC: Flow Controller

Table 10.16 Control system for Nutsche Filter NFD-101

Control Objective To maintain the efficiency of filtration by controlling the liquid level in the Nutsche Filter					
Control Variable	**Measured Variable**	**Manipulated Variable**	**Disturbance**	**Set Point**	**Configuration**
The liquid level in the Nutsche Filter	The liquid level in the Nutsche Filter	The inlet flow rate of the stream (S-120	Pressure changes in the crystallizer	The inlet flow rate of the stream (S-120) is 47305.8512 kg/batch	Feedback control

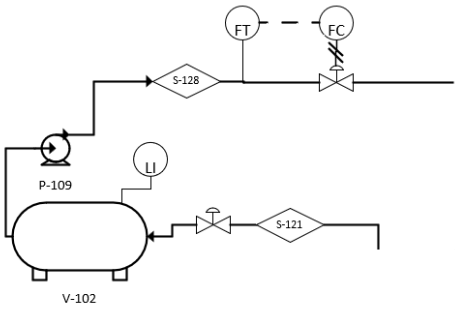
Diagram



Where,
LT: Level Transmitter

<table>
<tr><td>LC: Level Controller
LA: Level Alarm</td></tr>
</table>

Table 10.17 Control system for Storage Tank V-102

<table>
<tr><td colspan="6">Control Objective
To control the outlet flowrate of stream from storage tank</td></tr>
<tr><td>Control Variable</td><td>Measured Variable</td><td>Manipulated Variable</td><td>Disturbance</td><td>Set Point</td><td>Configuration</td></tr>
<tr><td>The outlet flowrate of stream from storage tank</td><td>The outlet flowrate of stream from storage tank</td><td>The outlet flowrate of stream from storage tank</td><td>The outlet flowrate of stream from storage tank</td><td>The outlet flowrate of stream (S-128) is always 90% of fluid in storage tank</td><td>Feedforward control</td></tr>
<tr><td colspan="6">Diagram


Where,
LI: Level Indicator
FT: Flow Transmitter
FC: Flow Controller</td></tr>
</table>

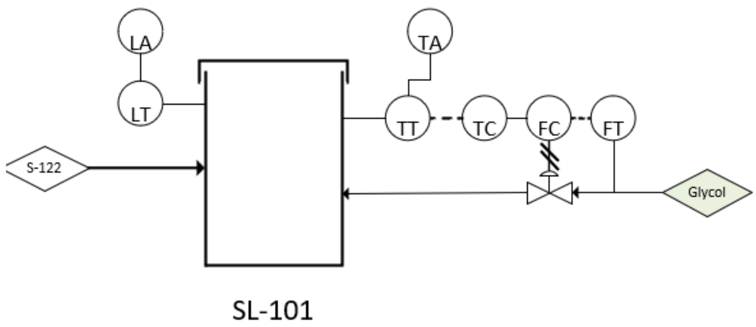
Table 10.18 Control system for Solid Storage Tank SL-101

Control Objective

To control the storing temperature in the solid storage

Control Variable	Measured Variable	Manipulated Variable	Disturbance	Set Point	Configuration
The temperature of ascorbic acid in the storage tank	The temperature of ascorbic acid in the storage tank	The inlet flow rate of glycol into the storage tank	Pressure changes in the crystallizer	The temperature of solid storage tank is 4°C	Cascade control
The inlet flow rate of glycol into the storage tank	The inlet flow rate of glycol into the storage tank		Pressure changes in the crystallizer	The temperature of solid storage tank is 4°C	

Diagram



Where,

LT: Level Transmitter

LA: Level Alarm

TT: Temperature Transmitter

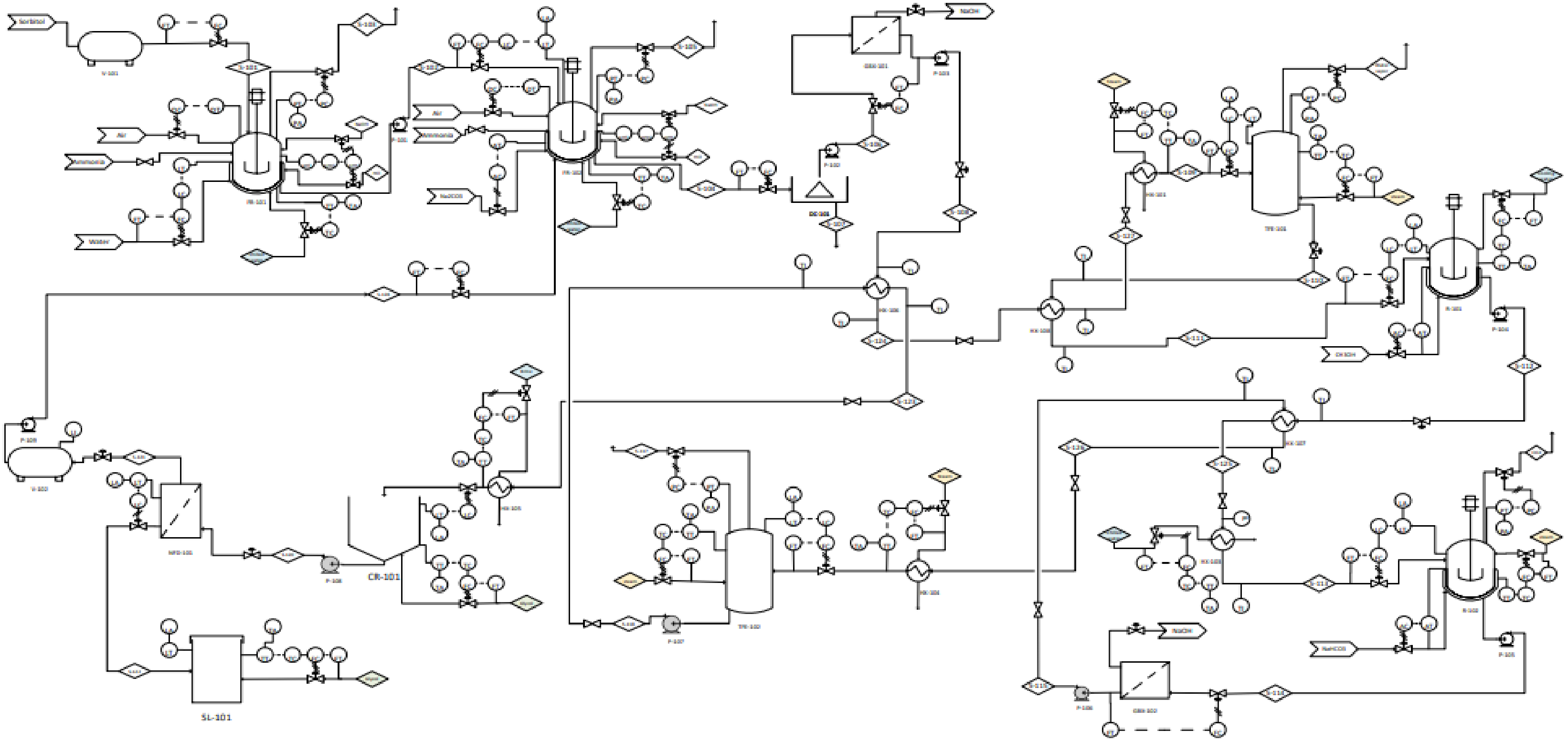
TC: Temperature Controller

TA: Temperature Alarm

FT: Flow Transmitter

FC: Flow Controller

10.1.2 P&ID DIAGRAM



V-101, 102 Storage 1 & 2	TT	Temperature Transmitter	PT	Pressure Transmitter
FR-101, 102 Fermenter 1 & 2	TC	Temperature Controller	PC	Pressure Controller
DC-101 Centrifuge	TA	Temperature Alarm	PA	Pressure Alarm
GBX-101, 102 Bipolar membrane electrodialysis 1 & 2	TI	Temperature Indicator	pHT	pH Transmitter
TFE-101, 102 Thin Film Evaporator 1 & 2	FT	Flow Transmitter	pHY	pH Calculation
R-101, 102 Stirred Tank Bioreactor 1 & 2	FC	Flow Controller	pHC	pH Controller
CR-101 Crystallizer	LT	Level Transmitter	AT	Analytical Transmitter
NFD-101 Nutsche Filter	LC	Level Controller	AC	Analytical Controller
SL-101 Solid storage	LI	Level Indicator		
HX-101, 103, 104, 105 Heaters/Coolers	LA	Level Alarm		
HX-106, 107, 108 Heat exchangers	DT	Density Transmitter		
P-101 to P-109 Pumps	DC	Density Controller		

Figure 10.1 P&ID diagram which is drawn by Microsoft Visio

10.2 GENERAL SAFETY ASSESSMENT

The general safety assessment for the ascorbic acid production plant encompasses determining the limits of the equipment, identifying potential hazards, assessing risks, and implementing appropriate safety measures to ensure the plant operates safely and efficiently. Determining equipment limits involves identifying the maximum and minimum operating conditions, ensuring material compatibility, defining capacity and load limits, and establishing maintenance requirements. This step ensures that all equipment is used within safe parameters and helps prevent failures and accidents.

Hazard identification is crucial for recognizing potential risks in the plant. Chemical hazards include the handling of raw materials such as glucose, acetone, and hydrochloric acid, which are flammable, toxic, or corrosive. Intermediates and by-products may also pose significant hazards. Although ascorbic acid itself is relatively safe, its dust can be irritating and potentially explosive. Solvents and reagents used in the process add to the chemical hazard profile. Biological hazards, though less common, can arise from microbial contamination of raw materials or water supply, improper hygiene practices by personnel, and inadequate waste disposal. Physical hazards involve risks from machinery and equipment, such as moving parts, pressure vessels, and high temperatures, which can cause injuries or burns. Manual handling of heavy items can lead to musculoskeletal injuries, while high noise levels from machinery can cause hearing loss. Electrical hazards, such as faulty wiring or equipment, and the risk of slips and falls from spills or wet surfaces, also need to be managed. Environmental hazards include air emissions of volatile organic compounds (VOCs) and dust, water pollution from chemical effluents, soil contamination from spills or leaks, and improper waste management.

Risk identification and assessment involves evaluating the likelihood and severity of each hazard, using a risk matrix to rate them as low, medium, high, or extreme. This helps prioritize risks that require immediate attention and mitigation. Checking equipment for safety entails regular inspections, testing, and performance monitoring to ensure compliance with safety standards and to detect deviations from safe operating conditions. If equipment is deemed safe, proper documentation is maintained. If not, risk reduction measures are implemented.

Risk reduction measures include engineering controls like containment systems, proper ventilation, and safety features such as interlocks and alarms. Administrative controls involve regular training, clear standard operating procedures (SOPs), and a robust maintenance schedule. Personal protective equipment (PPE) such as gloves, goggles, and respirators must be used appropriately. Emergency preparedness, including developing and practicing response plans and ensuring the availability of first aid supplies and trained personnel, is essential. Documentation involves maintaining detailed records of risk assessments, safety inspections, maintenance activities, and training. Effective communication ensures all stakeholders are informed about safety protocols and any changes in procedures.

10.2.1 HANDLING OF ASCORBIC ACID

Ascorbic acid does not contain any chemical groups identified with explosive properties. It is a stable compound, not sensitive to static discharge. However, it is sensitive to high intensity light. This is because the long chain of conjugated carbon double bonds present is ascorbic acid are prone to light degradation reactions. Light exposure during processing and storage also affects degradation. Thus, ascorbic acid needs to be put in a place where light most of the time is minimized to ensure it remains stable. Besides, ascorbic acid needs a proper storage at 4°C with a tightly closed container as it is a heat sensitive compound. Proper handling needs to be done to avoid contamination from foreign matter and microbes. The storage shall be kept far from harmful chemicals, potential hazardous materials, food, drink, and animal feed. In the storage facilities, local and general ventilation mechanisms shall also be implemented to prevent dust or aerosol collection that may become potential ignition sources. However, ascorbic acid is a non-pyrophoric organic acid, and hence, it is not flammable and, therefore, will not yield flammable gases in contact with water.

10.2.2 POTENTIAL HAZARD

Generally, ascorbic acid is considered an innocuous compound at biologically relevant concentrations based on its non-persistent and nonbioaccumulative nature, along with its nontoxic disposition. Ascorbic acid is an environmentally green product that would not give a strong negative impact to the environment. It has feebly adsorptive potential, thereby resulting in reduced mobility in the event of its disposal in soil.

10.2.3 DISPOSAL CONSIDERATION

Though ascorbic acid is regarded as non-toxic, it is always advisable to dispose of the waste in a professional and safe way. Even though ascorbic acid, the product itself is non-toxic, but in the production and manufacturing process, there are also reactants involved that would produce some by-product or waste that would bring negative effects to the environment if it were not being treated properly, such as sodium hydroxide. Other than that, packaging that has been contaminated because of spillage apart from unused products is to be disposed of.

10.2.4 HOUSE KEEPING

Industrial cleanliness in the production workplace goes hand in hand with industrial safety. Housekeeping should ensure clean working conditions and make an organization a much safer place to work and thus improve its image. It improves efficiency and productivity, maintains product quality, and assures process control. Housekeeping activities are visible indicators of the general standards of quality and safety in the production area. Effective housekeeping reduces injury rates and creates a positive impression for visitors. Some of the indicators of bad housekeeping and cleanliness include cluttered and poorly organized work areas, dirty or congested spaces for material storage, dusty and slippery floors and workplaces, and broken containers holding damaged materials.

10.3 HAZARD AND OPERABILITY STUDIES (HAZOP)

HAZOP is a procedure to identify plant hazards and operability problems. This technique can be used in both continuous and batch processes. HAZOP study also focusing to review operation to determine which systems can contribute to malfunction of a system and unit operation. The purpose of identifying the problem is to reduce risks of exposure to failure of workers when operating the equipment.

10.3.1 OBJECTIVE OF HAZOP

The main objective of HAZOP is to determine the possibility of failure in each piece of equipment to prevent future problems and safety. The other objectives of HAZOP are:

- To provide systematic approach in analyzing each equipment and coordinating various disciplines involved in the project.
- To determine the potential operability problems that may lead to major accident such as fire, explosion, toxic release and others
- To identify hazard in systems or deficiency in each equipment that can cause malfunction.

10.3.2 TECHNIQUE OF HAZOP

The HAZOP procedures will begin with the detailed flowsheet. The flowsheet will break into several process units (the reactor will be one unit). The study note will be described, and all parameters will be chosen, and the guide word will be applied to suggest possible deviations. Possible causes and protective systems will be determined based on the guide word. All recommended action will be recorded in a specific form of HAZOP. The guide word can sometimes be conceptually different to apply. The HAZOP procedure is very important where the company needs to record and use the results.

Guide words	Meaning	Comments
NO, NOT, NONE	The complete negation of the intention	No part of the design intention is achieved, but nothing else happens.
MORE, HIGHER, GREATER	Quantitative increase	Applies to quantities such as flow rate and temperature and to activities such as heating and reaction.
LESS, LOWER	Quantitative decrease	Applies to quantities such as flow rate and temperature and to activities such as heating and reaction.
AS WELL AS	Qualitative increase	All the design and operating intentions are achieved along with some additional activity, such as contamination of process streams.
PART OF	Qualitative decrease	Only some of the design intentions are achieved, some are not.
REVERSE	The logical opposite of	Most applicable to activities such as flow or chemical reaction. Also applicable to substances, for example, poison instead of antidote.
OTHER THAN	Complete substitution	No part of the original intention is achieved — the original intention is replaced by something else.
SOONER THAN	Too early or in the wrong order	Applies to process steps or actions.
LATER THAN	Too late or in the wrong order	Applies to process steps or actions.
WHERE ELSE	In additional locations	Applies to process locations, or locations in operating procedures.

Figure 10.2 List of guide words HAZOP flowsheets

10.3.3 HAZOP STUDIES ON UNIT OPERATIONS

This section explained the HAZOP method applied on each of the major equipment in this plant. From Table 10.23 to Table 10.31 shows the HAZOP study on the equipment discussed such as main fermenter, centrifuge, electrodialysis with bipolar membrane, thin film evaporator, CSTR, crystallizer, etc.

Table 10.19 HAZOP study on Fermenter

Parameter	Guide Word	Deviation	Possible Causes	Consequences	Action Required
Flowrate	More	High flowrate	•system malfunction •sudden changes in	• low efficiency of ion separation, affect quality	• reduce applied voltage to bring flowrate within acceptable limits

			feedstock concentration or flow	and purity ascorbic acid •unintended mixing of solutions	•monitor flowrates continuously •Conduct inspections of equipment
	Less	Low flowrate	•membrane fouling •pump malfunction •Electrolyte imbalance	•incomplete ion exchange, lower purity •delays production due to inadequate flowrates	•clear pipelines or membranes to restore normal flow •Adjust operating parameters to optimize flowrate
	No	No flowrate	•physical blockage in piping or membranes •power failure	•lead to corrosion or fouling of equipment	•shutdown procedures • restore flow and resume operations safely
	Reverse	Reverse flowrate	• system malfunction •contamination of process stream	•unintended mixing of ions •contamination desired product streams	•operate reverse flow •conduct inspection and analysis
Temperature	More	High temperature	•Failure of temperature control system •Malfunction of cooling systems	•degradation of bipolar membrane •reduced efficiency	•monitoring system •regular maintenance and calibration
	Less	Low temperature	•failure of temperature control system •malfunction of heating systems	•reduce reaction rate leading to lower efficiency •potential for precipitation or	•regular maintenance and calibration of heating system •implement automatic heating systems

				crystallization within the system	

Table 10.20 HAZOP study on Centrifuge

Parameter	Guide Word	Deviation	Possible Causes	Consequences	Action Required
Flowrate	More	High flowrate	• Failure from the control valve to open.	• Low filtration efficiency. •More impurities in the final output.	• Operator should check the controller regularly. • Install the manual hand valve to close the pipeline.
	Less	Low flowrate	• Failure from the control valve to close. • Partial plugged pipeline streams. • Leakage on pipeline.	• Low filtration efficiency. • More impurities in the final output. • Less production. • Less purity of Ascorbic acid.	• Operator should make the checkup on the control system regularly. • Install the detector and controller.
	No	No flowrate	• Failure from the control valve to close. • Partial plugged pipeline streams. • Leakage on pipeline.	• Product cannot be filtered and separated from the impurities.	• Operator should check the controller regularly. • Install the detector and controller. • Should make a maintenance.

	Reverse	Reverse flow	• Because of the backpressure. • Reverse differential pressure.	• Product cannot be filtered and separated from the impurities. • The mixture will be stuck in the pipeline.	• Install pressure detector. • Install pump to make pressure increase.
Level	More	High level of mixture in centrifuge	• Failure from the valve to open. • Failure at the level indicator in the inlet flow.	• Loss of product. • Flooding will happen. • Biomass unable to be separated.	• Operator should check the controller regularly. • Install the high-level controller alarm. • Install alternative pipeline for output.
	Less	Low level of mixture in centrifuge	• Leaking from vessel. • Failure from the valve to close. • Clogging in the pipeline.	• Contamination will occur. • Production will not be achieved.	• Operator should make the checkup on the control system regularly. •Install the low-level controller alarm.

Table 10.21 HAZOP study on Thin Film Evaporator

Parameter	**Guide Word**	**Deviation**	**Possible Causes**	**Consequences**	**Action Required**
Flowrate	More	High flowrate	• Failure of control valve.	• Mixture will not properly separate.	• Operator should regularly check the controller. • Install flowrate controller alarm. • Install the manual hand valve to close the pipeline.
	Less	Low flowrate	• Failure of control valve. • Pipeline leakage.	• Less water will be separated.	• Operator should regularly make the check-up on the control system. • Install alternative channel for gas and product outlet.
	No	No flowrate	• Control valve fail closed. • Pipeline leakage.	• No water will be separated.	• Operator should regularly check the controller.
	More	High temperature	• Failure of control valve. • Cooling system failure. • High heating steam temperature supplied.	• More water will be separated. • Product might vaporize if reaching boiling temperature.	• Operator should regularly check the controller. • Install the high temperature controller alarm

	Less	Low temperature	• Failure of control valve. • Cooling or heating jacket pipeline leakage. • Low steam temperature supplied.	• Water might not get separated.	• Operator should regularly make the check-up on the control system. • Install the low temperature controller alarm.
Pressure	More	High pressure	• Failure of control valve.	• Vessel might rupture.	• Operator should regularly check the controller. •Install safety relieve valve. • Install pressure alarm indicator.
	Less	Low pressure	• Failure of control valves. • Pipeline leakage.	• Water might not get separated.	• Operator should regularly make the check-up on the control system. • Install alternative pumps • Inspect the system. • Install pressure alarm indicator.

Table 10.22 HAZOP study on Bipolar Membrane Electrolysis

Parameter	Guide Word	Deviation	Possible Causes	Consequences	Action Required
Flowrate	More	High flowrate	•system malfunction •sudden changes in feedstock concentration or flow	• low efficiency of ion separation, affect quality and purity ascorbic acid •unintended mixing of solutions	• reduce applied voltage to bring flowrate within acceptable limits •monitor flowrates continuously • Conduct inspections of equipment
	Less	Low flowrate	•membrane fouling •pump malfunction •Electrolyte imbalance	•incomplete ion exchange, lower purity •delays production due to inadequate flowrates	•clear pipelines or membranes to restore normal flow •Adjust operating parameters to optimize flowrate
	No	No flowrate	•physical blockage in piping or membranes •power failure	•lead to corrosion or fouling of equipment	•shutdown procedures • restore flow and resume operations safely
	Reverse	Reverse flowrate	• system malfunction •contamination of process stream	•unintended mixing of ions •contamination desired product streams	•operate reverse flow •conduct inspection and analysis
Temperature	More	High temperature	•Failure of temperature control system •Malfunction of cooling systems	•degradation of bipolar membrane •reduced efficiency	•monitoring system •regular maintenance and calibration

	Less	Low temperature	•failure of temperature control system •malfunction of heating systems	•reduce reaction rate leading to lower efficiency •potential for precipitation or crystallization within the system	•regular maintenance and calibration of heating system •implement automatic heating systems

Table 10.23 HAZOP study on Continues Stirred Tank Reactor

Parameter	**Guide Word**	**Deviation**	**Possible Causes**	**Consequences**	**Action Required**
Temperature	More	High temperature	•Excessive heat input •Insufficient cooling •Exothermic reaction running out of control	•Thermal degradation of product •Increased reaction rate, potentially leading to runaway reaction •Pressure build-up due to increased vapor generation	•Install high-temperature alarms and automatic shutdown systems •Ensure adequate cooling capacity and maintenance of cooling systems
	Less	Low temperature	•Insufficient heat input •Excessive cooling (e.g.,	•Reduced reaction rate, leading to incomplete conversion	•Install low-temperature alarms and control systems

			coolant flow increase) •Endothermic reaction consuming heat	•Formation of unwanted by-products •Possible solidification or increased viscosity of the reactants	•Design for redundant heating systems •Monitor and control reactant feed rates and cooling system operation
Pressure	More	High pressure	•Excessive reactant feed rate •Blockage in the outlet line •High temperature increasing vapor pressure	•Risk of equipment rupture or explosion •Release of hazardous chemicals •Potential for fire or toxic exposure	•Install pressure relief valves and rupture discs •Implement feed rate control systems •Regular inspection and maintenance of outlet lines and valves
	Less	Low pressure	•Insufficient reactant feed •Leak in the system Condensation of vapors	•Poor mixing and incomplete reaction •Vacuum conditions leading to contamination •Possible collapse of the reactor vessel	•Install pressure monitoring and control systems •Perform regular leak checks and maintenance •Ensure proper venting and condensation control
Level	More	High level	•Excessive feed rate •Faulty level control system •Inadequate outflow	•Spillage of hazardous materials •Damage to equipment and containment systems •Interruption of reaction due to insufficient headspace	•Implement high-level alarms and automatic shutdown •Regularly test and maintain level control systems •Design for overflow containment

	Less	Low level	•Insufficient feed rate •Excessive outflow •Leak in the reactor	•Poor mixing and reaction efficiency •Potential for gas entrainment and cavitation •Damage to pumps and other downstream equipment	•Install low-level alarms and control systems •Monitor and adjust feed and outflow rates •Regular maintenance to detect and repair leaks

Table 10.24 HAZOP study on Nutsche Filter

Process Parameter	Guide Word	Deviation	Possible Causes	Possible Consequences	Action
Pressure	Low	Low Pressure	- Pressure drops across the filter membrane. - Malfunction of pump system.	- Poor separation efficiency. - Low throughput of products - Backward flow of feeds occurs	- Install low pressure alarm. - Install flow check valve.
	High	High Pressure	- A rise in pressure of feed side. - Overwork of pump system. - Failure of pressure control system.	- Membrane damage/fouling. - Incomplete separation. - Low purity of product	- Install high pressure alarm. - Install flow check valve.
Flow	No	No Flow	- Pump leakage or blockage - Valve fails to open	- No separation process	- Install flow indicator and controller
	Less	Low Flow	- Malfunction of control system. - Pipe leakage or blockage	- Poor separation efficiency of materials. - Low throughput of products	- Install low flow alarm
	More	High Flow	- Overwork of pump system. - Failure of control system.	- Membrane fouling. - Reduce the shelf life of pump system. - Incomplete separation of materials	- Install flow indicator and controller. - Install flow check valve

Table 10.25 HAZOP study on Crystallizer

Process Parameter	Guide Word	Deviation	Possible Causes	Possible Consequences	Action
Temperature	Less	Low Temperature	- Cooling system failure	- Poor crystal formation	• Install temperature controller and alarm
	More	High Temperature	• Excessive heating	- Possible damage to crystals	- Monitor heating system and install temperature alarm
Agitation	No	No Agitation	- Agitator motor failure	- Inconsistent crystal size, poor mixing	- Inspect and maintain agitator motor regularly
	Less	Low Agitation	- Agitator operating at low speed	- Inconsistent crystal size, poor mixing	- Install speed controller and monitor agitation speed
	More	High Agitation	- Agitator speed too high	- Crystal breakage, excessive nucleation	- Install speed controller and monitor agitation speed
Concentration	Less	Low Concentration	- Inadequate feed	- Incomplete crystallization	- Monitor feed rate and adjust concentration
	More	High Concentration	- Excessive feed	- Poor quality crystals	- Install concentration sensor and control feed rate

Table 10.26 HAZOP study on Heat Exchanger

Process Parameter	Guide Word	Deviation	Possible Causes	Possible Consequences	Action
Hot fluid Flow	No	No Flow	- Manual valve closed - Pipeline plugged and blocked	- Not achieved desired temperature	- Install flow meters or low flow alarm - Regular check the valve and pump
	Less	Less Flow	- Manual valve is partially closed - Partial failure of mixtures supply - Leakage of pipeline	- Less fluids flow - Low output products	- Install flow meter or low flow alarm - Install low temperature alarm - Install check valve
	More	More flow	- Failure of control valve to close	- Temperature remains constant or too high compared to desired temperature	- Install high temperature alarm - Install check valve
	Reverse	Reverse process fluid	- Failure of process fluid inlet valve	- Product off set	- Install check valve
	Other than	Contamination of process fluid line	- Leakage of tube and cooling water goes in	- Contamination of process fluid	- Proper maintenance and operator alert
Cooling water Flow	None	No cooling water flow	- Failure of inlet cooling water valve to open - Blockage of pipelines	- The temperature of fluids in the process is higher than desired temperature	- Install temperature indicator before and after the process fluid line - Install temperature alarm high

					- Install check valve
	Less	Less flow of cooling water	- Partially blockage or leakage of pipe - Malfunction of control valve	- Temperature of process fluid remains constant or too high	- High temperature alarm - Install flow meter - Install check valve
	More	More flow of cooling water	- Failure of cooling water valve	- Temperature of process fluid too low compared to desired temperature	- Install temperature indicator before and after the process fluid line - Low temperature alarm - Install check valve
	Reverse	Reverse process fluid	- Failure of process fluid inlet valve	- Product off set	- Install check valve
	Other than	Contamination of process fluid line	- Leakage of tube and cooling water goes in	- Contamination of process fluid	- Proper maintenance and operator alert
Temperature	Low	Low Temperature	- Failure of temperature controller - Overflow of cooling water into the heat exchanger	- Upset of downstream process - Thermal process runaway	- Install temperature indicator and controller - Scheduling inspection and maintenance of heat exchanger
	High	High Temperature	- Failure of temperature controller - Underflow of cooling water into the heat exchanger	- Upset of downstream process - Thermal process runaway	- Install temperature indicator and controller - Scheduling inspection and maintenance of heat exchanger

Pressure	Less	Less pressure on the tube side	- Failure of process fluid valve	- Less fluids flow - Malfunction of exchange temperature	- Install low pressure alarm - Install pressure indicator or controller - Install relief valve - Scheduling inspection and maintenance of piping system
	More	More pressure on tube side	- Blockage at the pipelines - Failure of process fluid valve to close	- Bursting of tube	- Install high pressure alarm

Table 10.27 HAZOP study on Storage

Process Parameter	Guide Word	Deviation	Possible Causes	Possible Consequences	Action
Level	Less	Low Level	- Leak in tank	- Insufficient material for process	- Inspect and repair leaks, install level sensor
	More	High Level	- Overfilling	- Overflow, potential safety hazard	- Install level alarm and monitor filling process
Pressure	Less	Low Pressure	- Pressure drops in the storage tank - Blockage or leakage in the pipelines system.	- Temperature drops to product - Low throughput of product	- Install pressure transmitter and controller. - Install low pressure alarm.
	More	High Pressure	- A rise in pressure of feed side. - Accumulation of stream in storage tank. - Inlet pipeline blockages. - Failure of pressure control system.	- Pressure builds up - Low purity of product. - Rupture of storage tank - Explosions occur	- Install pressure transmitter and controller. - Install high pressure alarm. - Install pressure relief valve
Temperature	Less	Low Temperature	- Excessive cooling	- Component solidification or spoilage	- Install temperature controller and monitor
	More	High Temperature	- Heating system failure	- Component degradation	- Install temperature alarm and maintain cooling system

CHAPTER 11

PROFITABILITY ANALYSIS

11.1 INTRODUCTION

The profitability analysis is used to assist to evaluate the potential production process. It helps to visualize overall financial viability and analyse the potential earning. The return on investment (ROI) which is also called as rate on return (ROR)A and payback period (PBP) are used to observe the economic performance of the designed process. Total production cost, revenue sales and net income will be calculated in this chapter. The costs are calculated annually with total 7920 operating hours per year.

11.2 TOTAL CAPITAL INVESTMENT (TCI)

The total capital investment (TCI) is an expense incurred once for the design, construction, and startup a new plant. There are few ways to estimate the TCI. In this chapter, the TCI is calculated by using Guthrie method which is shown in Table 9.2. The estimation of TCI is RM 113,821,562.67 regarding to the bare-module cost for the equipment on the production of ascorbic acid.

11.3 TOTAL PRODUCTION COST

The total production cost is sum of the cost of manufacture and general expenses. The cost of manufacture is including feedstocks, utilities, labour-related operations, maintenance, operating overhead, property taxes and insurance, etc.

11.3.1 RAW MATERIALS COST

The annual raw materials cost is tabulated in Table 11.2.

Table 11.1 Raw materials cost per year

Material	**kg/batch**	**RM/kg**	**RM/year**
sorbitol	45000	3.81	5657850.00
ammonia	43	2.81	3987.39
Sodium carbonate	8532	0.86	242138.16
sodium bicarbonate	13524.024	0.91	406126.44
methanol	5158.3413	2.73	464714.97
Total			**6774816.96**

11.3.2 LABOUR-RELATED OPERATIONS

Based on the type and arrangement of the equipment, the operating labour is estimated by dividing the process into few sections. For the ascorbic acid plant, three shift is accounted daily. Each shift operator is working and paid for 40 hours per week. The cost of operating labour is illustrated in Table 11.3.

Table 11.2 Cost estimation of labour-related cost annually

Type of process	**Equipment**	**Operator per shift**	**Total operator**
Fermentation system	fermenter 1&2	4	20
liquid-solid separation system	centrifuge	2	10
Dialysis system	BME 1 & 2	2	10

Liquid separation system	TFE 1 & 2 with HEX	2	10
Reactor system	CSTR 1 & 2 with HEX	2	10
Crystallizing system	Crystallizer with HEX	2	10
Filtration system	Nutsche filter	2	10
Liquid recovery system	recycling	1	5
Storing system	solid storage	1	5
Waste treatment	Storage 2	1	5
Total		19	85
Direct wages and benefits (DW&B)	*RM 7.21/hr*		1274728.00
Direct salary and benefits	*15% of DW&B*		191209.20
operating supplies and services	*6% of DW&B*		76483.68
technical assistance to manufacturing	*RM 40896 per month -Average range in Malaysia*		122688.00
control laboratory	*Rm61800 per month -Average range in Malaysia*		185400.00
Total			1850508.88

11.3.3 UTILITIES COST

From the process flow sheet of ascorbic acid production, the amount of energy, water, heating and cooling agents that are required to drive the unit operations are determined. The utilities costs are calculated and tabulated from Table 11.4, Table 11.5 and Table 11.6.

Table 11.3 Summary of energy cost

Equipment	**Equipment label**	**ΔH (kJ/batch)**	**Q (kW)**	**Cost (RM/year)**
Fermenter	FR-101	36571617.3230	725.6273	112975.82
	FR-102	9450630.1987	36.4608	29194.57
Centrifuge	DC-101	1465.6911	0.0313	4.53

BME	GBX-101	22516022.5397	79.3410	69555.75
	GBX-102	22544649.5455	79.4419	69644.18
TFE	TFE-101	135387625.4868	477.0731	418234.94
	TFE-102	21441322.7439	75.5540	66235.82
HEX	HX-106	-	13.7523	12056.19
	HX-107	-	9.8880	8668.52
	HX-108	-	9.6039	8419.40
Heater	HX-101	-	51.2538	44932.58
	HX-104	-	25.1977	22090.05
Cooler	HX-103	-	4.1200	3611.88
	HX-105	-	10.2617	8996.11
CSTR 1	R-101	7116205.6382	25.0758	21983.15
	R-102	6139749.1377	21.6350	18966.71
Storage tank	SL-101	-	0.1000	266.90
Total				**915837.09**

Table 11.4 Summary of water cost

Equipment	Utility	Unit/batch	Unit	RM/unit	RM/year
Fermenter 1 (FR-101)	water	50.358	m^3	3.3	5483.99

Table 11.5 Summary of heating agent and cooling agent cost

Equipment	Utility	Unit/batch	Unit	RM/unit	RM/year
Fermenter 1 (FR-101)	chilled water	1730.68	MT	1.88	107371.39
Fermenter 2 (FR-102)	chilled water	4.32	MT	1.88	268.01
Heater (HX-101)	steam	7.0947	MT	56.5	13228.07
Thin Film Evaporator (TFE-101)	steam	70.947	MT	56.5	132280.68
Stirred Tank Bioreactor 1 (R-101)	cooling water	339.7573	MT	0.235	2634.82

Stirred Tank Bioreactor 2 (R-101)	hot water	2.3649	MT	0.235	18.34
Cooler (HX-103)	cooling water	59.1225	MT	0.235	458.49
Heater (HX-104)	steam	5.5181	MT	56.5	10288.50
Cooler (HX-105)	NaCl Brine	92.2311	MT	1.17	3561.04
Thin Film Evaporator (TFE-102)	steam	7.883	MT	56.5	14697.85
Storage (SL-101)	Glycol	0.2	MT	1.65	10.89
Total					**284818.09**

11.4 ANNUAL PROFIT ANALYSIS

The annual profit analysis of this project is shown in Table 11.7.

Table 11.6 Annual profit analysis of ascorbic acid plant

Cost factor	Specification	Annual cost (RM/year)
Direct cost		
Raw material		
sorbitol	RM 3.81/kg	5657850.00
ammonia	RM 2.81/kg	3987.39
Sodium carbonate	RM 0.86/kg	242138.16
sodium bicarbonate	RM 0.91/kg	406126.44
methanol	RM 2.73/kg	464714.97
Total		6774816.96
Labour-related operations		
Direct wages and benefits (DW&B)		1274728.00
Direct salary and benefits	15% of DW&B	191209.20
operating supplies and services	6% of DW&B	76483.68
technical assistance to manufacturing		122688.00
control laboratory		185400.00
Total		1850508.88
Additional variable costs		
Consumables		
G.oxydans	10% of sorbitol cost	565785.00
Pseudoglyconobacter Saccharoketogenes	10% of sorbitol cost	565785.00
NaOH	1% of feed in, RM 1.29/kg	92999.61
HCl	0.5% of feed in, RM 0.12/kg	4243.38
Total		1228812.99
Byproducts		
NaOH	RM 1.29/kg	(548215.76)
General expenses		
Selling/transfer Expenses	1% of sales	306479.83
Direct research	4.8% of sales	1471103.18
Allocation research	0.5% of sales	153239.91
Administrative expense	2% of sales	612959.66
management incentive compensation	1.25% of sales	383099.79
Total		2926882.36
Indirect costs		
Utilities		
Electricity	RM 0.337/kWh	915837.09
water	RM 3.3/m3	5483.99
chilled water	RM 1.88/MT	107639.40

cooling water	RM 0.235/MT	3093.31
hot water	RM 0.235/MT	18.34
steam	RM 56.5/MT	170495.10
NaCl Brine	RM 1.17/MT	3561.04
Glycol	RM 1.65/MT	10.89
Total		1206139.17
Maintenance		
Wages and benefits (MW&B)	3.5% C_{TDC}	220503.08
salaries and benefits	25% MW&B	55125.77
Material & Service	100% of MW&B	220503.08
Maintenance Overhead	5% MW&B	11025.15
Total		507157.08
Operating overhead		
General plant overhead	7.1% of M&O -SW&B	65536.69
Mechanical department services	2.4% of M&O -SW&B	22153.25
Employee relations department	5.9% of M&O -SW&B	54460.06
business service	7.4% of M&O -SW&B	68305.84
Total		210455.84
Property taxes and insurance	2% of C_{TDC}	1260017.59
Total production cost		**15416575.10**
Depreciation		1890026.38
Revenue sales		
Ascorbic acid		59697898.90
Total expenses, ATE	ATE = APC + ABD	17306601.48
Net Annual Profit, ANP		42391297.42
Income taxes	30% ANP (2023, LHDN)	12717389.23
Net Annual Profit After Income Taxes, ANNP	-	29673908.19
Total capital investment (C_{TCI})	C_{TPI} + C_{WC}	94180975.50
Rate of Return, (ROR) %	((ANNP+ABD)/TCI) *100%	33.51

11.5 CASH FLOW ANALYSIS

The final step in profitability analysis is to determine Payback Period (PBP), discounted break event period (DBEP), and Net Present Value (NPV) of the plant. These values can be obtained by using graphical method as proposed in Ulrich (1984). The total plant operating period is 20 years, including 3 years of start-up operation with the total capital investment (TCI) of RM67032912.51. The following assumptions are made in this analysis:

i. The total capital cost is invested with the rate of 10 %, 25 % and 65 % during the first 3 years of construction period.
ii. The plant operation life is 20 years (for typical chemical and allied products manufacturing).
iii. The annual revenue from sales of succinic acid crystals for the first year is expected to be 80 % of normal rate.
iv. Straight-line depreciation is assumed, this the plant will depreciate in 17 years with a constant value each year.
v. The Malaysian corporate income tax is assumed to be 30 % of the net annual profit.
vi. Pioneer tax exemption is considered in the analysis with 100% of federal income tax exemption for first 5 years, which is the privilege offered by Malaysian Investment Development Authority (MIDA).

Payback Period (PBP)

Payback Period (PBP) is the time that must elapse after start-up until the cumulative undiscounted cash flow repays the fixed capital investment. In illustration, PBP is the point, where undiscounted cash flow rises to the level of negative working capital in order to get the payback period, an undiscounted cash flow has been performed as in Figure 11.1. As shown in Figure 11.1, PBP of 2.6 years is expected after start-up with undiscounted cash flow.

Plant life: 20 years
Annual Total production Cost: RM 15,416,575.10
Annual Depreciation Value: RM 1,890,026.38
Total Capital Investment: RM 94,180,975.50

Table 11.7 Undiscounted Cash Flow Analysis

Years	Annual Capital Investment	Sales Income (S)	Depreciation (BD)	Production cost (PC)	Cash Income (CI)=(S)-(PC)	Net profit ANP=(CI)-(BD)	Federal Income Taxes 30% (IT)	Net profit after taxes NNP=NP-(IT)	Net Cash Income (NCI)	Accumulation of cash flows
1	9418097.55								-9418097.55	-9418097.55
2	23545243.87								-23545243.87	-32963341.42
3	61217634.07								-61217634.07	-94180975.50
4		47758319.12	1890026.38	15416575.10	32341744.02	30451717.64		30451717.64	32341744.02	-61839231.48
5		59697898.90	1890026.38	15416575.10	44281323.80	42391297.42		42391297.42	44281323.80	-17557907.68
6		59697898.90	1890026.38	15416575.10	44281323.80	42391297.42	12717389.23	29673908.19	31563934.57	14006026.89
7		59697898.90	1890026.38	15416575.10	44281323.80	42391297.42	12717389.23	29673908.19	31563934.57	45569961.47
8		59697898.90	1890026.38	15416575.10	44281323.80	42391297.42	12717389.23	29673908.19	31563934.57	77133896.04
9		59697898.90	1890026.38	15416575.10	44281323.80	42391297.42	12717389.23	29673908.19	31563934.57	108697830.61
10		59697898.90	1890026.38	15416575.10	44281323.80	42391297.42	12717389.23	29673908.19	31563934.57	140261765.19
11		59697898.90	1890026.38	15416575.10	44281323.80	42391297.42	12717389.23	29673908.19	31563934.57	171825699.76
12		59697898.90	1890026.38	15416575.10	44281323.80	42391297.42	12717389.23	29673908.19	31563934.57	203389634.34
13		59697898.90	1890026.38	15416575.10	44281323.80	42391297.42	12717389.23	29673908.19	31563934.57	234953568.91
14		59697898.90	1890026.38	15416575.10	44281323.80	42391297.42	12717389.23	29673908.19	31563934.57	266517503.48
15		59697898.90	1890026.38	15416575.10	44281323.80	42391297.42	12717389.23	29673908.19	31563934.57	298081438.06
16		59697898.90	1890026.38	15416575.10	44281323.80	42391297.42	12717389.23	29673908.19	31563934.57	329645372.63
17		59697898.90	1890026.38	15416575.10	44281323.80	42391297.42	12717389.23	29673908.19	31563934.57	361209307.20
18		59697898.90	1890026.38	15416575.10	44281323.80	42391297.42	12717389.23	29673908.19	31563934.57	392773241.78
19		59697898.90	1890026.38	15416575.10	44281323.80	42391297.42	12717389.23	29673908.19	31563934.57	424337176.35
20		59697898.90	1890026.38	15416575.10	44281323.80	42391297.42	12717389.23	29673908.19	31563934.57	455901110.92

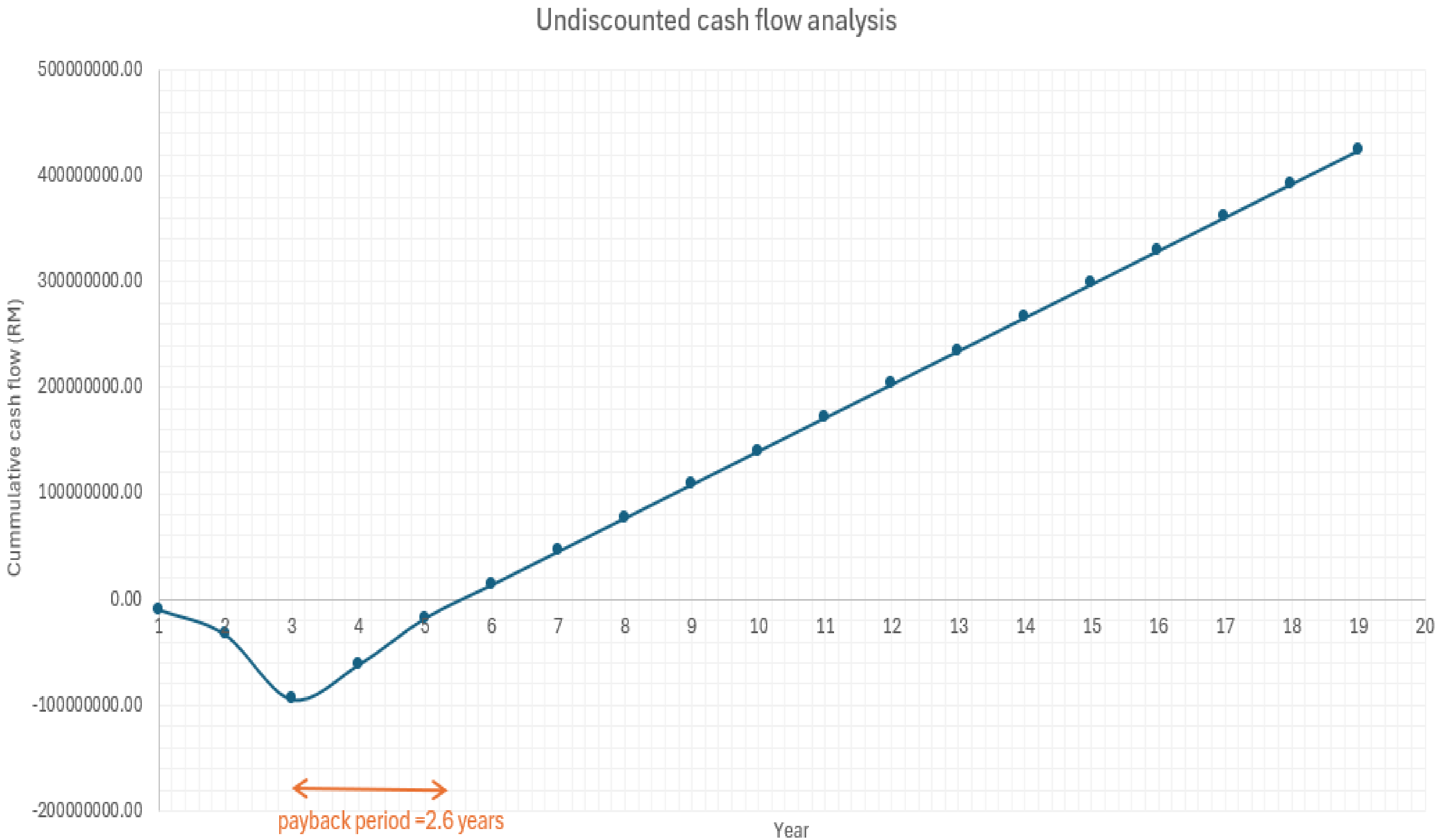


Figure 11.1 Undiscounted cash flow analysis with PBP of 2.6 year excluding 3 years of startup period

Table 11.8 Discounted Factor Cash Flow Analysis for 5 % and 7%

Years	Net Cash Income (NCI)	Discount Factor, fd (i=5%)	Discounted Cash Flow for 5% sum[(NCI)*fd]	Discounted Cash Flow for i=5% Cumulative	Discount Factor, fd (i=7 %)	Discounted Cash Flow for 7% sum[(NCI)*fd]	Discounted Cash Flow for i= 7 % Cumulative
1	-9418097.55	0.95	-8969616.71	-8969616.71	0.93	-8801960.33	-8801960.33
2	-23545243.87	0.91	-21356230.27	-30325846.99	0.87	-20565327.87	-29367288.19
3	-61217634.07	0.86	-52882094.01	-83207940.99	0.82	-49971824.72	-79339112.92
4	32341744.02	0.82	26607632.84	-56600308.15	0.76	24673361.66	-54665751.26
5	44281323.80	0.78	34695575.88	-21904732.27	0.71	31571971.88	-23093779.38
6	31563934.57	0.75	23553493.96	1648761.69	0.67	21032382.36	-2061397.02
7	31563934.57	0.71	22431899.01	24080660.70	0.62	19656432.11	17595035.09
8	31563934.57	0.68	21363713.34	45444374.04	0.58	18370497.30	35965532.39
9	31563934.57	0.64	20346393.66	65790767.70	0.54	17168689.06	53134221.45
10	31563934.57	0.61	19377517.77	85168285.46	0.51	16045503.80	69179725.25
11	31563934.57	0.58	18454778.83	103623064.29	0.48	14995797.94	84175523.19
12	31563934.57	0.56	17575979.84	121199044.13	0.44	14014764.43	98190287.62
13	31563934.57	0.53	16739028.41	137938072.54	0.41	13097910.68	111288198.30
14	31563934.57	0.51	15941931.82	153880004.37	0.39	12241038.02	123529236.33
15	31563934.57	0.48	15182792.21	169062796.58	0.36	11440222.45	134969458.78
16	31563934.57	0.46	14459802.11	183522598.69	0.34	10691796.68	145661255.46
17	31563934.57	0.44	13771240.10	197293838.79	0.32	9992333.35	155653588.81
18	31563934.57	0.42	13115466.76	210409305.55	0.30	9338629.30	164992218.10
19	31563934.57	0.40	12490920.73	222900226.28	0.28	8727690.93	173719909.04
20	31563934.57	0.38	11896114.98	234796341.26	0.26	8156720.50	181876629.53

Table 11.9 Discounted Factor Cash Flow Analysis for 10 % and 15 %

Years	Net Cash Income (NCI)	Discount Factor, fd (i=10%)	Discounted Cash Flow for 10% sum[(NCI)*fd]	Discounted Cash Flow for i=10% Cumulative	Discount Factor, fd (i=15%)	Discounted Cash Flow for 15% sum[(NCI)*fd]	Discounted Cash Flow for i=15% Cumulative
1	-9418097.55	0.91	-8561906.86	-8561906.86	0.87	-8189650.04	-8189650.04
2	-23545243.87	0.83	-19458879.24	-28020786.10	0.76	-17803587.05	-25993237.09
3	-61217634.07	0.75	-45993714.56	-74014500.65	0.66	-40251588.11	-66244825.21
4	32341744.02	0.68	22089846.34	-51924654.32	0.57	18491497.11	-47753328.10
5	44281323.80	0.62	27495218.16	-24429436.16	0.50	22015644.00	-25737684.10
6	31563934.57	0.56	17817018.20	-6612417.96	0.43	13645959.95	-12091724.14
7	31563934.57	0.51	16197289.27	9584871.31	0.38	11866052.13	-225672.01
8	31563934.57	0.47	14724808.43	24309679.73	0.33	10318306.20	10092634.19
9	31563934.57	0.42	13386189.48	37695869.21	0.28	8972440.18	19065074.36
10	31563934.57	0.39	12169263.16	49865132.38	0.25	7802121.89	26867196.26
11	31563934.57	0.35	11062966.51	60928098.89	0.21	6784453.82	33651650.07
12	31563934.57	0.32	10057242.28	70985341.17	0.19	5899525.06	39551175.13
13	31563934.57	0.29	9142947.53	80128288.70	0.16	5130021.79	44681196.93
14	31563934.57	0.26	8311770.48	88440059.18	0.14	4460888.51	49142085.44
15	31563934.57	0.24	7556154.98	95996214.17	0.12	3879033.49	53021118.93
16	31563934.57	0.22	6869231.80	102865445.97	0.11	3373072.60	56394191.53
17	31563934.57	0.20	6244756.18	109110202.16	0.09	2933106.61	59327298.14
18	31563934.57	0.18	5677051.08	114787253.23	0.08	2550527.49	61877825.63
19	31563934.57	0.16	5160955.52	119948208.76	0.07	2217849.99	64095675.61
20	31563934.57	0.15	4691777.75	124639986.51	0.06	1928565.21	66024240.82

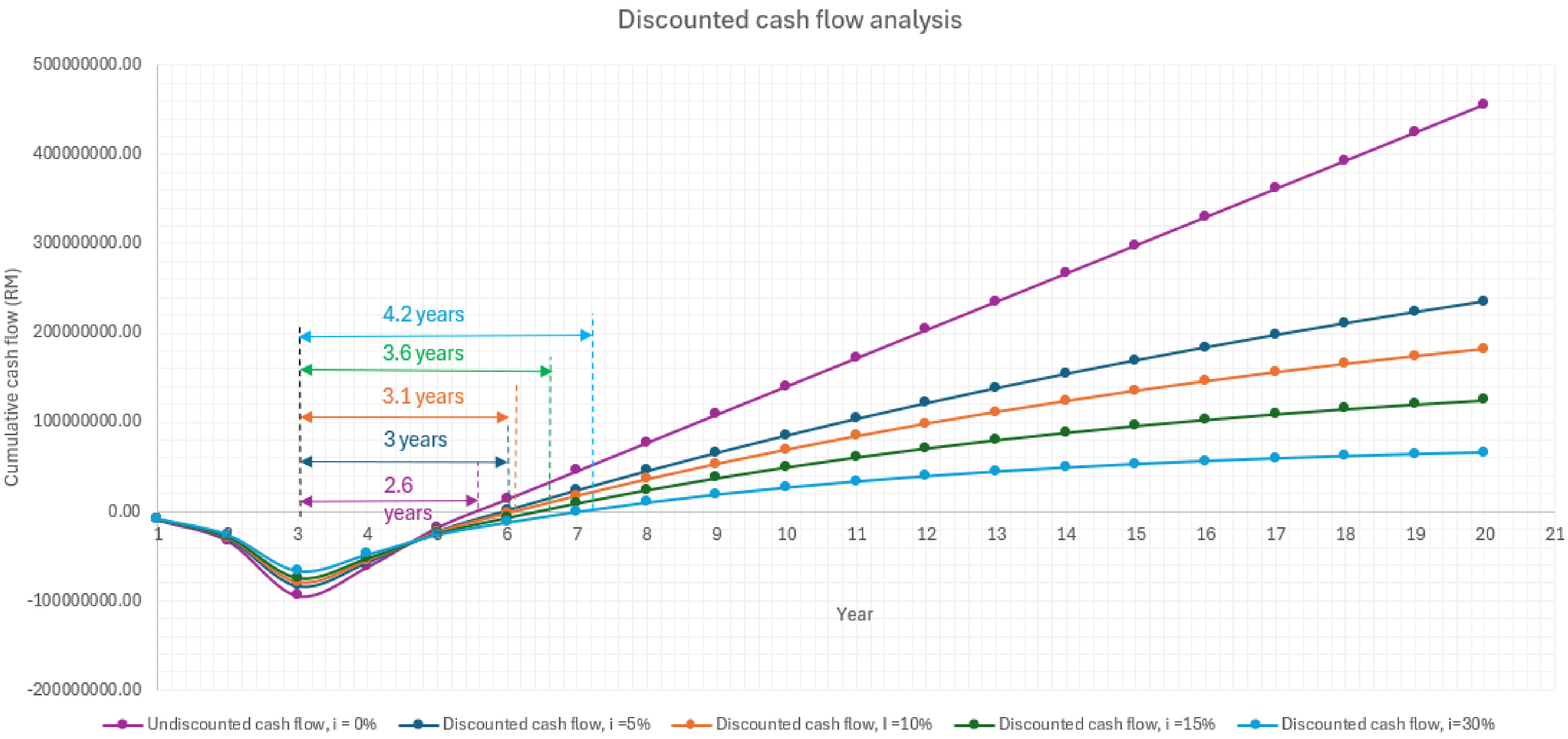


Figure 11.2 Discounted cash flow diagram

Table 11.10 Summary of Cash Flow Analysis for Various Interest Rate, i

rate of interest (%)	Payback period (year)
0	2.6
5	3.0
7	3.1
10	3.6
15	4.2

11.6 NET PRESENT VALUE (NPV) AND DISCOUNTED CASH FLOW RATE OF RETURN (DCFRR)

Net present value (NPV) is the final cumulative discounted cash flow value for any project conclusion, as depicted in Table 11.8 and Table 11.10. By calculating NPV for various interest rates, it is possible to determine an interest rate at which cumulative net present value at the end of the project is zero, which is known as Discounted Cash Flow Rate of Return". It is a measure of the maximum rate of the project could pay and still break even by the end of the project life.

The following formula is used to calculate NPV:

$$NPV = \Sigma \frac{R_t}{(1+i)^t}$$

Where:

Rt = Net cash inflow-outflows during a single period t

i = Discount rate

t = number of years

Table 11.11 Summary of NPV for various interest rate

rate of interest (%)	Net Present Value (RM)
0	455901110.9243
5	234796341.2590
7	181876629.5335
10	124639986.5074
15	66024240.8208

Hence, DCFRR provides a useful way of comparing the performance of capital for different projects as it is independent of the amount of capital used and the life of the plant, or the actual interest rates prevailing at any time. In this case the zero value of NPV cannot be exactly obtained, but the interest rate of 15% is least to the zero NPV, as shown in table.

CHAPTER 12

CONCLUSION AND RECOMMENDATIONS

12.1 CONCLUSION

The primary objective of this study is to produce 600 tonnes of ascorbic acid annually with cost effectiveness. The production of sorbitol and ascorbic acid involves intricate steps that highlight the importance of efficient and strategic approaches in chemical manufacturing. There are several biosynthesis processes manufacturing ascorbic acid naturally or chemically. Ascorbic acid, or vitamin C, is essential for numerous biological processes and is widely used in the food, pharmaceutical, and feed industries due to its antioxidative properties. The global market for ascorbic acid is substantial, valued at $2 billion in 2022 and projected to reach $3.56 billion by 2032. This growth is driven by increasing demand in food and beverages, pharmaceuticals, and animal feed sectors.

China dominates the production of ascorbic acid, with key manufacturers like CSPC Weisheng, Luwei Pharmaceutical, and Northeast Pharmaceutical contributing significantly to the global supply. Despite challenges such as high production costs and raw material availability, the demand for ascorbic acid continues to grow, highlighting its critical role in health and industrial applications. Evaluating potential production sites, Tanjung Langsat in Pasir Gudang, Johor, emerges as the most strategic location due to its ample labor availability and safe distance from residential areas, minimizing contamination risks. Among production methods, the two-step fermentation process is preferred over the Reichstein process for producing ascorbic acid. This method offers higher efficiency, product quality, and yield while being more environmentally friendly and cost-effective.

By following the process synthesis and flow sheets, the base case manual calculations of mass and energy balances are performed. To review and compare the results with the manual approach, SuperPro Designer 9.5 is often used to produce the simulation data. Upon comparison, every percentage of mistakes is determined which is still within the allowable range of 15% error. The optimization efforts focused on Fermenter (FR-102) and Thin Film Evaporator 2 (TFE-102) have yielded significant improvements in operational efficiency and cost-effectiveness within the plant. By optimizing sorbitol and ascorbic acid production in Fermenter FR-102, we achieved a substantial profit increase of 62.97% through the implementation of a recycle stream. Similarly, optimization of TFE-102 identified that operating at 90°C reduces equipment costs by 23.08% and overall costs by 6.46% compared to operating at 100°C. For waste treatment, solid waste would be collected and sent to Quality Alam for disposal while liquid waste will be treated to grade B following Environmental Quality Act 1947 guidelines.

For any industrial process to operate as efficiently, economically, and as well as possible, the right size of equipment is essential. Properly sized equipment guarantees that the system functions within its intended parameters, lowering the possibility of operational problems like excessive wear and tear, underutilization, or bottlenecks. Besides, control system is necessary to be installed in the plant as it controls and regulates the operating temperature, pressure and effluent to desired conditions. Nevertheless, safety is an important thing to be considered in the plant design. The risk assessment has to be conducted such as HAZOP by listing the potential hazard of the plant to ensure the safety of workers and production efficiently.

As a result, the Total Capital Investment (TCI) of this plant is RM 94,180,975.50 and the total annual expenses are RM 17,306,601.48. The net annual profit after income taxes is RM 29,673,908.19. The plant would operate for 20 years, including 3 years for start-up, with a depreciation of 10 %. For undiscounted cash flow, the payback period is determined to be 2.6 years. In contrast, for different discount cash flow rates, the value of Discounted Break-Even Point (DBEP) will vary. Nevertheless, the rate of investment of this project is 33.51 %.

Generally, the production of ascorbic acid is a feasible project from an economical and technical standpoint. It is predicted that the product will have a considerably high demand in local and international markets and have good prospects for expansion in the future.

12.2 RECOMMENDATIONS

Justification for Incorporating a Seed Fermentation System in Plant Design

The stages of seed fermentation are recommended to be added with a few parallel streams to optimize the growth conditions and reduce the contamination risk for main streams. To ensure that the microorganisms adapt to the culture medium and ambient conditions and shorten the lag time when they are moved to the main fermenter, as seed fermenters offer an initial controlled environment that regulates temperature, pH, and aeration. Therefore, the seed fermenters would be proposed for the two stages of fermentation, each representing a fraction of the main fermenter's volume. This setup ensures smooth scale-up, reduces contamination risks through effective sterilization, and maintains efficiency with proper aeration, agitation, and temperature control systems. While the initial investment in seed fermenters, including installation and commissioning, falls within a reasonable budget, the projected annual operating costs are manageable. Adding seed fermenters brings multiple benefits. It enhances process control, keeps the microbial culture healthy and viable, minimizes contamination risk, and ensures an efficient scale-up from smaller volumes to full production. These fermenters help maintain production consistency, meet regulatory standards, and contribute to long-term cost savings through reduced operational costs and higher profitability. Considering our main fermenters each have a volume of 50 m^3, with three units for fermenter 1 and four units for fermenter 2, we suggest primary seed fermenters of 5 m^3 for total seven units and secondary seed fermenters of 0.5 m^3 for total seven units with a 10% of scale up from inoculum process. The estimated total costs are approximately RM 84,988.85 for the seven units of primary seed fermenters and RM 588,384.34 for the seven units secondary seed fermenters according to the current marketing for the volume size of 0.5 m^3 and 5 m^3. By introducing the seed fermenters, the estimated total production cost for the whole system is RM 15,439,738.30 with RM 95,255,565.98 of Total Capital investment. The payback period is 2.7 years excluding the 3 years of startup period with a 33.13% of rate of return (ROR) for 0% interest rate. The potential interest rate for companies to invest can be up to 15% interest rate with 4.3 years payback period and 14.32% of ROR.

Suggestion improvement of the Fermenter 1 with justification

To improve the fermentation process, a fermenter optimization suggestion is provided. As *G.oxydans* is a microbe that produces sorbose from sorbitol, indicating that its strain has a high cell density and biomass production, as an obligate aerobe, requires an abundance of oxygen during the oxidation of sorbitol to sorbose. This suggests that oxidation processes play an important role in the *G. oxydans* bioprocess. The addition of oxygen carriers may improve sorbose conversion performance. Although various Dissolved Oxygen (DO) control strategies had already been implemented to improve sorbose production efficiency, there was still potential for improvement. Thus, bio-oxidation is investigated in a (pure) oxygen-aerated stirred bioreactor (O-ASB). The initial DO level in O-ASB was significantly higher than that in air-aerated stirred bioreactors (A-ASB). As predicted, increased oxygen supply significantly improved *G. oxydans* performance, allowing it to increase productivity and reduce production time.

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APPENDIX A – MATERIAL SAFETY DATA SHEET (MSDS)

SAFETY DATA SHEET

Creation Date 03-Jun-2014 **Revision Date** 25-Dec-2021 **Revision Number** 4

1. Identification

Product Name	**L(+)-Ascorbic acid**
Cat No. :	**AC401470000; AC401470025; AC401470050; AC401471000; AC401475000**
CAS No	50-81-7
Synonyms	Vitamin C
Recommended Use	Laboratory chemicals.
Uses advised against	Food, drug, pesticide or biocidal product use.

Details of the supplier of the safety data sheet

Company
Fisher Scientific Company
One Reagent Lane
Fair Lawn, NJ 07410
Tel: (201) 796-7100

Acros Organics
One Reagent Lane
Fair Lawn, NJ 07410

Emergency Telephone Number
For information **US** call: 001-800-ACROS-01 / **Europe** call: +32 14 57 52 11
Emergency Number **US:**001-201-796-7100 / **Europe:** +32 14 57 52 99
CHEMTREC Tel. No.**US:**001-800-424-9300 / **Europe:**001-703-527-3887

2. Hazard(s) identification

Classification
Classification under 2012 OSHA Hazard Communication Standard (29 CFR 1910.1200)

This chemical is not considered hazardous by the 2012 OSHA Hazard Communication Standard (29 CFR 1910.1200)

Label Elements
None required

Hazards not otherwise classified (HNOC)
None identified

3. Composition/Information on Ingredients

Component	CAS No	Weight %
L-Ascorbic acid	50-81-7	>95

4. First-aid measures

Eye Contact Rinse immediately with plenty of water, also under the eyelids, for at least 15 minutes. Get medical attention.

Skin Contact Wash off immediately with plenty of water for at least 15 minutes. Get medical attention immediately if symptoms occur.

Inhalation Remove to fresh air. If breathing is difficult, give oxygen. Get medical attention immediately if symptoms occur.

Ingestion Do NOT induce vomiting. Get medical attention.

Most important symptoms and effects No information available.

Notes to Physician Treat symptomatically

5. Fire-fighting measures

Suitable Extinguishing Media Water spray, carbon dioxide (CO2), dry chemical, alcohol-resistant foam.

Unsuitable Extinguishing Media No information available

Flash Point No information available
Method - No information available

Autoignition Temperature 380 °C / 716 °F

Explosion Limits
Upper No data available
Lower No data available
Sensitivity to Mechanical Impact No information available
Sensitivity to Static Discharge No information available

Specific Hazards Arising from the Chemical
Thermal decomposition can lead to release of irritating gases and vapors. Keep product and empty container away from heat and sources of ignition.

Hazardous Combustion Products
Carbon monoxide (CO). Carbon dioxide (CO_2).
Protective Equipment and Precautions for Firefighters
As in any fire, wear self-contained breathing apparatus pressure-demand, MSHA/NIOSH (approved or equivalent) and full protective gear.

NFPA

Health	Flammability	Instability	Physical hazards
1	1	1	N/A

6. Accidental release measures

Personal Precautions Use personal protective equipment as required. Ensure adequate ventilation. Avoid dust formation. Avoid contact with skin, eyes or clothing.

Environmental Precautions Avoid release to the environment.

Methods for Containment and Clean Up	Sweep up and shovel into suitable containers for disposal. Avoid dust formation.

7. Handling and storage

Handling	Wear personal protective equipment/face protection. Ensure adequate ventilation. Avoid dust formation. Avoid contact with skin, eyes or clothing. Avoid ingestion and inhalation.
Storage.	Keep in a dry, cool and well-ventilated place. Keep container tightly closed. Protect from direct sunlight. Store under an inert atmosphere. Incompatible Materials. Strong oxidizing agents. Metals. copper.

8. Exposure controls / personal protection

Exposure Guidelines	This product does not contain any hazardous materials with occupational exposure limitsestablished by the region specific regulatory bodies.
Engineering Measures	Ensure adequate ventilation, especially in confined areas. Ensure that eyewash stations and safety showers are close to the workstation location.

Personal Protective Equipment

Eye/face Protection	Wear appropriate protective eyeglasses or chemical safety goggles as described by OSHA's eye and face protection regulations in 29 CFR 1910.133 or European Standard EN166.
Skin and body protection	Wear appropriate protective gloves and clothing to prevent skin exposure.
Respiratory Protection	No protective equipment is needed under normal use conditions.
Hygiene Measures	Handle in accordance with good industrial hygiene and safety practice.

9. Physical and chemical properties

Physical State	Solid
Appearance	Off-white
Odor	Odorless
Odor Threshold	No information available
pH	2.1-2.6 5% aq. soln
Melting Point/Range	190 - 192 °C / 374 - 377.6 °F
Boiling Point/Range	No information available
Flash Point	No information available
Evaporation Rate	Not applicable
Flammability (solid,gas)	No information available
Flammability or explosive limits	
Upper	No data available
Lower	No data available
Vapor Pressure	No information available
Vapor Density	Not applicable
Specific Gravity	No information available
Solubility	333 g/L (20°C)
Partition coefficient; n-octanol/water	No data available
Autoignition Temperature	380 °C / 716 °F
Decomposition Temperature	No information available
Viscosity	Not applicable
Molecular Formula	C6 H8 O6
Molecular Weight	176.13

10. Stability and reactivity

Reactive Hazard None known, based on information available

Stability Stable under normal conditions. Air sensitive. Light sensitive.

Conditions to Avoid Avoid dust formation. Incompatible products. Excess heat. Exposure to air. Exposure to light.

Incompatible Materials Strong oxidizing agents, Metals, copper

Hazardous Decomposition Products Carbon monoxide (CO), Carbon dioxide (CO_2)

Hazardous Polymerization Hazardous polymerization does not occur.

Hazardous Reactions None under normal processing.

11. Toxicological information

Acute Toxicity

Product Information
Component Information

Component	LD50 Oral	LD50 Dermal	LC50 Inhalation
L-Ascorbic acid	LD50 = 11900 mg/kg (Rat)	Not listed	Not listed

Toxicologically Synergistic Products No information available

Delayed and immediate effects as well as chronic effects from short and long-term exposure

Irritation No information available

Sensitization No information available

Carcinogenicity The table below indicates whether each agency has listed any ingredient as a carcinogen.

Component	CAS No	IARC	NTP	ACGIH	OSHA	Mexico
L-Ascorbic acid	50-81-7	Not listed	Not listed	Not listed	Not listed	Not listed

Mutagenic Effects No information available

Reproductive Effects No information available.

Developmental Effects No information available.

Teratogenicity No information available.

STOT - single exposure None known
STOT - repeated exposure None known

Aspiration hazard No information available

Symptoms / effects,both acute and delayed No information available

Endocrine Disruptor Information No information available

Other Adverse Effects The toxicological properties have not been fully investigated. See actual entry in RTECS for complete information.

12. Ecological information

Ecotoxicity
Do not empty into drains.

Persistence and Degradability Soluble in water. Persistence is unlikely based on information available.

Bioaccumulation/ Accumulation No information available.

Mobility Will likely be mobile in the environment due to its water solubility.

13. Disposal considerations

Waste Disposal Methods Chemical waste generators must determine whether a discarded chemical is classified as a hazardous waste. Chemical waste generators must also consult local, regional, and national hazardous waste regulations to ensure complete and accurate classification.

14. Transport information

DOT Not regulated
TDG Not regulated
IATA Not regulated
IMDG/IMO Not regulated

15. Regulatory information

United States of America Inventory

Component	CAS No	TSCA	TSCA Inventory notification - Active-Inactive	TSCA - EPA Regulatory Flags
L-Ascorbic acid	50-81-7	X	ACTIVE	-

Legend:
TSCA US EPA (TSCA) - Toxic Substances Control Act, (40 CFR Part 710)
X - Listed
'-' - Not Listed

TSCA 12(b) - Notices of Export Not applicable

International Inventories
Canada (DSL/NDSL), Europe (EINECS/ELINCS/NLP), Philippines (PICCS), Japan (ENCS), Japan (ISHL), Australia (AICS), China (IECSC), Korea (KECL).

Component	CAS No	DSL	NDSL	EINECS	PICCS	ENCS	ISHL	AICS	IECSC	KECL
L-Ascorbic acid	50-81-7	X	-	200-066-2	X	X	X	X	X	KE-01947

KECL - NIER number or KE number (http://ncis.nier.go.kr/en/main.do)

U.S. Federal Regulations

SARA 313 Not applicable

SARA 311/312 Hazard Categories See section 2 for more information

CWA (Clean Water Act) Not applicable

Clean Air Act Not applicable

OSHA - Occupational Safety and Health Administration Not applicable

CERCLA Not applicable

California Proposition 65 This product does not contain any Proposition 65 chemicals.

U.S. State Right-to-Know Regulations Not applicable

U.S. Department of Transportation

Reportable Quantity (RQ):	N
DOT Marine Pollutant	N
DOT Severe Marine Pollutant	N

U.S. Department of Homeland Security This product does not contain any DHS chemicals.

Other International Regulations

Mexico - Grade No information available

Authorisation/Restrictions according to EU REACH

Safety, health and environmental regulations/legislation specific for the substance or mixture

Component	CAS No	OECD HPV	Persistent Organic Pollutant	Ozone Depletion Potential	Restriction of Hazardous Substances (RoHS)
L-Ascorbic acid	50-81-7	Listed	Not applicable	Not applicable	Not applicable

Component	CAS No	Seveso III Directive (2012/18/EC) - Qualifying Quantities for Major Accident Notification	Seveso III Directive (2012/18/EC) - Qualifying Quantities for Safety Report Requirements	Rotterdam Convention (PIC)	Basel Convention (Hazardous Waste)
L-Ascorbic acid	50-81-7	Not applicable	Not applicable	Not applicable	Annex I - Y34

16. Other information

Prepared By Regulatory Affairs
Thermo Fisher Scientific
Email: EMSDS.RA@thermofisher.com

Creation Date	03-Jun-2014
Revision Date	25-Dec-2021
Print Date	25-Dec-2021
Revision Summary	This document has been updated to comply with the US OSHA HazCom 2012 Standard replacing the current legislation under 29 CFR 1910.1200 to align with the Globally Harmonized System of Classification and Labeling of Chemicals (GHS).

Disclaimer
The information provided in this Safety Data Sheet is correct to the best of our knowledge, information and belief at the date of its publication. The information given is designed only as a guidance for safe handling, use, processing, storage, transportation, disposal and release and is not to be considered a warranty or quality specification. The information relates only to the specific material designated and may not be valid for such material used in combination with any other materials or in any process, unless specified in the text

End of SDS

Substances

Chemical identity	Common name and synonyms	CAS number	Content in percent (%)*
L-ASCORBIC ACID		50-81-7	100%

* All concentrations are percent by weight unless ingredient is a gas. Gas concentrations are in percent by volume.

4. First-aid measures

General information: Get medical advice/attention if you feel unwell. Show this safety data sheet to the doctor in attendance.

Ingestion: Rinse mouth thoroughly. Call a POISON CENTER or doctor/physician if you feel unwell.

Inhalation: Move to fresh air. Get medical attention if symptoms persist.

Skin contact: Wash skin thoroughly with soap and water. Get medical attention if irritation persists after washing. Wash contaminated clothing before reuse.

Eye contact: Flush thoroughly with water. If irritation occurs, get medical assistance.

Most important symptoms/effects, acute and delayed

Symptoms: May cause irritation to skin, eyes, and respiratory tract.

Indication of immediate medical attention and special treatment needed

Treatment: Treat symptomatically. Symptoms may be delayed.

5. Fire-fighting measures

General fire hazards: The product is non-combustible.

Suitable (and unsuitable) extinguishing media

Suitable extinguishing media: Use fire-extinguishing media appropriate for surrounding materials.

Unsuitable extinguishing media: None known.

Specific hazards arising from the chemical: During fire, gases hazardous to health may be formed.

Special protective equipment and precautions for firefighters

Special fire fighting procedures: Move containers from fire area if you can do so without risk. Use water spray to keep fire-exposed containers cool. Cool containers exposed to flames with water until well after the fire is out.

Special protective equipment for fire-fighters: Firefighters must use standard protective equipment including flame retardant coat, helmet with face shield, gloves, rubber boots, and in enclosed spaces, SCBA.

6. Accidental release measures

IATA

Not regulated.

15. Regulatory information

US federal regulations

TSCA Section 12(b) Export Notification (40 CFR 707, Subpt. D)
US. OSHA Specifically Regulated Substances (29 CFR 1910.1001-1050)
None present or none present in regulated quantities.

CERCLA Hazardous Substance List (40 CFR 302.4):
None present or none present in regulated quantities.

Superfund amendments and reauthorization act of 1986 (SARA)

Hazard categories
Not listed.

SARA 302 Extremely hazardous substance
None present or none present in regulated quantities.

SARA 304 Emergency release notification
None present or none present in regulated quantities.

SARA 311/312 Hazardous chemical

Chemical identity	Threshold Planning Quantity

SARA 313 (TRI reporting)
None present or none present in regulated quantities.

Clean Water Act Section 311 Hazardous Substances (40 CFR 117.3)
None present or none present in regulated quantities.

Clean Air Act (CAA) Section 112(r) Accidental Release Prevention (40 CFR 68.130):
None present or none present in regulated quantities.

US state regulations

US. California Proposition 65
No ingredient regulated by CA Prop 65 present.

US. New Jersey Worker and Community Right-to-Know Act
No ingredient regulated by NJ Right-to-Know Law present.

US. Massachusetts RTK - Substance List
No ingredient regulated by MA Right-to-Know Law present.

US. Pennsylvania RTK - Hazardous Substances
No ingredient regulated by PA Right-to-Know Law present.

US. Rhode Island RTK
No ingredient regulated by RI Right-to-Know Law present.

Disclaimer:

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SAFETY DATA SHEET

1. Identification

Product identifier: Ascorbic acid

Other means of identification
Product No.: 4407, 1852, B581, 0939, 0938, 0937, 0936, 8829

Recommended use and restriction on use
Recommended use: Not available.
Restrictions on use: Not known.

Manufacturer/Importer/Supplier/Distributor information

Manufacturer

Company Name:	Avantor Performance Materials, Inc.
Address:	3477 Corporate Parkway, Suite 200 Center Valley, PA 18034
Telephone:	
	Customer Service: 855-282-6867
Fax:	
Contact Person:	Environmental Health & Safety
e-mail:	info@avantormaterials.com

Emergency telephone number:
24 Hour Emergency: 908-859-2151

Chemtrec: 800-424-9300

2. Hazard(s) identification

Hazard classification
Not classified

_

Label elements

Hazard symbol:	No symbol
Signal word:	No signal word.
Hazard statement:	Not applicable
Precautionary statement	Not applicable

Other hazards which do not result in GHS classification: None.

3. Composition/information on ingredients

Personal precautions, protective equipment and emergency procedures: Keep unauthorized personnel away. Use personal protective equipment. See Section 8 of the MSDS for Personal Protective Equipment.

Methods and material for containment and cleaning up: Sweep up and place in a clearly labeled container for chemical waste. Clean surface thoroughly to remove residual contamination.

Notification Procedures: Prevent entry into waterways, sewer, basements or confined areas. Inform authorities if large amounts are involved.

Environmental precautions: Prevent further leakage or spillage if safe to do so. Avoid discharge into drains, water courses or onto the ground.

7. Handling and storage

Precautions for safe handling: Use personal protective equipment as required. Avoid contact with eyes, skin, and clothing. Avoid inhalation of dust. Wash thoroughly after handling.

Conditions for safe storage, including any incompatibilities: Keep containers tightly closed. Store in cool, dry place. Store in a well-ventilated place.

8. Exposure controls/personal protection

Control parameters

Occupational exposure limits

None of the components have assigned exposure limits.

Appropriate engineering controls No data available.

Individual protection measures, such as personal protective equipment

General information: Good general ventilation (typically 10 air changes per hour) should be used. Ventilation rates should be matched to conditions. If applicable, use process enclosures, local exhaust ventilation, or other engineering controls to maintain airborne levels below recommended exposure limits. If exposure limits have not been established, maintain airborne levels to an acceptable level.

Eye/face protection: Use tight fitting goggles if dust is generated.

Skin protection

Hand protection: Wear protective gloves.

Other: Wear suitable protective clothing.

Respiratory protection: In case of inadequate ventilation use suitable respirator.

Hygiene measures: Always observe good personal hygiene measures, such as washing after handling the material and before eating, drinking, and/or smoking. Routinely wash work clothing and protective equipment to remove contaminants. Provide eyewash station and safety shower.

9. Physical and chemical properties

Appearance

Physical state: Solid

Form: Crystals or powder

Color:	White to slightly yellow
Odor:	Odorless
Odor threshold:	No data available.
pH:	2 - 3 pH = 3 (5 mg/mL); pH = 2 (50 mg/mL)
Melting point/freezing point:	190 °C
Initial boiling point and boiling range:	No data available.
Flash Point:	Not applicable
Evaporation rate:	No data available.
Flammability (solid, gas):	No data available.
Upper/lower limit on flammability or explosive limits	
Flammability limit - upper (%):	No data available.
Flammability limit - lower (%):	No data available.
Explosive limit - upper (%):	No data available.
Explosive limit - lower (%):	No data available.
Vapor pressure:	0.01 kPa (192.15 °C)
Vapor density:	No data available.
Relative density:	1.65 (20 °C)
Solubility(ies)	
Solubility in water:	330 g/l
Solubility (other):	absolute ethanol: 0.02 g/ml propylene glycol: 0.05 g/ml USP glycerol: 0.01 g/ml
Partition coefficient (n-octanol/water):	No data available.
Auto-ignition temperature:	No data available.
Decomposition temperature:	No data available.
Viscosity:	No data available.

Other information

Molecular weight:	176.12 g/mol ($C_6H_8O_6$)

10. Stability and reactivity

Reactivity:	No dangerous reaction known under conditions of normal use.
Chemical stability:	Material is stable under normal conditions.
Possibility of hazardous reactions:	Hazardous polymerization does not occur.
Conditions to avoid:	Contact with incompatible materials.
Incompatible materials:	Strong oxidizing agents. Alkalies. Iron. Copper.
Hazardous decomposition products:	By heating and fire, irritating vapors/gases may be formed.

11. Toxicological information

Information on likely routes of exposure

Ingestion:	May cause irritation of the gastrointestinal tract.
Inhalation:	May cause irritation to the respiratory system.
Skin contact:	May cause irritation.
Eye contact:	May cause temporary eye irritation.

Information on toxicological effects

Acute toxicity (list all possible routes of exposure)

Oral
Product: LD 50 (Rat): 11,900 mg/kg

Dermal
Product: No data available.

Inhalation
Product: No data available.

Repeated dose toxicity
Product: No data available.

Skin corrosion/irritation
Product: May cause skin irritation.

Serious eye damage/eye irritation
Product: May irritate eyes.

Respiratory or skin sensitization
Product: Not a skin sensitizer.

Carcinogenicity
Product: This substance has no evidence of carcinogenic properties.

IARC Monographs on the Evaluation of Carcinogenic Risks to Humans:
No carcinogenic components identified

US. National Toxicology Program (NTP) Report on Carcinogens:
No carcinogenic components identified

US. OSHA Specifically Regulated Substances (29 CFR 1910.1001-1050):
No carcinogenic components identified

Germ cell mutagenicity

In vitro
Product: No mutagenic components identified

In vivo
Product: No mutagenic components identified

Reproductive toxicity
Product: No components toxic to reproduction

Specific target organ toxicity - single exposure
Product: None known.

Specific target organ toxicity - repeated exposure
Product: None known.

Aspiration hazard
Product: Not classified

Other effects: None known.

12. Ecological information

Ecotoxicity:

Acute hazards to the aquatic environment:

Fish
Product: No data available.

Aquatic invertebrates
Product: No data available.

Chronic hazards to the aquatic environment:

Fish
Product: No data available.

Aquatic invertebrates
Product: No data available.

Toxicity to Aquatic Plants
Product: No data available.

Persistence and degradability

Biodegradation
Product: There are no data on the degradability of this product.

BOD/COD ratio
Product: No data available.

Bioaccumulative potential
Bioconcentration factor (BCF)
Product: No data available on bioaccumulation.

Partition coefficient n-octanol / water (log Kow)
Product: No data available.

Mobility in soil: The product is water soluble and may spread in water systems.

Other adverse effects: The product components are not classified as environmentally hazardous. However, this does not exclude the possibility that large or frequent spills can have a harmful or damaging effect on the environment.

13. Disposal considerations

Disposal instructions: Discharge, treatment, or disposal may be subject to national, state, or local laws.

Contaminated packaging: Since emptied containers retain product residue, follow label warnings even after container is emptied.

14. Transport information

DOT
Not regulated.

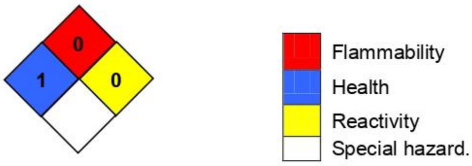
IMDG
Not regulated.

Inventory Status:

Australia AICS:	On or in compliance with the inventory
Canada DSL Inventory List:	On or in compliance with the inventory
EINECS, ELINCS or NLP:	On or in compliance with the inventory
Japan (ENCS) List:	On or in compliance with the inventory
China Inv. Existing Chemical Substances:	Not in compliance with the inventory.
Korea Existing Chemicals Inv. (KECI):	On or in compliance with the inventory
Canada NDSL Inventory:	Not in compliance with the inventory.
Philippines PICCS:	On or in compliance with the inventory
US TSCA Inventory:	On or in compliance with the inventory
New Zealand Inventory of Chemicals:	On or in compliance with the inventory
Japan ISHL Listing:	On or in compliance with the inventory
Japan Pharmacopoeia Listing:	On or in compliance with the inventory

16.Other information, including date of preparation or last revision

NFPA Hazard ID



Hazard rating: 0 - Minimal; 1 - Slight; 2 - Moderate; 3 - Serious; 4 - Severe

Issue date:	03-28-2014
Revision date:	No data available.
Version #:	1.0
Further information:	No data available.

SIGMA-ALDRICH

Material Safety Data Sheet

Version 3.1
Revision Date 03/12/2008
Print Date 04/07/2010

1. PRODUCT AND COMPANY IDENTIFICATION

Product name : L-Ascorbic acid

Product Number : A92902
Brand : Sigma-Aldrich

Company : Sigma-Aldrich Canada, Ltd
2149 Winston Park Drive
OAKVILLE ON L6H 6J8
CANADA
Telephone : +19058299500
Fax : +19058299292
Emergency Phone # : 800-424-9300

2. COMPOSITION/INFORMATION ON INGREDIENTS

Synonyms : Antiscorbutic factor
L-Threoascorbic acid
Vitamin C

Formula : C6H8O6
Molecular Weight : 176.12 g/mol

CAS-No.	EC-No.	Index-No.	Concentration
Ascorbic acid			
50-81-7	200-066-2	-	-

3. HAZARDS IDENTIFICATION

WHMIS Classification
Not WHMIS controlled. **Not WHMIS controlled.**

HMIS Classification
Health Hazard: 0
Flammability: 0
Physical hazards: 0

Potential Health Effects

Inhalation May be harmful if inhaled. May cause respiratory tract irritation.
Skin May be harmful if absorbed through skin. May cause skin irritation.
Eyes May cause eye irritation.
Ingestion May be harmful if swallowed.

4. FIRST AID MEASURES

If inhaled
If breathed in, move person into fresh air. If not breathing give artificial respiration

In case of skin contact
Wash off with soap and plenty of water.

In case of eye contact
Flush eyes with water as a precaution.

If swallowed
Never give anything by mouth to an unconscious person. Rinse mouth with water.

5. FIRE-FIGHTING MEASURES

Flammable properties

Flash point	no data available
Ignition temperature	no data available

Suitable extinguishing media
Use water spray, alcohol-resistant foam, dry chemical or carbon dioxide.

Special protective equipment for fire-fighters
Wear self contained breathing apparatus for fire fighting if necessary.

6. ACCIDENTAL RELEASE MEASURES

Personal precautions
Avoid dust formation.

Environmental precautions
Do not let product enter drains.

Methods for cleaning up
Sweep up and shovel. Keep in suitable, closed containers for disposal.

7. HANDLING AND STORAGE

Handling
Provide appropriate exhaust ventilation at places where dust is formed. Normal measures for preventive fire protection.

Storage
Keep container tightly closed in a dry and well-ventilated place.

Light sensitive.

8. EXPOSURE CONTROLS/PERSONAL PROTECTION

Contains no substances with occupational exposure limit values.

Personal protective equipment

Respiratory protection
Respiratory protection is not required. Where protection from nuisance levels of dusts are desired, use type N95 (US) or type P1 (EN 143) dust masks. Use respirators and components tested and approved under appropriate government standards such as NIOSH (US) or CEN (EU).

Hand protection
For prolonged or repeated contact use protective gloves.

Eye protection
Safety glasses

Hygiene measures
General industrial hygiene practice.

9. PHYSICAL AND CHEMICAL PROPERTIES

Appearance

Form	**solid**

Safety data

pH	**1.0 - 2.5 at 176 g/l at 25 °C (77 °F)**
Melting point	193 °C (379 °F)
Boiling point	**no data available**
Flash point	**no data available**
Ignition temperature	**no data available**
Lower explosion limit	**no data available**
Upper explosion limit	**no data available**
Water solubility	**176 g/l at 20 °C (68 °F)** - completely soluble

10. STABILITY AND REACTIVITY

Storage stability
Stable under recommended storage conditions.

Conditions to avoid
Light.

Materials to avoid
Strong oxidizing agents

Hazardous decomposition products
Hazardous decomposition products formed under fire conditions. - Carbon oxides

11. TOXICOLOGICAL INFORMATION

Acute toxicity

LD50 Oral - rat - 11,900 mg/kg
Remarks: Sense Organs and Special Senses (Nose, Eye, Ear, and Taste):Eye:Lacrimation. Behavioral:Somnolence (general depressed activity). Diarrhoea

Irritation and corrosion

no data available

Sensitisation

no data available

Chronic exposure

IARC: No component of this product present at levels greater than or equal to 0.1% is identified as probable, possible or confirmed human carcinogen by IARC.

Genotoxicity in vitro - mouse - Liver
Other mutation test systems

Genotoxicity in vivo - mouse - Intraperitoneal
Micronucleus test

Signs and Symptoms of Exposure

Chronic ingestion of large doses may cause gastrointestinal disturbances including nausea and diarrhea, urinary effects involving urine acidification, oxalate and uric crystallizaton in the bladder and kidney, and decreased reaction times and psychomotor coordination.

Potential Health Effects

Inhalation	May be harmful if inhaled. May cause respiratory tract irritation.
Skin	May be harmful if absorbed through skin. May cause skin irritation.
Eyes	May cause eye irritation.
Ingestion	May be harmful if swallowed.

Additional Information
RTECS: CI7650000

12. ECOLOGICAL INFORMATION

Elimination information (persistence and degradability)

no data available

Ecotoxicity effects

no data available

Further information on ecology

no data available

13. DISPOSAL CONSIDERATIONS

Product
Observe all federal, state, and local environmental regulations.

Contaminated packaging
Dispose of as unused product.

14. TRANSPORT INFORMATION

DOT (US)
Not dangerous goods

IMDG
Not dangerous goods

IATA
Not dangerous goods

15. REGULATORY INFORMATION

TSCA Status
On TSCA Inventory

DSL Status
All components of this product are on the Canadian DSL list.

WHMIS Classification
Not WHMIS controlled. Not WHMIS controlled.

16. OTHER INFORMATION

Further information

The above information is believed to be correct but does not purport to be all inclusive and shall be used only as a guide. The information in this document is based on the present state of our knowledge and is applicable to the product with regard to appropriate safety precautions. It does not represent any guarantee of the properties of the product. Sigma-Aldrich Co., shall not be held liable for any damage resulting from handling or from contact with the above product. See reverse side of invoice or packing slip for additional terms and conditions of sale.

APPENDIX B – CALCULATION FOR EQUIPMENT SIZING

Sizing of Storage Tank 1

Total mass per batch, m = 45000 kg/batch

Average density, ρ = 1270.74 kg/m^3

Working volume, V_w = $\frac{Total\ mass\ per\ batch}{Average\ Density} = \frac{45000}{1270.74}$ = 35.41 m^3

Assume working volume is equivalent to 80%

Volume of Storage tank, V = $\frac{35.41}{0.8}$ = 44.27 m^3

Length to Diameter ratio = 3:1

For torispherical shape,

Volume, V = $0.1D^3 + \pi(\frac{D}{2})^2 l = 0.1D^3 + \pi\left(\frac{D}{2}\right)^2 (3D)$ = 44.27 m^3

Diameter, D = 2.6219 m

Length, L = 7.8657 m

Sizing of Storage Tank 2

Total mass per batch, m = 19474.663 kg/batch

Average density, ρ = 1239.50 kg/m^3

Working volume, V_w = $\frac{Total\ mass\ per\ batch}{Average\ Density} = \frac{19474.663}{1239.50}$ = 15.712 m^3

Assume working volume is equivalent to 80%

Volume of Storage tank, V = $\frac{15.712}{0.8}$ = 19.64 m^3

Length to Diameter ratio = 3:1

For torispherical shape,

Volume, V = $0.1D^3 + \pi(\frac{D}{2})^2 l = 0.1D^3 + \pi\left(\frac{D}{2}\right)^2 (3D)$ = 19.64 m^3

Diameter, D = 2.000 m

Length, L = 6.000 m

Sizing of Fermenter 1

Total mass per batch, m = 107822 kg/batch

Average density, ρ = 990.91 kg/m^3

Total working volume, V_w $= \frac{Total\ mass\ per\ batch}{Average\ Density} = \frac{107822}{990.91}$ = 108.811 m^3

Assume working volume is equivalent to 80%

Total Volume of Fermenter, V $= \frac{108.811}{0.8}$ = 136.014 m^3

Assume Fermenter capacity at 50000L each,

No of unit $= \frac{136.041}{50} \approx 3$

Height to Diameter ratio = 3:1

Volume of each unit, V $= \frac{4}{3}\pi r^3 + \pi r^2 h = \frac{11}{12}\pi D^3$ = 50 m^3

Diameter, D = 2.59 m

Height, H = 7.77 m

Sizing of Fermenter 2

Total mass per batch, m = 146440.80 kg/batch

Average density, ρ = 946.06 kg/m^3

Total working volume, $= \frac{Total\ mass\ per\ batch}{Average\ Density} = \frac{14644.80}{946.06}$ = 154.79 m^3

Assume working volume is equivalent to 80%

Total volume of Fermenter, $= \frac{154.79}{0.8}$ = 193.49 m^3

Assume Fermenter capacity at 50000 L each,

No of unit $= \frac{193.49}{50} \approx 4$

Height to Diameter ratio = 3:1

Volume of each fermenter, V $= \frac{4}{3}\pi r^3 + \pi r^2 h = \frac{11}{12}\pi D^3$ = 50 m^3

Diameter, D = 2.59 m

Height, H = 7.77 m

Sizing of Decanter Centrifuge (Dolphin Centrifuge, 2024)

Total mass per batch, m = 124205.35 kg/batch

Average density, ρ = 1038.55 kg/m^3

Working volume, V_w $= \frac{Total\ mass\ per\ batch}{Average\ Density} = \frac{124205.35}{1038.55}$ = 119.595 m^3

Volume of Centrifuge, V $= \frac{119.595}{0.8}$ = 149.494 m^3

Operating capacity, Q $= \frac{149.494}{13}$ = 11.5 m^3/h

Bowl Diameter, D = 0.3530 m

Bowl Length, L = 1.016 m

Sizing of Bipolar Membrane Electrodialysis 1 (*ASTOM > Bipolar Membrane Electrodialyzer [ACILYZER BPED Products]*, n.d.)

Total mass flowrate, kg/h = 1571.734 kg/h

Average density, ρ = 1038.53 kg/m^3

Volumetric flowrate, Q $= \frac{Total\ mass\ flowrate}{Average\ Density} = \frac{1571.734}{1038.53} = 1.5134$ m^3/h

Assume flux value of 30 L/m²/h,

Membrane area, A $= \frac{1.5134}{0.03} = 50.45$ m^2

Working volume, V_w $= \frac{Total\ mass\ per\ batch}{Average\ Density} = \frac{123899.79}{1038.53} = 119.30$ m^3

Assume 80% working volume,

Volume, V $= \frac{119.30}{0.8} = 149.13$ m^3

Thickness of BME, t_m $= \frac{149.13}{50.45} = 2.96$ m

Sizing of Bipolar Membrane Electrodialysis 2

Total mass flowrate, kg/h = 858.2206 kg/h

Average density, ρ = 1052.81 kg/m^3

Volumetric flowrate, Q $= \frac{Total\ mass\ flowrate}{Average\ Density} = \frac{858.2206}{1052.82} = 0.815$ m^3/h

Assume flux value of 30 L/m²/h,

Membrane area, A $= \frac{0.815}{0.03} = 27.172$ m^2

Working volume, V_w $= \frac{Total\ mass\ per\ batch}{Average\ Density} = \frac{67653.532}{1052.81} = 64.26$ m^3

Assume 80% working volume,

Volume, V $= \frac{64.26}{0.8} = 80.325$ m^3

Thickness of BME, t_m $= \frac{80.325}{50.45} = 2.9561$ m

Sizing of Thin Film Evaporator 1

Total mass flowrate, = 1490.06 kg/h

Average density, ρ = 1003.79 kg/m^3

Volumetric flowrate, $= \frac{1490.06}{1003.79} = 1.4844$ m^3/h

Height to Diameter ratio = 2:1

Heat transfer area, A = $2\pi(\frac{D}{2})2D = 2\pi D^2$ = 2.844 m^2

Diameter, D = 0.6728 m

Height, H = 1.3456 m

Sizing of Thin Film Evaporator 2

Total mass flowrate, = 776.54 kg/h

Average density, ρ = 1050.16 kg/m^3

Volumetric flowrate, = $\frac{776.54}{1050.16}$ = 0.74 m^3/h

Height to Diameter ratio = 2:1

Heat transfer area, A = $2\pi(\frac{D}{2})2D = 2\pi D^2$ = 0.404 m^2

Diameter, D = 0.2536 m

Height, H = 0.5072 m

Sizing of Reactor 1

Total mass flowrate, kg/h = 776.54 kg/h

Average density, ρ = 1029.02 kg/m^3

Retention time, τ = 1 hr

Working volume, V_w = $\frac{Total\ mass\ flowrate}{Average\ Density}\tau = \frac{776.54}{1029.02} \times 1$ = 0.7546 m^3

Assuming 80% working volume,

Volume of Bioreactor, V_T = $\frac{0.7546}{0.80}$ = 0.9433 m^3

Height to Diameter ratio = 2.5:1

Volume, V = $\frac{4}{3}\pi r^3 + \pi r^2 h = \frac{19}{24}\pi D^3$ = 0.9433 m^3

Diameter, D = 0.7239 m

Height, H = 2.1717 m

Sizing of Reactor 2

Total mass flowrate, kg/h = 948.11 kg/h

Average density, ρ = 1161.55 kg/m^3

Working volume, V_w = $\frac{Total\ mass\ flowrate}{Average\ Density} \times \tau = \frac{948.11}{1161.55} \times 1$ = 0.8162 m^3

Assuming 80% working volume,

Volume of Reactor, V_T = $\frac{0.8162}{0.80}$ = 1.0203 m^3

Height to Diameter ratio = 2.5:1

Volume of each Reactor, V $= \frac{4}{3}\pi r^3 + \pi r^2 h = \frac{19}{24}\pi D^3$ = 1.0203 m^3

Diameter, D = 0.743 m

Height, H = 2.229 m

<u>Sizing of Crystallizer</u>

Total mass per batch, m = 47305.8512 kg/batch

Average density, ρ = 1425.38 kg/m^3

Volume of Crystallizer, V $= \frac{Total\ mass\ per\ batch}{Average\ Density} = \frac{47305.8512}{1425.38}$ = 33.19 m^3

Height to Diameter ratio = 3:1

Volume, V $= \pi r^2 h = \frac{3}{4}\pi D^3$ = 33.19 m^3

Diameter, D = 2.415 m

Height, H = 7.2450 m

<u>Sizing of Nutsche Filter</u>

Total mass per batch, m = 47305.8512 kg/batch

Average density, ρ = 1425.38 kg/m^3

Total working volume, $= \frac{Total\ mass\ per\ batch}{Average\ Density} = \frac{47305.8512}{1425.38}$ = 33.19 m^3

Assuming 80% working volume,

Total volume of filter, $= \frac{33.19}{0.8}$ = 41.485 m^3

Assume each filter volume at 25 m^3,

No of unit, $= \frac{41.485}{25} \approx 2$

Filter Area of each unit, A $= \pi(\frac{D}{2})^2$ = 15 m^2

Diameter, D = 4.3702 m

Volume, V $= \pi(\frac{D}{2})^2 L$ = 25 m^3

Length, L = 1.6667 m

<u>Sizing of Solids Storage</u>

Total mass per batch, m = 27831.19 kg/batch

Average density, ρ = 1622.02 kg/m^3

Working volume, V_w $= \frac{Total\ mass\ per\ batch}{Average\ Density} = \frac{27831.19}{1622.02} = 17.16\ m^3$

Assume working volume is equivalent to 80%

Volume of Storage tank, V $= \frac{16.19}{0.8} = 21.45\ m^3$

Height to Diameter ratio = 3:1

Volume, V $= \frac{4}{3}\pi r^3 + \pi r^2 h = \frac{11}{12}\pi D^3 = 21.45\ m^3$

Diameter, D = 1.9529 m

Height, H = 5.8587 m

<u>Sizing of Heat Exchanger 1</u>

$T_{hot,\ in} = 363.15$ K $T_{hot,\ out} = 314.75$ K

$T_{cold,\ in} = 303.15$ K $T_{cold,\ out} = 313.15$ K

R $= \frac{Thot,in-Thot,out}{Tcold,out-Tcold,in} = \frac{363.15-314.75}{313.15-303.15} = 4.3103$

S $= \frac{Tcold,out-Tcold,in}{Thot,in-Tcold,in} = \frac{313-303}{363-303} = 0.1933$

LMTD, ΔT_{lm} $= \frac{(Thot,in-Tcold,out)-(Thot,out-Tcold,in)}{ln[\frac{(Thot,in-Tcold,out)}{(Thot,out-Tcold,in)}]}$

$= \frac{(363.15-313.15)-(314.75-303.15)}{ln[\frac{(363.15-313.15)}{(314.75-303.15)}]}$

= 24.35 K

Correction factor, F_T = 0.86 (refer to graph due to it is 1-4 exchanger, 2.44 tube length)

Assume U = 100 W/m^{2}K,

Heat Duty, Q = 13.7523 kW

Area of Heat Exchanger, A $= \frac{Q}{UF_T\Delta T} = \frac{13.7523 \times 1000}{100 \times 0.86 \times 24.35} = 6.5668\ m^2$

<u>Sizing of Heat Exchanger 2</u>

$T_{hot,\ in} = 363.15$ K $T_{hot,\ out} = 337.15$ K

$T_{cold,\ in} = 314.75$ K $T_{cold,\ out} = 322.55$ K

R $= \frac{Thot,in-Thot,out}{Tcold,out-Tcold,in} = \frac{363.15-337.15}{322.55-314.75} = 3.33$

S $= \frac{Tcold,out-Tcold,in}{Thot,in-Tcold,in} = \frac{322.55-314.75}{363.15-314.75} = 0.1612$

LMTD, ΔT_{lm} $= \frac{(Thot,in-Tcold,out)-(Thot,out-Tcold,in)}{ln[\frac{(Thot,in-Tcold,out)}{(Thot,out-Tcold,in)}]}$

$$= \frac{(363.15-322.55)-(337.15-314.75)}{ln[\frac{(363.15-322.55)}{(337.15-314.15)}]}$$

$= 30.60$ K

Correction factor, F_T $= \frac{\sqrt{R^2+1}\,[\ln(\frac{1-S}{1-RS})]}{(R-1)\left[ln\frac{2-S(R+1-\sqrt{R^2+1})}{2-S(R+1+\sqrt{R^2+1})}\right]} = 0.96$ (1-2 exchanger, 2.44 tube length)

Assume U = 150 W/m^{2}K,

Heat Duty, Q = 9.6039 kW

Area of Heat Exchanger, A $= \frac{Q}{UF_T\Delta T} = \frac{9.6039 \times 1000}{150 \times 0.96 \times 30.60} = 2.1793$ m^2

Sizing of Heat Exchanger 3

$T_{hot,\,in} = 337.15$ K $T_{hot,\,out} = 324.85$ K

$T_{cold,\,in} = 303.15$ K $T_{cold,\,out} = 313.15$ K

R $= \frac{Thot,in-Thot,out}{Tcold,out-Tcold,in} = \frac{337.15-324.85}{313.15-303.15} = 1.1060$

S $= \frac{Tcold,out-Tcold,in}{Thot,in-Tcold,in} = \frac{313-303}{337-303} = 0.6382$

LMTD, ΔT_{lm} $= \frac{(Thot,in-Tcold,out)-(Thot,out-Tcold,in)}{ln\left[\frac{(Thot,in-Tcold,out)}{(Thot,out-Tcold,in)}\right]}$

$$= \frac{(337.15-313.15)-(324.85-303.15)}{ln[\frac{(337.15-313.15)}{(324.85-303.15)}]}$$

$= 11.11$ K

Correction factor, F_T = 0.91 (2-4 exchanger, 2.44m tube length)

Assume U = 100 W/m^{2}K,

Heat Duty, Q = 9.8880 kW

Area of Heat Exchanger, A $= \frac{Q}{UF_T\Delta T} = \frac{9.8880 \times 1000}{100 \times 0.91 \times 11.11} = 9.7800$ m^2

Sizing of Heater 1

$T_{hot,\,in} = 425.15$ K $T_{hot,\,out} = 425.15$ K

$T_{cold,\,in} = 322.55$ K $T_{cold,\,out} = 363.15$ K

R $= \frac{Thot,in-Thot,out}{Tcold,out-Tcold,in} = \frac{425.15-425.15}{363.15-322.55} = 0$

S $= \frac{Tcold,out-Tcold,in}{Thot,in-Tcold,in} = \frac{363.15-322.55}{425.15-322.55} = 0.3957$

LMTD, ΔT_{lm} $= \frac{(Thot,in-Tcold,out)-(Thot,out-Tcold,in)}{ln\left[\frac{(Thot,in-Tcold,out)}{(Thot,out-Tcold,in)}\right]}$

$$= \frac{(425.15-363.15)-(425.15-322.55)}{ln[\frac{(425.15-363.15)}{(425.15-322.55)}]}$$

$= 80.6$ K

Double pipe Heat exchanger

Assume U = 1000 W/m^{2}K,

Heat Duty, Q = 51.2538 kW

Area of Heater, A $= \frac{Q}{U\Delta T} = \frac{51.2538 \times 1000}{1000 \times 48.6368} = 0.6359$ m^2

Sizing of Heater 2

$T_{hot, in} = 425.15$ K $T_{hot, out} = 425.15$ K

$T_{cold, in} = 324.85$ K $T_{cold, out} = 363.15$ K

R $= \frac{Thot,in-Thot,out}{Tcold,out-Tcold,in} = \frac{425.15-425.15}{363.15-324.85} = 0$

S $= \frac{Tcold,out-Tcold,in}{Thot,in-Tcold,in} = \frac{363.15-324.85}{425.15-324.85} = 0.3819$

LMTD, ΔT_{lm} $= \frac{(Thot,in-Tcold,out)-(Thot,out-Tcold,in)}{ln[\frac{(Thot,in-Tcold,out)}{(Thot,out-Tcold,in)}]}$

$$= \frac{(425.15-363.15)-(425.15-324.85)}{ln[\frac{(425.15-363.15)}{(425.15-324.85)}]}$$

$= 79.62$ K

Double pipe heat exchanger

Assume U = 900 W/m^{2}K,

Heat Duty, Q = 25.1977 kW

Area of Heater, A $= \frac{Q}{UF_T\Delta T} = \frac{25.1977 \times 1000}{900 \times 79.62} = 0.3516$ m^2

Sizing of Cooler 1

$T_{hot, in} = 313.15$ K $T_{hot, out} = 303.15$ K

$T_{cold, in} = 278.15$ K $T_{cold, out} = 283.15$ K

R $= \frac{Thot,in-Thot,out}{Tcold,out-Tcold,in} = \frac{313.15-303.15}{283.15-278.15} = 2$

S $= \frac{Tcold,out-Tcold,in}{Thot,in-Tcold,in} = \frac{283.15-278.15}{313.15-278.15} = 0.1429$

LMTD, ΔT_{lm} $= \frac{(Thot,in-Tcold,out)-(Thot,out-Tcold,in)}{ln[\frac{(Thot,in-Tcold,out)}{(Thot,out-Tcold,in)}]}$

$$= \frac{(313.15-283.15)-(303.15-278.15)}{ln[\frac{(313.15-283.15)}{(303.15-278.15)}]}$$

$= 27.42$ K

Double pipe heat exchanger

Assume U = 250 W/m^{2}K,

Cooling Duty, Q = 4.12 kW

Area of Cooler, A $= \frac{Q}{U\Delta T} = \frac{4.12 \times 1000}{250 \times 27.42} = 0.6009$ m^2

Sizing of Cooler 2

$T_{hot, in} = 313.15$ K $T_{hot, out} = 277.15$ K

$T_{cold, in} = 263.15$ K $T_{cold, out} = 273.15$ K

R $= \frac{Thot,in-Thot,out}{Tcold,out-Tcold,in} = \frac{313.15-277.15}{273.15-263.15} = 3.6$

S $= \frac{Tcold,out-Tcold,in}{Thot,in-Tcold,in} = \frac{273.15-263.15}{313.15-263.15} = 0.2$

LMTD, ΔT_{lm} $= \frac{(Thot,in-Tcold,out)-(Thot,out-Tcold,in)}{ln[\frac{(Thot,in-Tcold,out)}{(Thot,out-Tcold,in)}]}$

$$= \frac{(313.15-273.15)-(277.15-263.15)}{ln[\frac{(313.15-273.15)}{(277.15-263.15)}]}$$

$= 24.77$ K

Double pipe heat exchanger

Assume U = 200 W/m^{2}K,

Cooling Duty, Q = 10.2617 kW

Area of Cooler, A $= \frac{Q}{U\Delta T} = \frac{10.2617 \times 1000}{200 \times 24.77} = 2.0717$ m^2

Sizing of Pump 1

Total mass per batch, m = 97675.5223 kg/batch

Average density, ρ = 994.97 kg/m^3

Inlet Pressure, P_i = 1.0 bar

Outlet Pressure, P_o = 1.1 bar

Head Pump $= \frac{\Delta P}{\rho g} = \frac{10{,}000\ Nm^2}{994.97 \times 9.81} = 1.1270$ m

Safety Factor 10%,

Differential Head $= 1.1270 \times 1.10 = 1.2397$ m

Volumetric Flow Rate, Q $= \frac{Mass\ flow\ rate}{Average\ density} = \frac{97675.5223}{994.97\times 1}$ = 98.1693 m^3/h

Assume efficiency, n_p is 75%,

Power $= \frac{\Delta P \times Q}{n_p} = \frac{10000 \times 98.1693}{0.75 \times 3600}$ = 363.59 W

Horsepower, hp $= \frac{P}{550} = \frac{363.59\ W}{550}$ = 0.6611 hp

Sizing of Pump 2

Total mass per batch, m = 123899.7949 kg/batch

Average density, ρ = 1038.53 kg/m^3

Inlet Pressure, P_i = 1.0 bar

Outlet Pressure, P_o = 1.1 bar

Head Pump $= \frac{\Delta P}{\rho g} = \frac{10{,}000\ Nm^2}{1038.53 \times 9.81}$ = 0.9815 m

Safety Factor 10%,

Differential Head = 0.9815 × 1.10 = 1.0797 m

Volumetric Flow Rate, Q $= \frac{Mass\ flow\ rate}{Average\ density} = \frac{123899.7949}{1038.53\times 1}$ = 119.3030 m^3/h

Assume efficiency, n_p is 75%,

Power $= \frac{\Delta P \times Q}{n_p} = \frac{10000 \times 119.3030}{0.75 \times 3600}$ = 441.86 W

Horsepower, hp $= \frac{P}{550} = \frac{441.86}{550}$ = 0.8034 hp

Sizing of Pump 3

Total mass flowrate, = 1490.06 kg/h

Average density, ρ = 1027.09 kg/m^3

Volumetric flowrate, Q $= \frac{1490.06}{1027.09}$ = 1.4508 m^3/h

Inlet Pressure, P_i = 1.0 bar

Outlet Pressure, P_o = 1.1 bar

Head Pump $= \frac{\Delta P}{\rho g} = \frac{10{,}000\ Nm^2}{1027.09 \times 9.81}$ = 0.9925 m

Safety Factor 10%,

Differential Head = 0.9925 × 1.10 = 1.0917 m

Assume efficiency, n_p is 75%,

Power $= \frac{\Delta P \times Q}{n_p} = \frac{10000 \times 1.4508}{0.75 \times 3600}$ = 5.37 W

Horsepower, hp = $\frac{P}{550} = \frac{5.37}{550}$ = 0.0098 hp

Sizing of Pump 4

Total mass flowrate, = 776.55 kg/batch

Average density, ρ = 901.31 kg/m^3

Volumetric Flow Rate, Q = $\frac{Mass\ flow\ rate}{Average\ density} = \frac{776.55}{901.31}$ = 0.8616 m^3/hr

Inlet Pressure, P_i = 1.0 bar

Outlet Pressure, P_o = 1.1 bar

Head Pump = $\frac{\Delta P}{\rho g} = \frac{10{,}000\ Nm^2}{901.31 \times 9.81}$ = 1.1310 m

Safety Factor 10%,

Differential Head = 1.1310 × 1.10 = 1.2441 m

Assume efficiency, n_p is 75%,

Power = $\frac{\Delta P \times Q}{n_p} = \frac{10000 \times 0.8616}{0.75 \times 3600}$ = 3.19 W

Horsepower, hp = $\frac{P}{550} = \frac{3.19}{550}$ = 0.0058 hp

Sizing of Pump 5

Total mass flowrate = 858.221 kg/h

Average density, ρ = 1052.81 kg/m^3

Volumetric Flow Rate, Q = $\frac{Mass\ flow\ rate}{Average\ density} = \frac{858.221}{1052.81}$ = 0.8152 m^3/h

Inlet Pressure, P_i = 1.0 bar

Outlet Pressure, P_o = 1.1 bar

Head Pump = $\frac{\Delta P}{\rho g} = \frac{10{,}000\ Nm^2}{1052.81 \times 9.81}$ = 0.9682 m

Safety Factor 10%,

Differential Head = 0.9682 × 1.10 = 1.0651 m

Assume efficiency, n_p is 75%,

Power = $\frac{\Delta P \times Q}{n_p} = \frac{10000 \times 0.8152}{0.75 \times 3600}$ = 3.02 W

Horsepower, hp = $\frac{P}{550} = \frac{3.02}{550}$ = 0.0055 hp

Sizing of Pump 6

Total mass flowrate = 776.543 kg/h

Average density, ρ = 1254.32 kg/m^3

Volumetric Flow Rate, Q $= \frac{Mass\ flow\ rate}{Average\ density} = \frac{776.543}{1254.32} = 0.6191$ m^3/h

Inlet Pressure, P_i = 1.0 bar

Outlet Pressure, P_o = 1.1 bar

Head Pump $= \frac{\Delta P}{\rho g} = \frac{10{,}000\ Nm^2}{1254.32 \times 9.81} = 0.8127$ m

Safety Factor 10%,

Differential Head = 0.8127 × 1.10 = 0.8940 m

Assume efficiency, n_p is 75%,

Power $= \frac{\Delta P \times Q}{n_p} = \frac{10000 \times 0.6191}{0.75 \times 3600} = 2.29$ W

Horsepower, hp $= \frac{P}{550} = \frac{2.29}{550} = 0.0042$ hp

Sizing of Pump 7

Total mass flowrate = 600.10 kg/h

Average density, ρ = 1358.71 kg/m^3

Volumetric Flow Rate, Q $= \frac{Mass\ flow\ rate}{Average\ density} = \frac{600.10}{1358.71} = 0.4417$ m^3/hr

Inlet Pressure, P_i = 1.0 bar

Outlet Pressure, P_o = 1.1 bar

Head Pump $= \frac{\Delta P}{\rho g} = \frac{10{,}000\ Nm^2}{1358.71 \times 9.81} = 0.7502$ m

Safety Factor 10%,

Differential Head = 0.7502 × 1.10 = 0.8253 m

Assume efficiency, n_p is 75%,

Power $= \frac{\Delta P \times Q}{n_p} = \frac{10000 \times 0.4417}{0.75 \times 3600} = 1.64$ W

Horsepower, hp $= \frac{P}{550} = \frac{1.64}{550} = 0.0030$ hp

Sizing of Pump 8

Total mass per batch, m = 47305.8512 kg/batch

Average density, ρ = 1425.38 kg/m^3

Inlet Pressure, P_i = 1.0 bar

Outlet Pressure, P_o = 1.1 bar

Head Pump $= \frac{\Delta P}{\rho g} = \frac{10{,}000\ Nm^2}{1425.38 \times 9.81} = 0.7152$ m

Safety Factor 10%,

Differential Head = 0.7152 × 1.10 = 0.7867 m

Volumetric Flow Rate, Q $= \frac{Mass\ flow\ rate}{Average\ density} = \frac{47305.8512}{1425.38 \times 1}$ = 33.1882 m^3/hr

Assume efficiency, n_p is 75%,

Power $= \frac{\Delta P \times Q}{n_p} = \frac{10000 \times 33.1882}{0.75 \times 3600}$ = 122.92 W

Horsepower, hp $= \frac{P}{550} = \frac{122.92}{550}$ = 0.2235 hp

Sizing of Pump 9

Total mass per batch, m = 17212.2753 kg/batch

Average density, ρ = 1239.49 kg/m^3

Inlet Pressure, P_i = 1.0 bar

Outlet Pressure, P_o = 1.1 bar

Head Pump $= \frac{\Delta P}{\rho g} = \frac{10,000\ Nm^2}{1239.49 \times 9.81}$ = 0.8824 m

Safety Factor 10%,

Differential Head = 0.8824 × 1.10 = 0.9047 m

Volumetric Flow Rate, Q $= \frac{Mass\ flow\ rate}{Average\ density} = \frac{17212.2753}{1239.49 \times 1}$ = 13.8866 m^3/hr

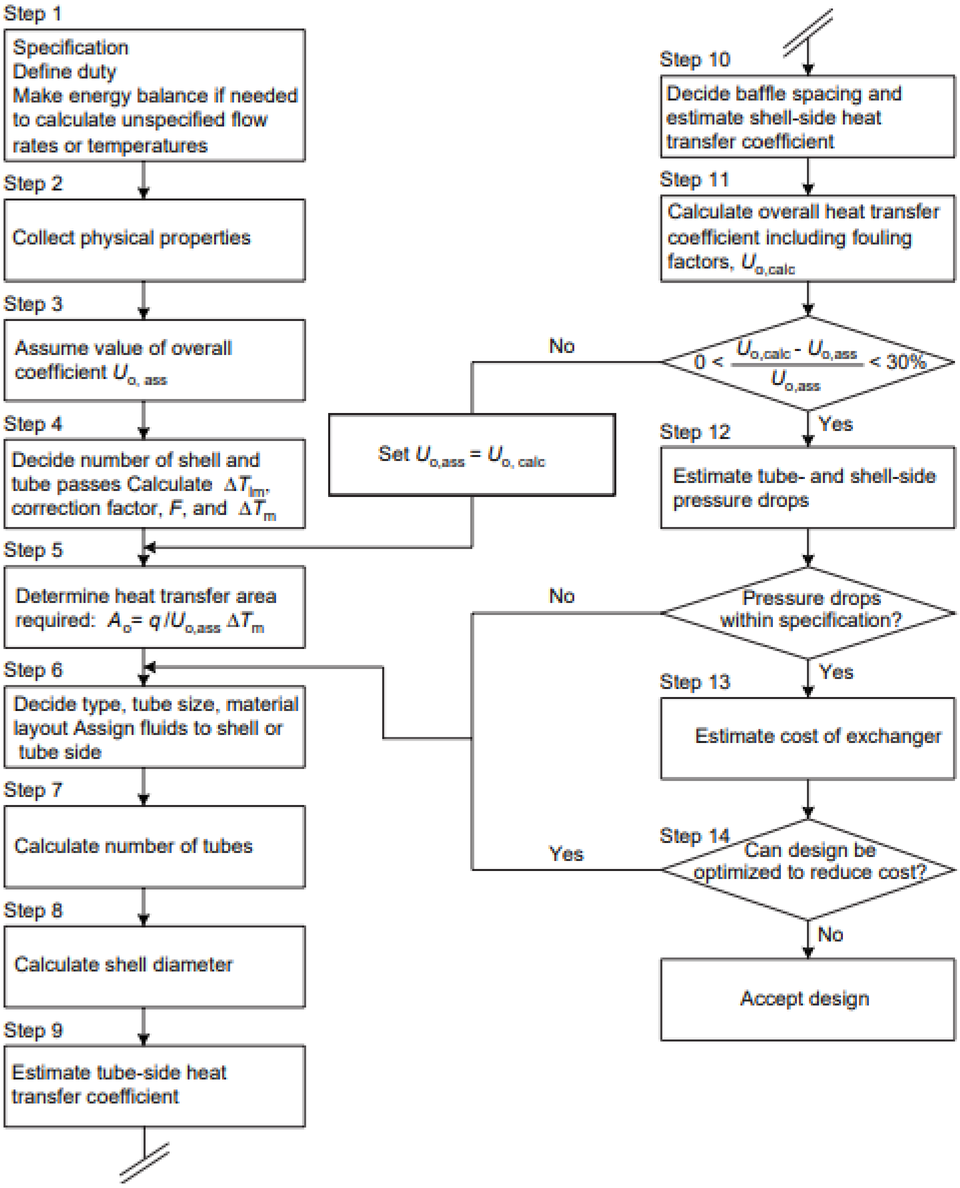
Assume efficiency, n_p is 75%,

Power $= \frac{\Delta P \times Q}{n_p} = \frac{10000 \times 13.8866}{0.75 \times 3600}$ = 51.43 W

Horsepower, hp $= \frac{P}{550} = \frac{51.43}{550}$ = 0.0935 hp

APPENDIX C – MECHANICAL DESIGN CALCULATION

Mechanical Design calculation of heat exchanger



Design procedure for shell-and-tube heat exchanger

Define all the related properties

Medium	hot fluid	cold fluid
	organic solvents	organic solvents
Inlet temperature (K)	363.15	303.15

Outlet temperature (K)	313.15	314.15
Mass flow rate (kg/s)	0.1667	0.3603
Heat duty, Q (kW)	13.7523	13.7523
Cp (kJ/kg K)	1.65	3.29
viscosity (kg/m s)	0.0006910	0.0007284
density (kg/m3)	1005.2715	1405.7810
k (W / m K)	0.1442	0.5849
NPr	7.9062	4.0968

Counter current flow

Tube side: Hot fluid

Shell side: cold fluid

Overall coefficient: 100 ≤U_o≤ 300

Let assume U_o = 100 W/m K

$\Delta T_1 = 363.15\ K - 314.75K = 48.4K$

$\Delta T_2 = 313.15\ K - 303.15K = 10K$

$\Delta T_{LM} = \frac{\Delta T_1 - \Delta T_2}{\ln \frac{\Delta T_1}{\Delta T_2}}$ = 24.35K

$$R = \frac{T_{hi} - T_{ho}}{T_{co} - T_{ci}} = \frac{363.15 - 313.15}{314.75 - 303.15} = 4.3103$$

$$S = \frac{T_{co} - T_{ci}}{T_{hi} - T_{ci}} = \frac{314.75 - 303.15}{363.15 - 303.15} = 0.1933$$

To define temperature correction factor, F_t refer to the Figure in Product and Process Design Principles: Synthesis, Analysis, and Evaluation textbook (Seider et al., 2017),

$\Delta T_m = F_t \Delta T_{LM} = 0.86 \times 24.35 = 20.94\ K$

Heat transfer area required, $A_o\ = \frac{Q}{U\Delta T_m} = \frac{13.7523}{100\times 20.94} = 6.5668\ m^2$

Tube side

Material: stainless steel

The diameter of tube refers to the ASTM A269/ ASME SA 269,

Outer diameter, D_o = 0.016m

Wall thickness = 0.0016 m

Inner diameter, D_i = 0.01280m

Tube length = 2.44 m

Number of passes = 4

Number of tubes, N_t

$$= \frac{Heat\ transfer\ area\ required, A_o}{Outside\ surface\ area\ of\ one\ tube\ , A_t} = \frac{A_o}{\pi DL} = \frac{6.5668}{\pi \times 0.01280 \times 2.44} = 53.54 \approx 56$$

Cross section area of one tube, $A_{ct} = \frac{\pi D^2}{4} = \frac{\pi \times 0.01280^2}{4} = 0.00012 m^2$

Number of tubes per pass = 56/4 =14

Tube velocity for one pass, $U_t = \frac{mass\ flow\ rate\ of\ hot\ fluid}{\rho A_{ct}} = \frac{0.1667}{1005.2715 \times 0.00012} = 0.1\ m/s$

Reynolds number, $N_{Re} = \frac{\rho U_t D}{\mu} = \frac{1005.2715 \times 0.1 \times 0.0128}{0.00069} = 1713.902$ (laminar flow)

Fouling factor of tube, $h_i = \frac{k j_h N_{Re} N_{Pr}^{0.33}}{D_i} = \frac{0.1442 \times 0.00286 \times 1713.902 \times 7.9062^{0.33}}{0.0128} = 109.27\ W/m^2K$

$$\Delta P_t = N_p \left(8 j_f \left(\frac{L}{D_i}\right) + 2.5\right)\left(\frac{\rho U_t^2}{2}\right)$$

$$= 4\left(8 \times 0.0079 \left(\frac{2.44}{0.0128}\right) + 2.5\right)\left(\frac{1005.27 \times 0.1^2}{2}\right) = 0.2478\ kPa$$

Shell side

Material: stainless steel

Pitch type: Square pitch

Shell type: one pass shell (TEMA-E)

Number of passes = 1

$p_t = 1.25D_o = 1.25 \times 0.016 = 0.02m$

Bundle diameter, $D_B = D_o(\frac{N_t}{K_1})^{\frac{1}{n_1}} = 0.016 \times (\frac{56}{0.158})^{\frac{1}{2.263}} = 0.2142$

Bundle diameter clearance, BDC = 0.5m

Shell diameter (inner), D_s = 0.2142 + 0.5 =0.2642 m

Wall thickness = 0.0032 m

Outer shell diameter, D_{so} = 0.2674 m

Baffle cut: 25%   Baffle spacing, $B_f = 0.2\mathrm{D}_s = 0.2(0.2642) = 0.0528$ m

Cross flow area, $A_s = \frac{p_t - D_o}{p_t}\mathrm{D}_s B_f = \frac{0.02-0.016}{0.02} \times 0.2642 \times 0.0528 = 0.00279\ m^2$

Linear velocity, $U_s = \frac{mass\ flow\ rate\ of\ cold\ fluid, m_s}{\rho A_s} = \frac{0.3603}{1405.78 \times 0.00279} = 0.1\ m/s$

Equivalent diameter, $D_e = \frac{1.27}{D_o}(p_t^2 - 0.785D_o^2) = \frac{1.27}{0.016}(0.02^2 - 0.7850.016^2) = 0.0158\ m$

Reynolds number, $N_{Re} = \frac{m_s D_e}{A_s \mu} = \frac{0.3603 \times 0.0158}{0.00279 \times 0.00073} = 2800.257$ (laminar flow)

Fouling factor of shell,

$$h_s = \frac{k j_n N_{Re} N_{Pr}^{0.33}}{D_e} = \frac{0.5849 \times 0.0122 \times 2800.257 \times 4.0968^{0.33}}{0.0158} = 2014.41\ W/m^2K$$

$$\Delta P_s = \left(8j_f\left(\frac{D_s}{D_e}\right)\left(\frac{L}{B_f}\right)\right)\left(\frac{\rho U_s^2}{2}\right)$$

$$= \left(8 \times 0.06 \times \left(\frac{0.2642}{0.0158}\right)\left(\frac{2.44}{0.0528}\right)\right)\left(\frac{1405.78 \times 0.1^2}{2}\right) = 2.1973\ kPa$$

Mechanical Design Calculation of Stirred Tank Bioreactor

Sizing: Rushton Turbine

Number of impellers, = H/D= $\frac{2.1717}{0.7239} = 4$

Impeller Diameter, D = D/3 = $\frac{0.7239}{3} = 0.2413$

Width blade, W= 0.2 x D = 0.2 x 0.2413 = 0.04826

Length of blade, L = 0.25 x D = 0.25 X 0.2413 = 0.060325

Thickness of blade = 0.02 x D = 0.02 x 0.2413 = 0.04826

Hub diameter = 0.2 x D = 0.2 x 0.2413 = 0.04826

Impeller off-bottom clearance = 0.3 x D = 0.3 X 0.2413 = 0.07239

Sizing: Baffle

Width of baffle = D/10 = $\frac{0.7239}{10} = 0.07239$

Height of baffle = Height of tank= 2.1717

Diameter of baffle = 0.5D= 0.5x 0.7239 = 0.36195

Space between baffle = 0.4 x 0.36195 = 0.14478

Length baffle between wall = 1/6 (Wb) = $\frac{1}{6} x\ 0.07239 = 0.012065$

Mechanical design calculations for pump

Mass flowrate = 21178.796 kg/hr

Average density = 980.502 kg/m^3

Differential pressure = 100000kg/ms^2

Head pump, H =$\frac{\Delta p}{\rho g}$

Where,

ΔP = differential pressure, $\frac{kg}{ms^2}$

ρ = average density of component, $\frac{kg}{m^3}$

G= acceleration velocity, $\frac{m}{s^2}$

H = $\frac{\Delta P}{\rho g}$

$$= \frac{100000\ \frac{kg}{ms^2}}{\left(\frac{980.502kg}{m^3}\right)\left(9.81\ \frac{m}{s^2}\right)}$$

= 10.396 m

Required safety factor (10%) = 1.0396m

Required differential head = 10.396 + 1.040

= 11.436 m

Volumetric flowrate,

$$Q = \frac{211786.796\ \frac{kg}{hr}}{980.502\ \frac{kg}{m^3}}$$

= 215.998 $\frac{m^3}{hr}$

= 6.0 $\times 10^{-2}$ $\frac{m^3}{s}$

= 951.019 gal/min

Pump shaft power,

$$\text{P} = \frac{\Delta P \cdot Q}{n\rho}$$

Efficiency, $\eta\rho = 0.75$

$$= \frac{\left(\frac{100000kg}{ms^2}\right)(6.0 \times 10^{-2} m^3/s)}{0.75}$$

= 8000 W

Pump Speed, N = 1780 rpm

Pump specific speed, N_s

$$N_s = \frac{NQ^{0.5}}{H^{0.75}}$$

$$N_s = \frac{1780 \times 951.019^{0.5}}{37.52^{0.75}}$$

= 3620 rpm

Referring to Sinnot, R. (2005). Chemical Engineering Design: Chemical EngineeringVolume

6. Elsevier.pg.200 - single stage of centrifugal pump is used

Horsepower, water, $hp = \frac{gHQ}{3960}$

$$= \frac{(9.81)(37.52)(951.0.19)}{3960}$$

= 88.39

Horsepower, Brake, $hp = \frac{water\ hp}{Pump\ effciency}$

$$= \frac{88.39}{0.75}$$

= 117.86

APPENDIX D – EQUIPMENT COSTING CALCULATION

Storage tank V-101

$$C_P = 60\, V^{0.72}$$

Specification

Spherical, 0–30 psig, Carbon steel

P= 1atm	14.696 psig
V= 64.16m3 = 16949.279 gal	16949.279
Cp	66548.78563
Cp in RM	312779.2925

Storage tank V-102

Specification

Spherical, 0–30 psig, Carbon steel

P= 1atm	14.696 psig
V= 29.64m3 = 7830.0596gal	7830.0596
Cp	38164.72164
Cp in RM	179374.1917

Solid storage tank SL-101

Specification

Spherical, 0–30 psig, Carbon steel

P= 1atm	14.696 psig

V= 21.45m3 = 5666.4905gal	5666.4905
Cp	30236.91292
Cp in RM	142113.4907

Fermenter FR-101

Specification	
Stainless steel, Fm	2
Base Cost, Cv	
Cv = exp {7.0132 + 0.18255 [ln (W)] + 0.02297 [ln (W)]2}	34176.88542
Weight of Shell and 2 Heads, W = π (Di + ts) (L + 0.8Di)	
$ts\rho$ in lb	7111.39818
Diameter = 2.51 m =8.235 ft	8.235
ts = tp + tc	0.0173103
tp, Thickness of wall at top in ft	0.0069103
tc, Corrosion allowance, 0.125 in, 0.0104 ft	0.0104
L, Length/ Height = 7.53 m = 24.705 ft	24.705
density of steel 7.85 lb/ ft3	481
Added Cost, CPL = 361.8 (Di)0.73960(L)0.70684	16602.34418
Cp	84956.11502
Cp in RM	399293.7406

Centrifugal pump P-101

Specification	
Cast iron, Fm	1
Size factor of pump, S=Q(H)^0.5	871.638811
Volumetric flowrate, Q in gal/min	432.1987
Pump head, ft	4.0673
CB = exp { 9.7171-0.6019 [ln (S)] + 0.0519[ln (S)]2}	3044.227156
Ft=1	1
Cp = FTFMCB	3044.227156
Cp in RM	14307.86763

Fermenter FR-102

Specification	
Stainless steel, Fm	2
Base Cost, Cv	
Cv = exp {7.0132 + 0.18255 [ln (W)] + 0.02297 [ln (W)]2}	34997.27465
Weight of Shell and 2 Heads, W = π (Di + ts) (L + 0.8Di)	
$ts\rho$ in lb	7402.66265
Diameter = 2.561m =8.402 ft	8.402
ts = tp + tc	0.0173103
tp, Thickness of wall at top in ft	0.0069103
tc, Corrosion allowance, 0.125 in, 0.0104 ft	0.0104
L, Length/ Height = 7.683 m = 25.207 ft	25.207

density of stainless steel lb/ ft^3	481
Added Cost, C_{PL} = 361.8 $(D_i)^{0.73960}(L)^{0.70684}$	17092.01276
Cp	87086.56205
Cp in RM	409306.8416

Decanter Centrifuge DC-101

Horizontal auto-batch, stainless steel	
Diameter = 0.353m =13.898 in	13.898
Cp	39913.10559
Cp in RM	187591.5963

Centrifugal pump P-102

Specification	
Cast iron, Fm	1
Size factor of pump, S=Q(H)^0.5	988.6205849
Volumetric flowrate, Q in gal/min	525.2753
Pump head, ft	3.5423
C_B = exp {9.7171-0.6019 [ln (S)] + 0.0519[ln (S)]^2}	3085.681862
Ft=1	1
C_p = FTFMCB	3085.681862
Cp in RM	14502.70475

Bipolar membrane electrolysis GBX-101

Specification	
Stainless steel, Fm	2

Base Cost, Cv	118700.4311
Cv = exp {7.139 + 0.18255 [ln (W)] + 0.02297 [ln (W)]2}	
Weight of Shell and 2 Heads, W = π (Di + ts) (L + 0.8Di) $ts\rho$ in lb	41934.94651
Diameter = 2.96m =9.711ft	9.711
ts = tp + tc	0.1609
tp, Thickness of wall at top in ft	0.0359
tc, Corrosion allowance, 0.125 in, 0.0104 ft	0.125
L, Length/ Height = 2.3647m = 7.758ft	7.758
density of steel 481 lb/ ft3	481
Added Cost, CPL = 361.8 (Di)0.73960(L)0.70684	8271.032249
Purchase cost of membrane (2 pieces) = \$120/m2 x 50.45 m2 x 2	56907.6
Cp	302579.4945
Cp in RM	1422123.624

Centrifugal pump P-103

Specification	
Cast iron, Fm	1
Size factor of pump, S=Q(H)^0.5	952.9403749
Volumetric flowrate, Q in gal/min	503.5251
Pump head, ft	3.5817
CB = exp { 9.7171-0.6019 [ln (S)] + 0.0519[ln (S)]2}	3073.001137
Ft=1	1

Cp = FTFMCB	3073.001137
Cp in RM	14443.10534

Heat exchanger HX-106

Shell-and-Tube Heat Exchangers: Stainless steel/stainless steel	
Total heat transfer area, A=6.5668m2 in ft2	70.6844
Fixed head, CB = exp{11.0545-0.9228[ln(A)]+ 0.09861 [ln(A)]^2}	7428.311415
Tube length, L=2.44m=8ft	8
Tube length correction, FL	0.86
Pressure = 2.013 bar = 15.6923 psig	15.6923
FP= 0.9803+0.018(P/100)+ 0.0017 [(P/100)]^2]	0.983166476
For stainless steel/stainless steel materials	
a	2.7
b	0.07
FM=a+(A/100)^b	3.676006366
Cp	23088.29538
Cp in RM	108514.9883

Heat exchanger HX-108

Shell-and-Tube Heat Exchangers: Stainless steel/stainless steel	
Total heat transfer area, A=2.1793m2 in ft2	23.4578

Fixed head, CB = exp{11.0545-0.9228[ln(A)]+ 0.09861 [ln(A)]^2}	9178.062225
Tube length, L=2.44m=8ft	8
Tube length correction, FL	0.96
Pressure = 2.013 bar = 14.6923 psig	15.6923
FP= 0.9803+0.018(P/100)+ 0.0017 [(P/100)]^2]	0.983166476
For stainless steel/stainless steel materials	
a	2.7
b	0.07
FM=a+(A/100)^b	3.603483259
Cp	31215.60821
Cp in RM	146713.3586

Heater HX-101

Double Pipe Heater: Stainless steel/stainless steel	
Total heat transfer area, A=0.6359m2 in ft2	6.8448
CB = exp{7.146+0.16[ln(A)]}	1726.339031
Tube length, L=2.44m=8ft	8
Pressure = 2.013 bar = 15.6923 psig	15.6923
FP= 0.851+0.1292(P/600)+ 0.00198 [(P/600)]^2]	0.85438043
For stainless steel/stainless steel materials	
a	2.7
b	0.07
FM=3 for both stainless steel material	3

Cp	4424.85085
Cp in RM	20796.79899

Thin film evaporator TFE-101

Falling film evaporator	
Heat transfer area, 2.844m2 = 30.613ft2	30.613
D, 2m=6.562ft	6.562
Height, H, 4m=13.1234ft	13.1234
Cp	89943.29788
Cp in RM	422733.5001

Stirred tank bioreactor R-101

Stainless steel, Fm	2
Base Cost, Cv	
Cv = exp {7.0132 + 0.18255 [ln (W)] + 0.02297 [ln (W)]2}	9104.93829
Weight of Shell and 2 Heads, W = π (Di + ts) (L + 0.8Di)	
$ts\rho$ in lb	594.5617511
Diameter = 0.7239 m =2.375 ft	2.375
ts = tp + tc	0.0173103
tp, Thickness of wall at top in ft	0.0069103
tc, Corrosion allowance, 0.125 in, 0.0104 ft	0.0104
L, Length/ Height = 2.1717m = 7.125 ft	7.125
density of stainless steel 481lb/ ft3	481
Added Cost, CPL = (Di)0.73960(L)0.70684	2748.475234

Cp	20958.35181
Cp in RM	98504.25353

Centrifugal pump P-104

Specification	
Cast iron, Fm	1
Size factor of pump, S=Q(H)^0.5	604.1448961
Volumetric flowrate, Q in gal/min	299.0340
Pump head, ft	4.0817
CB = exp {9.7171-0.6019 [ln (S)] + 0.0519[ln (S)]2}	2954.25809
Ft=1	1
Cp = FTFMCB	2954.25809
Cp in RM	13885.01302

Heat exchanger HX-107

Shell-and-Tube Heat Exchangers: Stainless steel/stainless steel	
Total heat transfer area, A=9.78m2 in ft2	105.271
Fixed head, CB = exp {11.0545-0.9228[ln(A)]+ 0.09861 [ln(A)]^2}	7300.086651
Tube length, L=2.44m=8ft	8
Tube length correction, FL	0.91
Pressure = 2.013 bar = 15.6923 psig	15.6923
FP= 0.9803+0.018(P/100) + 0.0017 [(P/100)]^2]	0.983166476

For stainless steel/stainless steel materials

a	2.7
b	0.07
FM=a+(A/100) ^b	3.703602218
Cp	24189.16097
Cp in RM	113689.0566

Cooler HX-103

Double Pipe cooler: Stainless steel/stainless steel

Total heat transfer area, A=0.6009m2 in ft2	6.468
CB = exp{7.146+0.16[ln(A)]}	1710.769778
Tube length, L=2.44m=8ft	8
Pressure = 2.013 bar = 15.6923 psig	15.6923
FP= 0.851+0.1292(P/600) + 0.00198 [(P/600)]^2]	0.85438043
For stainless steel/stainless steel materials	
a	2.7
b	0.07
FM=3 for both stainless steel material	3
Cp	4384.944653
Cp in RM	20609.23987

Stirred tank bioreactor R-102

Stainless steel, Fm	2
Base Cost, Cv	9386.957068

Cv = exp {7.0132 + 0.18255 [ln (W)] + 0.02297 [ln (W)]2}

Weight of Shell and 2 Heads, W = π (Di + ts) (L + 0.8Di)

$ts\rho$ in lb	633.7859476
Diameter = 0.75m =2.4606 ft	2.4606
ts = tp + tc	0.0173103
tp, Thickness of wall at top in ft	0.0069103
tc, Corrosion allowance, 0.125 in, 0.0104 ft	0.0104
L, Length/ Height = 2.23m = 7.3163ft	7.3163
density of stainless steel 481lb/ ft3	481
Added Cost, CPL = (Di)0.73960(L)0.70684	2874.738254
Cp	21648.65239
Cp in RM	101748.6662

Centrifugal pump P-105

Specification	
Cast iron, Fm	1
Size factor of pump, S=Q(H)^0.5	528.886764
Volumetric flowrate, Q in gal/min	282.9283
Pump head, ft	3.4944
CB = exp {9.7171-0.6019 [ln (S)] + 0.0519[ln (S)]2}	2932.364658
Ft=1	1
Cp = FTFMCB	2932.364658
Cp in RM	13782.11389

Bipolar membrane electrolysis GBX-102

Specification	
Stainless steel, Fm	2
Base Cost, Cv	102067.9245
Cv = exp {7.139 + 0.18255 [ln (W)] + 0.02297 [ln (W)]2}	
Weight of Shell and 2 Heads, W = π $(Di + ts)$ $(L + 0.8Di)$ $ts\rho$ in lb	33433.45169
Diameter = 3.96m =9.711ft	9.711
$ts = tp + tc$	0.1609
tp, Thickness of wall at top in ft	0.0359
tc, Corrosion allowance, 0.125 in, 0.0104 ft	0.125
L, Length/ Height = 1.2852m = 4.2165 ft	4.2165
density 481 lb/ $ft3$	481
Added Cost, CPL = 361.8 (Di)0.73960(L)0.70684	5375.144312
Purchase cost of membrane (2 pieces) = \$120/m2 x 27.17 m2 x 2	30647.76
Cp	240158.7533
Cp in RM	1128746.14

Centrifugal pump P-106

Specification	
Cast iron, Fm	1
Size factor of pump, S=Q(H)^0.5	374.8436916
Volumetric flowrate, Q in gal/min	218.8740

Pump head, ft	2.933
CB = exp {9.7171-0.6019 [ln (S)] + 0.0519[ln (S)]2}	2901.09737
Ft=1	1
Cp = FTFMCB	2901.09737
Cp in RM	13635.15764

Heater HX-104

Double Pipe Heater: Stainless steel/stainless steel

Total heat transfer area, A=0.3516m2 in ft2	3.7845
CB = exp{7.146+0.16[ln(A)]}	1570.181041
Tube length, L=2.44m=8ft	8
Pressure = 2.013 bar = 15.6923 psig	15.6293
FP= 0.851+0.1292(P/600) + 0.00198 [(P/600)]^2]	0.854366853
For stainless steel/stainless steel materials	
a	2.7
b	0.07
FM=3 for both stainless steel material	3
Cp	4024.531903
Cp in RM	18915.29994

Thin film evaporator TFE-102

Falling film evaporator

Heat transfer area, 0.404m2 = 4.3486ft2	4.3486
D, 3.49m=11.45ft	11.45

Height, H, 6.98m=22.9ft	22.9
Cp	30747.70962
Cp in RM	144514.2352

Centrifugal pump P-107

Specification	
Cast iron, Fm	1
Size factor of pump, S=Q(H)^0.5	252.2404098
Volumetric flowrate, Q in gal/min	153.2902
Pump head, ft	2.7077
CB = exp {9.7171-0.6019 [ln (S)] + 0.0519[ln (S)]2}	2909.484065
Ft=1	1
Cp = FTFMCB	2909.484065
Cp in RM	13674.57511

Cooler HX-105

Double Pipe Heater: Stainless steel/stainless steel	
Total heat transfer area, A=2.0717m2 in ft2	22.2996
CB = exp{7.146+0.16[ln(A)]}	2085.431357
Tube length, L=2.44m=8ft	8
Pressure = 2.013 bar = 15.6923 psig	15.6293
FP= 0.851+0.1292(P/600) + 0.00198 [(P/600)]^2]	0.854366853
For stainless steel/stainless steel materials	
a	2.7

b	0.07
FM=3 for both stainless steel material	3
Cp	5345.170275
Cp in RM	25122.30029

Crystallizer CR-101

Continuous cooling with jacketed scraped wall, stainless steel;	
Cp=14500(L)^0.67	
L=7.245m =23.77ft	23.77
Cp	121145.5746
Cp in RM	569384.2004

Centrifugal pump P-108

Specification	
Cast iron, Fm	1
Size factor of pump, S=Q(H)^0.5	234.754095
Volumetric flowrate, Q in gal/min	146.1232
Pump head, ft	2.581
CB = exp {9.7171-0.6019 [ln (S)] + 0.0519[ln (S)]2}	2916.091652
Ft=1	1
Cp = FTFMCB	2916.091652
Cp in RM	13705.63076

Nutsche Filter NFD-101

Cp = 25A	4036.475
D in ft	14.338
H in ft	5.479
Actual membrane area, 15m2, ft	161.459
Purchase cost in RM	18971.4325
For safety and avoid clogging, 20% of additional area is added	3794.2865
Cp in RM	22765.719

Centrifugal pump P-109

Specification	
Cast iron, Fm	1
Size factor of pump, S=Q(H)^0.5	105.3363845
Volumetric flowrate, Q in gal/min	61.1409
Pump head, ft	2.9682
CB = exp {9.7171-0.6019 [ln (S)] + 0.0519[ln (S)]2}	3101.440175
Ft=1	1
Cp = FTFMCB	3101.440175
Cp in RM	14576.76882