PRODUCTION OF 438 × 10^3 TPA OF HYDROGEN FROM RICE STRAW FOR (FUEL CELLS)

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ABSTRACT

The conversion of Biomass into Biofuel is a viable and long-term solution to the rising demand for clean energy sources. In current project, we have produced Hydrogen gas from the steam gasification of Rice Straw (which is a waste of rice crop and frequently available in all over the Pakistan) for Hydrogen Fuel Cells. This project focuses on the production of hydrogen from biomass, specifically through the gasification of rice straw. By utilizing this sustainable feedstock, we aim to address the increasing demand for hydrogen while reducing reliance on fossil fuels. The project incorporates advanced equipment design and process simulation to ensure the feasibility and efficiency of large-scale production.This procedure entails the thermochemical, biochemical, and electrochemical conversion of biomass into hydrogen gas. The most extensively researched procedures for generating hydrogen from biomass are thermochemical ones like gasification and pyrolysis. In this project hydrogen, production for fuel cells is a environmental friendly and can be used in electric vehicles, laptops, cell phones, marines, spacecraft and aerospace applications. Furthermore, a comprehensive economic analysis, considering capital and operational costs was also made to evaluate the financial viability of the project. The analysis indicates a rate of return of 3.7 years, demonstrating the project's potential for favourable economic outcomes. By achieving six SDGs (1,7,8,9,12 and 13) which shows that this project is environmentally and economically feasible and sustainable.

Keywords: Gasification, biomass, hydrogen, fuel cells, clean energy etc.

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CHAPTER # 01

INTRODUCTION

1 Introduction

As the energy, crises of Pakistan are increasing and economy of Pakistan in decreasing daily. According to the survey and analysis, fossils fuels are depleting and oil gas reserved are finishing into the second half of the current century. As the demand of the energy expanding every day as Pakistan's population does as well. For this reason in order to improve the situation, alternative sources of energy are being analyzed. So biofuels are efficient way to convert the waste (biomass) into the energy [1].

In this case the biomass gasification of hydrogen production (for fuel cells) will help to overcome the energy crises. Combination of the fuel cells and hydrogen is a route forward to solve the long-term of climate change and it will work as energy security for Pakistan. Production of hydrogen gas will give us green fuel which can be used for transportation vehicles, electricity generation, fertilizer industry, hydrogen fuel cells and other chemical industries. This is a renewable source of energy, economical and environmental friendly way to produce biofuels [1].

Renewable sources of energy has several advantages.

- Reduce pollution
- Reduction in global warming.
- Most economical route
- Energy saving

1.1 Hydrogen

In the future, the importance of hydrogen as a secondary renewable energy source cannot be overstated. Today, fossil fuels are the main source of hydrogen production. Future decarbonized applications that depend on renewable and carbon-dioxide-neutral hydrogen production may benefit from biomass gasification. Hydrogen is extremely flammable, tasteless, colourless, odourless, and non-toxic [2].

The production of gasoline and lubricants in the automotive industry uses hydrogen as a standard feedstock. In the fertilizer business, hydrogen is largely employed in the manufacture of ammonia. . When unsaturated oils from soybeans, fish, nuts, and coconut are hydrogenated, it is used in the food industry. In the cosmetics industry, hydrogen is used to hydrogenate non-edible oils and greases for the production of soap. In the glass industry, oxygen hydrogen is used to make both float glass and cut glass. In the electronics industry, hydrogen is essential for the manufacturing and treating of silicon. It serves as a refiner successfully in the metallurgical industry. As a fundamental component in the creation of fuel cells, hydrogen will always be required [2].

Despite finding uses in a variety of industries, hydrogen is thought to have the biggest impact on the energy industry. If hydrogen were to be used in the transportation industry, it is estimated that 40 million tonnes of hydrogen would be needed in one year. It will eventually replace other fuels as the preferred fuel due to its high energy density, quick burning rate, high octane rating, and lack of any hazardous potential. The tincture of human life, hydrogen, therefore, provides a potential non-polluting, endless, potent, and financially alluring energy source. Hydrogen is sponsored as the fuel of the upcoming days, as shown by a number of funded activities from various national governmental organizations around the world [2].

1.2 Hydrogen Occurrence

Hydrogen is the most abundant element in the universe, accounting for about 75% of its elemental mass. However, on Earth, it is not found in its elemental form in significant quantities because it is so reactive and tends to bond with other elements [2].

On Earth, hydrogen occurs primarily in combination with other elements, such as in water (H2O), organic compounds, and minerals. Water is the most common hydrogen-containing compound on Earth, making up about 70% of the Earth's surface and a significant portion of its atmosphere. Hydrogen is also found in many hydrocarbons, including natural gas, crude oil, and coal [2].

In addition to its occurrence in natural sources, hydrogen can also be produced industrially through a variety of methods, including electrolysis of water, steam methane reforming, and coal gasification [2].

1.3 Production of Hydrogen

The first artificial production of hydrogen gas occurred in the early 16th century as a result of the reaction between acids and metals. Henry Cavendish was the first to distinguish hydrogen gas as a distinct substance between 1766 and 1781. . Additionally, he noticed that burning hydrogen gas produces water, giving the gas its name (hydrogen is Greek for "water-former").

The main sources of industrial output are coal gasification, oil reforming, and natural gas reforming with steam. Additionally, a small quantity is produced using methods that require more energy, such as water electrolysis. Most hydrogen is used in the region where it is produced. The production of ammonia, mostly for the fertilizer sector, and the processing of fossil fuels (such as hydrocracking), are the two main uses. As the only immediate emission, water can be burned to generate heat or mixed with oxygen in fuel cells to generate electricity. In metallurgy, hydrogen atoms (but not gaseous molecules) can weaken different metals, which is a concern [3].

1.4 Properties of Hydrogen

The table below lists the physical and thermal characteristics of hydrogen:

Values at 25^{o}C (77^{o}F, 298 K) and atmospheric pressure.

Table 1.1 Properties of Hydrogen

Molecular Weight	2.1016
Specific Gravity air =1	0.070
Specific volume(ft3/lb, m3/kg)	194,12.1
Density of liquid at atmospheric pressure (lb/ft3, kg/m3)	4.43, 71.0
Absolute velocity(lbm/fts, centipoises)	6.05*10^-6, 0.009
Sound velocity in gas (m/s)	1315
Specific heat cp (Btu/lb°F)	3.42, 14310
Specific heat ratio (-cp/cv)	1.405
Gas constant –R- (ftlb/lb°, J/kg°C)	767,4126
Thermal conductivity (Btu/hr ft °F, W/m°C)	0.105, 0.182
Boiling point – saturation pressure 14.7 psia and 760 mmHg (°F. °K)	-423,20.4
Latent heat of evaporation at boiling point(Btu/lb, J/kg)	192,447000
Freezing or melting point at 1 at,(°F, °C)	-434.6, -259.1
Latent heat of fusion (Btu/lb, J/kg)	25.0, 58000
Critical temperature (°F, °C)	-399.8, -240.0
Critical pressure(psia, MN/m2)	189,1.30
Critical Volume	0.53, 0.033
Flammable	yes
Heat of combustion (Btu/ft3, Btu/lb, kJ/Kg)	320,62050, 144000

1.5 Handling Storage and Safety of Hydrogen

In the processing of chemicals, numerous chemical process sectors, including petroleum refining , hydrogen is widely employed for hydrogenation and other operations.. It has great potential as a fuel. When constructing the machinery and systems that handle or contain hydrogen, though, great care should be given because it is a highly explosive gas that is also disposed to to leaks and penetration and is problematic to sense. This understanding and attention to detail are even more important because hydrogen-based reactions usually entail exothermic processes that take place at high pressures and temperatures [4].

Numerous pieces reactors, catalyst feed vessels, spent catalyst filters, pumps, valves, pressure relief devices, pressure regulators, and check valves are examples of process equipment, instrumentation, and pipework, are used in hydrogenation and other hydrogen-handling processes. In a building, there are many similar systems, particularly those for hydrogenating organic compounds. Such facilities must be built with consideration for four degrees of safety [4].

- High levels of automation, including interlocks, alarms, and remote operations to monitor environmental and process conditions.
- Devices for piping and process equipment that offer certified relief. It is necessary to guide the vent discharges from the relief devices to safe locations.
- Reliable, adequate space ventilation for systems inside buildings to avoid hydrogen gas pockets building up.
- Damage-limiting building design to safeguard people and property.

1.6 Shipping of Hydrogen

When large volume transit is required but pipelines are not available, hydrogen is typically supplied and conveyed as a liquid. Hydrogen cannot liquefy unless it is cooled to cryogenic temperatures and then put through a liquefaction procedure. Liquid tanker trucks are those that carry hydrogen in a liquid state [4]

1.7 Reaction of Product

Except noble gases hydrogen made compound with nonmetals. Here we will discuss few compounds of hydrogen with nonmetals.

Hydrogen compound with nitrogen

$$Mg_3N_2(s) + 6H_2O(l) \longrightarrow 3Mg(OH)_2(s) + 2NH_3(g) \qquad (1.1)$$

The production of ammonia commercially is the combination of elements known as Haber Process.

$$N_2(g) + 3H_2(g) \longrightarrow 2NH_3(g) \quad \Delta H^o = -92KJ \qquad (1.2)$$

Hydrogen Compounds with phosphorus

$$AIP\ (s) + 3H_3O+\ (aq) \longrightarrow PH_3(g) + Al^{3+}\ (aq) + 3H_2O\ (l) \quad (1.3)$$

$$P_4(s) + 4OH^-\ (aq) + 2H_20(l) \longrightarrow 2HPO_3^{2-}\ (aq) + 2PH_3\ (g) \quad (1.4)$$

Hydrogen Compounds with Sulfur

$$FeS(s) + 2H_3O^+\ (aq) \longrightarrow Fe^{2+}(aq) + H_2S(g) + 2H_2O(l) \quad (1.5)$$

$$2H_2S(g) + O_2(g) \longrightarrow 2S(s) + 2H_2O(l) \quad (1.6)$$

$$HS^-\ (aq) + H_2O(l) \longrightarrow H_2S(g) + OH^-(aq) \quad (1.7)$$

$$S^{2-}\ (aq) + H_2O(l) \longrightarrow HS^-(aq) + OH^-(aq) \quad (1.8)$$

Hydrogen Compounds with Halogens

$$CaF_2(s) + H_2SO_4(aq) \longrightarrow CaSO_4(s) + 2HF(g) \quad (1.9)$$

$$H_3PO_4(l) + Br^-\ (aq) \longrightarrow HBr(aq) + H_2PO_4^-(aq) \quad (1.10)$$

$$Br_2(aq) + 2HI(aq) \longrightarrow 2HBr(aq) + I_2(aq)\ E^o = 0.55V \quad (1.11)$$

$$SiO_2(s) + 4HF\ (aq) \longrightarrow SiF_4(g) + 2H_2O(l) \quad (1.12)$$

$$CaSiO_3(s) + 6HF(aq) \longrightarrow CaF_2(s) + SiF_4(g) + 3H_2(l) \quad (1.13)$$

1.8 Applications of Hydrogen

1.8.1 Numerous industrial processes use hydrogen.

In the United States, industry uses nearly all of the hydrogen that is consumed to refine petroleum, treat metals, produce fertilizer, and process food. U.S. petroleum refineries use hydrogen to lower the sulfur content of fuels [5].

1.8.2 For space exploration, hydrogen is used.

The National Aeronautics and Space Administration (NASA) was one of the first organizations to utilize hydrogen fuel cells to power the electrical systems on spacecraft, and it started utilizing liquid hydrogen as rocket fuel in the 1950s [5].

1.8.3 In hydrogen fuel cells, energy is generated.

By combining hydrogen and oxygen atoms, hydrogen fuel cells generate energy. In a battery-like electrochemical cell, hydrogen and oxygen combine to form electricity, water, and very minute quantities of heat [5].

For a wide range of applications, there are many different kinds of fuel cells available. Small fuel cells can power laptop computers, even mobile phones, and military applications. Large fuel cells can provide electricity to electric power grids, backup or emergency power in buildings, as well as provide electricity in regions that are not connected to electric power grids. There were around 166 functioning fuel cell electric power generators at 113 locations in the United States as of the end of October 2021, with a combined capacity of about 260 megawatts (MW) of electricity generation. The Bridgeport (Connecticut) Fuel Cell, LLC, which has a generation capacity of around 16 MW, is the biggest single fuel cell. Each of the following two operational fuel cells has a 6 MW generating capacity. One of them is located in the Red Lion Energy Center in Delaware, along with five more smaller fuel cells, which together have a 25 MW total facility electric generation capacity.The hydrogen source for the majority of all operational fuel cells is pipeline natural gas, but three also use landfill gas and three also use biogas produced during wastewater treatment [5].

The San Diego Gas and Electric power-to-gas-to-power project will produce electrolyze hydrogen using the electrical grid and then use the hydrogen in a fuel cell to produce electricity [5].

1.8.4 Burning hydrogen for Energy reduction

The use of hydrogen as a fuel for power plants is gaining popularity. Several power plants in the US have announced plans to use combustion gas turbines powered by a fuel mixture of natural gas and hydrogen. One example is the 485 MW Long Ridge Energy Generation Project facility in Ohio, which has a gas-fired combustion turbine and will initially run on a fuel blend of 95% natural gas and 5% hydrogen before switching to 100% green hydrogen derived from renewable sources. Another illustration is the conversion of an existing coal-fired power plant in Utah by Intermountain Power Agency into a combined-cycle gas-fired plant that would initially use up to 30% hydrogen and ultimately use 100% green hydrogen [5].

1.8.5 Vehicular use of hydrogen.

Hydrogen can be used as a fuel in vehicles by converting it into electricity through a fuel cell, which then powers an electric motor. This process produces only water vapor as a byproduct, making it a very clean and efficient form of transportation [5].

There are currently a number of hydrogen fuel cell vehicles (FCVs) available on the market, including the Toyota Mirai, Honda Clarity, and Hyundai Nexo. These vehicles typically have a range of around 300-400 miles on a single tank of hydrogen, and can be refueled in just a few minutes, similar to the time it takes to fill up a gasoline-powered vehicle [5].

One of the challenges facing the widespread adoption of hydrogen fuel cell vehicles is the availability of hydrogen refueling infrastructure. While there are currently [5].

1.9 Biomass (Rice Straw)

As the bioenergy is the planet's most plentiful a source of power and biomass energy has a great potential to solve the energy crises of developing countries and of Pakistan also. Bioenergy projects are the efficient way to convert the waste (biomass) which are producing greenhouse gases when burned and cause global warming into the useful energy. Biomass is a renewable energy source to take the place of biofuels. Additionally, biofuels can be utilised for lighting, cooking, and heating. As using hydrogen fuel cells to create power is a possibility. in vehicles and rockets and hydrogen can be used in vehicles and for power generation. The biofuels are now common due to the availability of the raw material (biomass). By using the biomass for the power generation will decrease the global warming as well as environmental pollution it yields many benefits for future. As the fuel cells requires hydrogen as a fuel so we are hydrogen from rice straw for fuel cells. As the production of rice is greater among all the crops in all over the Pakistan. The amount of rice straw in rice crop is varies from 1.0 to 4.3 and 0.74–0.79 [6].

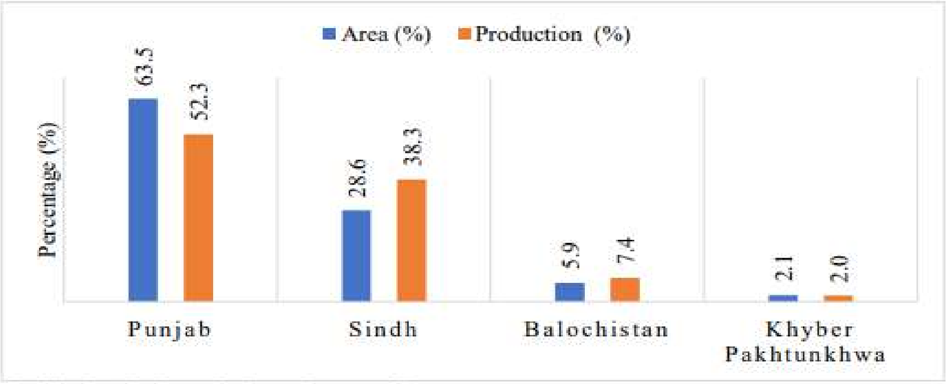


Figure 1.1 Provincial share in rice straw production

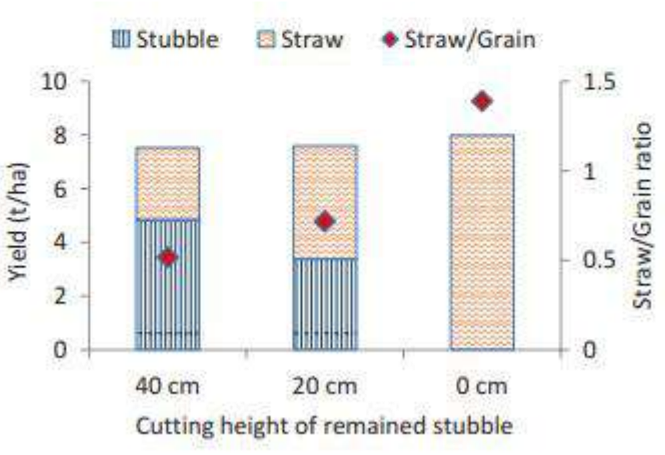


Figure 1.2 Biomass ratios of rice straw production

We will hydrogen from steam gasification of rice straw. It yields the 79 % hydrogen which is a green fuel for fuel cells. Typically, cellulose, lignin, hemicellulose, and ash make up rice straw. The composition of the rice straw is as follows**:**

Table 1.2 Composition of Rice Straw

Main constitutes of wheat and rice straw versus spruce wood				
Material	Hemi Cellulose %	Cellulose %	Lignin %	Ash %
Wheat Straw	26.4	40.8	22.9	9.9
Rice Straw	25.9	40.8	17.9	15.4
Spruce wood	30.17	44.31	25.20	0.32

We have used the rice straw as the biomass feed stock for the hydrogen production. So to find the components in the rice straw composition the most thorough and immediate evaluation of rice straw is as follows:

Table 1.3 Proximate Analysis of Rice Straw

Proximate Analysis			
Moisture(%)	Ash(%)	Volatiles(%)	Fixed Carbon(%)
9.35[a]	18.28[a]	57.67[a]	14.70[a]
7.43[b]	19.07[b]	67.95[b]	12.98[b]

Table 1.4 Ultimate Analysis of Rice Straw

Ultimate Analysis					
C(%)	H(%)	N(%)	S(%)	O(%)	HHV(cal/g)
35.64[a]	4.90[a]	0.84[a]	0.14[a]	40.20[a]	3432[a]
37.87[b]	4.61[b]	0.63[b]	0.14[b]	34.87[b]	3515[b]

1.10 Production and Consumption of Hydrogen

Making the Hydrogen Economy Possible, a report released in April 2021 by the Energy Transitions Commission, a think tank based in London, UK, describes how clean hydrogen might help create a highly electrified, net-zero economy. By 2030, clean hydrogen production will increase to 50 million tonnes, and by 2050, annual clean hydrogen consumption will range between 500 and 800 million tonnes. Green hydrogen probably makes up 85% of this. The total final energy demand would then consist of roughly 17% hydrogen and fuels made from it (in addition to 68% electricity) [3].

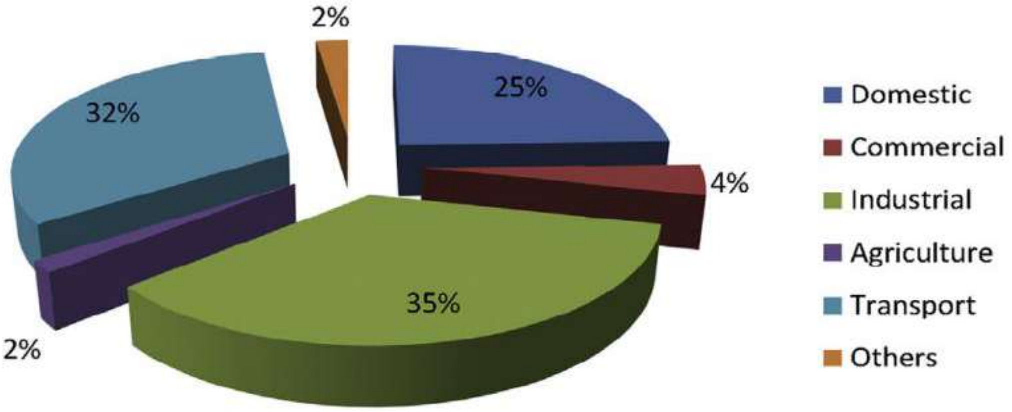


Figure 1.3 Consumption of hydrogen in industrial sector

The main increase in demand would come from industries like steel production and shipping that are difficult or expensive to directly electrify [3].

In addition to 90,000 TWh/yr for direct electrification, up to 30,000 TWh/yr of electrolysis is required to produce all of this hydrogen using zero carbon. The report claimed that $2/kg green hydrogen would be possible in "average" locations with 50 GW of global electrolysis capacity [7].

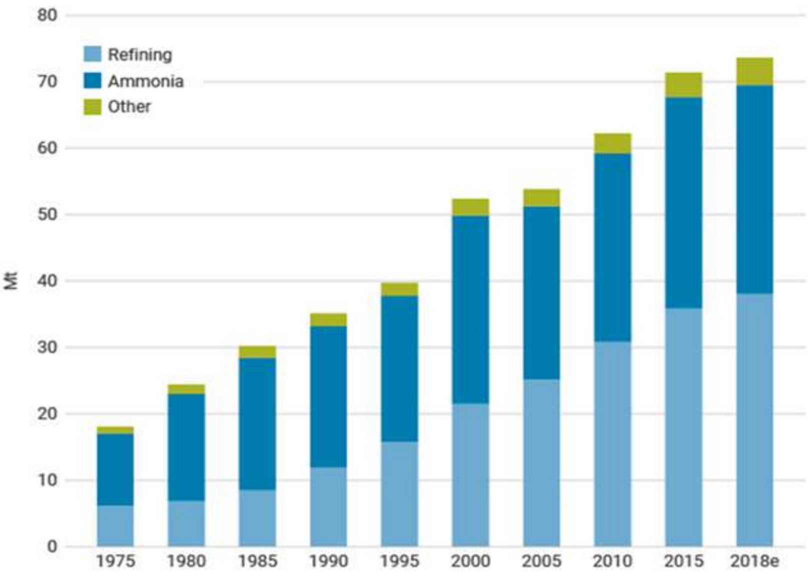


Figure 1.4 Global Annual demand of hydrogen in different sectors

In Sustainable Development Scenario, According to the International Energy Agency (IEA), global hydrogen production will double by 2070. will have increased significantly to approximately 445 Mt and 75 Mt for process utilization, respectively. 40% of the 520 Mt of hydrogen would be produced with carbon capture and storage from fossil fuels, and 58% from electrolysis. (CCS). Transport accounts for 60% of the energy needed, and 60% of the processes seem to be chemical and 40% are used to make steel [7].

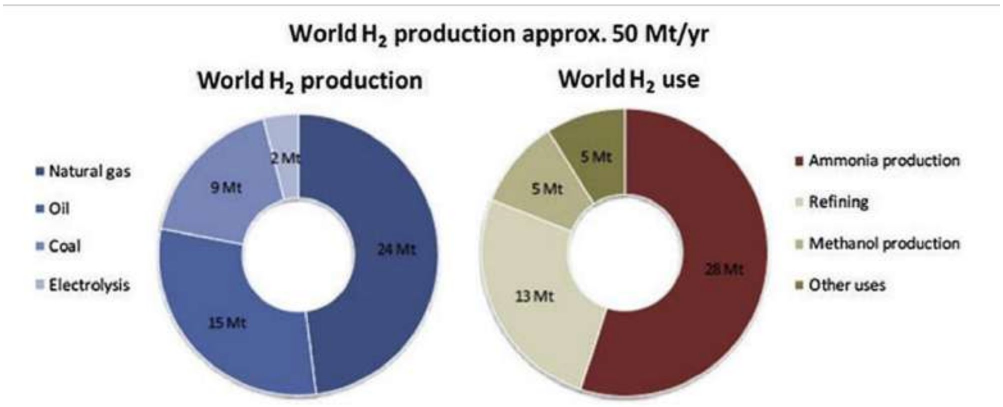


Figure 1.5 World Hydrogen production and consumption

According to information released, Sindh will be home to Pakistan's first green hydrogen plant, with a daily production capacity of roughly 150,000 kg. According to them, the sponsors hoped to find customers in China and the surrounding area for the green hydrogen produced at this plant in Sindh. The first-of-its-kind unit will produce 150,000 kg of fuel per day [7].

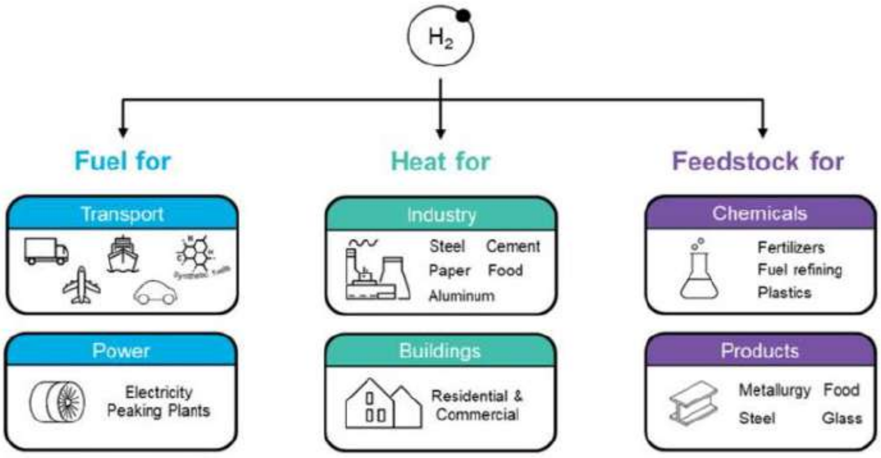


Figure 1.6 Demand of Hydrogen

1.11 Market Assessment of Hydrogen

Global demand for hydrogen generation in 2020 was expected to reach USD 160.5 billion. From 2022 to 2027, the market for hydrogen production is anticipated to expand at a CAGR of 10.5%. and reach USD 263.5 billion. The increase in demand for hydrogen for FECVs and rockets in the aerospace industry is the factor driving market expansion. The application of hydrogen fuel cells to light-weight vehicles like forklifts and material-handling machinery, as well as bicycles, cars, buses, trains, boats, ships, and auxiliary power units (APUs) of aircraft, is promoting market expansion in the transportation sector. (The study "Hydrogen Generation Market, 2021-2028" by Fortune Business Insights contains this data.) [8].

The majority of hydrogen is used in fertilizer production and petroleum refineries. Fossil fuel reforming produces 99% of all hydrogen because it is the most dependable and cost-effective method. It is risky for the environment because of the CO2 emissions, though. Green hydrogen is produced during electrolysis. Electrolysis, which produces no carbon dioxide while separating the process used to create green hydrogen splits water into hydrogen and oxygen. One of the objectives many governments have set for 2050 is the global DE-carbonization. Production of a substance like hydrogen, which generates green hydrogen and currently contributes to more than 2% of global CO2 emissions, is one of the most crucial steps in achieving this goal. The European Union (EU), for example, unveiled a novel hydrogen policy in 2020 that combines measures to support the swift expansion of green hydrogen generation capacities [8].

By 2023, Florida Power & Light hopes to begin using a green hydrogen station with a capacity of 20 MW. At FP&L's 1.75 gigawatt Okeechobee gas-fired plant, this hydrogen will be used in a 20% blend [8].

The demand for hydrogen is anticipated to increase between 500 and 680 million tonnes (MT) by 2050 from the 87 million metric tonnes estimated (MT) in 2020. In 2020, the value of the market for hydrogen production was $130.billion, and through 2030, It is projected to increase by up to 9.2% per year . The problem is that only a relatively small part of the current hydrogen production is "green," with fossil fuels being responsible for more than 95% of it. The production of hydrogen currently uses 2% of coal and 6% of natural gas worldwide [8].

1.12 Hydrogen Fuel Cells

Utilizing hydrogen's chemical energy , a hydrogen fuel cell produces electricity. It is a clean kind of energy because the only byproducts are water, heat, and electricity. Fuel cells are helpful for transportation as well as the use of backup energy since they are capable of managing systems as big as power plants or as small as laptops [9].

Hydrogen is a clean fuel since hydrogen fuel cells only release water when they burn it. Hydrogen can be produced domestically using solar, wind, biomass, nuclear, natural gas, and renewable energy sources. These are only a few of the resources that can be employed. As a result, it is a great fuel option for both producing energy and using in transportation. In addition to a plethora of other applications, it can be used for portable power, cars, and even residences [9].

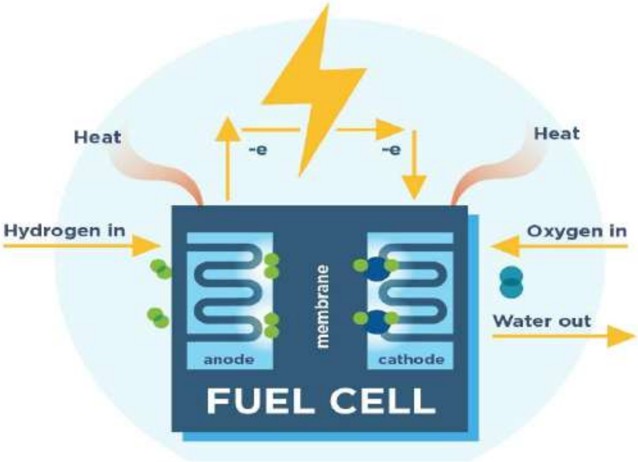


Figure 1.7 Hydrogen fuel cell

Fuel cells are more effective than traditional combustion-based technologies and emit fewer pollutants. Only water is released into the environment by hydrogen fuel cells; no carbon dioxide or other contaminants are. Since fuel cells have fewer moving components than combustion technologies, they operate more quietly [9].

1.13 Applications of Hydrogen Fuel Cells

Hydrogen fuel cells have several applications. Some of fuel cells made of hydrogen: uses are as follows:

- Hydrogen fuel cells can be for the electric vehicles, as they use clean fuel and are environmental friendly than the internal combustion engine vehicles [10].
- The major sources can also be hydrogen fuel cells. or the backup sources of the electricity in the remote areas [10].
- Space missions can employ hydrogen fuel cells to generate electricity [10].
- NASA is using the liquid hydrogen in 1950s for power generation in rockets and NASA was a pioneer in the usage of fuel cells for spacecraft power generation. Hydrogen fuel cells can also be cast-off in many electronic devices like laptops [10].

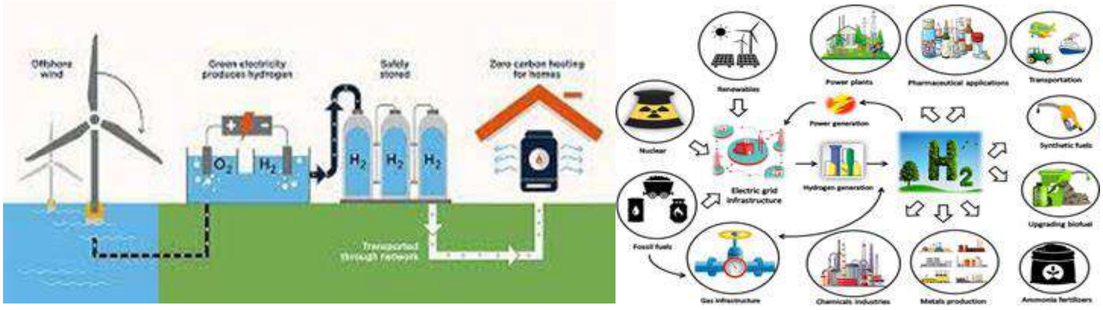


Figure 1.8 Applications of hydrogen fuel cells

CHAPTER # 02

MANUFACTURING PROCESSES

2 Available Manufacturing Processes

The available manufacturing processes for the production of hydrogen are comes in four major categories.

1. Natural gas reforming
2. Coal gasification
3. Electrolysis
4. Biomass Gasification

2.1 Natural Gas Reforming

Methane gas is utilised in the manufacturing process known as natural gas reforming, which produces hydrogen. In the presence of a catalyst, methane and steam are cooked to manufacture a fuel-producing mixture of CO and hydrogen. The method most frequently used in the energy sector to create hydrogen is steam reforming of natural gas [11].

- Under 3 to 25 bar of pressure, natural gas (methane) interacts with steam using carbon monoxide and a little quantity of carbon dioxide as a catalyst for the creation of hydrogen.
- From the gas stream, carbon dioxide and other pollutants are removed in the process' last stage using a separation device called a pressure swing adsorption, which results in the making of pure hydrogen [11].
- Through the steam reforming process, hydrogen may also be made from other fuels like ethanol, propane, and gasoline [11].
- This process of natural gas steam reforming cost effective and produce high purity hydrogen which can be further used for power generation and also for fuel cells [11].
- Since the reaction is endothermic, heat must be added for it to continue [11].

Reactions

Steam-Methane Reforming Reaction

$$CH_4 + H_2O\ (+\text{heat}) \rightarrow CO + 3H_2 \qquad (2.1)$$

Water-Gas Shift Reaction

$$CO + H_2O \rightarrow CO_2 + H_2 \qquad (2.2)$$

Process Flow Diagram

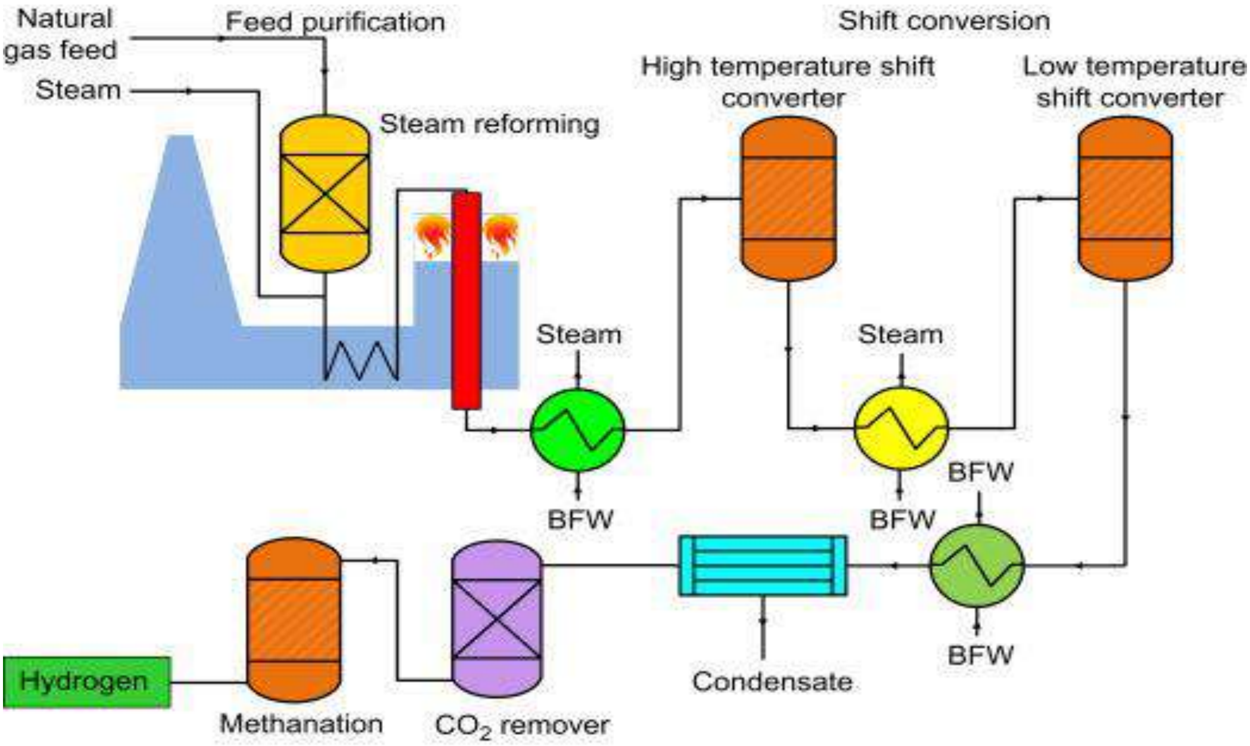


Figure 2.1 Process flow diagram of Natural gas steam reforming

2.2 2.2 Gasification Process of Coal

Coal gasification is a well stablished technology, used by many industries for the production of hydrogen which is further used in fertilizer industry for ammonia production. In this process gasification technique is used in which coal is used as a raw material heated at high temperature to create the synthesis gas, which is rich in CO_2, CO, and hydrogen. Using water shift gas reactors, the syngas is then used to transform carbon monoxide to CO_2 and high purity hydrogen. The Carbon dioxide then further removed by using separation technique selexol separation or pressure swing adsorption. This process yields the 99.8 % pure hydrogen [12].

- High moisture content in coal and coal ash are more effectively converted into usable products during the coal gasification process of producing hydrogen [12].
- The hydrogen produced from coal gasification can further be used for the generation of electricity or for ammonia production. This process also decreases the carbon dioxide emissions [12].
- By undergoing extra processing, such as hydrogen and methanol utilisation, the syngas generated by the coal gasification process can also be converted for the transportation fuels like petrol and diesel [12].

Reactions

The combustion reactions are

$$C + \frac{1}{2} O_2 \rightarrow CO \qquad (-111\ MJ/kmol) \qquad (2.3)$$

$$CO + \frac{1}{2} O_2 \rightarrow CO_2 \qquad (-283\ MJ/kmol) \qquad (2.4)$$

$$H_2 + \frac{1}{2} O_2 \rightarrow H_2O \qquad (-242\ MJ/kmol) \qquad (2.5)$$

Additional significant gasification reactions comprise:

The water gas reaction

$$C + H_2O \leftrightarrow CO + H_2 \qquad (+131\ MJ/kmol) \qquad (2.6)$$

The boudouard reaction

$$C + CO_2 \leftrightarrow 2CO \qquad (+172\ MJ/kmol) \qquad (2.7)$$

The water gas shift reaction

$$CO + H_2O \leftrightarrow CO_2 + H_2 \qquad (-41\ MJ/kmol) \qquad (2.8)$$

Process flow Diagram

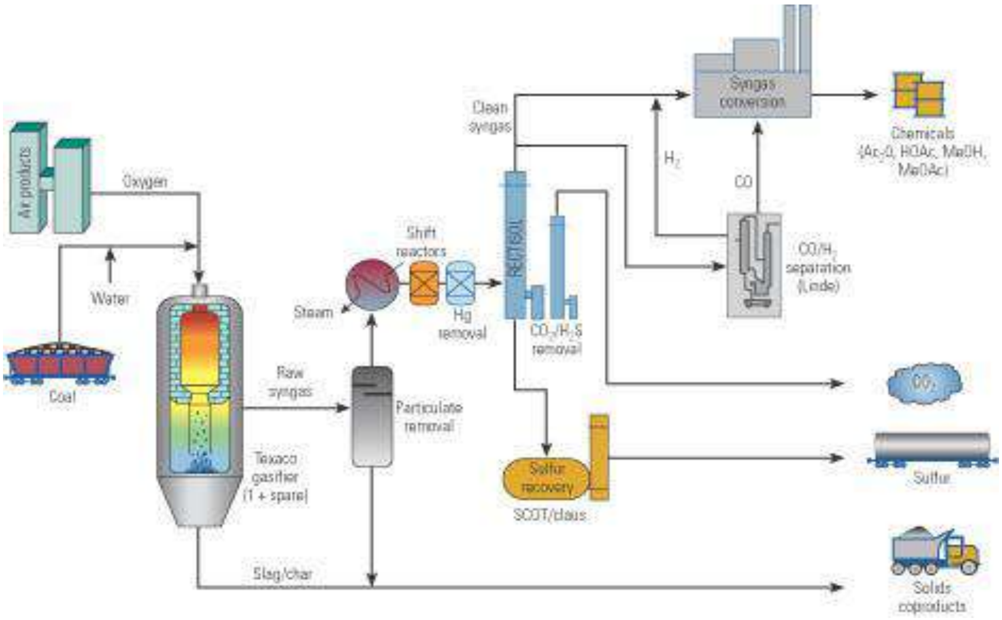


Figure 2.2 Process flow diagram of Coal gasification

2.3 Electrolysis for Hydrogen Production

Electrolysis is possible technique for manufacturing carbon-free H_2 from nuclear and renewable sources. Electricity is used in the electrolysis process to divide water into hydrogen and oxygen. The electrolyser, a unit, is where this process is running. The electrolyzer has two electrode called anode and cathode. Both anode and cathode are separated by membrane called the electrolyte which is surrounded by the water. The function of the electrolyser depends on the type of the electrolyte [13].

- The electrolysis process of hydrogen production can quickly ramped up and down the production of hydrogen [13]
- Electrolyzers can also alter the production of hydrogen rates almost instantaneously if the flexibility is required [13].
- The electrolyzer is commonly a series of cells in which the electrolysis reaction take place [13].

Reactions

$$2\ H_2O_{(l)} \leftrightarrow H_{2(g)} + O_{2(g)} \qquad (2.9)$$

Process flow Diagram

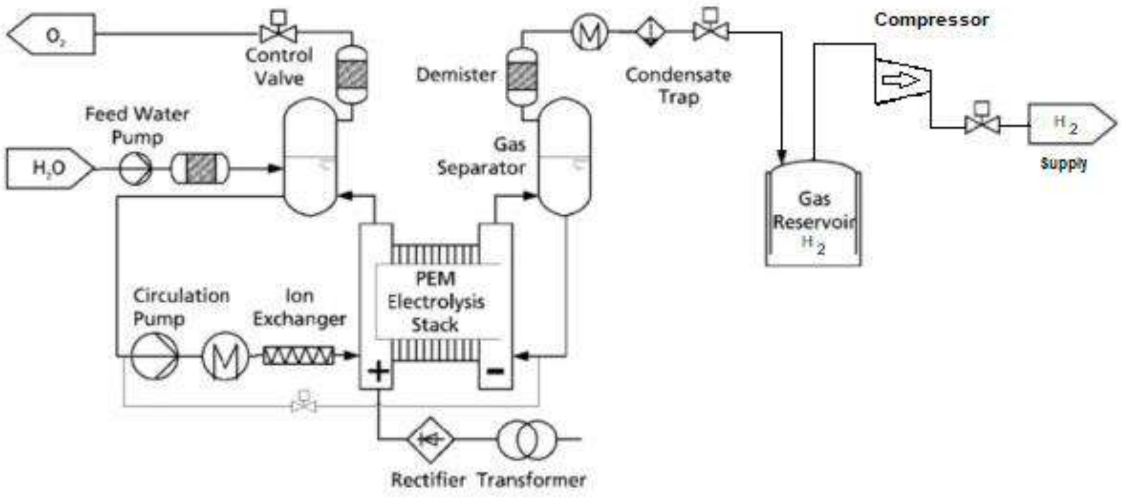


Figure 2.3 Process flow diagram of Electrolysis

2.4 Production of Hydrogen from Biomass Gasification

Biomass gasification is an efficient, mature and environmental pathway gasification is a way of producing hydrogen by converting biomass (waste) and steam into hydrogen and carbon dioxide. Because the atmosphere's principal source of greenhouse gases is the growth of biomass, this procedure emits no carbon dioxide, especially when using a carbon capture unit [14].

- This method involves treating the biomass with oxygen and lots of steam while it is being gasified at high pressures and temperatures (up to 700 ^{O}C) [14].
- As a result the product we received after the gasifier is impure, several gases, including hydrogen, methane, carbon dioxide, and carbon monoxide, are combined to form syngas [14].
- The carbon dioxide and other gases are further separated from the selexol process. The carbon monoxide and water then combine in shift gas reactors to form hydrogen and carbon dioxide [14].
- The shift gas reactions are moderately exothermic To move forward and achieve the necessary conversion, it is important to eliminate the surplus heat from the reaction [14].
- Pressure swing adsorption and membrane technologies are used to remove carbon dioxide. From this process we will get high purity hydrogen [14].
- The hydrogen produced from biomass gasification can also be used for the electricity generation, hydrogen fuel cells, transportation vehicle as a fuel. Since hydrogen has a calorific value of 142. 6 MJ/Kg [14].
- The syngas produced from the gasification process can replace the fossil fuels. As the heating values of syngas are 4-10MJ/m^3 [14].
- This process is the renewable source of energy as the raw material (biomass) is available in huge amount and this is efficient method of green hydrogen production with zero carbon dioxide emissions, environmental friendly route of producing fuels [14].

Reactions

Biomass Reaction

$$C_6H_{12}O_6 + O_2 + H_2O \rightarrow CO + CO_2 + H_2 + \text{other species} \qquad (2.10)$$

The reactions of combustion are

$$C + \frac{1}{2} O_2 \rightarrow CO \qquad (-111\ \text{MJ/kmol}) \qquad (2.11)$$

$$CO + \frac{1}{2} O_2 \rightarrow CO_2 \qquad (-283\ \text{MJ/kmol}) \qquad (2.12)$$

$$H_2 + \frac{1}{2} O_2 \rightarrow H_2O \qquad (-242\ \text{MJ/kmol}) \qquad (2.13)$$

Other important gasification reactions include:

The reaction of water shift gas is

$C + H_2O \leftrightarrow CO + H_2$ (+131 MJ/kmol) (2.14)

The boudouard reaction

$C + CO_2 \leftrightarrow 2CO$ (+172 MJ/kmol) (2.15)

Water gas Reaction:

$C+H_2O \longrightarrow CO+H_2$ (+131 MJ/kmol) (2.16)

Methanation Reaction:

$C + 2H_2 \longrightarrow CH_4$ (-75 MJ/kmol) (2.17)

The water gas shift reaction

$CO + H_2O \leftrightarrow CO_2 + H_2$ (-41 MJ/kmol) (2.18)

Process Flow Diagram

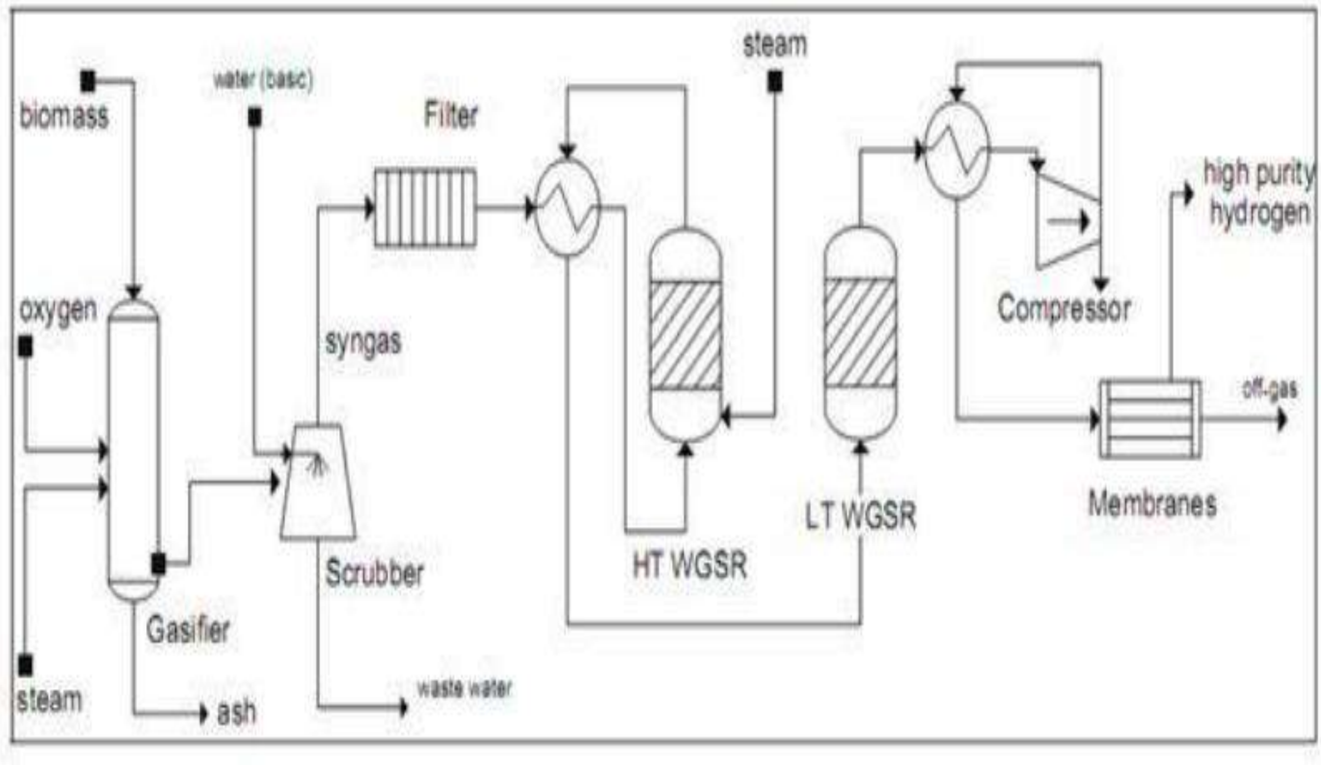


Figure 2.4 Process flow diagram of biomass gasification

2.5 Process Selection

Table 2.1 Comparison of Processes

Processes	Pressure	Temperature	Advantages	Disadvantages	Efficiency
Natural Gas reforming	3-25 bar	700-1000 °C	▪ High Efficiency ▪ economical	▪ Consumes fossil fuel as a raw material. ▪ Generates CO_2 as a by product.	50-80 %
Coal Gasification	100 bar	1600-1900 °C	▪ Conventional ▪ Cost Efficient	▪ CO_2 by product ▪ Cheap Hydrogen	63 %
Electrolysis	4-25 bar	700-800 °C	▪ Emission free ▪ Proven technology	▪ Low overall efficiency ▪ High cost	60-80 %
Biomass gasification	25-30 bar	700-1000 °C	▪ Renewable, Energy saving and efficient. ▪ Emission free	▪ Seasonal availability of raw material. ▪ Operational difficulties	30-40

2.6 Process Selection

From the above processes we have selected the biomass Gasification of hydrogen production due to the following reasons.

- Biomass is the renewable and natural source of energy.
- Plentiful sources of rice straw easily accessible in Pakistan.
- It is an economical process because we are using waste (rice straw) and converting into useful product (hydrogen).
- It is an efficient, energy saving and eco-friendly route of hydrogen production with no carbon dioxide emissions.
- As the mass proportion of the hydrogen element in biomass is about 6%, 1 kilogram of biomass will create nearly 0.672 m^3 of hydrogen.

2.7 Process Description

These are the following major steps, which involved in the manufacturing process of biomass gasification using steam to produce hydrogen.

1. Pretreatment of Rice Straw
2. Gasification of Rice Straw

3. Cyclone Separation
4. Gas Purification
5. Water Gas shift Membrane Reactor

2.7.1 Pretreatment of Rice Straw

In this section the rice straw enters the grinder to achieve the required size of biomass which is 0.25mm to 0.50mm. After that we need rice straw free of any dirt particle so rice will enters in the washing section. However this will increase the moisture content in the biomass so and it will decrease the efficiency of the gasifier. After this the rice straw will enters in the dryer to remove the excess the moisture and we need moisture less than 9.5% in the gasifier. For this purpose we will use rotary dryer. The rotary dryer is in contact with the dry air. After that the rice straw will go to the storage tank. The pulverized rice straw will mix with the oxygen and enters in gasifier.

2.7.2 Gasification of Rice Straw

For the gasification of the rice straw the gasifier is the fluidized bed gasifier. Now the rice straw will mix with the purified oxygen and reach the gasifier through the belt conveyor. Here the operating temperature of the gasifier is 950 ^{o}C and pressure is 10 bar. As the gasification will occur at very high temperature. So the temperature will be provided by the two sources. One will be saturated steam which temperature is 174 ^{o}C and pressure is 10 bar and the second source will be the gasification reactions which are exothermic. Due to the high temperature at which gasification is taking place, haret of sublimation will result, which will further produce syngas, CH_4 and H_2S.

2.7.3 Cyclone Separation

After the gasification section the impure syngas will move towards the cyclone separator as it contain ash, water vapours and some amount of unburn rice straw for the removal of the solid particles of the biomass from the syngas.

2.7.4 Gas Purification

As we have a significant amount of the CO_2, H_2S and CH_4 in the syngas so we will sue scrubber (absorber) for the removal of the unwanted gases from the produced gas. For this purpose will use selexol technique in the absorber. We are using selexol as a solvent for the removal of H_2S and bulk of CO_2. Selexol is a combination of polyethylene glycol dimethyl ethers. and has a chemical formula $CH_3C\ (CH_2CH_2O)_n\ CH_3$ where n is lie between 3 to 9 and has an ability to absorb all fuel contaminants in a single purification unit. It is ture physical solvent and donot react chemically with the absorbed gases. The high temperature syngas will enters the absorber at a temperature of 35 ^oC and a pressure of 10 bar. While the selexol solvent will enters the scrubber by the help of the centrifugal pump at a pressure of 10 bar and a temperature of 35 ^oC. The scrubber or absorber is functioning at this temperature and pressure. After that there is stripping column for the regeneration of the selexol solvent which will be done by the means of the vapour circulation by using the 140 ^oC and a pressure of 1 bar for saturated steam of 10 bar. After this the selexol will extracted from the stripper in plenty and then reintroduced to the absorber section.For further purification we will use filter before shift gas reactions.

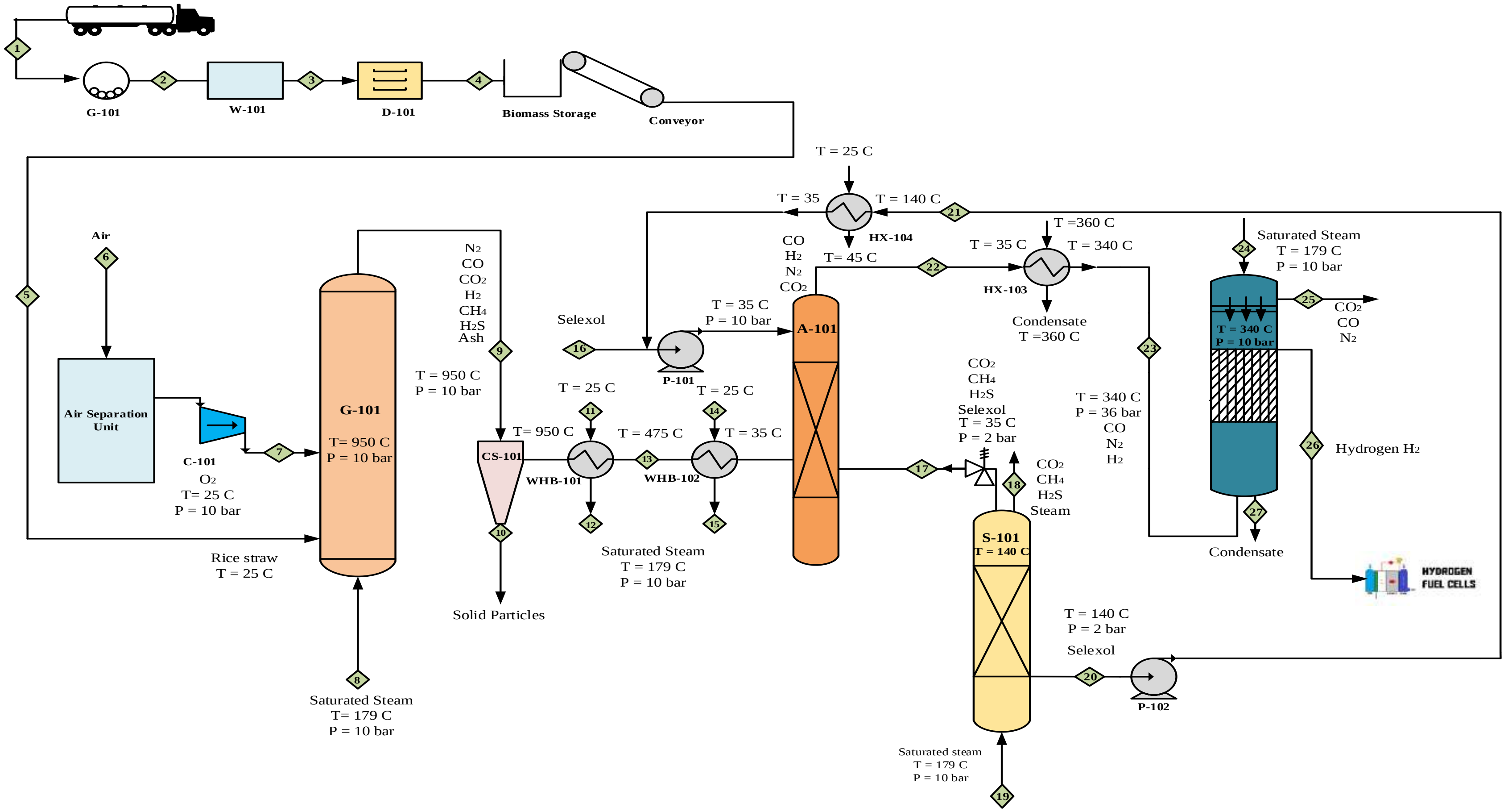
2.7.5 Membrane Water Gas Shift Reactor

The gas mixture of CO and H_2O entering the Membrane water gas shift reactor of 340 ^oC and pressure of 10 bar. As the shift gas reaction is moderately exothermic reactions whose heat of reaction is $\Delta H = -41.2$ KJ/mol. The shift gas reaction will first proceed in the HTSGR in the presence of Fe_2O_3, which is catalyst we are using here. The $Fe_2O_3$3 has outstanding performance for shift reactions. Its selectivity decreases with the decrease in temperature. It is cheap, readily available and non-toxic. As the reaction is reversible so to avoid the equilibrium, we are using the membrane reactor in which membrane will be selectively permeable and will allow only hydrogen gas to pass from the membrane. By removing the product continuously, we will disturb the equilibrium. Even enabling CO_2 simultaneously. This simultaneous H_2 production and CO_2 Capture will increase the overall efficiency 30%.

2.8 Capacity Selection

- In year **(2022-2023)** the production of the rice straw in Pakistan is = **8900,000 Tons**
- Punjab takes **55 %** part in the production of rice is = **4890,000 Tons**
- As **1 kg** of rice contain **0.7 kg** of **rice straw** so total rice straw is = **3420,000 Tons**
- So, we can get rice straw on yearly basis = 1095000 MT/ year
- We will conveniently collect **32 %** of the rice straw on yearly basis = **1095000 tons/year**
- Hydrogen yield from biomass gasification is **40 %**
- So we can produce = **438000 Ton/ year of hydrogen**

2.9 Process Flow Diagram



G-101	W-101	D-101	G-101	CS-101	A-101	S-101	MR-101	C-101	P-101-102	HX-103-104	WHB-101-102
Grinder	Washer	Dryer	Gasifier	Cyclone Separator	Absorber	Stripper	Membrane Reactor	Compressor	Pump	Heat Exchanger	Waste Heat Boilers

CHAPTER # 03

MATERIAL BALANCE

3 Material Balance

General equation of Material Balance

Mass Input – Mass Output + Generation – Consumption = Accumulation

At Steady state, Accumulation becomes zero so,

Input – Output + Generation – Consumption = 0

Basis:

1 hr of operation

Assumption:

Plant is at Steady state conditions

Plant Capacity:

Production capacity of plant per year = 438000 ton/year

Production rate:

$$\frac{438000\text{ton}}{\cancel{\text{Year}}} \bigg| \frac{1000\text{kg}}{1\cancel{\text{ton}}} \bigg| \frac{1\cancel{\text{year}}}{330\cancel{\text{days}}} \bigg| \frac{1\text{day}}{24\text{hrs}}$$

The hydrogen production rate for the working days of 330 is 55303 kg/hr

Yield = 40 %

Reactant Rate:

$$\text{Reactant Flowrate} = \frac{Hydrogen\ Produced}{Yield}$$

Reactant Flowrate:

$$\text{Reactant Flowrate} = \frac{55303}{0.40}$$

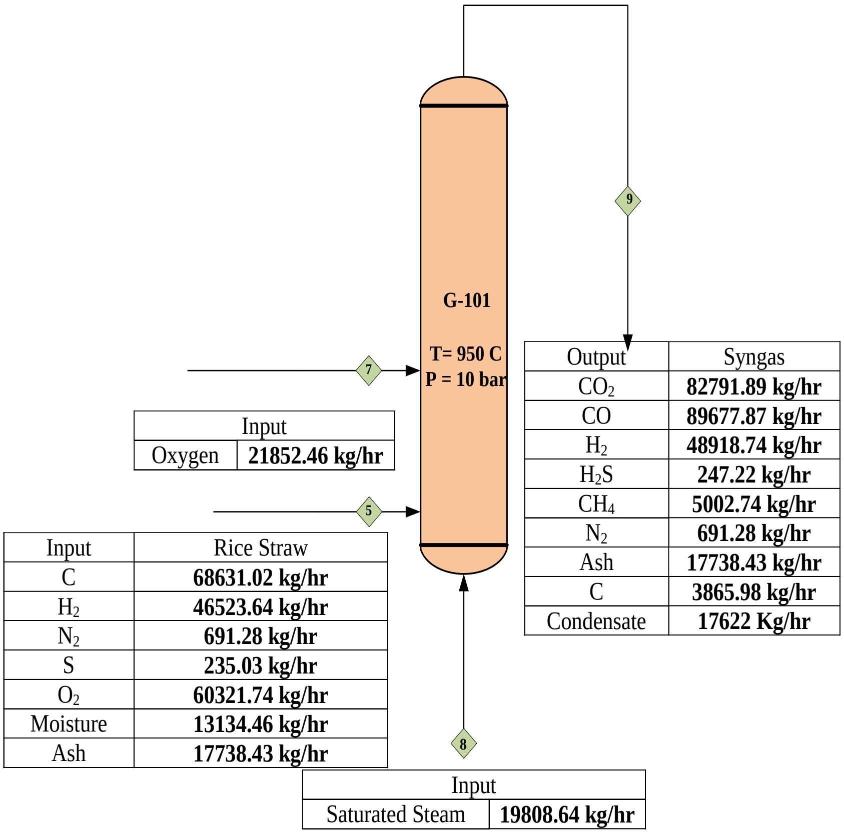
Reactant Flowrate = 138257 kg/hr

Unreacted Reactant Flowrate:

Unreacted Reactant Flowrate = 138257 × 0.60 = 83116.2 kg/hr

3.1 Material balance around Gasifier (G-101)

In Gasifier, the Biomass (Rice Straw) is fed with the Oxygen, steam and the product is Syngas, Methane, hydrogen sulfide and nitrogen.



Input	
Oxygen	21852.46 kg/hr

Input	Rice Straw
C	68631.02 kg/hr
H_2	46523.64 kg/hr
N_2	691.28 kg/hr
S	235.03 kg/hr
O_2	60321.74 kg/hr
Moisture	13134.46 kg/hr
Ash	17738.43 kg/hr

Input	
Saturated Steam	19808.64 kg/hr

Output	Syngas
CO_2	82791.89 kg/hr
CO	89677.87 kg/hr
H_2	48918.74 kg/hr
H_2S	247.22 kg/hr
CH_4	5002.74 kg/hr
N_2	691.28 kg/hr
Ash	17738.43 kg/hr
C	3865.98 kg/hr
Condensate	17622 Kg/hr

Figure 3.1Gasifier (G-101)

Reactions

$C + H_2O \longrightarrow CO + H_2$ **Conversion = 32%**

$C + ½ O_2 \longrightarrow CO$ **Conversion = 24%**

$C + O_2 \longrightarrow CO_2$ **Conversion = 32.9%**

$C + 2H_2 \longrightarrow CH_4$ **Conversion = 5.46%**

$S + H_2 \longrightarrow H_2S$ **Conversion = 99%**

Table 3.1 Flowrates and compositions of stream 7

Components	Compositions	Mass Flowrate (kg/hr)	Molar Flowrate (kmol/hr)
Carbon	49.64 %	68630.77	5719.16
Oxygen	43.63 %	60321.52	3770
Hydrogen	33.65 %	46523	23261
Nitrogen	0.5 %	691.28	49.3
sulfur	0.17 %	235	7.34
Moisture	9.5 %	13134.4	729
Ash	12.83 %	17738.37	17738.37

Reaction # 01

$$C+H_2O \longrightarrow H_2 + CO$$

Conversion = 32%

C in feed = 6860.77 kg/hr

Consumed = 21961.84 kg/hr

= 1830 kmol/hr

C : H_2O	**C : H_2**	**C : CO**
1	**1**	**1**

H_2O consumed = 32942.77 kg/hr

H_2 Formed = 3660 kg/hr

CO Formed = 51244 kg/hr

Reaction #c02

$$C+O_2 \longrightarrow CO_2$$

Conversion = 32.9%

C in Feed =68630.77 kg/hr

C Consumed =22579.52 kg/hr

= 1881.6 kmol/hr

C:O_2 C:CO_2

1:1 1:1

O_2 Consumed = 60212.28 kg/hr

CO_2 Formed = 82791.59 kg/hr

Reaction#03

$$C+2H_2 \longrightarrow CH4$$

Conversion = 5.467%

C in Feed = 68630.77 kg/hr

C Consumed= 3752 kg/hr

=312.6 kmol/hr

C:$2H_2$ C:CH_4

1:2 1:1

H_2 Consumed =1250 kg/hr

CH_4 Formed = 5002.72 kg/hr

Reaction # 04

$$C+\frac{1}{2}O_2 \longrightarrow CO$$

Conversion = 24%

C in Feed = 68630.77 kg/hr

C Consumed=16471 kg/hr

=1372.6 kmol/hr

C: $\frac{1}{2}$O2

1: $\frac{1}{2}$

O_2 Consumed = 21961.92 kg/hr

CO formed = 38433 kg/hr

Reaction # 05

$$S + H_2 \longrightarrow H_2S$$

Conversion = 99%

S in Feed = 235 kg/hr

=232.6 kg/hr

=7.25 kmol/hr

$S : H_2$ $S : H_2S$

1:1 1:1

H_2S formed = 246.5 kg/hr

H_2 Consumed = 14.5 kg/hr

Unreacted carbon = Carbon in feed – Carbon consumed

C Consumed = 68630.77 – (21961.84 +22579.52+3752+16471)

= 3865.98 kg/hr

H_2 at Output = H_2 in Feed + H_2 produced – H_2 required

= 46523 + 3660 - 1264.5

= 48918 kg/hr

Unreacted Sulfur = S in feed **-** S Consumed

Unreacted = 0

O_2 Required = O_2 in Feed – O_2 Consumed

= 60321.74 - (60212 + 21961.92)

= 21852. 46 kg/hr

Steam Required:

Steam = H_2 Consumed – Moisture Content

= 32942.7713134

= 19808 kg/hr (From material balance required for reaction).

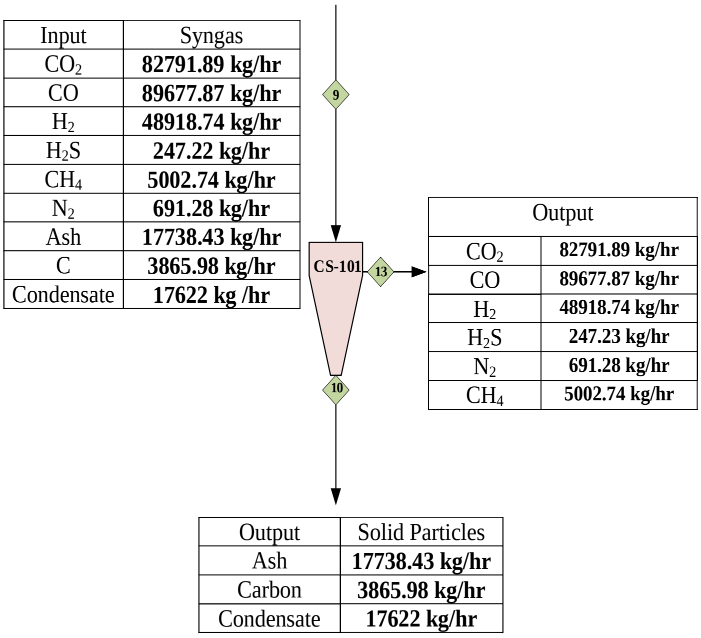
Steam = 17622 Kg/hr (From energy balance required for heating purpose).

Total Steam = 37430 kg/hr (Total steam from energy balance required for reaction and for heating purpose).

Figure 3.2 Material Balance on Gasifier (G-101)

Components	Material Input(kg/hr)			Material Output(kg/hr)	
	Stream-05	Stream-07	Stream08	Stream-09	
	Rice Straw	Steam	Oxygen	Solid + water	Gases
Carbon	68631.02	-	-	3865.98	-
Sulfur	235.03	-	-		-
Ash	17738.43	-	-	17738.43	-
CO_2		-	-		82791.89
CO		-	-		89677.87
N_2	691.28	-	-		691.28
O_2	60321.74	-	21852.46		-
H_2	46523.64	-	-		48918.74
H_2S		-	-		247.23
H_2O	13134.46	37340	-	17622	-
CH_4			-		5002.74
Total	**266556**			**266556**	

3.2 Material Balance around Cyclone Separator (CS-101)



Input	Syngas
CO_2	**82791.89 kg/hr**
CO	**89677.87 kg/hr**
H_2	**48918.74 kg/hr**
H_2S	**247.22 kg/hr**
CH_4	**5002.74 kg/hr**
N_2	**691.28 kg/hr**
Ash	**17738.43 kg/hr**
C	**3865.98 kg/hr**
Condensate	**17622 kg /hr**

Output	
CO_2	**82791.89 kg/hr**
CO	**89677.87 kg/hr**
H_2	**48918.74 kg/hr**
H_2S	**247.23 kg/hr**
N_2	**691.28 kg/hr**
CH_4	**5002.74 kg/hr**

Output	Solid Particles
Ash	**17738.43 kg/hr**
Carbon	**3865.98 kg/hr**
Condensate	**17622 kg/hr**

Figure 3.3 Cyclone Separator

Material going in at stream 09:

Table 3.2 Flowrates of stream 9

Components	Mass Flowrate (kg /hr)	Mass Fraction
CO_2	82791.89	0.310
CO	89677.87	0.34
H_2	48918.74	0.184
H_2S	247.23	0.000927
N	691.28	0.00259
CH_4	5002.74	0.0188
Ash	17738.43725	0.0665
Carbon	3865.98	0.0145
Condensate	17622	0.0661
Total	**266556**	**1**

Material going out from stream 10:

Solid compounds (Ash and Carbon) and liquid Condensate is going out from stream 10.

Material going out at stream 13:

Table 3.3 Flowrates of Stream 13

Components	Mass Flowrate kg/hr	Mass Fraction
CO_2	82791.89	0.37
CO	89677.87	0.4
H_2	48918.74	0.22
H_2S	247.23	0.0011
N	691.28	0.003
CH_4	5002.74	0.022
Total	**227329.75**	**1**

Figure 3.4 Material Balance on Cyclone Separator

Components	Material Input(kg/hr)		Material Output(kg/hr)	
	Stream-09		Stream-10	Stream-13
	Gases	Solids	Solid + water	Gases
CO_2	82791.89	-	-	82791.89
CO	89677.87	-	-	89677.87
H_2	48918.74	-	-	48918.74
H_2S	247.23	-	-	247.23
N_2	691.28	-	-	691.28
CH_4	5002.74	-	-	5002.74
Ash	-	17738.43	17738.43	-
Carbon	-	3865.98	3865.98	-
Condensate			17622	
Total	**266558**		**266558**	

3.3 Material Balance around Scrubber (A-101):

Solubility of gases like (H_2S, CH_4, and CO_2) in solvent are (8.82, 0.066, and 1.0) kg/L of solvent.

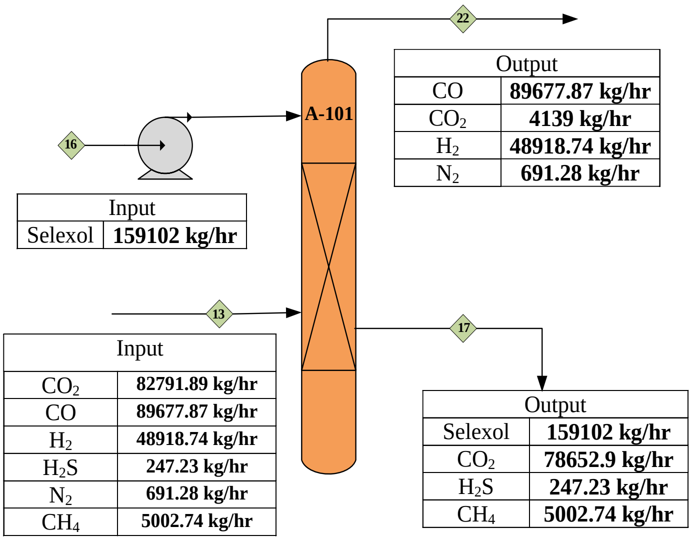


Figure 3.5 Scrubber (A-101)

Density of solvent = 1030 kg/m^3 = 1.03 kg/L

Amount of H_2S = 247 kg/hr

Solvent required for H_2S = (247/8.82)(1.03) = 28.8 kg/hr

Amount of CH_4 = 5002.74 kg/hr

Solvent required for CH_4 = (5002.74/0.066)(1.03) = 78062 kg/hr

Amount of CO_2 = 82791.59 kg/hr

Solvent required for CO_2 = (82791.59/1) (1.03) = 81012 kg/hr

Total Solvent = (28.8 + 78061.5 + 81012) kg/hr = 159102 kg/hr (Makeup solvent amount is 1.5 % of total feed)

Material going in at Stream 13:

Figure 3.6 Flowrates of Stream 13

Components	Mass Flowrate kg/hr	Mass Fraction
CO_2	82791.89	0.37
CO	89677.87	0.4
H_2	48918.56	0.22
H_2S	247.23	0.0011
N_2	691.28	0.003
CH_4	5002.74	0.022
Total	**227329.57**	**1.0161**

Material going in at Stream 16:

Solvent is going in from stream 16 in liquid form with flowrate of 159102 kg/hr.

Material going out at Stream 17:

Table 3.4 Flowrates of Stream 17

Components	Flowrate (kg/hr)	Mass fraction
CO_2	78652.9	0.32
H_2S	247	0.001
CH_4	5002	0.020
Selexol	159102	0.654
Total	**243003.9**	**1**

Material going out at Stream 22:

Table 3.5 Flowrates of Stream 22

Components	Flowrate (kg/hr)	Mass fraction
CO	89677.54	0.63
H_2	48918.56	0.34
N_2	691	0.0048
CO_2	4139	0.028
Total	**143426**	**1**

Table 3.6 Material Balance around Scrubber (A-101)

Component	Material Input (kg/hr)		Material Output (kg/hr)	
	Stream-13	Stream-14	Stream-17	Stream-22
	Gases	Solvent	Solvent + Acid gases	Gases
CO_2	82791.89	-	78652.9	4139
CO	89677.87	-	-	89677.54
N_2	691.28	-	-	691.28
H_2	48918.56	-	-	48918.56
H_2S	247.23	-	247.23	-
CH_4	5002.74	-	5002.74	-
Selexol	-	159102	159102	-
	227329.57	159102	243003.9	143426
Total	**386430**		**386430**	

3.4 Material Balance around Stripper (ST-101):

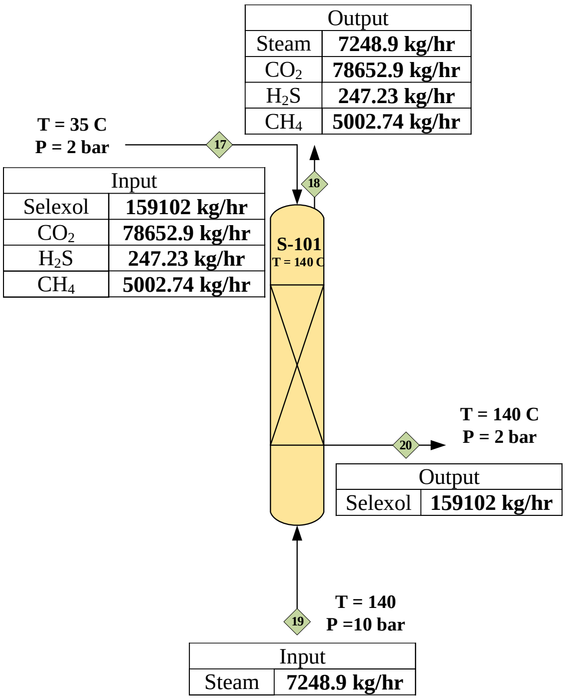


Figure 3.7 Stripper (ST-101)

Material going in at Stream 17:

Table 3.7 Flowrates of Steam 17

Components	Flowrate (kg/hr)	Mass fraction
CO_2	78652.9	0.32
H_2S	247	0.001
CH_4	5002	0.020
Selexol	159102	0.654
Total	**243003.9**	**1**

Material going in at Stream 19:

Steam is going in from stream 19 in Vapor form with flowrate of 7248 kg/hr.

Material going out at Stream 18:

Table 3.8 Flowrates of Stream 18

Components	Flowrates kg/hr	Mass Fraction %
CO_2	78652.9	0.86
CH_4	247	0.0027
H_2S	5002	0.05
Steam	8369.28	0.07
Total	**91151**	**1**

Material going out at Stream 20:

Solvent is coming out from stream 20 is liquid form with flowrate of 159102 kg/hr.

Table 3.9 Material Balance around Stripper (ST-101)

Material In			Material out	
Components	**Flowrate (kg/hr)**		**Components**	**Flowrate (kg/hr)**
	Steam 17	**Stream 19**	**Stream 18**	**Stream 20**
CO_2	78652.9		78652.9	
CH_4	5002		5002	
H_2S	247		247	
Selexol	159102		-	159102
Steam	-	7248	8369.28	
Total	**250251**		**Total**	**250251**

3.5 Material Balance around Membrane Reactor (MR-101)

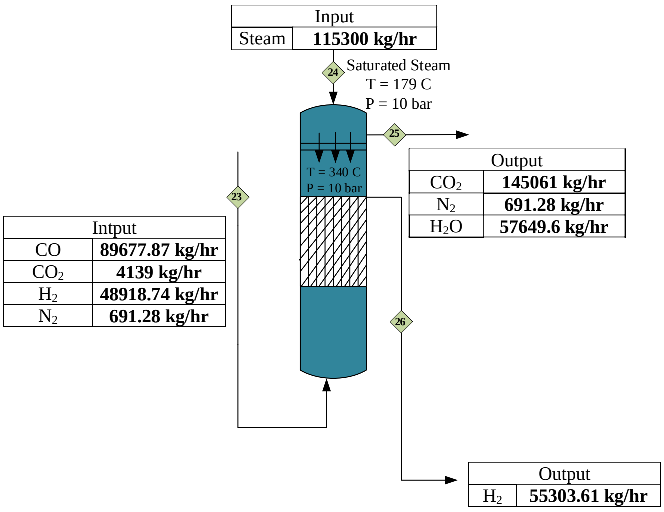


Figure 3.8 Membrane Reactor (MR-101)

Reaction:

$$CO + H_2O \longleftrightarrow H_2 + CO_2$$

Conversion = 100 %

CO in Feed = 89677.54 kg/hr

= 3202.7 kmol/hr

$\frac{CO}{H_2O}$ **=1:2**

$CO : H_2O$

1 : 2

3202.7: 6405.4 kmol/hr

H_2O Required = 6405.4 × 18

= 115299 kg/hr

Now

CO Consumed = 89677.54 × 1

= 89678 kg/hr

= 3202.7 kmol/hr

$CO : H_2O$

1 : 1

H_2O Consumed = 3202 × 18

= 57648.6 kg/hr

$CO = H_2$

1 = 1

H_2 Produced = 3202.7 × 2

= 6405.6 kg/hr

CO2 Produced = 3202.7 × 44

= 140919 kg/hr

CO Balance:

CO at Output = CO in Feed - CO Consumed

=89677.54 – 89677.54 = 0

H_2 Balance:

H_2 at Output = H_2 in Feed + H_2 Produced

= 48918.56 + 6405.6

=55303.56 kg/hr

H_2O Balance:

H_2O at Output = H_2O in Feed – H_2O Consumed

=115299 – 57648.6

= 57649.6 kg/hr

CO_2 Balance:

CO_2 at Output = CO_2 in Feed + CO_2 Produced

= 4139 + 140919

= 145061 kg/hr

Figure 3.9 Material Balance on (MR-101)

Material In			**Material out**	
Components	**Flowrate kg/hr**		**Flowrate kg/hr**	
	Stream -23	**Stream-24**	**Stream-25**	**Stream- 26**
CO_2	4139		145061	
CO	89677.54		0	
H_2	48918.56		55303.5	
N_2	691		691	
H_2O	-	115299	-	57649.6
Total	**258726**		**258726**	

CHAPTER # 04

ENERGY BALANCE

4 Energy Balance

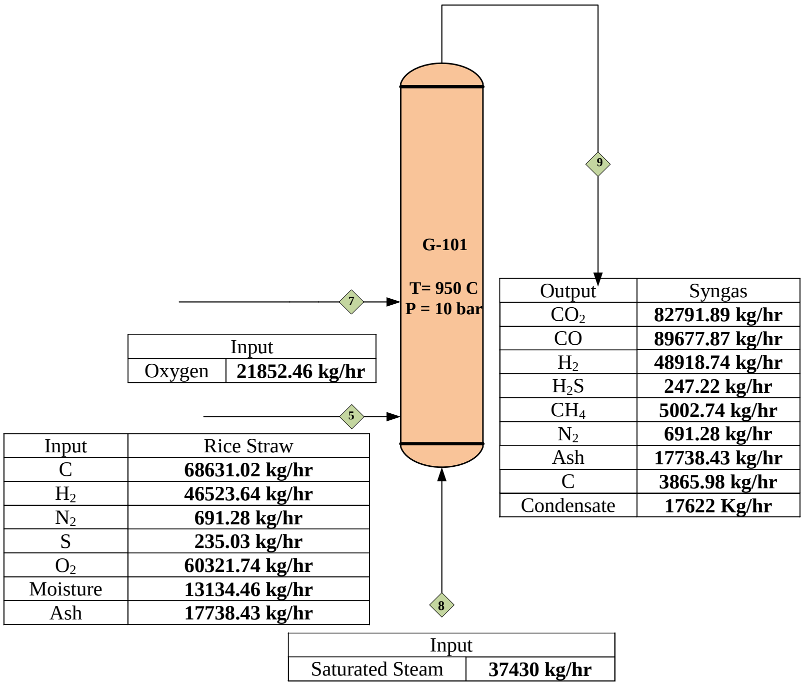
General Equation of Energy Balance

(Rate of heat input) - (Rate of heat output) ± (Rate of heat generation/consumption) ± (Rate of heat Accumulation/ Depletion) = 0

Assumption

Steady state operation

4.1 Energy balance around Gasifier (G-101)



Input	
Oxygen	21852.46 kg/hr

Input	Rice Straw
C	68631.02 kg/hr
H_2	46523.64 kg/hr
N_2	691.28 kg/hr
S	235.03 kg/hr
O_2	60321.74 kg/hr
Moisture	13134.46 kg/hr
Ash	17738.43 kg/hr

Output	Syngas
CO_2	82791.89 kg/hr
CO	89677.87 kg/hr
H_2	48918.74 kg/hr
H_2S	247.22 kg/hr
CH_4	5002.74 kg/hr
N_2	691.28 kg/hr
Ash	17738.43 kg/hr
C	3865.98 kg/hr
Condensate	17622 Kg/hr

Input	
Saturated Steam	37430 kg/hr

Figure 4.1 Gasifier (G-101)

Reactions

$$C + H_2O \longrightarrow CO + H_2 \qquad \Delta H_r = 131 \text{ KJ/mol}$$

$$C + \tfrac{1}{2} O_2 \longrightarrow CO \qquad \Delta H_r = -393 \text{ KJ/mol}$$

$$C + O_2 \longrightarrow CO_2 \qquad \Delta H_r = -238.01 \text{ KJ/mol}$$

$$C + 2H_2 \longrightarrow CH_4 \qquad \Delta H_r = -75 \text{ KJ/mol}$$

$$S + H_2 \longrightarrow H_2S \qquad \Delta H_r = -19.96 \text{ KJ/mol}$$

Calculations

$$T_{In} = T_{Ref} = 25°C = 298 \text{ K}, \ T_{Out} = 950°C = 1223 \text{ K}, \ T_{Steam} = 179°C$$

$$T_{ave} = \frac{25+950}{2} = 760.5\ K$$

For Cp calculation the following equation is being used:

$$\mathbf{Cp = A + BT + CT^2 + DT^3}$$

Table 4.1 Constants for all components

Component	$A\times10^{-3}$	$B\times10^{-5}$	$C\times10^{-8}$	$D\times10^{-12}$
C	11.8	1.095	-4.52	-
S	15.2	2.68	-	-
H_2O	33.46	0.6880	0.7604	-3.593
CO	28.95	0.4110	0.3548	-2.22
H_2	28.84	0.00765	0.3288	-0.8698
O_2	29.10	1.158	-0.6076	1.311
CO_2	36.11	4.233	-2.887	7.464
CH_4	34.3	5.469	0.366	-11
H_2S	33.51	1.547	0.3012	-3.292

Cp for Methane (CH_4):

$$Cp = (A) + (B)(T) + (C)(T^2) + (D)(T^3)$$

$$(34.31 \times 10^{-3}) + (5.469 \times 10^{-5})(760.5) + (0.3661 \times 10^{-8})(760.5^2) - (11 \times 10^{-12})(760.5^3)$$

$$Cp = 77.75\ \frac{KJ}{Kmol.K} = \frac{77.75\ (KJ).(mol)}{16\ (Kmol).(kg)} = 4.85\ \frac{KJ}{Kg.K}$$

$Cp_{weighted} = x_1Cp_1 + x_2Cp_2 + x_3Cp_3$ + - - - -

$$Cp_w = 4.114\ \frac{KJ}{KG.K}$$

Table 4.2 Heat Capacities of all components

Component	Flow rate (kg/hr)	Cp (kJ/kg.K)	Q_{in} (MJ/hr)	Q_{out} (MJ/hr)
Ash	17738.43	0.74	54×10^3	94×10^4
C	68631	1.625		
S	235	0.475		
CO_2	82791.89	1.304		
CO	89677.87	1.232		
N_2	691	1.217		
O_2	60321.74	1.181		
H_2	46523.64	15.6		
H_2S	247	1.44		
H_2O	13134	4.16		
CH_4	5002.74	4.85		

Heat of reaction at 925 ^{o}C:

$$\Delta \mathbf{H}_{1223} = \Delta \mathbf{H}_{25} + \int_{To}^{T} [(nCp)_p - (nCp)_R] \, \mathbf{dT}$$

For First Reaction

$$C + H_2O \longrightarrow CO + H_2 \qquad \Delta H_r = 131 \text{ KJ/mol}$$

$$\Delta H_{1223} = (131000 \ \frac{\text{KJ}}{\text{Kmol}}) + \int_{298}^{1223} \left(65.79 \ \frac{\text{KJ}}{\text{Kmol.K}}\right) - \left(62.4 \ \frac{\text{KJ}}{\text{Kg.K}}\right) . (925)$$

$$\Delta H_{1223} = 134136 \ \frac{\text{KJ}}{\text{Kmol.K}} \times 1830 \ \frac{\text{Kmol}}{\text{hr}}$$

$$\Delta H_{1223} = 24 \times 10^4 \ \frac{\text{MJ}}{\text{hr}}$$

Total Heat of Reaction:

$\Delta H_{Total} = \mathbf{-91 \times 10^4} \ \frac{MJ}{hr}$

Q $_{\text{Output}}$ for Gases:

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

Q_{out} = 248934 × 4.114 × (1223-298)

$Q_{out} = 947305 \frac{MJ}{hr}$

$Q_{Net} = Q_{output} - \Delta H_r$

$Q_{Net} = 947305890 – 910237185$

$Q_{Net} = 37068705 \frac{KJ}{hr}$

Mass Flowrate Required for Steam

T = 179 ^{O}C P = 10 bar

$Q = \dot{m}\lambda$

$\dot{m} = \frac{37068705}{2103.6}$

$\dot{m} = 17622 \frac{Kg}{hr}$

$$Q_{Input} + \Delta H_r - Q_{Output} - Q_{consumed} = 0$$

$$54137410 + 910237185 - 927305890 - 37068705 = 0$$

$$Q_{Input} + \Delta Hr = Q_{output} + Q_{consumed}$$

$$54137410 + 910237185 = 927305890 + 37068705$$

$$964374595 \frac{KJ}{hr} = 964374595 \frac{KJ}{hr}$$

$$\mathbf{96 \times 10^4 \frac{MJ}{hr} = 96 \times 10^4 \frac{MJ}{hr}}$$

4.2 Energy Balance around Waste Heat Boiler (WHB-101)

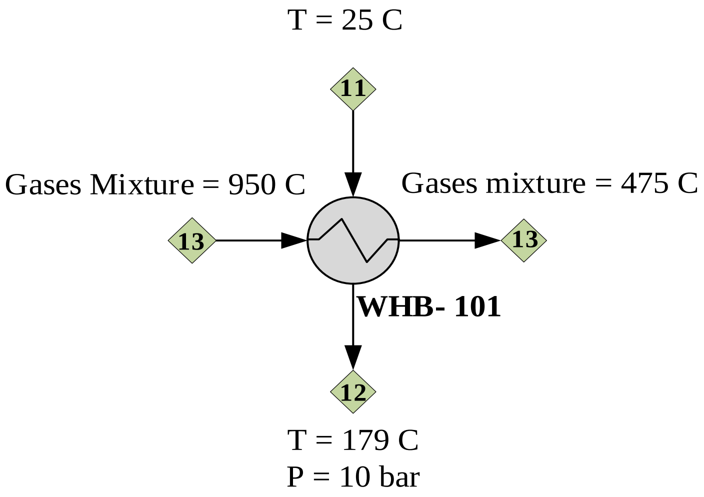


Figure 4.2 Waste heat boiler (WHB-101)

Table 4.3Energy Balance on WHB-101

Component	Specific Heat Capacity	Mass Fraction	Heat Load
	Cp KJ/ Kg. K		**MJ /hr**
CO_2	1.294	0.37	48×10^4
CO	1.226	0.4	
N_2	1.214	0.003	
H_2	15.6	0.22	
CH_4	5.08	0.022	
H_2S	1.429	0.0011	

$T_{in} = 950\ ^oC = 1223$ K , $T_{out} = 475\ ^oC = 748$ K

Tave = 986 K, $\Delta T = 475$ K

$Cp_w = 4.52\ \frac{KJ}{Kg.K}$

Heat Duty:

$Q = mcp\Delta T$

$= 227329 \times 4.52 \times 475$

$= 48 \times 10^4$ MJ/hr

Water Requirement:

Saturated Steam Conditions

$T = 179\ ^OC$, $P = 10$ bar

$Q = mcp\Delta T + m\lambda$

$$\frac{488075363}{4.16 \times 154 \times 2103.6} = m$$

$\dot{m} = 177854$

4.3 Energy Balance around Waste Heat Boiler (WHB-102)

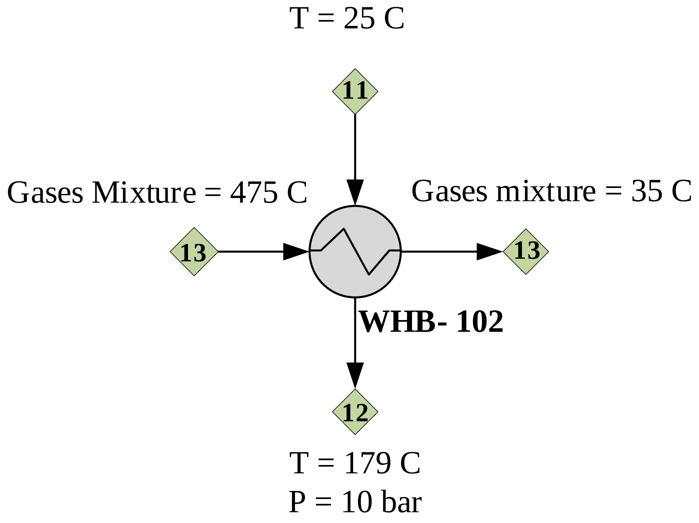


Figure 4.3Waste Heat Boiler (WHB-102)

Table 4.4 Energy Balance on WHB-102

Component	Specific Heat Capacity	Mass Fraction	Heat Load
	Cp KJ/ Kg. K		**MJ /hr**
CO_2	1.170	0.37	42×10^4
CO	1.136	0.4	
N_2	1.12	0.003	
H_2	14.48	0.22	
CH_4	3.913	0.022	
H_2S	1.235	0.0011	

$T_{in} = 475\ ^{o}C = 748\ K$, $T_{out} = 35\ ^{o}C = 308\ K$

Tave = 528 K

$\Delta T = 440\ K$

$Cp_w = 4.25\ \frac{KJ}{Kg.K}$

Heat Duty:

$$\mathbf{Q = mcp\Delta T}$$

$$= 227329 \times 4.25 \times 440$$

$$\mathbf{= 42 \times 10^4\ MJ/hr}$$

Water Requirement:

Saturated Steam Conditions

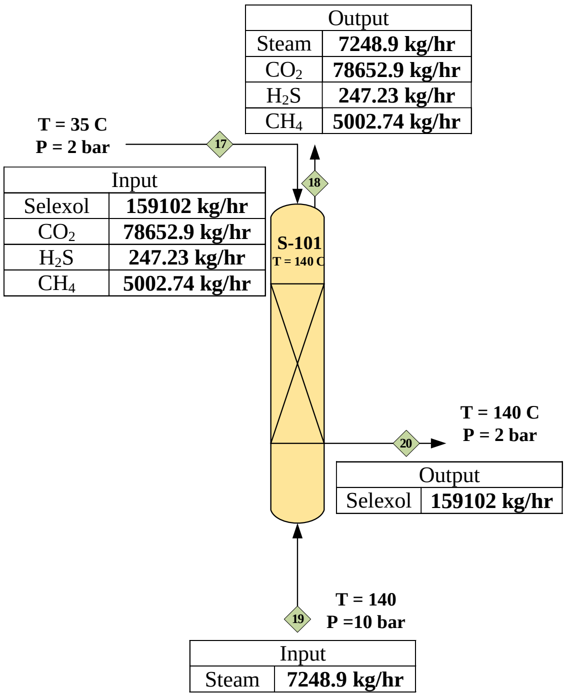
$$\mathbf{T = 179\ ^{O}C,\ P = 10\ bar}$$

$$Q = mcp\Delta T + m\lambda$$

$$\frac{425105230}{4.16 \times 154 \times 2103.6} = m$$

$$\dot{m} = 154908\ \frac{kg}{hr}$$

4.4 Energy Balance around Stripper



Output	
Steam	**7248.9 kg/hr**
CO_2	**78652.9 kg/hr**
H_2S	**247.23 kg/hr**
CH_4	**5002.74 kg/hr**

Input	
Selexol	**159102 kg/hr**
CO_2	**78652.9 kg/hr**
H_2S	**247.23 kg/hr**
CH_4	**5002.74 kg/hr**

Output	
Selexol	**159102 kg/hr**

Input	
Steam	**7248.9 kg/hr**

Figure 4.4 Energy Balance on Stripper

Table 4.5 Energy Balance around Stripper

Components	Specific Heat Capacity	Mass Fractions	Heat Load
	Cp (KJ/Kg. K)		**MJ/hr**
CO_2	1.089	0.314	17×10^3
CH_4	3.37	0.0199	
H_2S	1.156	0.00098	
Selexol	0.45	0.63	

T_{in} = 25 °C = 298 K, T_{out} = 140 °C = 413 K

T_{ave} = 356 K

ΔT = 115 K

$Cp_{weighted} = x_1Cp_1 + x_2Cp_2 + x_3Cp_3 + - - - -$

Cp_w = 0.69 KJ/Kg.K

$Q = mCp\Delta T$

$Q = 243004 \times 0.69 \times 105$

$Q = 17 \times 10^3$ MJ/hr

Saturated Steam Conditions

T = 179 °C , P = 10 bar

$\lambda = 2103.6$

$Q = m\lambda$

$$\frac{17605632.56}{2144} = m$$

m = 8369.28 kg/hr

4.5 Energy Balance around Heat Exchanger (HX-103)

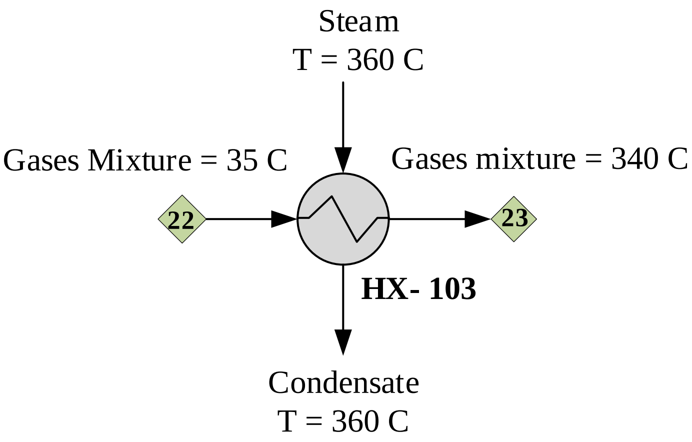


Figure 4.5 Heat Exchanger HX-103

Table 4.6 Energy Balance around HX-103

Components	Specific Heat Capacity	Mass Fractions	Heat Load
	Cp (KJ/Kg. K)		MJ/hr
CO_2	1.141	0.028	24×10^3
CO	1.121	0.63	
H_2	14.7	0.34	
N_2	1.105	0.0048	

$T_{in} = 35\ ^oC = 308$ K, $T_{out} = 340\ ^oC = 613$ K

$T_{ave} = 460.5$ K

$\Delta T = 305$ K

$Cp_{weighted} = x_1Cp_1 + x_2Cp_2 + x_3Cp_3 + - - - -$

$\mathbf{Cp_w = 5.74}$ **KJ/Kg.K**

$Q = mCp\Delta T$

$Q = 143427 \times 3.21 \times 375$

$\mathbf{Q = 24 \times 10^4}$ **MJ/hr**

Saturated Steam Conditions

$T = 354.6\ ^oC$, $P = 175$ bar

$\lambda = 820$

$Q = m\lambda$

$$\frac{24978592}{820} = \dot{m}$$

$\dot{m}$ **= 30461.69 kg/hr**

4.6 Energy Balance around Heat Exchanger (HX-104)

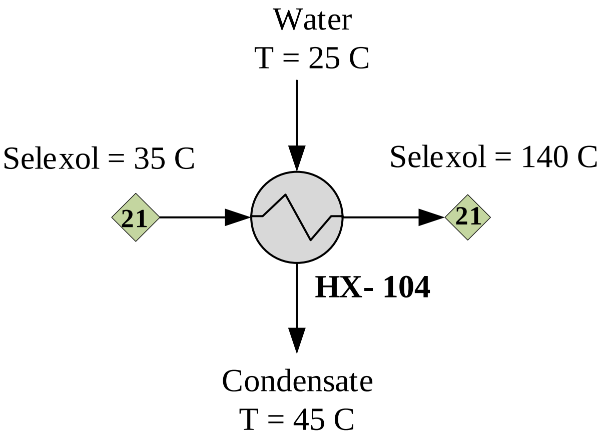


Figure 4.6 Heat Exchanger (HX-104)

$T_{in} = 140\ ^oC = 418$ K, $T_{out} = 35\ ^oC = 308$ K

$T_{ave} = 361$ K

$\Delta T = 105$ K

Heat Capacity of Selexol = Cp = 0.45 KJ/Kg.K

$Q = mCp\Delta T$

$Q = 159102 \times 0.45 \times 105$

$\mathbf{Q = 75 \times 10^2}$ **MJ/hr**

Cooling Water Requirement

T = 45 °C,

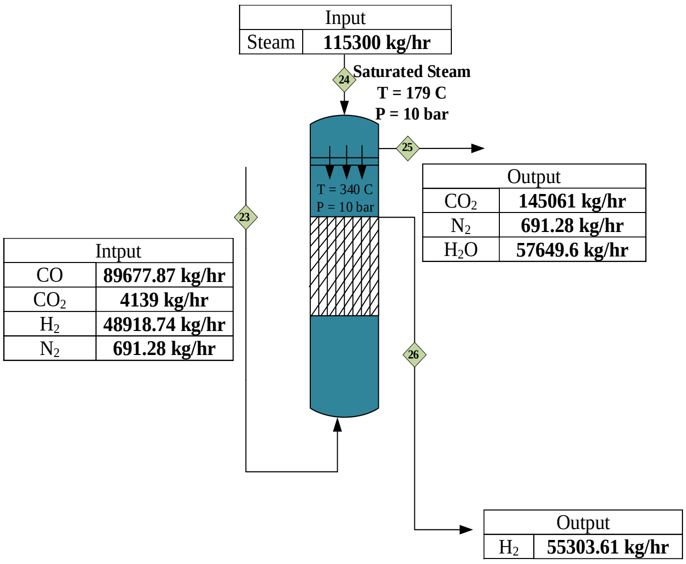
$\Delta T = 20$

$Q = \dot{m}Cp\Delta T$

$$\frac{7516569.5}{83.2} = \dot{m}$$

$\dot{m}$ = 90343 kg/hr

4.7 Energy Balance around Membrane Reactor (MR-101)



Input	
Steam	**115300 kg/hr**

Intput	
CO	**89677.87 kg/hr**
CO_2	**4139 kg/hr**
H_2	**48918.74 kg/hr**
N_2	**691.28 kg/hr**

Output	
CO_2	**145061 kg/hr**
N_2	**691.28 kg/hr**
H_2O	**57649.6 kg/hr**

Output	
H_2	**55303.61 kg/hr**

Figure 4.7 Membrane Reactor (MR-101)

T_{in} = 25 °C = 298 K, T_{out} = 340 °C = 613 K

T_{ave} = 456 K

ΔT = 315 K

Heat Input

$Cp_{weighted} = x_1Cp_1 + x_2Cp_2 + x_3Cp_3 + - - - -$

Cp_w = 3.25 KJ/Kg.K

$Q = mCp\Delta T$

$Q = 258726 \times 3.25 \times 315$

Q = 26 × 10^4 MJ/hr

Heat Output

$Cp_{weighted} = x_1Cp_1 + x_2Cp_2 + x_3Cp_3$ + - - - -

Cp_w = 4.28 KJ/Kg.K

Q = mCpΔT

Q = 258726 × 4.28 × 315

Q = 34 × 10^4 MJ/hr

Heat of Reaction

$$\mathbf{CO + H_2O \longrightarrow H_2 + CO_2 \qquad \Delta H_r = -41.6\ KJ/mol}$$

= -41600 +$\int_{298}^{613}[(52.92 + 29.92) - (32.29 + 37.29)]$

= -41600 + 3856

= -37744 $\frac{KJ}{Kmol}$ × 3202.78 $\frac{Kmol}{hr}$

= **-12 × 10^4 MJ/hr**

Q_{NET} = Q_{out} - ΔH_r – Q_{Input}

Q_{NET} = -37757064

Saturated Steam Conditions

T = 179 ^{O}C, P = 10 bar

Q = mλ

$\dot{m} = \frac{37757064}{2130.6}$

m = 17948 kg/hr

Overall Energy Balance Equation

$Q_{Input} + \Delta H_r = Q_{output} + Q_{Removed}$

264870742 + 120885728 = 347999406 + 37757064

385756470 = 385756470

Table 4.7 Energy Balance around (MR-101)

Components	Heat Capacities	Q_{Input}	Heat Capacities	$Q_{outpout}$
	Cp (KJ/Kg.K)	MJ/hr	Cp (KJ/Kg.K)	MJ/hr
CO_2	1.20	26×10^4	1.230	34×10^4
CO	1.15		1.172	
H_2	14.96		15.10	
N_2	1.137		1.156	

CHAPTER # 05

PROCESS EQUIPMENT DESIGN

5 Process Equipment Design

5.1 Design of Fluidized Bed Gasifier

Any raw resource (Carbon-based) that contains carbon, like coal, can be [illegible] technical process to create fuel gas, or syngas for small. In a gasifier, which is a high-temperature/pressure vessel, when oxygen (or air) and steam are brought into through contact with coal or biomass, a series of chemical reactions start that turn the feed into syngas and ash/slag (mineral wastes).

Table 5.1Comparison between different types of gasifier

Gasifier Type	Gasifier specific design	Temp. & pressure ranges
Fixed bed	Updraft	300–1,000°C
Moving bed	Downdraft	300–1,000°C
Fluidized Bed	Bubbling fluidized Bed	650–950°C 1–35 bar

Selection of Gasifier:

We have selected **Fluidized Bed Gasifier** for the following reasons.

Both up draught and down draught gasifiers are affected by the fuel's morphological, physical, and chemical characteristics. The usual issues include low bunker flow, slagging, and significant pressure loss above the gasifier.

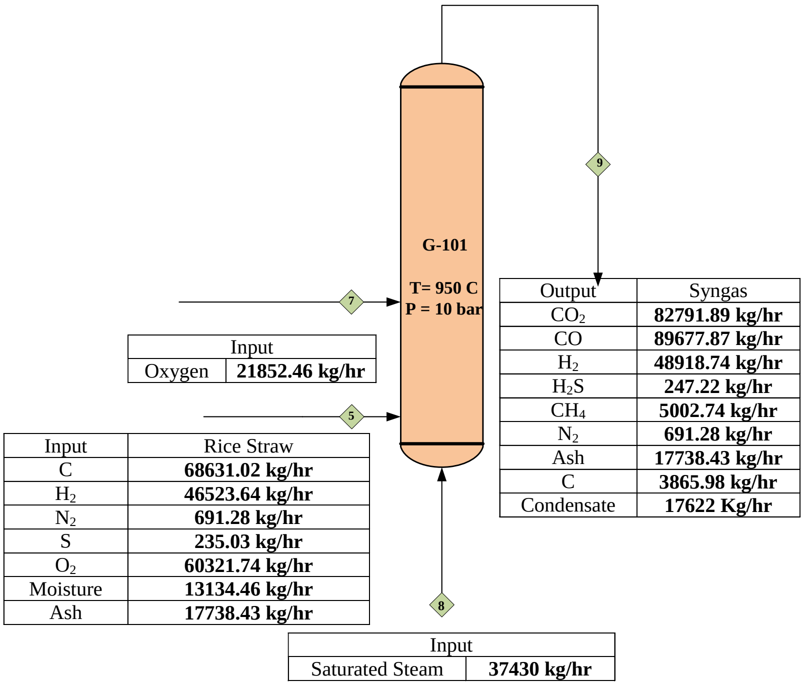
In order to keep solid particles suspended, steam is pushed across a bed of them at a high enough velocity. When the bed, which is originally heated externally, achieves a suitable a high degree of temperature, the feedstock is immediately injected. in the reactor's basement, the fuel particles are introduced, heated to the bed temperature after being quickly mixed with the bed material, almost immediately. This process causes the fuel to pyrolyze rather quickly, resulting in a component mix with a significant quantity of gaseous

A fluid-solid mixture with fluid-like properties makes up a fluidized bed. As a result, the Hydrostatic behaviour is comparable to the practically horizontal upper surface of the bed. A single bulk density can be used to describe the bed's heterogeneous mixture of fluid and solid. Further evidence that the fluid behaviour is visible in the bed indicated by Archimedes' principle comes from the fact that objects with densities that are higher than the bed will collapse while those with densities that are lower will float. Items of various densities relative to the bed can be made to float by changing either the liquid or the solid component because the bed's "density" (really the solid volume percent of the suspension) can be transformed by changing the fluid element.

Advantages:

The advantages of bubbling fluidized bed gasification are as follows

- Yields a uniform syngas.
- Almost consistent spread of temperature throughout the reactor
- Capable of accepting a variety of fuel particle sizes
- Provides high heat transfer rates between the fuel, gas, and inert material.
- Low tar and unconverted carbon allow for high conversion rates.



Input	
Oxygen	**21852.46 kg/hr**

Input	Rice Straw
C	**68631.02 kg/hr**
H_2	**46523.64 kg/hr**
N_2	**691.28 kg/hr**
S	**235.03 kg/hr**
O_2	**60321.74 kg/hr**
Moisture	**13134.46 kg/hr**
Ash	**17738.43 kg/hr**

Input	
Saturated Steam	**37430 kg/hr**

Output	Syngas
CO_2	**82791.89 kg/hr**
CO	**89677.87 kg/hr**
H_2	**48918.74 kg/hr**
H_2S	**247.22 kg/hr**
CH_4	**5002.74 kg/hr**
N_2	**691.28 kg/hr**
Ash	**17738.43 kg/hr**
C	**3865.98 kg/hr**
Condensate	**17622 Kg/hr**

Figure 5.1Fluidized Bed gasifier

Design Calculations

Reaction Conditions

Temperature = 950 ^{o}C

T_{ref} = 25 ^{o}C

Pressure = 10 bar

Reactions

$$C + H_2O \longrightarrow CO + H_2 \qquad \Delta H_r = 131 \text{ KJ/mol}$$

$$C + \tfrac{1}{2} O_2 \longrightarrow CO \qquad \Delta H_r = -393 \text{ KJ/mol}$$

$$C + O_2 \longrightarrow CO_2 \qquad \Delta H_r = -238.01 \text{ KJ/mol}$$

$$C + 2H_2 \longrightarrow CH_4 \qquad \Delta H_r = -75 \text{ KJ/mol}$$

$$S + H_2 \longrightarrow H_2S \qquad \Delta H_r = -19.96 \text{ KJ/mol}$$

Calculation of Weight of Rice Straw

$$W_S = \rho_S \ h A(1 - \varepsilon)$$

Where

ρ_s =Density of Rice Straw = 420 kg/m^3

$\varepsilon =$ Porosity of Rice Straw $= \varepsilon = 0.78$

$\emptyset =$ Spherecityof Rice Straw $= 0.6$

$$\text{Area of Solid} = \frac{\pi d^2}{4} = 1.1304 m^2$$

Assume

d = Internal diameter = 1.2m

h = Height of bed = 2.4m (Height is Twice of diameter)

$$W_S = (420)\ (2.4)(1.1304)(1 - 0.78) = 250.6 \text{ kg of solids}$$

Volume of Rice husk bed in Gasifier

$$\text{Volume of Rice Straw Bed} = \frac{\text{Weight of Rice Straw}}{\text{Bulk Density of Rice Straw}}$$

Where

Bulk density of rice husk = 112.87 kg/m^3

$$\text{Volume of Rice Straw Bed} = \frac{250.6}{112.87} = 2.22 \text{ m}^3$$

Volume of Gasifier

$$\text{Volume of Gasifier} = \frac{\text{Volume of Rice Straw Bed}}{1 - \text{Voidage}}$$

Where

$\varepsilon = Porosity\ of\ Rice\ Husk = 0.6$

$$\text{Volume of Gasifier} = \frac{2.22}{1-0.78} = 10\ \text{m}^3$$

Length of Gasification Section

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

Putting value of L

$$\text{V}_{\text{gasifier}} = \frac{\pi \text{D}^2(5\text{D})}{4}$$

$$\text{D} = 1.2\text{m (Assume Diameter 1.2m)}$$

$$\frac{\text{L}}{\text{D}} = 10\ (2 < \frac{\text{L}}{\text{D}} < 10)$$

$$\text{Taking } \frac{\text{L}}{\text{D}} = 10$$

$$\text{L} = 5(1.2)$$

$$\text{L} = 12\ \text{m}$$

Superficial Velocity

Superficial Velocity is given as

$$Q = U_f A$$

$$\frac{m_f}{\rho} = U_f A$$

$$U_f = \frac{m_f}{\rho A}$$

Where

Density of Fluid = 1.42 kg/m^3

Area $= \dfrac{\pi \text{d}^2}{4} = 1.1304\ \text{m}^2$

Mass flowrate of fluid = 21853 kg/hr

$$U_f = 3.78m/s$$

Minimum Fluidization Velocity

For minimum fluidization velocity

$$u_{m\,f} = \left[\frac{g(\rho_p - \rho_f){d_p}^2}{150\mu}\right]\left[\frac{\varepsilon^3 \emptyset^2}{1-\varepsilon}\right] = u_{mf} = 0.251m/s$$

Where

$g = 9.8$ m/s

$d_p = 500 \mu m$

$\rho_p = 420$ kg/m^3

$\rho_f = 1.42$ kg/m^3

$\mu = 2.11 \times 10^{-5}$ Pa.s

$\emptyset = 0.6$

Terminal Velocity

The relation for terminal velocity is

$$u = dp\ 0.333\sqrt{\frac{[4(\rho_p - \rho_f)^2 g^2]}{225\rho_f \mu}} = 16.6\ \frac{m}{s}$$

Bubble Velocity

Bubble velocity is given as

$$U_b = uo - umf + (0.71)(gdb)^{0.5}$$

Where

d_b = bubble size

$u_o = 3.78$ m/s

$U_{mf} = 0.251$ m/s

$g = 9.8$ m/s

$$d_b = 0.0037(u_o - umf)^2$$

$$d_b = 0.046 \text{ m}$$

Putting values of variable in above equation

$$U_b = 0.38 - 0.251 + (0.71)((9.8)(0.046))^{0.5}$$

$$U_b = 4 \text{ m/s}$$

Pressure Drop

$$\frac{\Delta P}{h} = \left(\rho_p - \rho_f\right)(1 - \varepsilon)g$$

$$\Delta P = 2.17 \text{ kPa}$$

Where

ρ_p = Density of particle(Rice Straw) = 420 kg/m^3

ρ_f= Fluid Density = 1.42 kg/ m^3

g = Gravity = 9.81 m/s

ε = Porosity of Bed = $\varepsilon = 0.78$

SPECIFICATION SHEET	
Identification	
Item	Gasifier
Item no.	G-101
No. of required	1
Operation	Continuous
Type	Bubbling Fluidized bed Reactor
Function	
Gasification of Rice Straw to produce syngas, H_2S,N_2	
Chemical Reaction $C + H_2O \rightleftharpoons CO + H_2$ $C + O_2 \rightleftharpoons CO_2$ $C + \frac{1}{2}O_2 \rightleftharpoons CO$ $C + 2H_2 \rightleftharpoons CH_4$ $S + H_2 \rightleftharpoons H_2S$	
Length of reactor	12 m
Diameter of reactor	1.2 m
Volume of Reactor	10 m^3
Pressure Drop	2.17kPa

5.2 Design of Cyclone Separator

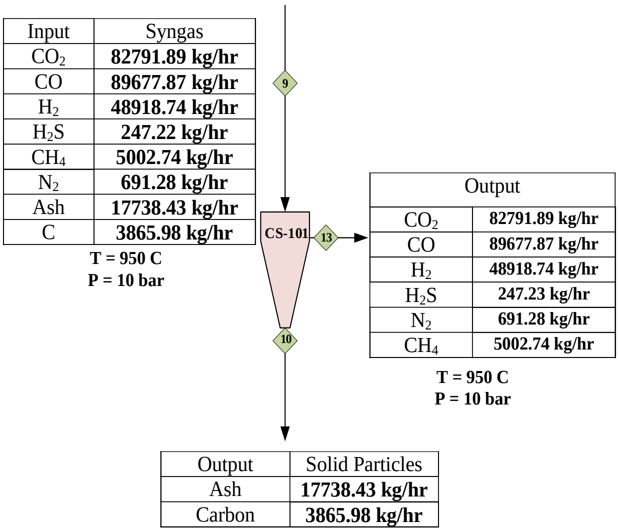
High Efficiency cyclone separator:

A rotating airflow (vortex) is created when tangentially approaching the separator from the top, the dust-filled air stream enters. Centrifugal force is used to move the dust particles around the exterior wall, where they're split apart and deposited in spiral pattern to the ultimate collection location. The vortex in the bottom part of the covering forces the air stream to turn around and move upward. The separation of dust with a low fibre and granule content is particularly well suited to the use of cyclone separators.

Fast separation rates and little pressure loss are combined by cyclones with return air plenums by using a pressure recoup in the head side. These cyclones can handle extremely high material loads while maintaining the best separation rates since they are built for larger air volumes and when used with spiral intakes. The cyclone separators' air volume ranges from 100 to 20,000 m3/h at 60 CFM to 11,770 CFM. Their robust design and protected internal lining offer the highest levels of dependability, safety, and reliability in addition to a long service life.

Advantages:

- High separation efficiency
- Simple separation of fine and finest particles
- Continuous operation
- Robust design
- Can be operated with positive or negative pressure
- Pressure drop is reduced thanks to a pressure recover piece in the top portion
- Exact variation to any air volume due to a wide range of obtainable sizes



Input	Syngas
CO_2	**82791.89 kg/hr**
CO	**89677.87 kg/hr**
H_2	**48918.74 kg/hr**
H_2S	**247.22 kg/hr**
CH_4	**5002.74 kg/hr**
N_2	**691.28 kg/hr**
Ash	**17738.43 kg/hr**
C	**3865.98 kg/hr**

T = 950 C
P = 10 bar

Output	
CO_2	**82791.89 kg/hr**
CO	**89677.87 kg/hr**
H_2	**48918.74 kg/hr**
H_2S	**247.23 kg/hr**
N_2	**691.28 kg/hr**
CH_4	**5002.74 kg/hr**

T = 950 C
P = 10 bar

Output	Solid Particles
Ash	**17738.43 kg/hr**
Carbon	**3865.98 kg/hr**

Figure 5.2 Cyclone Separator

Design Calculations

Number of Cyclones

$$\text{No of cyclone} = \frac{\text{Dc Proposed}}{\text{Dc Standard}}$$

$$\textbf{No of cyclones} = \mathbf{3}$$

Standard velocity = 9-27 $\frac{m}{s}$ $(R.K.Sinnott)$

Using;

Velocity= 18 $\frac{m}{s}$

$$\text{Volumetric flowrate} = \frac{\text{Massflowrate}}{\text{Density}} = \frac{266556}{94} = 0.78\,\frac{\text{m}^3}{\text{s}}$$

$$\text{Inlet duct area} = \frac{\text{Volumetric flowrate}}{\text{Velocity}} = 0.044\text{m}^2$$

$$\text{Duct area} = 0.044\text{m}^2 = 0.5\text{Dc} \times 0.2\text{Dc}$$

Dc proposed = 0.63

Calculation for single cyclone

$$\text{Flowrate enteringof the gas} = \frac{266556}{3} = 88852\,\frac{\text{kg}}{\text{hr}}$$

$$\text{Volumetric flowrate} = \frac{\text{Massflowrate}}{\text{Density}} = \frac{88852}{94} = 945\,\frac{\text{m}^3}{\text{hr}} = 0.263\,\frac{\text{m}^3}{\text{s}}$$

Inlet duct area

$$\text{Inlet duct area} = \frac{\text{volumetric flowrate}}{\text{velocity}} = \frac{0.263}{18} = 0.014\text{m}^2$$

$$\text{Duct area} = 1.5\text{Dc} \times 1.2\text{Dc} \quad (\text{from fig 10.44 R. K sinnott vol} - 6)$$

$$\text{Dc} = 0.6\text{m}$$

No of effective Turns

$$N = \left(\frac{1}{4}\right)\left(\frac{L_B + L_C}{2}\right)$$

$\mathrm{T} = 0.314$ secc

$Dc = 0.60m$

Height $= 0.5(0.6) = 0.3\mathrm{m}$

$\mathrm{L_B} = 1.5\mathrm{Dc} = (1.5)(0.6) = 0.9\mathrm{m}$

$\mathrm{L_C} = 2.5\mathrm{Dc} = (2.5)(0.6) = 1.5\mathrm{m}$

$$\mathbf{N = 4}$$

Gas Residence Time

$$\mathrm{T} = \frac{\text{Path Lenght}}{\text{Speed}} = \frac{\pi \mathrm{DcN}}{\mathrm{V_1}}$$

$V = 18\frac{m}{s}$

$$\mathbf{T = 0.418\ sec}$$

Particle Drift Velocity

$$\mathrm{V_t} = \frac{\mathrm{W}}{\mathrm{T}}$$

$\mathrm{W} = 0.2\mathrm{Dc} = 0.12\mathrm{m}$

$\mathrm{T} = 0.418$ sec

Pressure Drop Calculation

$$\Delta \mathrm{P} = \frac{\rho_\mathrm{f}}{203}\left[\mathrm{u}_1^2\left(1 + 2\emptyset^2\left\langle\frac{2\mathrm{r}_1}{\mathrm{r_e}} - 1\right\rangle\right) + 2\mathrm{u}_{12}^2\right]$$

$\Delta P =$ cyclone pressure drop $=$ millibar

$\rho_f =$ Gas density at outlet $= 0.5\ \frac{kg}{m^3}$, $u_1 = Inlet\ duct\ velocity = 18\frac{m}{s}$

$u_2 = E$xit duct velocity $= \frac{\text{Volumetric Flowrate}}{\text{Area of Exist Pipe}} = 3.7\frac{\mathrm{m}}{\mathrm{s}}\mathrm{r_1}$

$\mathrm{r_1} =$ Radius to circle to which the center line of the inlet is tangential,

$r_1 = \left[0.6 - \left(\frac{0.12}{2}\right)\right] = 0.55\ m$

$$r_e = Exist\ pipe,\ m = 0.5\mathrm{Dc} = 0.3\mathrm{m}$$

$$\frac{r_1}{r_e} = 1.83$$

SPECIFICATION SHEET	
Identification	
Item	Cyclone Separator
Item no.	CL-101
No. of required	3
Operation	Continuous
Function	
To remove ash, unburn carbon from mixture of gases	
Operating Pressure	10 bar
Operating Temperature	950℃
Inlet Duct Area	0.0145 m^2
Inlet Duct diameter	0.6 m
Total Height	2.4m
Outlet duct area	0.07 m^2
Outlet duct diameter	0.375m
Scaling factor	6.7
No of effective turns	4
Gas residence time	0.418sec
Particle drift velocity	0.287 m/s
Pressure Drop	0.1bar

5.3 Design of Waste Heat Boiler (WHB-101)

Waste Heat Boiler

A waste heat boiler converts heat generated as a byproduct of another operation, heat that would otherwise be squandered, into steam. Steam may be used to power turbines that generate energy. The boiler may also be used to merely heat water or other types of fluid. A waste heat boiler, also known as a waste heat recovery boiler, can lower a system's fossil fuel consumption and operating costs by recycling part of the energy utilized. This also implies that less greenhouse gases enter the atmosphere.

Types of waste heat boiler:

Waste heat boiler design have main two types:

- fire-tube boilers
- water-tube boilers

We have selected water tube waste heat boiler due to following reasons

Advantage:

- More intense operating pressures
- Higher output temperature
- reliable Design
- Handling of precise load fluctuation
- Generation of superheated steam
- Fast recovery of heat
- Better turn down

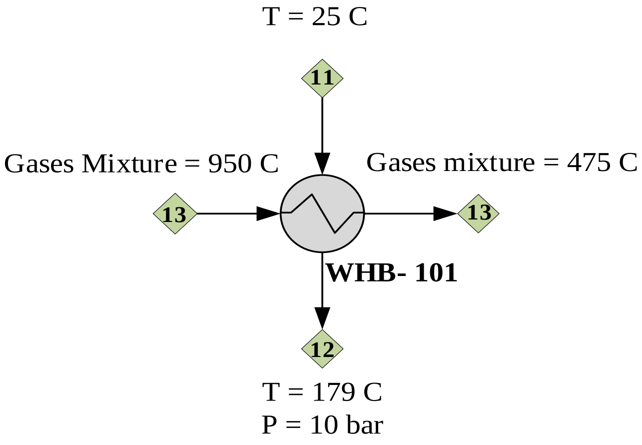


Figure 5.3 Waste Heat Boiler (WHB-101)

Design Calculations

Conditions

$T_{in} = 950\ ^0C$

$T_{out} = 475\ ^0C$

Heat Duty

$T_{in} = 950\ ^0C$

$T_{out} = 475\ ^0C$

$Q = 6.3 \times 10^7$ BTU/hr

Steam Requirement

Pressure =10 bar

$\dot{m} = 29642$ Kg/hr

Energy Requirement and Heat Production

2% Heat Loss

$Q_T = Q_u + 0.02\ Q_t$

$Q_T = 6 \times 10^7$ Btu/hr

Water Requirement

M_F= Mass flow of steam (M_F) + Blow Down (M_B)

$M_s = M_F - 0.1M_f$

$M_s = 64145$ lb/hr

$\Delta t_1 = 950-179 = 771^0C$

$\Delta t_2 = 475-25 = 450^0C$

Log Mean Temperature Difference:

$$\text{LMTD} = \frac{\Delta t_1 - \Delta t_2}{\ln\left(\frac{\Delta t_1}{\Delta t_2}\right)}$$

LMTD = 1104°F

U_D = 50 BTU/hrft^2 ^{0}F (Table 08)

Area

Q = AU_DΔt

A = 1056 ft^2

Heat Balance

Gases (Hot Fluid)

Q = mc_pΔt

Q = 6.3 × 10^7 BTU/hr.

Steam

Q = mλ

Q = 6.3 × 10^7 BTU/hr

Suppose

a= 0.3925 ft^2 (Table 10) (Tube OD 1.5 in)

Number of tubes

$$N_t = \frac{A}{L \times a}$$

N_t = 168

Nearest Count Nt=170 , ID of Shell=33 inch

Corrected U_D:

$$A_t = \frac{N_t}{L \times a}$$

A = 1056 ft^2

U_D = Q/AΔt

U_D = 53.4 BTU/hrft^2 ^{0}F

Tube Side (Steam) Calculations

Flow Area

$a_t = 0.302\ in^2$ (Table#10)

$$a_t = \frac{N_t \times a_t}{144 \times n}$$

$a_t = 1.8\ ft^2$

Mass Velocity

$$G_t = \frac{w}{a_t}$$

$G_t = 28410.2$ lb/hr ft^2

μ = 0.363 lb/ft hr

Tube ID = 1.40 in (Table 10) = 0.11 ft

Reynold Number

$$R_e = \frac{D_i \times G_t}{\mu}$$

Re = 5609

h_{io}=1500 BTU/hr ft^2. F

Shell Side (Gases) Calculations

Flow Area

$$a_s = \frac{ID \times C \times B}{144 \times P_t}$$

$a_s = 1.4\ ft^2$

Mass Velocity

$$G_s = \frac{w}{a_s}$$

$G_s = 46677$ lb/hr.ft^2

$\mu = 0.024\ c_p \times 2.42$

μ = 0.05 lb/ft.hr

D_e = 1.48 in (Fig 28) = 0.12 ft

Reynold Number

$$R_e = \frac{D_e \times G_s}{\mu}$$

R_e = 93354

J_h =180 (Fig 28)

k= 0.05 BTU/hr.ft^2. F

C_p = 1.07 BTU/lb. F

$$\frac{(C_p \times \mu)^{\frac{1}{3}}}{(k)^{\frac{1}{3}}} = 1.02$$

$$\frac{h_o}{\Phi_s} = \frac{J_h \times k}{D_e \times 1.02}$$

h_o =92 BTU/hr ft^2. F

Clean Overall Coefficient

$$U_c = \frac{h_{io} \times h_o}{h_{io} + h_o}$$

U_C= 86 BTU/hr ft^2.°F

Dirt Factor:

$$R_d = \frac{U_c - U_d}{U_c \times U_d}$$

R_d = 0.0004

$$\frac{1}{U_d} = \frac{1}{U_c} + R_d$$

U_D = 53 BTU/hr ft^2.°F

Pressure Drop Calculations

Tube Side

R_e = 8609

Ƒ = 0.04

S_G = 0.0931

$$\mathbf{\Delta P_t = \frac{f \times n_p \times L \times G^2}{7.5 \times 10^{12} \times D_i \times \text{Ƨ} \times \phi_s}}$$

ΔP_t = 0.006 psi

Shell Side

R_e = 93354

f= 0.0018 (Figure # 2) (PHT Donald Q.Kern)

No. of Crosses: N+1= $\frac{12 \times L}{B} = \frac{12 \times 16}{6.6} = 29$

D_s = 33 inch

$$\Delta P_s = \frac{f \times G^2 \times d_s \times (N+1)}{\mathbf{7.5 \times 10^{12} \times D_e} \times \text{Ƨ} \times \phi_s}$$

ΔP_s = 0.0004 psi

<table>
<tr><th colspan="4">SPECIFICATION SHEET</th></tr>
<tr><th colspan="4">Identification</th></tr>
<tr><td colspan="2">Item</td><td colspan="2">Waste Heat Boiler (WHB-101)</td></tr>
<tr><td colspan="2">Type</td><td colspan="2">Water Tube Boiler</td></tr>
<tr><th colspan="4">Function</th></tr>
<tr><td colspan="4">To Decrease The Temperature Of Process Stream</td></tr>
<tr><td colspan="2">Heat Duty</td><td colspan="2">6.3*10^7 Btu/hr.</td></tr>
<tr><td colspan="2">Heat Transfer Area</td><td colspan="2">1056 ft^2</td></tr>
<tr><td colspan="2">Uc Calculated</td><td colspan="2">86 Btu/hr.ft^2. °F</td></tr>
<tr><td colspan="2">UD Calculated</td><td colspan="2">53 Btu/hr.ft^2. °F</td></tr>
<tr><td colspan="2">Dirt Factor</td><td colspan="2">0.0004 Btu/hr.ft^2. °F</td></tr>
<tr><th colspan="2">FLUID ALLOCATION</th><th>SHELL SIDE</th><th>TUBE SIDE</th></tr>
<tr><td colspan="2">Fluid Name</td><td>Gases</td><td>Steam</td></tr>
<tr><td colspan="2">Fluid Quantity (Total)</td><td>65212 lb/hr.</td><td>51031 lb/hr</td></tr>
<tr><td colspan="2">Temperature (in/out)</td><td>950 °C to 475 °C</td><td>25 °C to 179 °C</td></tr>
<tr><td colspan="2">Pressure</td><td>10 bar</td><td>10 bar</td></tr>
<tr><td colspan="2">Viscosity</td><td>0.05 lb/ft.hr.</td><td>0.363 lb/ft.hr.</td></tr>
<tr><td colspan="2">Thermal Conductivity</td><td>0.05 Btu/hr. ft. °F</td><td></td></tr>
<tr><td colspan="2">Pressure Drop</td><td>0.0004 psi</td><td>0.0002 psi</td></tr>
<tr><td>Tubes No: 170</td><td>OD: 11/2</td><td>BWG:18</td><td>Pitch:17/8-in (Square)</td></tr>
<tr><td colspan="4">Shell ID: 33 in</td></tr>
</table>

5.4 Design of Packed Bed Scrubber (A-101)

Scrubber

A scrubber's operation is based on the ideas of mass transfer and gas-liquid contact. A gas stream carrying pollutants is passed through a liquid in a scrubber, where the contaminants are extracted from the gas.

The scrubbing liquid can be water or a chemical solution, depending on the nature of the pollutants to be removed. The liquid is usually sprayed into the gas stream, which is composed of tiny droplets or a mist.

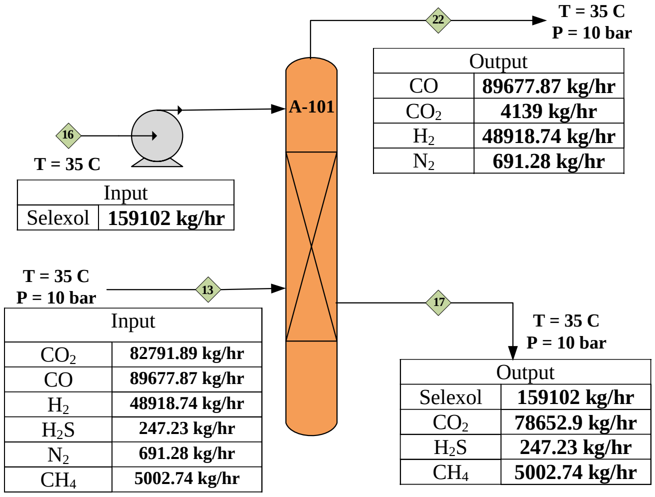
Types of Scrubber Plate Columns

- Packed bed absorbesr/scrubbers
- Plate column absorbers/scrubbers
- Venturi scrubbers
- Spray tower scrubbers.
- Bubble column absorbers/scrubbers

Section Criteria

We have selected Packed column due to following reasons:

- In packed column there is low pressure drop.
- Packed column are more appropriate for corrosive and foamy services.
- Liquid holdup requirement is also low.
- There are more options for packing construction materials, especially for corrosive service (such plastic, ceramic, and metal alloys).



Input	
Selexol	**159102 kg/hr**

Input	
CO_2	**82791.89 kg/hr**
CO	**89677.87 kg/hr**
H_2	**48918.74 kg/hr**
H_2S	**247.23 kg/hr**
N_2	**691.28 kg/hr**
CH_4	**5002.74 kg/hr**

Output	
CO	**89677.87 kg/hr**
CO_2	**4139 kg/hr**
H_2	**48918.74 kg/hr**
N_2	**691.28 kg/hr**

Output	
Selexol	**159102 kg/hr**
CO_2	**78652.9 kg/hr**
H_2S	**247.23 kg/hr**
CH_4	**5002.74 kg/hr**

Figure 5.4 Scrubber (A-101)

Design Calculations

Flow Factor (F_{LV})

$$F_{Lv} = \frac{L}{G}\sqrt{\frac{\rho g}{\rho l}} = 0.04$$

$$\text{Flow rate of entering gas} = G = 63.14\ {}^{kg}/_{s}$$

$$\text{Flow rate of entering slovent} = L = 44.195\ {}^{kg}/_{s}$$

$$\text{Density of liquid(solvent)} = \rho_l = 1030\ \text{kg/m3}$$

$$\text{Density of gas mixture} = \rho_g = 3.37\ \text{kg/m3}$$

$$\text{For 32.5mm of} \frac{H_2O}{m} \text{of packing} \quad (\text{R. K Sinnott})$$

$$k_4 = 1.5\ (\text{From fig 11.44})$$

Diameter of Column

$$Vw^* = \left[\frac{K_4\rho_g(\rho_L - \rho_g)}{13.1F_P({}^{\mu_L}/_{\rho_L})^{0.1}}\right]^{0.5} \qquad = 7.84\ {}^{kg}/_{m2s}$$

$$\text{Viscosity of liquid(solvent)} = \mu l = 0.0058\ \text{Pa.s}$$

$$\text{Density of liquid(solvent)} = \rho_l = 1030\ \text{kg/m3}$$

$$\text{Density of gas mixture} = \rho_g = 10.37\ \text{kg/m3}$$

$$\text{Size Of Packing } 1.5 - \text{inch ceramic}$$

$$\text{intalox saddles} = \text{Fp} = 170\text{m}^{-1}\ (\text{R. K Sinnott})$$

$$A = \frac{G}{Vw^*} = \frac{63.14}{7.84} = 8.6\text{m2}$$

$$\text{Diameter of column} = D = \sqrt{\frac{4\times A}{\pi}} = 3.2\text{m}$$

Calculation of height of transfer units of Scrubber

$$\frac{a_w}{a} = 1 - \exp\left[-1.45(\frac{\sigma_c}{\sigma_L})^{0.75}(\frac{L_W}{a\mu_L})^{0.1}(\frac{Lw^2 a}{\rho_{2L} g})^{-0.05}(\frac{L_W}{\rho_L \sigma_L a})^{0.2}\right]$$

$$\mathbf{a_w = 743\ {m^2}/{m^3}}$$

a_w = Effective interficial area of packing per unit volume = $743\ {m^2}/{m^3}$

a = Actual area of packing per unit volum = $194\ {m^2}/{m^3}$ (Table 11.2)

σ_c = Critical surface tension for particular material = $61e - 3$ N/m

L_W =Liquid mass velocity =4.11 $\frac{kg}{m^2 S}$

$$\mu_L = 5.8 * 10e - 3\ \text{pa. sec}$$

$$\sigma_L = 32e - 3\ \text{N/m}$$

Calculation of Liquid film Mass transfer Coefficient

$$K_{L:}\left[\frac{\rho_L}{\mu_L g}\right]^{1/3} = 0.0051\left[\frac{L_W}{a_w \mu_L}\right]^{2/3}\left[\frac{\mu_L}{\rho_L D_L}\right]^{-1/2}[adp]^{0.4}$$

K_L= 4.4 × 10e-4m/s

K_L= liquid film coefficient m/s

d_p= packing size = 2in = 51mm (Table 11.2)

D_L = Diffusivity of liquid (solvent) = 0.538×10^{-9}m2/s

ρ_L= $1030\ {}^{kg}/_{m^3}$

$a = \text{ Actual area of packing per unit volum} = 108\ {}^{m^2}/_{m^3}$ (Table 11.2)

$L_W = 4.11\ \frac{kg}{m^2S}$

$\mu_L = 5.8$

$g = 9.8\ m/s$

Calculation of gas film Mass transfer Coefficient

$$K_G \frac{RT_g}{D_g a} = K_5 \left[\frac{V_W}{a\mu_g}\right]^{0.7} \left[\frac{\mu_g}{\rho_g D_g}\right]^{1/3} [adp]^{-2}$$

$$\mathbf{K_G = 1.5 \times 10^{-3}\ {}^{kmol}/_{m^2.s.atm}}$$

K_5=5.23 for packing above 15mm

V_w= $7.48\ \frac{kg}{m^2S}$

$a_w = 545\ {}^{m^2}/_{m^3}$

$a = \text{ Actual area of packing per unit volum} = 108\ {}^{m^2}/_{m^3}$ (Table 11.2)

$\sigma_c\ = \text{Critical surface tension for particular material} = 61e - 3\ N/m$

$D_g = \text{Diffusivity of gases} = 0.00001565 m^2/s$

d_p= packing size = 51mm

ρ_g= $1.37\ {}^{kg}/_{m^3}$

$T_g = 308K$

$g = 9.8\ m/s$

$\mu_g = 1.4 \times 10^{-5} Pa.s$

$R = 0.08314\ {}^{atm\ m^3}/_{kmol\ K}$

Gas Film Transfer Unit Height

$$H_G = \frac{G_m}{kga_w\rho}$$

$$\mathbf{H_G = 0.09m}$$

G_m = Gas mass velocity = 0.77 kgmol/m^2 .s

P_G = Pressure of gases = 10 bar

K_G = Gas film coefficient = 1.5 x 10^{-3} kmol/m^2 .s.bar

a_w = Effective interfacial area of packing per unit volume = 743 m^2 /m^3

H_G = Gas film transfer unit height, m

Calculation of Liquid transfer unit height

$$H_L = \frac{L_m}{K_L a_w C_t}$$

$$\mathbf{H_L = 1.69\ m}$$

L_m = Liquid mass velocity = 5.7 kg/m^2 .s

C_t = Total Concentration=ρ_L / Molecular weight of solvent = 3.68 kmol/m^3

K_L = Liquid film coefficient =4.4 *10^-6m/s

a_w = Effective interfacial area of packing per unit volume = 743 m^2 /m^3

H_L = Liquid film transfer unit height, m

Calculation of height of transfer unit

$$H_{OG} = H_G - \frac{mG_m}{L_m} \times H_L$$

$$\mathbf{H_{OG} = 1.35m}$$

$$H_G = 0.09m$$

$$H_L = 1.69m$$

$$\frac{mG_m}{L_m} = 0.75 \qquad (\text{Range } 0.7 - 0.8)$$

Equation for equilibrium curve

y_1 = Mole fraction of H2S, CO2 & CH4 in entering gas stream = 0.341

y_2 = Mole fraction of H2S, CO2 & CH4 in Leaving gas stream = 0.028

$^{y_1}/_{y_2} = 12.7$

$$N_{OG} = 5.2 \text{ (From Fig 11.40)}$$

Calculation of height of Tower

$$z = N_{OG} \times H_{OG}$$

$$\text{Allowance for liquid distribution \& redistribution} = 0.69\text{m} + 0.69\text{m}$$

$$\boldsymbol{z = 8.28m}$$

Calculation of Wetting rate

$$\text{wetting rate} = \frac{\text{volumetric flow rate}}{\text{a}} = \mathbf{3.9 \times 10^{-4}\ {}^{m^2}/_{s}}$$

$$\text{volumetric liquid flowrate} = 0.043\ {}^{m^3}/_{s}$$

$$\text{a} = \text{Actual area of packing per unit volume} = 108\ {}^{m^2}/_{m^3}$$

Percentage Flooding

$$Percentage\ \text{Flooding} = [\frac{\text{K4 at design pressure drop}}{\text{K4 at flooding}}]^{1/2}$$

$$\text{Percentage Flooding} = [\frac{1.5}{3.7}]^{\frac{1}{2}} \times 100 = \mathbf{67}\%$$

Pressure Drop

$$\Delta P = \alpha \times 10^{BL}\left(\frac{G^2}{\rho_A}\right)$$

$$\rho_{\ g} = 3.37\ {}^{kg}/_{m^3}$$

$$L_{\ m} = 4.8\ {}^{kg}/_{m^2 s}$$

$$G_{\ m} = 6.86\ {}^{kg}/_{m^2 s}$$

$\alpha = 0.14$ (From table)

$$\beta = 0.14$$

SPECIFICATION SHEET	
Identification	
Item	Scrubber
No. of required	A-101
Operation	Continous
Type	Packed
Packing	Ceramic Intalox saddles
Function	
To absorb H_2S, CH_4 and CO_2 gas from Product Stream	
Operating Temperature	35 ℃
Operating Pressure	10 bar
Diameter	3.3m
Interfacial Area of Packing	$545m^2/m^3$
Height of Transfer unit	1.35m
Number of Transfer Unit	5.2
Column Height	8.28m
Pressure Drop	1.5 Pascal

5.5 Design of Packed Bed Steam Stripper

Packed column can be due to following reasons:

- In packed column, there is low pressure drop.
- Packed column are more suited for corrosive and foamy services.
- There are more options for packing construction materials, especially for corrosive service (such plastic, ceramic, and metal alloys).

Flow Factor (F_{LV})

$$F_{LV} = \frac{L}{G}\sqrt{\frac{\rho_g}{\rho_l}} = 0.10$$

$$\text{Flow rate of entering gas} = G = 25.3\ {}^{kg}/_{s}$$

$$\text{Flow rate of entering slovent} = L = 44.195\ {}^{kg}/_{s}$$

$$\text{For 30 mm of} \frac{H_2O}{m} \text{of packing} \quad (\text{R. K Sinnott})$$

$$k_4 = 1.\ 5(\text{From fig 11.44 })$$

Diameter of Column

$$G^* = [\frac{K_4\rho_g(\rho_L - \rho_g)}{131F_P({}^{\mu_L}/_{\rho_L})^{0.1}}]^{0.5} \qquad = \mathbf{2.87}\ {}^{\mathbf{kg}}/_{\mathbf{m^2\ s}}$$

$$\text{Packing parameter for 2 − inch ceramic intalox saddles} = Fp = 130m^{-1}\ (\text{R. K Sinnott})$$

$$A = \frac{G}{G^*} = \frac{25.3}{2.87} = 8.8\ m^2$$

$$\text{Diameter of column} = D = \sqrt{\frac{4\times A}{\pi}} = 2.9m$$

Calculation of height of transfer units

$$\frac{a_w}{a} = 1 - \exp\left[-1.45(\frac{\sigma_c}{\sigma_L})^{0.75}(\frac{L_W}{a\mu_L})^{0.1}(\frac{Lw^2a}{\rho_{2L}g})^{-0.05}(\frac{L_W}{\rho_L\sigma_L a})^{0.2}\right]$$

$$\mathbf{a_w = 408}\ {}^{\mathbf{m^2}}/_{\mathbf{m^3}}$$

$$a_w = \text{Effective interficial area of packing per unit volume} = 408\ {}^{m^2}\!/_{m^3}$$

$$a = \text{ Actual area of packing per unit volum} = 108\,{}^{m^2}\!/_{m^3}\ \text{(Table 11.2)}$$

$$\sigma_c = \text{Critical surface tension for particular material} = 0.0061\ \text{N/m}$$

L_W =Liquid mass velocity = 3.4 $\frac{kg}{m^2S}$

$$\mu_L = 0.0058 N/m^2s$$

$$\sigma_L = 0.0032\ N/m$$

Calculation of Liquid film Mass transfer Coefficient

$$K_{L:}\left[\frac{\rho_L}{\mu_L g}\right]^{1/3} = 0.0051\left[\frac{L_W}{a_w \mu_L}\right]^{2/3}\left[\frac{\mu_L}{\rho_L D_L}\right]^{-1/2}[adp]^{0.4}$$

K_L= 5.2 $\times 10^{-6}$m/s

K_L= liquid film coefficient m/s

d_p= packing size = 51mm (Table 11.2)

$$D_L = \text{Diffusivity of liquid (solvent)} = 0.538 \times 10^{-9} m2/s$$

ρ_L= 1030 ${}^{kg}\!/_{m^3}$

$$a = \text{ Actual area of packing per unit volum} = 108\ {}^{m^2}\!/_{m^3}\ \text{(Table 11.2)}$$

L_W = 3.4 $\frac{kg}{m^2S}$

$$\mu_L = 0.0058\,{}^{N}\!/_{m^2}$$

$$g = 9.8\ m/s$$

Calculation of gas film Mass transfer Coefficient

$$K_G\frac{RT_g}{D_g a} = K_5\left[\frac{V_W}{a\mu_g}\right]^{0.7}\left[\frac{\mu_g}{\rho_g D_g}\right]^{1/3}[adp]^{-2}$$

$$\mathbf{K_G = 1.5 \times 10^{-3}\ {}^{kmol}\!/_{m^2.s.atm}}$$

K_5=5.23 for packing above 15mm

$L_W = 3.4 \frac{kg}{m^2 s}$

V_w= 1.94 $\frac{kg}{m^2 s}$

$$a_w = 408 \, {m^2}/{m^3}$$

$$a = \text{ Actual area of packing per unit volum } = 108 \, {m^2}/{m^3} \text{ (Table 11.2)}$$

$$\sigma_c = \text{Critical surface tension for particular material} = 0.0061 \text{ N/m}$$

$$D_g = \text{Diffusivity of gases} = \mathbf{1.565 \times 10^{-5}} \, m^2/s$$

d_p= packing size = 51mm

Gas Film Transfer Unit Height

$$H_G = \frac{G_m}{kga_w\rho}$$

H_G =0.051m

G_m = Gas mass velocity = 0.062 kgmol/m^2 .s

P_G = Pressure of gases = 10 bar

K_G = Gas film coefficient = 1.5×10^{-3} kmol/m^2 .s.bar

a_w = Effective interfacial area of packing per unit volume = 408 m^2 /m^3

H_G = Gas film transfer unit height, m

Calculation of Liquid transfer unit height

$$H_L = \frac{L_m}{K_L a_w C_t}$$

H_L = 1.4 m

L_m = Liquid mass velocity = 0.012 kg/m^2 .s

C_t = Total Concentration=ρ_L / Molecular weight of solvent = 3.68 kmol/m^3

K_L = Liquid film coefficient =4.2×10^{-6} m/s

a_w = Effective interfacial area of packing per unit volume = 408 m^2 /m^3

H_L = Liquid film transfer unit height, m

Calculation of height of transfer unit

$$H_{OG} = H_G - \frac{mG_m}{L_m} \times H_L$$

$$\mathbf{H_{OG} = 1.134m}$$

$$H_G = 0.051m$$

$$H_L = 0.75m$$

$$\frac{mG_m}{L_m} = 0.75 \qquad (\text{Range } 0.7 - 0.8)$$

Equation for equilibrium curve

$$y_1 = \text{Mole fraction of H2S, CO2 \& CH4 in entering gas stream} = 0.415$$

$$y_2 = \text{Mole fraction of H2S, CO2 \& CH4 in Leaving gas stream} = 0.1$$

$$y_1/y_2 = 4.25$$

$$N_{OG} = 2.3(\text{From Fig 11.40})$$

Calculation of height of Tower

$$z = N_{OG} \times H_{OG}$$

$$\text{Allowance for liquid distribution \& redistribution} = 0.5m + 0.5m$$

$$\mathbf{z = 3.7m}$$

Calculation of Wetting rate

$$wetting\ rate = \frac{\text{volumetric flow rate}}{a} = \mathbf{3.8 \times 10^{-4}\ m^2/s}$$

$$\text{volumetric liquid flowrate} = 0.043\ m^3/s$$

$$a = \text{Actual area of packing per unit volum} = 108\ {}^{m^2}/_{m^3}$$

Percentage Flooding

$$\text{Percentage Floodig} = [\frac{\text{K4 at design pressure drop}}{\text{K4 at flooding}}]^{1/2}$$

$$\text{Percentage Flooding} = [\frac{1.5}{3.6}]^{\frac{1}{2}} \times 100 = \mathbf{66}\%$$

Pressure Drop

$$\Delta P = \alpha \times 10^{BL}\left(\frac{G^2}{\rho_g}\right)$$

$$\mathbf{\Delta P = 1.2Pa}$$

$$\rho_{\ g} = 1.25\ {}^{kg}/_{m^3}$$

$$L_{\ m} = 4.11\ {}^{kg}/_{m^2 s}$$

$$G_{\ m} = 2.87\ {}^{kg}/_{m^2 s}$$

$\alpha = 0.13$ (From Figure)

$$\beta = 0.15$$

SPECIFICATION SHEET	
Identification	
Item	Stripper
No. of required	S-101
Operation	Continous
Type	Packed column
Packing	Ceramic Intalox saddles
Function	
To absorb H_2S, CH_4 and CO_2 gas from Product Stream	
Operating Temperature	140C
Operating Pressure	2bar
Diameter	3.3
Interfacial Area of Packing	$408m^2/m^3$
Height of Transfer unit	1.134m
Number of Transfer Unit	2.3
Column Height	3.3m
Pressure Drop	1.2 pascal

5.6 Design of Heat Exchanger (HX-103)

Heat Exchanger (Shell and Tube)

A shell and tube heat exchanger is a type of heat exchanger that is widely used in various industries to transfer heat between two fluids. It comprises of a shell, which is a outsized cylindrical vessel, and a tube bundle inside the shell. The two fluids flow in reverse directions through the shell and the tubes, allowing heat to be transferred from one fluid to the other.

The fluid that flows inside the tubes is typically the one that needs to be heated or cooled, while the fluid that flows outside the tubes is usually a coolant or a heating medium. The design of the shell and tube heat exchanger can vary reliant on the specific application and the properties of the fluids involved.

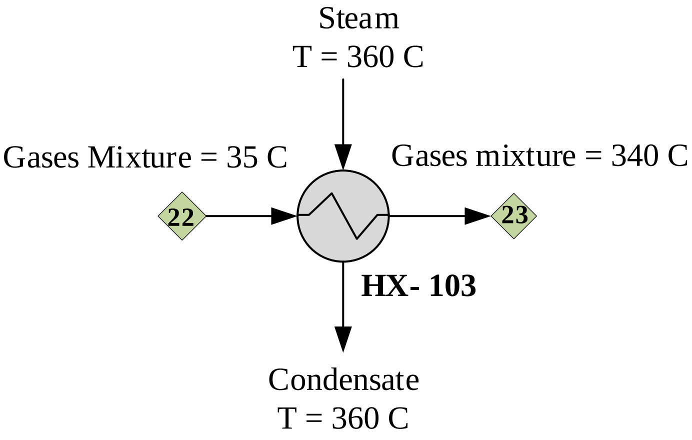


Figure 5.5 Shell and Tube Heat Exchanger (HX-103)

Design Calculations

$T_1 = 35$, $T_2 = 340$ ℃

$T_{out} = 357.4$ ℃

$\Delta t_1 = 322.4$ ℃

$\Delta t_2 = 17.4$ ℃

Log Mean Temperature Difference

$$\text{LMTD} = \frac{\Delta t_1 - \Delta t_2}{\ln\left(\frac{\Delta t_1}{\Delta t_2}\right)}$$

LMTD = 104.5 ℃ = 220 °F

Assume

U_D= 35 BTU/hr.ft^2 °F (Table 8) (Process Heat Transfer) (Donald Q. Kern)

Area

$$Q = AU_D\Delta t$$

A= 295.4 ft^2

Q= 2,274,761 BTU/hr.

Suppose

a = 0.2618 ft^2 (Table 10) (Tube OD $\frac{3}{4}$ in)

Number of tubes

$$N_t = \frac{A}{\pi \times d_o \times L}$$

$$N_t = \frac{295.4}{0.2618 \times 16}$$

$$N_t = 71$$

Corrected U_D

$$A = N_t \times L \times a$$

$$A = 71 \times 16 \times 0.2618$$

A= 318.3ft^2

$$U_D = \frac{Q}{A \times \Delta T}$$

$$U_D = \frac{2274761}{318.3 \times 220}$$

U_D= 33 BTU/hr.ft^2 °F

Tube Side (Gases Mixture) Calculations

N_t =76

Length =16 ft

OD =1 in

16 BWG

Pitch =1.25in (square)

Passes =

Flow Area

$$a_t = \frac{N_t \times a_t}{144 \times n}$$

$$a_t = \frac{76 \times 0.594}{144 \times 2}$$

$$a_t = 0.302 \text{ in}^2$$

Mass Velocity

$$G_t = \frac{w}{a_t}$$

$$G_t = \frac{316202}{0.156}$$

$$G_t = 2026935 \text{ lb/hr.ft}^2$$

μ= 2.42 lb/ft.hr

Tube ID = 0.870in (Table 10) = 0.0725 ft

Reynold Number

$$R_e = \frac{D_i \times G_t}{\mu}$$

R_e =60,724

Shell Side (Saturated Steam) Calculations

ID =15.25 in

Baffle space =3.05 in

Passes = 1

Flow Area

$$a_s = \frac{ID \times C \times B}{144 \times P_t}$$

$$a_s = \frac{15.25 \times 0.25 \times 3.05}{144 \times 1.25}$$

$$a_s = 0.156 \text{ ft}^2$$

Mass Velocity

$$G_s = \frac{w}{a_s}$$

$$G_s = \frac{67155}{0.25}$$

$$G_s = 268{,}620 \text{ lb/hr.ft}^2$$

μ=10cp × 2.42

μ=0.0605 lb/ft.hr

De = 0.99 in (Fig 28) = 0.0825 ft

Reynold Number

$$R_e = \frac{D_e \times G_s}{\mu}$$

R_e = 366,300

Clean Overall Coefficient

$$U_c = \frac{h_{io} \times h_o}{h_{io} + h_o}$$

U_C = 193.4 BTU/hr ft^2. °F

Dirt Factor

$$R_d = \frac{U_c - U_d}{U_c \times U_d}$$

R_d = 0.001 BTU/hr ft^2. °F

Pressure drop calculations

Tube Side

Ƒ= 0.00018 (Figure#26) (PHT Donald Q.Kern)

S_G =0.99756

$$\Delta P_t = \frac{f \times n_p \times L \times G^2}{5.22 \times 10^{12} \times D_i \times \text{ƨ} \times \phi_s}$$

ΔP_t = 0.39 psi

$$\Delta P_s = \frac{4n}{s \times \frac{V^2}{2g}}$$

$V^2/2g$ = 0.4 (fig.27)

ΔPs = 1.78

ΔP_T = 1.78 + 0.39 = 2.17psi

Shell Side

f = 0.0015 (Figure # 2) (PHT Donald Q.Kern)

No. of Crosses: N+1= $\frac{12 \times L}{B} = = 26.9$

$$\Delta \mathrm{P_s} = \frac{\mathrm{f} \times \mathrm{G}^2 \times \mathrm{d_s} \times (\mathrm{N}+1)}{\mathbf{7.5} \times \mathbf{10^{12}} \times \mathbf{D_e} \times \text{Ƨ} \times \phi_s}$$

$\Delta P_s = 1.57$ psi

<table>
<tr><th colspan="6">SPECIFICATION SHEET</th></tr>
<tr><th colspan="6">Identification</th></tr>
<tr><td colspan="2">**Item**</td><td colspan="4">Heat Exchanger (HX-103)</td></tr>
<tr><td colspan="2">**Type**</td><td colspan="4">Shell & Tube Heat Exchanger</td></tr>
<tr><th colspan="6">Function</th></tr>
<tr><td colspan="2">Heat Duty</td><td colspan="4">2274761 Btu/hr.</td></tr>
<tr><td colspan="2">Actual Surface Area</td><td colspan="4">318 ft^2</td></tr>
<tr><td colspan="2">Uc Calculated</td><td colspan="4">193.56 Btu/hr.ft^2. °F</td></tr>
<tr><td colspan="2">U$_D$ Calculated</td><td colspan="4">33 Btu/hr.ft^2. °F</td></tr>
<tr><td colspan="2">Dirt Factor</td><td colspan="4">0.0001 Btu/hr.ft^2. °F</td></tr>
<tr><th colspan="2">Fluid Allocation</th><th colspan="3">Shell side</th><th>Tube side</th></tr>
<tr><td colspan="2">Fluid Name</td><td colspan="3">Gases</td><td>Steam</td></tr>
<tr><td colspan="2">Fluid Quantity (Total)</td><td colspan="3">316,202 lb/hr.</td><td>67,155 lb/hr</td></tr>
<tr><td colspan="2">Temperature (in/out)</td><td colspan="3">35 to 340C</td><td>357.4C</td></tr>
<tr><td colspan="2">Viscosity</td><td colspan="3">0.0605 lb/ft.hr.</td><td>2.43 lb/ft.hr.</td></tr>
<tr><td colspan="2">Thermal Conductivity</td><td colspan="3">0.187 Btu/hr. ft. °F</td><td>0.48 Btu/hr. ft. °F</td></tr>
<tr><td colspan="2">Pressure Drop</td><td colspan="3">1.57 psi</td><td>2.17 psi</td></tr>
<tr><td>**Tubes No: 71**</td><td colspan="2">**OD:** 1</td><td>**BWG:**16</td><td colspan="2">**Pitch**:1.25 in Square</td></tr>
<tr><td colspan="6">**Shell ID:** 15.25 in</td></tr>
</table>

5.7 Design of Packed Bed Membrane Reactor (MR-101)

A membrane reactor is a type of reactor that combines a catalytic reaction with membrane separation process. A membrane in the membrane reactor used to separate selectively the products from the reaction mixture. This allows the reversible reaction to proceed in a control manner and increases the yield, selectivity and process effectiveness.

The gas mixture of CO and H_2O entering the Membrane reactor of 340 ^{o}C and pressure of 10 bar. As the shift gas reaction is moderately exothermic reactions whose heat of reaction is $\Delta H = -41.2$ KJ/mol. The shift gas reaction will first proceed in the HTSGR in the presence of Fe_2O_3, which is catalyst we are using here. The $Fe_2O_3$3 has outstanding performance for shift reactions.

As the reaction is reversible so to avoid the equilibrium, we are using the membrane reactor in which membrane will be selectively permeable (Pd based membrane) and will allow only hydrogen gas to pass from the membrane. By removing the product continuously, we will disturb the equilibrium. Even enabling CO_2 simultaneously. This simultaneous H_2 production and CO_2 Capture will increase the overall efficiency 30%.

Selection Criteria

- Gaseous phase reaction
- Due to solid catalyst
- Reaction is reversible

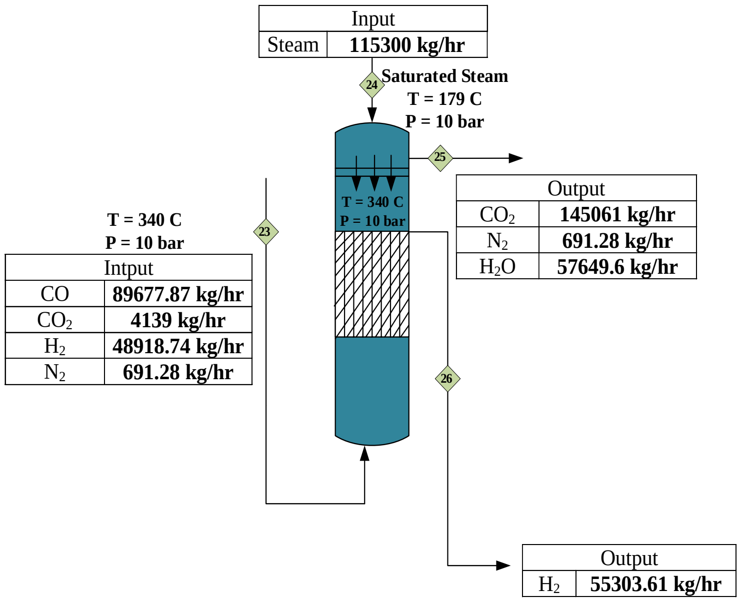


Figure 5.6 Packed Bed Membrane Reactor

Design Calculations

Reaction

$$CO + H_2O \longleftrightarrow H_2 + CO_2 \qquad \textbf{Conversion = 100 \%}$$

ΔH_r **= - 10 $\frac{Kcal}{mol}$ (low Exothermic)**

Reaction Conditions

T = 340 ℃

P = 10 bar

Rate Expression

$$r_{co} = k_o \exp^{\left(\frac{-E}{RT}\right)} \left[C_{C0}\, C_{H2O} - \frac{C_{CO2} C_{H2}}{K_e}\right]$$

Where,

$k_o = 2.16 \times 10^6 \frac{mol}{g.h.atm}$

$K_{e} = \exp\left(\frac{4577.8}{T} - 4.33\right)$

$E = 80 \frac{KJ}{mol}$

$R = 8.314 \frac{J}{mol.K}$

T = 613 K

Weight of the Catalyst Bed

$$\frac{W}{F_{AO}} = \int_0^{XA} \frac{d_X}{-r_A}$$

$$\frac{\mathbf{W}}{\mathbf{F_{Ao}}} = \mathbf{0.9} \text{ (} \textbf{Through area under the curve} \text{)}$$

$F_{AO} = 3202.7\ {}^{kmol}/_{hr}$

$$\textbf{Weight of Bed} = \mathbf{2883\ kg}$$

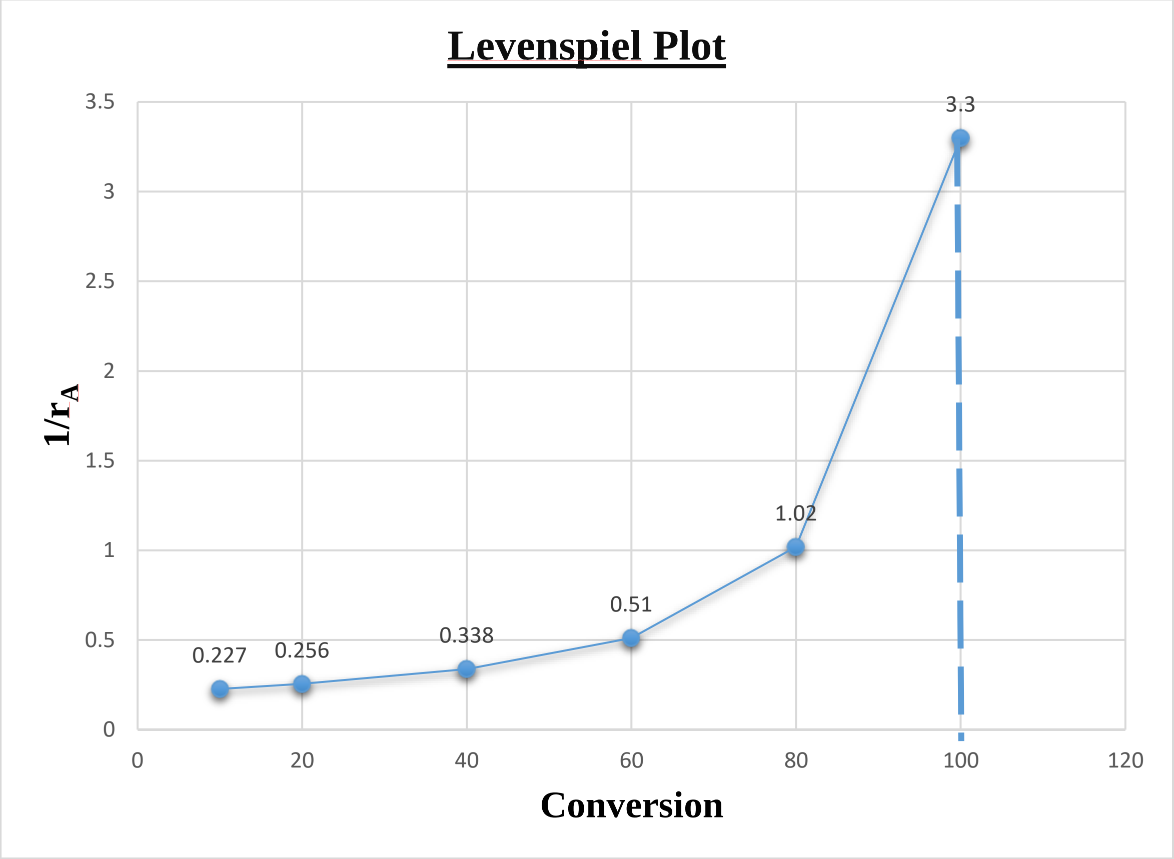


Figure 5.7 Levespiel plot for area under the curve

Volume of Catalyst Bed

Bulk density of catalyst $= 800\,{}^{\mathrm{kg}}/_{\mathrm{m^3}}$

Porosity $= \varepsilon = 0.26$

$$V = {}^{m}/_{\rho} = \frac{\text{weight of bed}}{\text{density}} = \frac{2883}{800} = \mathbf{3.6\ m^3}$$

Volume of Reactor

$$\text{Volume of reactor} = \frac{V_{\text{Catalyst}}}{1-\varepsilon} = \frac{3.6}{1-0.26} = \mathbf{5\ m^3}$$

Length of Reactor

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

$$\frac{\mathrm{L}}{\mathrm{D}} < 20$$

To maintain the plug flow in packed bed reactor we are putting

$$\frac{L}{D} = 40$$

$$L = 40\ D$$

$$\mathbf{D = 0.54\ m}$$

$$\mathbf{L = 22\ m}$$

With 5 % Safety Holdup Length = 23 m

Pressure Drop

$$\frac{\Delta P}{L} = \frac{150\mu G(1-\varepsilon)^2}{\rho D^2 \varepsilon^3} + \frac{1.75 G^2 (1-\varepsilon)}{\rho D \varepsilon^3}$$

$$\mathbf{\Delta P = 0.1\ kpa}$$

$$G = \text{Mass Velocity} = \frac{\text{Mass flowrate}}{\text{Diamter of reactor}} = 1.82\ {}^{\text{kg}}/_{\text{m}^2\text{s}}$$

$$A = \text{Area of Reactor} = \frac{\pi D^2}{2} + \pi\ D\ L\ = 39.4\ \text{m}^2$$

Weighted viscosity = 4.2×10^{-5} P

Weighted Density = 12.9 $\frac{\text{Kg}}{\text{m}^3}$

5.7.1 Design of Membrane

Selection of Membrane

- Pd-Ag 23 wt % Membrane
- Membrane separation is very affine
- Strong capacity for hydrogen production in pure form

Membrane Thickness = 0.1 mm

$$\text{Membrane Permeability} = 2.783\ \times 10^{-3} \exp\left(\frac{-22028}{RT}\right)$$

$$\mathbf{= 3.69 \times 10^{-5}\ \frac{mol.m}{m^2.s}}$$

Permeability Flux

$$J_H = \frac{P_{H2}}{\delta}\left(P_{H2}^{ret} - P_{H2}^{perm}\right)$$

$$\mathbf{J_H = 7.8 \times 10^{-4} \frac{mol}{m^2.s}}$$

Length of membrane = 16 m

Area of Membrane = $\frac{\pi D^2}{2}$ + π D L

Area of membrane = 27 m^2

5.7.2 Design of Cooling Jacket

In terms of control, effectiveness, and product quality, a jacket offers the best way to heat and cool a process vessel.

The three main types of Jackets are as follows

1. Spiral baffle Jacket
2. Half pipe coil Jacket
3. Dimple jacket

Selection of dimple Jacket

- Low pressure Drop
- Used for when low heat transfer rate are required
- As reaction is low exothermic

Design Calculations

Assuming 95 % area of PBR covered with jacket

$$A_j = \frac{\pi D^2}{2} + \pi D L = 37.5 \text{ m}^2$$

For Jacket:

$$\frac{h_o D_T}{k} = 0.85 \left(\frac{\rho D^2}{\mu}\right)^{0.33} \left(\frac{C_p \mu}{k}\right)^{0.66} \left(\frac{\mu}{\mu_s}\right)^{0.14}$$

Assume $\left(\frac{\mu}{\mu_s}\right) = 1$

$\mathbf{h_o = 215 \frac{W}{m^2 C}}$

Tank side

$$\frac{hD}{\lambda} = 0.73 \left(\frac{\rho D^2}{\mu}\right)^{0.33} \left(\frac{C_p \mu}{k}\right)^{0.66} \left(\frac{\mu}{\mu_s}\right)^{0.14}$$

h = $\mathbf{838} \ \frac{W}{m^2 \, C}$

$$U_c = \frac{h_o \times h}{h_o + h} = \mathbf{171} \ \frac{\mathbf{W}}{\mathbf{m^2 \, C}}$$

SPECIFICATION SHEET	
Identification	
Item	Reactor
Item no.	MR-101
No. of required	1
Operation	Continuous
Type	Packed Bed Membrane Reactor
Catalyst	Fe_2O_3
Function	
To Produce hydrogen from WGSR	
Chemical Reactions	
$CO + H_2O \rightleftharpoons H_2 + CO_2$	
Weight of Catalyst Bed	2883 Kg
Volume of Catalyst	3.6 m^3
Volume of Reactor	5 m^3
Space Time	1.1 sec
Diameter of Reactor	0.54 m
Type of Membrane	Pd-Ag wt %
Area of membrane	27 m^2
Pressure Drop	0.1 kPa

CHAPTER # 06

MECHANICAL DESIGN

6 Mechanical Design of Reactor (MR-101)

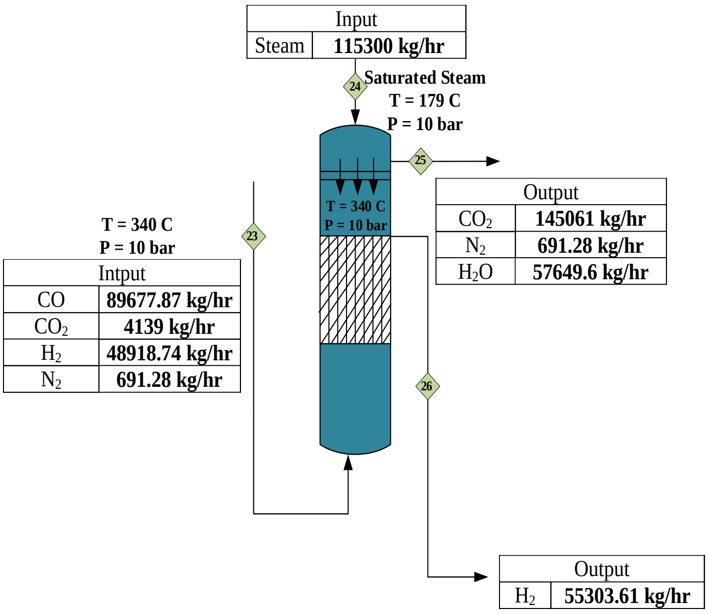


Figure 6.1 Packed Bed Reactor (MR-101)

6.1 Material Selection

We have selected Stainless Steel 304

- It has excellent toughness at high temperature and pressure applications.
- Used for high temperature gases and steam production processes.

6.2 Design Pressure and Temperature

Operating Temperature = 340 ℃

Design Temperature = **350** ℃

Operating Pressure = 10 bar = 146 psi

The maximum operating pressure is taken as 25 *psi above the normal operating pressure*

= 171 psi = **11.8 bar**

As the design, pressure is 10% above the maximum operating pressure

= 188 psi = **13 bar**

Diameter of Vessel

D_i = 0.54 m = 21.26 inch

6.3 Wall or Shell Thickness

For Cylindrical Shell

$$\mathrm{t} = \frac{\mathrm{PR}}{(\mathrm{S} - 0.6\ \mathrm{P})} = \mathbf{0.15\ inch}$$

Corrosion Allowance = 0.15 inch

t = Shell thickness = 0.3 inch = 7.37 mm

P = Design Pressure= 13 bar

R = Radius of Shell = 10.63 inch

S = Max Allowable tensile stress = 100 $N/_{mm^2}$ = 14504 psi

6.4 Outer Diameter of Shell

$$D_{\circ} = Di + 2t$$

$$D_{\circ} = 21.26 + (2 \times 0.3)$$

$$D_{\circ} = 21.84\ inch = 554\ \boldsymbol{mm}$$

6.5 Thickness of Domed Head

a) Torispherical Head

$$\mathrm{t} = \frac{(0.885\ \mathrm{PL})}{(\mathrm{SE} - 0.1\mathrm{P})} = 0.25\ \mathrm{inch} = \mathbf{6.35\ mm}$$

L = Crown Radius = Di = 21.26 inch

Diameter of Vessl= D_i = 21.26 inch

b) Ellipsoidal Head

$$\mathrm{t} = \frac{\mathrm{PDi}}{(2\mathrm{SE} - 0.2\mathrm{P})} = 0.14\ \mathrm{inch} = \mathbf{3.56\ mm}$$

6.6 Thickness of Flanged Head

$$\mathrm{t} = \mathrm{Di}\sqrt{0.3\ \frac{\mathrm{P}}{\mathrm{S}}} = 0.11\ \mathrm{inch} = \mathbf{2.79\ mm}$$

As we see that hemispherical head gives the minimum thickness so it will be more economical

6.7 Design Load

6.7.1 Dead weight of Vessel (W_v)

$$W_v = 240 C_w D_M (H_v + 0.8 D_M) t$$

$$\mathbf{W_v = 24178\ N}$$

C_w = factor to account for internal fittings = 1.08

D_M = mean dia of vessel = $(D_i + t \times 10^{-3})$ = 0.54 m

H_v = Height of Cylindrical shell = 23 m

Thickness of shell = 7.37 mm

6.7.2 Weight of fitting (by Ray Sinnott)

a. Caged Ladders (Steel) = 8280 N
b. Platform steel for vertical vessel = 39100 N

6.7.3 **Total Weight of Vessel**

$$W_T = W_v + W_f$$

$$W_T = 24178 + 8280 + 39100$$

$$\mathbf{W_T = 71558\ N = 71.5\ kN}$$

6.8 Wind Load

$$F_W = P_W + D_{eff}$$

$$\mathbf{F_W = 1326\ \frac{N}{m}}$$

P_w = Wind Pressure = 1280 $\frac{N}{m^2}$ (by Ray Sinnott)

D_{eff} = Effective column dia =

$$D_{eff} = D_o \times (\text{insulation thickness} + t) + \text{Allowance}$$

$$D_{eff} = 45.7\ m$$

Typical Insulation thickness = 75 mm

Allowance of added caged ladder = 0.4 m

Outer dia = D_o = 0.55 m

t = vessel thickness = 7.37 mm

6.9 Stress Calculations

6.9.1 Longitudinal Stresses

$$\sigma_h = \frac{PD_i}{2t} = \mathbf{47.63}\ \frac{\mathbf{N}}{\mathbf{m}\boldsymbol{m}^{\mathbf{2}}}$$

6.9.2 Circumferential Stresses

$$\sigma_L = \frac{PD_i}{4t} = \mathbf{23.8}\ \frac{\mathbf{N}}{\mathbf{mm^2}}$$

6.9.3 Dead Weight Stress

$$\sigma_W = \frac{W}{\pi(D_i + t)t} = \mathbf{5.64}\ \frac{\mathbf{N}}{\mathbf{mm^2}}$$

P = Design Pressure = 1.3 $^{N}/_{mm^2}$

D_i = Diameter of Shell = 554 mm

t = Thickness of Shell = 7.37 mm

W = Total weight of Vessel = 71558 N

6.9.4 Bending Stresses

$$\sigma_b = \frac{M_x}{l_v}\left(\frac{D_i}{2} + t\right) = \mathbf{180}\ \frac{\mathbf{N}}{\mathbf{mm^2}}$$

Bending moment = M_x = $\frac{wx^2}{2} = 350648\ Nm$

w = wind load per unit length = 1325.7 N/m

x = height of vessel = 23 m

l_v = second moment of area of vessel

$$= \frac{\pi}{64}\left(D_o^4 - D_i^4\right) = \mathbf{0.00054\ m}$$

D_i = Inner dia of reactor = 0.54 m

D_o = outer dia of reactor = 0.55 m

t = thickness of shell = 0.00737

6.9.5 Principal Stresses

$$\sigma_1 = \frac{1}{2}\left[\sigma_h + \sigma_z + \sqrt{(\sigma_h - \sigma_z)^2 + 4t^2}\right]$$

$$\sigma_1 = 209.44\ \mathrm{N/mm^2}$$

σ_h = longitudinal stress = 47.63 $\mathrm{N/mm^2}$

σ_z = total longitudinal stress = $\sigma_W + \sigma_b + \sigma_L$ = 209.44 $\mathrm{N/mm^2}$

t = Torsional Stress = 0

$$\sigma_2 = \frac{1}{2}\left[\sigma_h + \sigma_z - \sqrt{(\sigma_h - \sigma_z)^2 + 4t^2}\right]$$

$$\boldsymbol{\sigma_2 = 47.63\ \mathrm{N/mm^2}}$$

$$\sigma_3 = 0.5 \times P$$

$$\sigma_3 = -0.65\,\frac{\mathrm{N}}{\mathrm{mm^2}}$$

6.9.6 Allowable Stress Intensity

$$\sigma_1 - \sigma_2 = 161.81\ \mathrm{N/mm^2}$$

$$\sigma_1 - \sigma_3 = \mathbf{210.09\ N/mm^2}$$

(which is less than design stress)

$$\sigma_2 - \sigma_3 = 48.28\ \mathrm{N/mm^2}$$

CHAPTER # 07

POWER CALCULATIONS

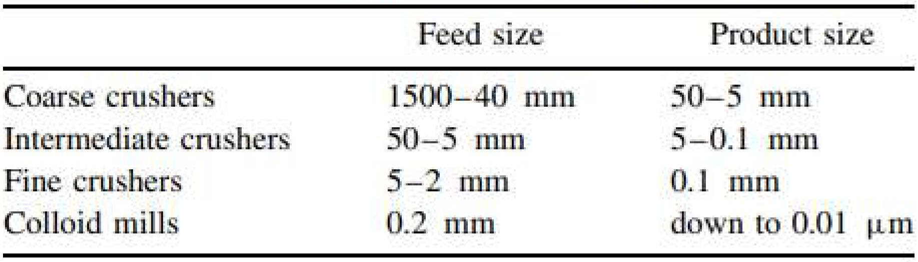
7 Power Calculations

7.1 Grinder

Grinding is a unit operation that involves the reduction of the size of solid particles to a desired average particle size distribution. In chemical engineering, grinding is often used as a preparatory step for other unit operations, such as mixing, separation, and extraction.

Grinding can be performed using a variety of equipment, including ball mills, hammer mills, roller mills, and impact mills. The characteristics of the material being ground and the desired particle size distribution will determine the equipment selection. For instance, brittle or friable materials are frequently ground in a ball mill, whereas hard or fibrous materials are typically ground in a hammer mill.

Table 2.1. Classification of size reduction equipment

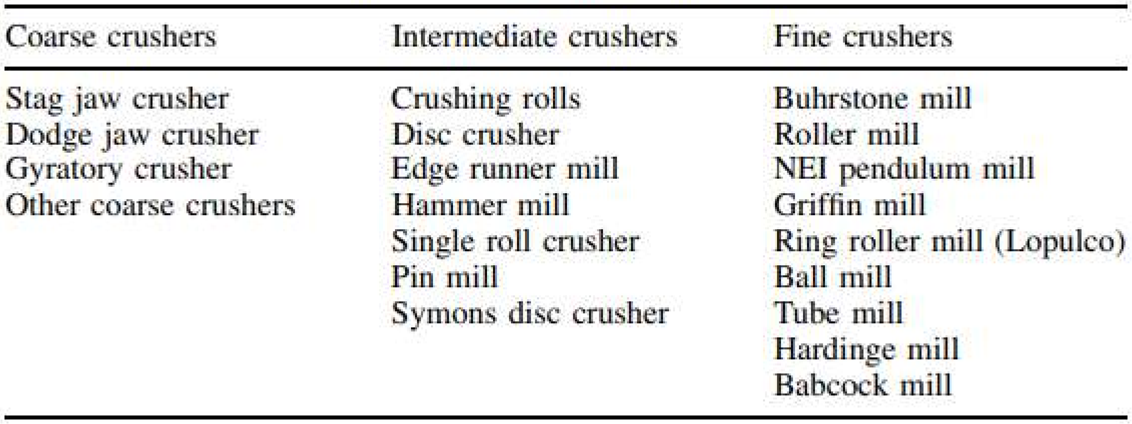


	Feed size	Product size
Coarse crushers	1500–40 mm	50–5 mm
Intermediate crushers	50–5 mm	5–0.1 mm
Fine crushers	5–2 mm	0.1 mm
Colloid mills	0.2 mm	down to 0.01 μm

Types of Crushing Equipment

The top coarse, intermediate, and fine crushers are included in the following Table.

Table 2.2. Crushing equipment



Coarse crushers	Intermediate crushers	Fine crushers
Stag jaw crusher	Crushing rolls	Buhrstone mill
Dodge jaw crusher	Disc crusher	Roller mill
Gyratory crusher	Edge runner mill	NEI pendulum mill
Other coarse crushers	Hammer mill	Griffin mill
	Single roll crusher	Ring roller mill (Lopulco)
	Pin mill	Ball mill
	Symons disc crusher	Tube mill
		Hardinge mill
		Babcock mill

Selection of Grinder

- As the particle size 50mm so it lies between intermediate crushers. So selecting the hammer mill for unit operation of size reduction

Hammer mil

The hammer mill is an impact mill that rotates at a high speed while holding several hammer bars that are swung outward by centrifugal force. Both a laboratory model and an industrial model are depicted. Material is fed into the machine from the top or the centre, and then it is centrifugally ejected out and crushed by being bashed between hammer bars or against breaker plates that are attached around the cylindrical casing's edge. The material is reduced in size until it can pass through the screen that makes up the lowest part of the casing. Any hard substance present does not harm the apparatus because the hammer bars are hinged. When necessary, the bars are easily replaced.

The hammer mill works well with hard materials, but because it generates a lot of fines, it's best to use positive pressure lubrication on the bearings to keep dust out. The size of the screen and the rate of rotation control the product's size.

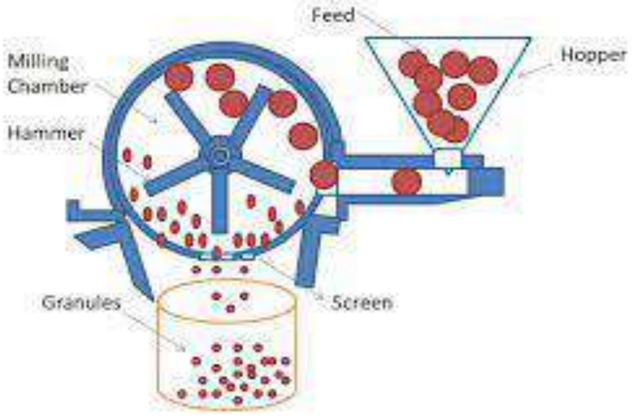


Figure 7.1 Hammer mill

7.2 Hammer mill Calculations

Mass flowrate entering the hammer mill = $\dot{m}$ = 152.40 $^{ton}/_{hr}$

Initial Particle Size = 50 mm

Final particle size = 0.5 mm

By using the Bond’s law of size reduction

$$p = \dot{m} \times 0.3162 \times w_i \left[\frac{1}{\sqrt{Dp_b}} - \frac{1}{\sqrt{Dp_a}}\right]$$

$$p = 152.40 \times 0.3162 \times 0.12 \times \left[\frac{1}{\sqrt{0.5}} - \frac{1}{\sqrt{50}}\right]$$

$$p = 7.34 \text{ KW}$$

$$\mathbf{p = 9.84\ h_p}$$

7.3 Pump

A mechanical device that moves fluids (liquids or gases) from one place to another by creating a low pressure area at the inlet and a high pressure area at the outlet. Examples include water pumps used to move water from a well to a home, or air pumps used to inflate tires or air mattresses.

7.3.1 Types of Pump

Pumps come in an assortment of sizes and shapes, but the two most common varieties are shown below:

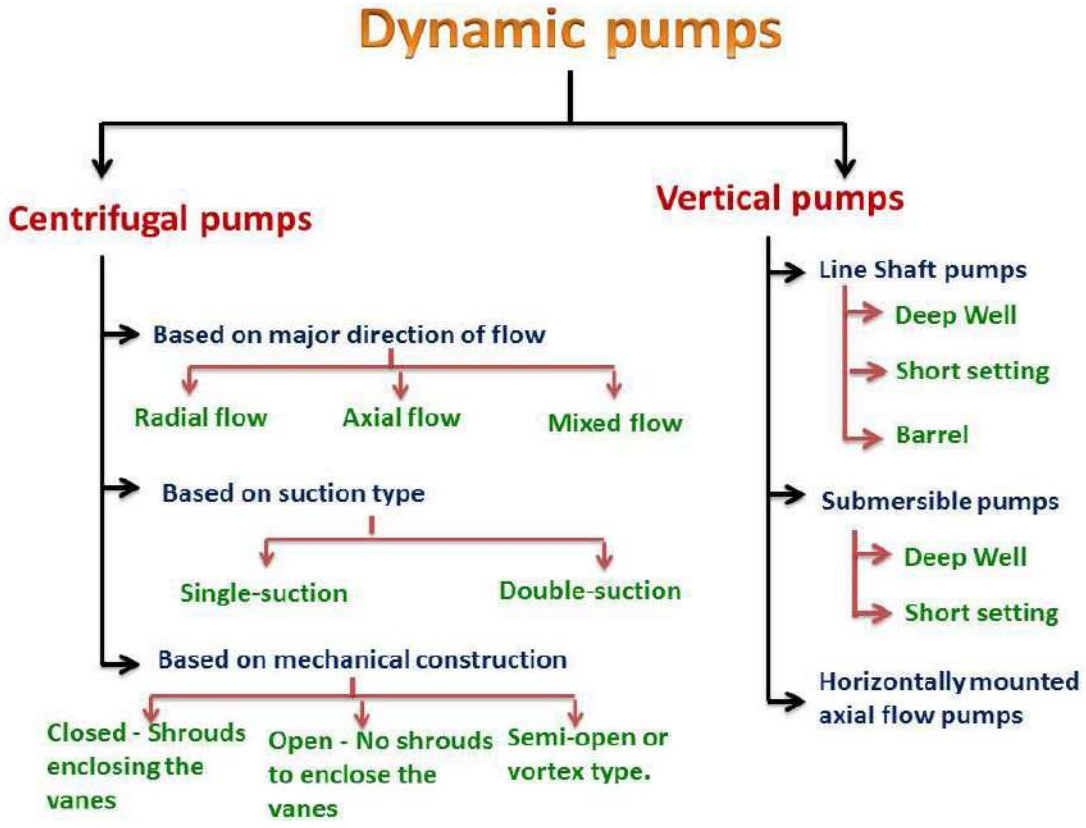


Figure 7.2 Different types of pump

Dynamic Pump

In these kinds of pumps, the piston or plunger goes up and down. Fresh liquid is pumped into the cylinder throughout the time of the pressure stroke. The discharge stroke starts as soon as the inlet valve closes. when the cylinder has been filled. Pressurised liquid ejections from the exit valve when the outlet opens during the discharge stroke. A checked valve is installed on the input and vent sides to stop the liquid from flowing backward.

Centrifugal Pump

Centrifugal pumps work by providing centrifugal force to fluids, which is often done with the useof impellers. These pumps are commonly used in chemical process industries for moderate to highflow applications with low-pressure head. Radial, mixed, and axial flow centrifugal pumps are thethree types of centrifugal pumps.

Special Effect Pump

Special effects pumps are another name for kinetic pumps. This sort of pump still uses kinetic andvelocity energy to provide energy, but it does it in a different way than centrifugal pumps.

Positive Displacement Pumps:

The liquid is moved through a positive displacement pump by reciprocating, rotational, or pneumatic action. In this case, instead of a steady liquid flow, the fluid is discharged in pulses. Through an input valve and an output valve, these pumps function by allowing a specific volume of fluid to enter the pump chamber and then releasing it. These pumps are employed because they can operate at high pressures and in high viscosity fluids.

Reciprocating Pump:

A reciprocating pump is a sort of positive displacement pump that practices a piston, plunger, or diaphragm to move fluid from one place to another. The reciprocating motion of the piston, plunger, or diaphragm generates a pressure difference, which allows the fluid to be forced out of the pump.

Reciprocating pumps are generally used in a range of applications, as well as oil and gas production, chemical treating, water treatment, and more. They are mainly useful for pumping fluids that are high in viscosity, abrasive, or contain solids.

Rotary Pump

A rotary pump is a form of positive displacement pump that uses rotating components to transfer fluids. It is a common type of pump used in a multiplicity of industries, including oil and gas, chemical processing, and food and beverage.

The main components of a rotary pump include a rotor and a housing. The rotor is a rotating component that is typically made up of multiple lobes or gears, and it moves the fluid through the pump by creating a sealed cavity that expands and contracts as the rotor rotates. The housing is the stationary component of the pump that surrounds the rotor and provides the fluid chambers through which the fluid is transferred.

7.3.2 Selection of Centrifugal pump

- They are easy to use and inexpensive.
- Fluid is given at a constant pressure with no pulsation or shocks.
- Pumping does not need the use of any valves.
- They run at a high speed (up to 4000 rpm), therefore they may be directly linked to an electric motor.
- Without altering the pump, the discharge line can be partially or totally shut off.
- They are a lot smaller than other pumps with the same capacity.
- Maintenance is less expensive compared with other types of pumps.

7.3.3 Power Calculation of Pump (P-102)

This centrifugal pump transport the solvent (Selexol) from stripper to scrubber.

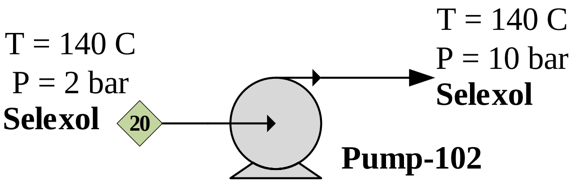


Figure 7.3 Pump (P-102)

Inlet and Outlet Pressures:

P_1 = 1 bar = 1 atm = 10^5 Pa

P_2 = 10 bar = 10 atm = 10×10^5 Pa

Total Flowrate of Selexol = 159102 ${kg}/_{hr}$

As the flowrate is quite large so we are installing 4 centrifugal pump in parallel to reduce cost and manage power consumption.

Density

Density of Selexol = ρ = 1030 ${kg}/_{m^3}$

Head

$$\text{Head} = \frac{\Delta P}{\rho g}$$

$$\text{Head} = \frac{900000}{1030 \times 9.8}$$

Head = 89 m

For power consumption

$$\boldsymbol{P = \gamma Q h}$$

$\gamma = \rho g$

Q = Volumetric flowrate for 1 pump = 0.010 m^3/s

$$P = \rho g Q h$$

$$P = 1030\,\frac{\text{kg}}{\text{m}^3} \times 9.8\,\frac{\text{m}}{\text{s}^2} \times 0.010\,\frac{\text{m}^3}{\text{s}} \times 89\ \text{m}$$

$$p = 8984\,\frac{\text{kg.m}^2}{\text{s}^3}$$

P = 8984 watt

P = 12 hp

Specification Sheet			
Item		Pump (P-102)	
Type		Centrifugal Pump	
Head		89 m	
Function To increase pressure from 1 bar to 10 bar			
Inlet Pressure	1 bar	Discharge Pressure	10 bar
Mass Flowrate		39775.5 kg/hr	
Density		1030 kg/m^3	
Pump Work		12 hp	

7.4 Compressors

A compressor is a mechanical device that is used to decrease the volume of a gas or a vapor. It mechanisms by increasing the pressure of the gas or vapor, which in turn reduces its volume. Compressors are widely used in various industries, including refrigeration, air conditioning, gas processing, and power generation.

7.4.1 Types of Compressors

Depending upon the task. Compressors are available in a variety of forms and sizes, these are as follows:

- **Positive displacement compressors:**

Positive displacement compressors are a type of compressor that work by trapping a fixed amount of gas and then compressing it into a smaller volume, resulting in an increase in pressure. There are several types of positive displacement compressors, comprising reciprocating compressors, rotary screw compressors, and rotary vane compressors.

- **Rotary compressor:**

Rotary compressors are a type of positive displacement compressor used in many applications, including air conditioning, refrigeration, and industrial processes. They work by using rotating components to compress air or gas, which is then transferred to a storage tank or a downstream system.

- **Reciprocating piston compressor:**

This kind of compressor draws air in and then compresses it using a piston that is constantly moving. In general, the piston moves in one direction to pull in air and in the other direction to compress it. Single- or double-chamber designs are available for reciprocating piston compressors, which determine whether air is compressed on only one side of the piston or both. These compressors have up to 1000 horsepower and can be either air- or water-cooled.

- **Dynamic Compressors:**

When you require a lot of horsepower, a dynamic compressor is the best option. They are available in both axial and radial configurations. They are commonly referred to as turbo compressors. Centrifugal compressors are those that have a radial design. In contrast to, say, a displacement compressor, which runs at a constant flow, a dynamic compressor runs at a constant pressure. External circumstances influence the performance of a dynamic compressor;

for example, achange in input temperature leads in a change in capacity.

- **Centrifugal Compressor:**

The centrifugal compressor is one of the most well known dynamic compressor types. By applying an inertial force (turning, deceleration, and acceleration) to the gas through a rotating impeller, this compressor compresses the gas. Air is pulled towards the core of the impeller of this compressor before being centrifugally accelerated towards the circumference. As the air is compressed into that area, the diffuser will scroll there.

Axial flow Compressor:

Another fundamental variety of dynamic compressor is the axial flow compressor. As a result, despite having a very tiny housing and little power requirements, it can handle high air flow rates. These compressors have a modest to moderate pressure range. The axial compressor forces air into ever-tinier spaces using a set of blades that resemble jet engines. These sorts of dynamic displacement compressors are still extensively available in the market. Axial compressors are often smaller, lighter, and faster-running than comparable centrifugal compressors.

7.4.2 Selection of the Compressor

A centrifugal compressor was chosen. The following are the benefits of a centrifugal compressor:

- Larger amounts of gas can be handled in one or two tiny casings, resulting in a smaller overall package.
- Vibration-free for the most part. Only a pad adequate for sustaining the package's static weight is required.
- Centrifugal compressors have a lengthy mean time between failures.
- Independent analysis has proven that the product has an industry-leading availability of 99.7%. Gear that is conservative and of good quality.
- For constant gas delivery, include intake guide vane control and bypass.
- For most operational situations, automatic operation and precise control are required.
- Control systems for PLCs (Programmable Logic Controller) are available.

7.4.3 Power Calculations of Compressor

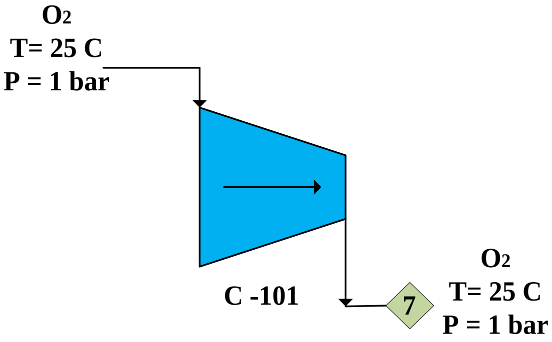


Figure 7.4 Compressor (C-101)

P_1 = 1 atm = 1 bar

P_2 = 10 atm = 10 bar

T = 25 ℃

Mass flowrate = 21852.46 $^{kg}/_{hr}$

Power Consumption

For power calculation of compressor we have a relation, which is:

$$P_B = \frac{1.304 \times 10^{-4}\, T_a\, q_o}{\eta} \ln\left(\frac{P_b}{P_a}\right)$$

P_B = Brake horse power

q_o = Volume of Compressed gas = 8969 $\frac{ft^3}{min}$

T_a = Inlet Temperature °R = 536.7 °R

r = Co-efficient constant = 1.4

P_b = Outlet Pressure = 30 bar

P_a = Inlet Pressure = 1 bar

Now putting the values in the equation.

$$\mathbf{P_B = 7\ h_p}$$

Specification Sheet	
Item	Compressor (C-101)
Type	Centrifugal Compressor
Function	To increase pressure from 1 bar to 10 bar
Mass Flowrate	21852.46 kg/hr
Inlet Pressure	1 bar
Outlet Pressure	10 bar
Power	7 h_p

CHAPTER # 08

COST ESTIMATION

8 Cost Estimation

Any industrial process necessitates a capital expenditure, and determining the required asset is an important aspect of the plant design plan. Although there are many names for these estimations, the five categories listed below capture the classification and accuracy range that are frequently employed in design.

- Order of magnitude estimates
- Study estimate (factorial estimate)
- Preliminary estimates (budget authorization estimate)
- Definitive estimate (project control estimate)
- Detailed estimate (Contractor's estimate)

8.1 Working Capital Investment

Working capital refers to the money needed to keep the plant running. The following items should be considered when calculating working capital:

- Stockpiles of raw materials and supplies
- Semi-finished items in the manufacturing process and final products in stock.
- Receivables (accounts receivable)
- Cash is maintained on hand to cover monthly operational costs including salaries, wages, and raw material purchases.
- Accounts receivable
- Taxes payable

8.2 Fixed Capital Investment

Fixed capital investments also cover maintenance and long-term asset investments. Investments in tangible assets like real estate, machinery, and equipment (PP&E) are included. Capital expenses on assets, plant, and equipment (PP&E) and other types of expensesand the sale of fixed assets is used to compute it. Fixed capital investment is a key component in calculating the firm's free cash flow (FCFF). Fixed capital investment for FCFF computation is computed using one of the following formulae if a firm's long-term assets are not sold during the financial year:

$$\text{FCINV} = \text{closing gross value of PP\&E} - \text{opening gross value of PP\&E}$$

8.3 Depreciation

Depreciation refers to the manner of dealing the cost of a physical asset over its convenient life. This is normally done for accounting and tax commitments, and it permits businesses to blowout the cost of an asset over its expedient life rather than recognizing the entire cost upfront.

Depreciation is important because it helps businesses to correctly reflect the value of their assets on their balance sheets and income statements. By dispersal of the cost of an asset over its useful life, businesses can more accurately reflect the asset's declining value over time and ensure that their financial statements

8.4 Cost Indexes

A cost is similar to an index number for a specific time period that displays the cost relative to a base period at that time. As a result, the current cost is approximated using the cost index as follows:

$$\frac{\text{Present Cost}}{\text{index at present Time}} = \frac{\text{Original cost}}{\text{Index Value at time of original Cost}}$$

Various forms of cost indices are released on a regular basis. Some may be used to estimate the cost of equipment, while others are more relevant to labor, construction, materials, or other specialist industries.

The most common of these indices are

- Equipment for various industries and processes, Marshal-and-Swift
- Engineering news contraction cost index records

8.5 Total Cost of Equipment in 2022

8.5.1 Cost of Grinder

Type: Hammer mill

Purchased cost of dryer for year 2015 = $ 17000

The average increase in the cost is about 2.5% per year.

Using this value we predict the heat exchanger purchased cost in year 2022:

So Purchased cost for 2022 = $\$17000 \times (1.025)^7$

Purchased cost for 2022 = **$ 20000**

8.5.2 Cost of Dryer

Type: Rotary Dryer

Purchased cost of dryer for year 2015 = $ 49000

The average increase in the cost is about 2.5% per year.

Using this value we predict the heat exchanger purchased cost in year 2022:

So Purchased cost for 2022 = $49000 × $(1.025)^7$

Purchased cost for 2022 = **$ 58245**

8.5.3 Cost of Conveyor

Type: Belt Conveyor

Purchased cost of dryer for year 2015 = $ 2240

The average increase in the cost is about 2.5% per year.

Using this value we predict the heat exchanger purchased cost in year 2022:

So Purchased cost for 2022 = $ 2240 × $(1.025)^7$

Purchased cost for 2022 = **$ 2663**

8.5.4 Cost of Cyclone Separator

Purchased cost of dryer for year 2015 = $ 5914.27

The average increase in the cost is about 2.5% per year.

Using this value we predict the heat exchanger purchased cost in year 2022:

So Purchased cost for 2022 = $ 5914.27 × $(1.025)^7$

Purchased cost for 2022 = **$ 7030**

8.5.5 Cost of Fluidized Bed Gasifier

Material of construction = Stainless Steel

Length = 12 m

Diameter = 1.2 m

Material Factor = 2

Pressure Factor = 1.1

Purchase Cost in 2004 = bare cost × material factor × pressure factor

= $ 22000 × 2 × 1.1

= $ 48400 (from fig A.14 Appendix A)

Cost index in 2004 = 444.2

Cost index in 2022 = 808.7

$$\text{Cost in 2022} = \text{Cost in 2004} \times \frac{\text{Cost Index in 2022}}{\text{Cost Index in 2004}}$$

Purchased Cost in 2022 = **$ 88116**

8.5.6 Cost of Waste Heat Boiler (WHB-101)

Type of heat exchanger: Shell and tube

Hot fluid = Process gases

Cold fluid = Cold water

Material: Stainless steel

Pressure = 10 bar

Type factor U tube = 0.85

Heat transfer Area = 98 m^2

Purchase Cost in 2004 = bare cost × material factor × pressure factor

= $ 102000 ×1 ×0.85

= $ 86700

Cost index in 2004 = 444.2

Cost index in 2022 = 808.7

$$\text{Cost in 2022} = \text{Cost in 2004} \times \frac{\text{Cost Index in 2022}}{\text{Cost Index in 2004}}$$

Purchased Cost in 2022 = **$ 157844**

8.5.7 Cost of Waste Heat Boiler (WHB-102)

Type of heat exchanger: Shell and Tube

Hot fluid = Process gases

Cold fluid = Cold water

Material: Stainless steel

Pressure = 10 bar

Type factor U tube = 0.85

Heat transfer Area = 143 m^2

Purchase Cost in 2004 = bare cost × material factor × pressure factor

= \$ 125000 ×1 ×0.85

= \$ 106250

Cost index in 2004 = 444.2

Cost index in 2022 = 808.7

Cost in 2022 = Cost in 2004 × $\frac{Cost\ Index\ in\ 2022}{Cost\ Index\ in\ 2004}$

Purchased Cost in 2022 = **\$ 193436**

8.5.8 Cost of Scrubber (A-101)

Column diameter = 3.3 m

Height of Column = 8.28 m

Packing height = 7 m

Packing volume = 18 m3

Packing: Ceramic Intalox saddle

Packing Material = Pall Rings

Cost of Packing = 1020 $\$/m^3$

Total Packing cost = \$ 18360

Pressure= 10 bar

Material: Stainless steel

Purchase Cost in 2004 = bare cost × material factor × pressure factor

= 40000 × 2 × 1.1

= $ 88000 (from fig A.16 Appendix)

Cost Index in 2004 = 444.2

Cost Index in 2022 = 808.7

$$\text{Cost in 2022} = \text{Cost in 2004} \times \frac{\text{Cost Index in 2022}}{\text{Cost Index in 2004}}$$

Purchased Cost in 2022 = **$ 193363**

8.5.9 Cost of Stripper (ST-101)

Column diameter = 3.3 m

Height of Column = 3.3 m

Packing height = 2.6 m

Packing volume = 6.7 m3

Packing: Ceramic Intalox saddle

Packing Material = Pall Rings

Cost of Packing = 1020 $\$/m^3$

Total Packing cost = $ 6834

Pressure= 10 bar

Material: Stainless steel

Purchase Cost in 2004 = bare cost × material factor × pressure factor

= $ 18000 × 2 × 1.1

= $ 46434 (from fig A.16 Appendix)

Cost Index in 2004 = 444.2

Cost Index in 2022 = 808.7

Cost in 2022 = Cost in 2004 × $\frac{\text{Cost Index in 2022}}{\text{Cost Index in 2004}}$

Purchased Cost in 2022 = **$ 84537**

8.5.10 Cost of Heat Exchanger (HX-103)

Type of heat exchanger: Shell and Tube

Hot fluid = gases

Cold fluid = water

Material: Stainless steel

Pressure = 10 bar

Type factor U tube = 0.85

Heat transfer Area = 27 m^2

Purchase Cost in 2004 = bare cost × material factor × pressure factor

= $ 42000 × 1 × 0.85

= $ 35700 (from fig A.13 Appendix A)

Cost Index in 2004 = 444.2

Cost index in 2022 = 808.7

Cost in 2022 = Cost in 2004 × $\frac{\text{Cost Index in 2022}}{\text{Cost Index in 2004}}$

Purchased Cost in 2022 = **$ 64995**

8.5.11 Cost of Heat Exchanger (HX-104)

Type of heat exchanger: Shell and Tube

Hot fluid = gases

Cold fluid = water

Material: Stainless steel

Pressure = 10 bar

Type factor U tube = 0.85

Heat transfer Area = 88 m^2

Purchase Cost in 2004 = bare cost × material factor × pressure factor

= $ 102000 × 1 × 0.85

= $ 86700 (from fig A.13 Appendix A)

Cost Index in 2004 = 444.2

Cost index in 2022 = 808.7

$$\text{Cost in 2022} = \text{Cost in 2004} \times \frac{\text{Cost Index in 2022}}{\text{Cost Index in 2004}}$$

Purchased Cost in 2022 = **$ 157844**

8.5.12 Cost of Packed Bed Membrane Reactor (MR-101)

Material = Stainless Steel

Pressure = 10 bar

Dia = 0.54 m

Height of vessel = 23 m

Purchase Cost in 2004 = bare cost × material factor × Pressure factor

= $30000 × 2 × 1.1

= $ 66000 (from fig A.13 Appendix A)

Cost Index in 2004 = 444.2

Cost index in 2022 = 808.7

$$\text{Cost in 2022} = \text{Cost in 2004} \times \frac{\text{Cost Index in 2022}}{\text{Cost Index in 2004}}$$

Purchased Cost in 2022 = **$ 120158**

8.5.13 Cost of Pump

Type = Centrifugal

$$C_e = CS^n$$

Power requirement = S = 12 hp

Cost Constant = 1920

Index = 0.8

$$C_e = 1920 \times (12)^{0.8}$$

Cost of Pump in (2004) = $ 14016

Cost index in 2004 = 444.2

Cost index in 2022 = 808.7

Cost in 2022 = Cost in 2004 × $\frac{\text{Cost Index in 2022}}{\text{Cost Index in 2004}}$

Purchased Cost in 2022 = **$ 25517**

Purchased cost for 4 pump in parallel **= $ 102068**

8.5.14 Cost of Compressor (C-101)

Type = Centrifugal

$$C_e = CS^n$$

Power requirement = S = 7 hp

Cost Constant = 1920

Index = 0.8

$$C_e = 1920 \times (7)^{0.8}$$

Cost of compressor in (2004) = $ 8477

Cost index in 2004 = 444.2

Cost index in 2022 = 808.7

Cost in 2022 = Cost in 2004 × $\frac{\text{Cost Index in 2022}}{\text{Cost Index in 2004}}$

Purchased Cost in 2022 = **$ 15433**

8.6 Total Purchased Cost of Equipment

Table 8.1 Total Purchased Cost of Equipment

Equipment	Cost ($)
Grinder	20000
Dryer	58245
Conveyor	2663
Cyclone (CL-101)	7030
Reactors	
(G-101)	116153
(R-101)	120158
Heat Exchangers	
(WHB-101)	157844
(WHB-102)	193436
(HX-103)	157844
(HX-104)	64995
Columns	
Scrubber (A-101)	193636
Stripper(ST-101)	84537
Pump and Compressors	
Pump(101/102)	204136
Compressor (C-101)	15433
Total	**1396110**

8.7 Direct Cost

Table 8.2 Direct Cost

Items	Range	%	Cost $
Purchased equipment	---	100%	1396110
Installation	25-55% of purchased equipment cost	40%	558444
Instrument and Control	6-30% of purchased equipment cost	18%	251299
Piping	40-80% of purchased equipment cost	60%	837666
Electricity	10-15% of purchased equipment cost	12.5%	174514
Building	15% of purchased equipment cost	15%	209417
Land	4-8% of purchased equipment cost	6%	83767
Service facility	30-80% of purchased equipment cost	55%	767861
Yard Improvement	10-20% of purchase equipment cost	15%	209417
Insulation cost	8-9% of purchased equipment cost	8.5%	118669
Total	**---**	**---**	**4607164**

8.8 Indirect Cost

Table 8.3 Indirect Cost

Items	Range	%	Cost $
Engg. & supervision	25% of total direct cost	25%	1151791
Contractor fee	2-8% of direct plant cost	5%	230358
Construction Expenses	10% of Total direct plant cost	10%	460716
Contingences	Direct plant cost	8%	3608573
Total	**-**	**---**	**2211438**

Total capital investment = Fixed capital + working capital investment

Fixed capital = direct cost + indirect Cost

Fixed capital = $ 6818602

Working capital investment = 15% of fixed capital investment

Working capital investment = $ 1022790

8.9 Total Capital Investment

Total capital investment = Fixed capital investment + working capital investment

Total capital investment = $ 7841392

8.10 Variable Cost

Raw material

Flow rate of Rice straw = 138257 kg/hr
For 300 days of operating time = 1094995440 kg/year
Price of rice straw per kg = $0.10/kg
Total price of Rice straw = $ 109499544 /year

Catalyst Cost

Price of Catalyst (Fe_2O_3) = $ 1.25 /kg

Weight of Catalyst = 2883 kg

Price of Catalyst = $ 3604 /year

Solvent Cost

Price of Selexol = $ 1.8/kg

Flowrate of Selexol = 159102 kg/hr

Flowrate for 330 days = 52503660 kg/hr

Price of Selexol = $ 94506588 /year

Utilities

Cooling Water Requirement = 432105 kg/hr

Cooling water cost = $ 0.000014 /kg

Cooling water required for 330 days = 3422271600 kg/year

Total price of cooling water = $ 4792 /year

Miscellaneous Material Cost

Maintenance cost = 7% of FCI

= $ 477302

Miscellaneous Material = (It is 10% of maintenance cost)

= $ 47730

Variable cost = raw material cost + miscellaneous cost + utilities cost

Variable cost = $ 204062258 /year

8.11 Fixed Operating Cost

Figure 8.1 Fixed Operating Cost

Type	FCI (%)	Cost $
Maintenance	7	477302
Operating Cost of Labor	10	681860
Laboratory Cost	20	1363720
Supervision Cost	15	1022790
Plant Overheads	50	3409301
Capital Charges	10	681860
Insurance	1	68186
Local Taxes	2	136372
Royalties	1	68186
Total	**-**	**7909577**

Direct production cost = variable cost + fixed cost

Direct production cost = 204062258 + 7909577

Direct production cost = $ 211971835

8.12 Overhead Charges

30 % of direct production cost

Overhead charges = (0.3)(211971835)= $ 63591550

Manufacturing Cost = Direct Production Cost + Overhead Charges

Manufacturing cost = $ 275563385

8.13 General Expenses

Figure 8.2 General Expenses

Function	% of Manufacturing Cost	Cost $
Administration	2 %	55511268
Distribution and Marketing	2 %	55511268
Research and Development	5 %	138778169
Total		**249800705**

8.14 Total production cost

Total production cost = manufacturing cost + general expense

= $ 525364090

Production Cost

Total production rate = 438×10^6 kg/yr

Production cost = $\frac{\text{total production cost}}{\text{total production rate}}$ = $ 1.19 / kg

8.15 Profitability Analysis

• Selling Price

Price of hydrogen in Market = 2 $/kg

Selling price of product = 1.7 $/kg

• Profit

Profit = Selling price - production cost= $ 0.51 /kg

Profit per year = $ 223380000 /yr

• Total Income

Selling Price = 1.7 $/kg

Total Production rate = 438×10^6 kg/yr

Total Income = $ 744600000 /yr

Gross Profit = Total Income - Total Production Cost

Gross Profit = $ 219235910

• Depreciation

Machinery and equipment = 20% of FCI= $ 1363720/yr

Building = 4% of Building cost= $ 8377 /yr

Total Depreciation = Machinery and equipment + Building

Total Depreciation = $ 1372097/yr

- **Taxes**

Let the tax rate is 40%

Taxes = 0.4 × Gross Profit = \$ 8769436

- **Net Profit**

Net Profit before Taxation = Gross profit – Depreciation = \$ 217863813

Net Profit after Taxation = Net Profit before Taxation – Taxes = \$ 209094377

- **Rate of Return**

$$\text{Rate of Return} = \frac{\text{Net Profit}}{\text{Total Capital Investment}} \times 100$$

Rate of Return = 26.7 %

- **Payback Period**

$$\text{Payback Period} = \frac{1}{\text{Rate of Return}}$$

Payback Period = 3.7 years

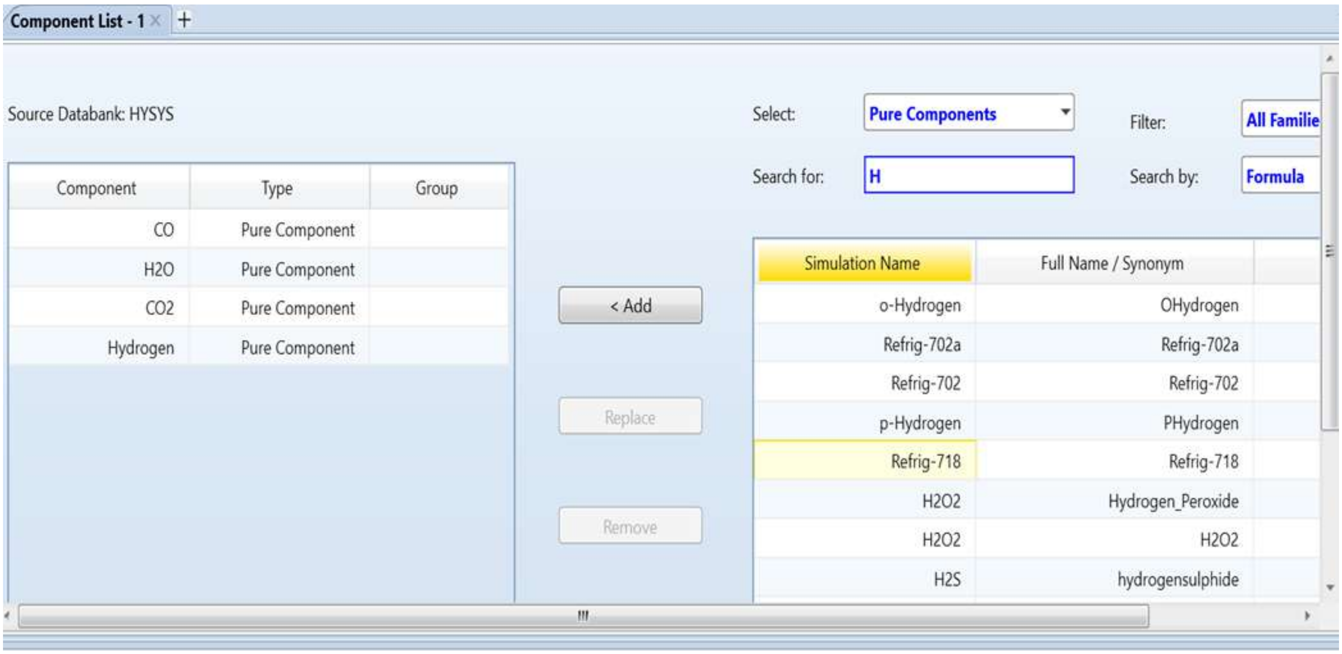
CHAPTER # 09

PROCESS SIMULATION

9 Process Simulation

9.1 Simulation of Packed Bed Membrane Reactor on Aspen Hysys.

9.1.1 List of Components



Source Databank: HYSYS

Select: Pure Components

Filter: All Familie

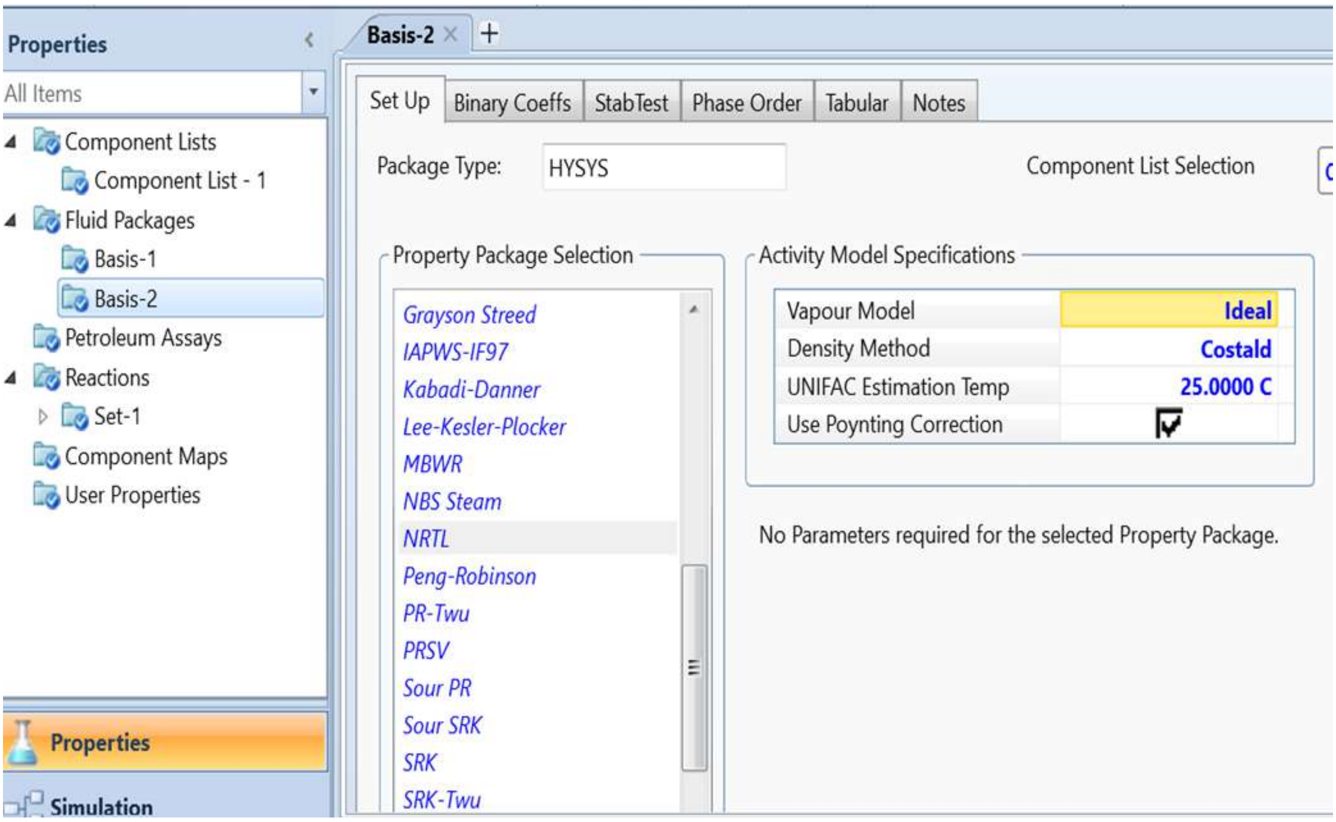
Search for: H

Search by: Formula

Component	Type	Group
CO	Pure Component	
H2O	Pure Component	
CO2	Pure Component	
Hydrogen	Pure Component	

Simulation Name	Full Name / Synonym
o-Hydrogen	OHydrogen
Refrig-702a	Refrig-702a
Refrig-702	Refrig-702
p-Hydrogen	PHydrogen
Refrig-718	Refrig-718
H2O2	Hydrogen_Peroxide
H2O2	H2O2
H2S	hydrogensulphide

9.1.2 Basis Selection



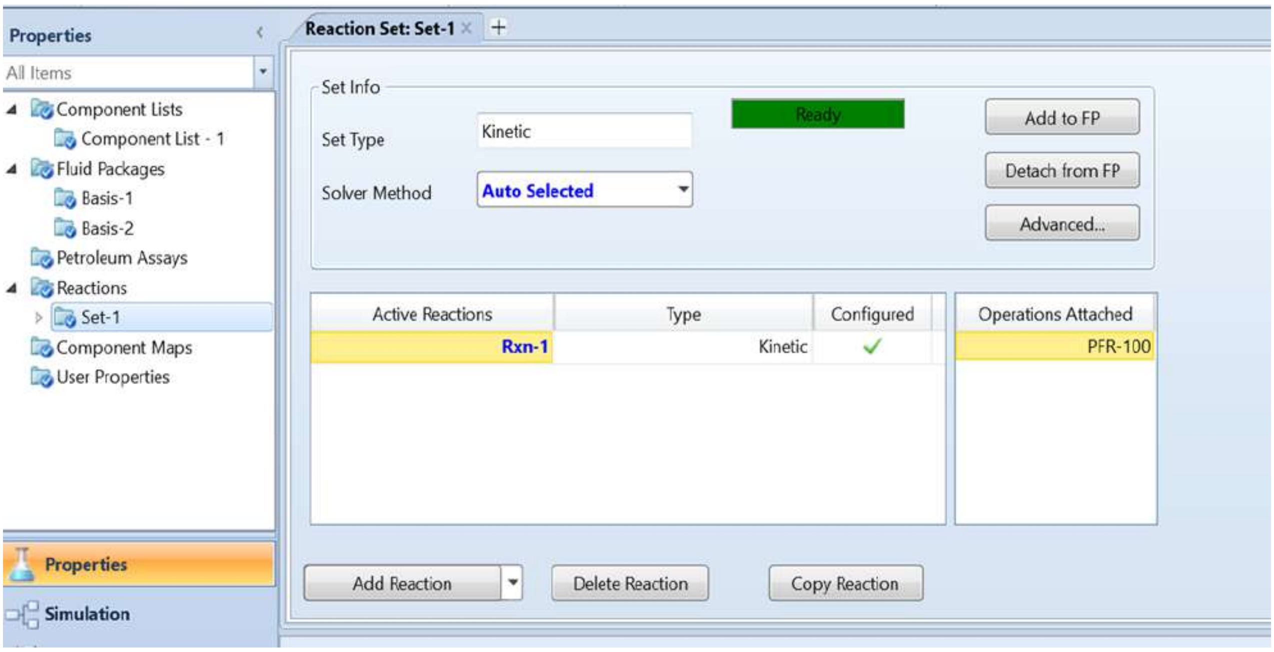
Package Type: HYSYS

Activity Model Specifications

Vapour Model	Ideal
Density Method	Costald
UNIFAC Estimation Temp	25.0000 C
Use Poynting Correction	☑

No Parameters required for the selected Property Package.

9.1.3 Reaction Set



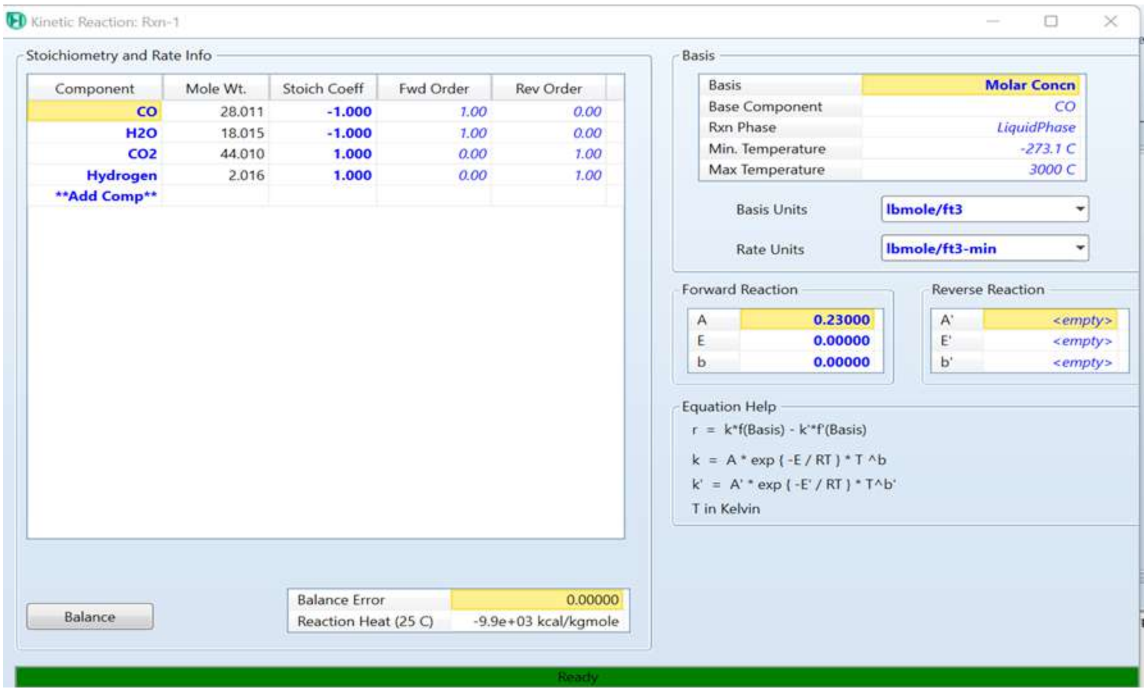
Set Type: Kinetic

Solver Method: Auto Selected

Active Reactions	Type	Configured
Rxn-1	Kinetic	✓

Operations Attached
PFR-100

9.1.4 Kinetics Selection



Component	Mole Wt.	Stoich Coeff	Fwd Order	Rev Order
CO	28.011	-1.000	1.00	0.00
H2O	18.015	-1.000	1.00	0.00
CO2	44.010	1.000	0.00	1.00
Hydrogen	2.016	1.000	0.00	1.00
Add Comp				

Basis	Molar Concn
Base Component	CO
Rxn Phase	LiquidPhase
Min. Temperature	-273.1 C
Max Temperature	3000 C

Basis Units: lbmole/ft3

Rate Units: lbmole/ft3-min

Forward Reaction	
A	0.23000
E	0.00000
b	0.00000

Reverse Reaction	
A'	<empty>
E'	<empty>
b'	<empty>

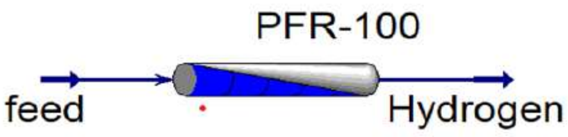
r = k*f(Basis) - k'*f'(Basis)

k = A * exp { -E / RT } * T ^b

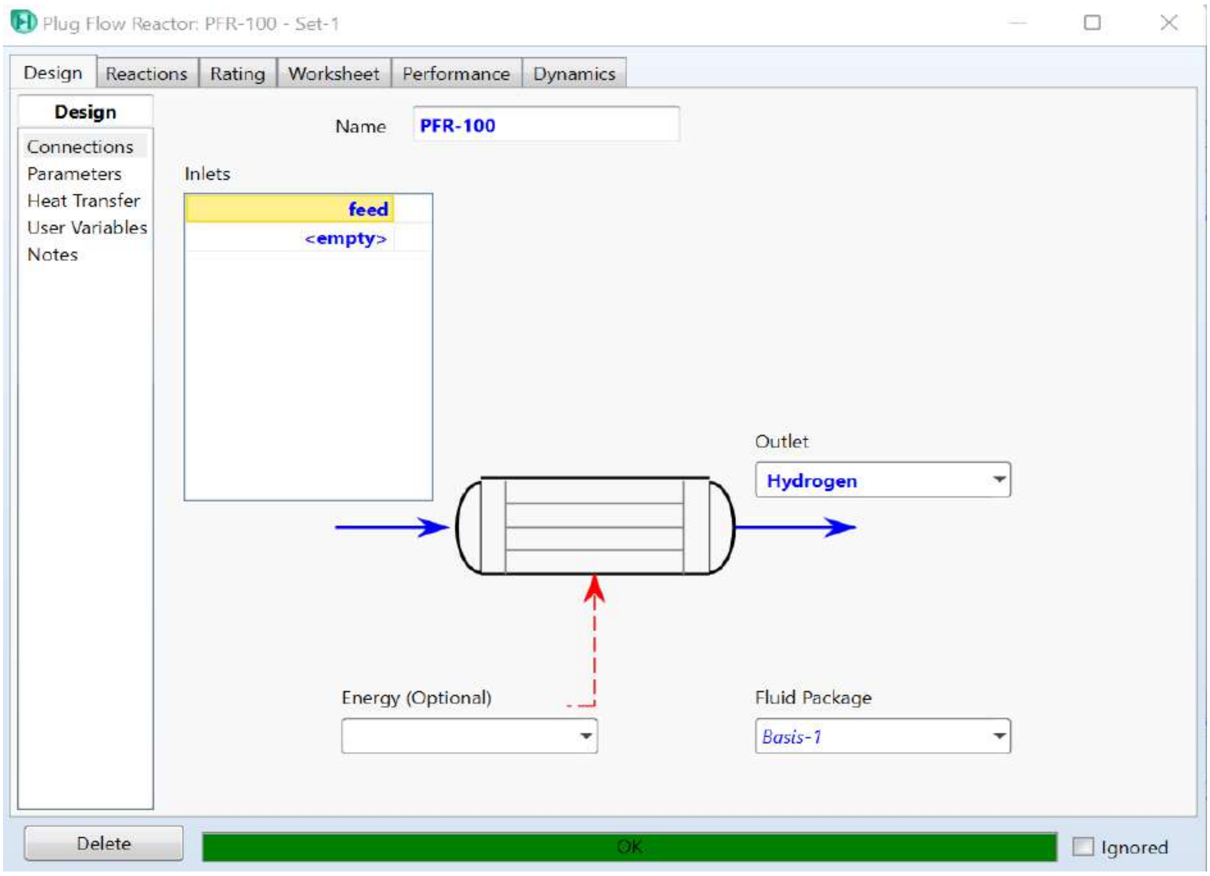
k' = A' * exp { -E' / RT } * T^b'

T in Kelvin

Balance Error	0.00000
Reaction Heat (25 C)	-9.9e+03 kcal/kgmole



9.1.5 Connections of Reactor



Name: PFR-100

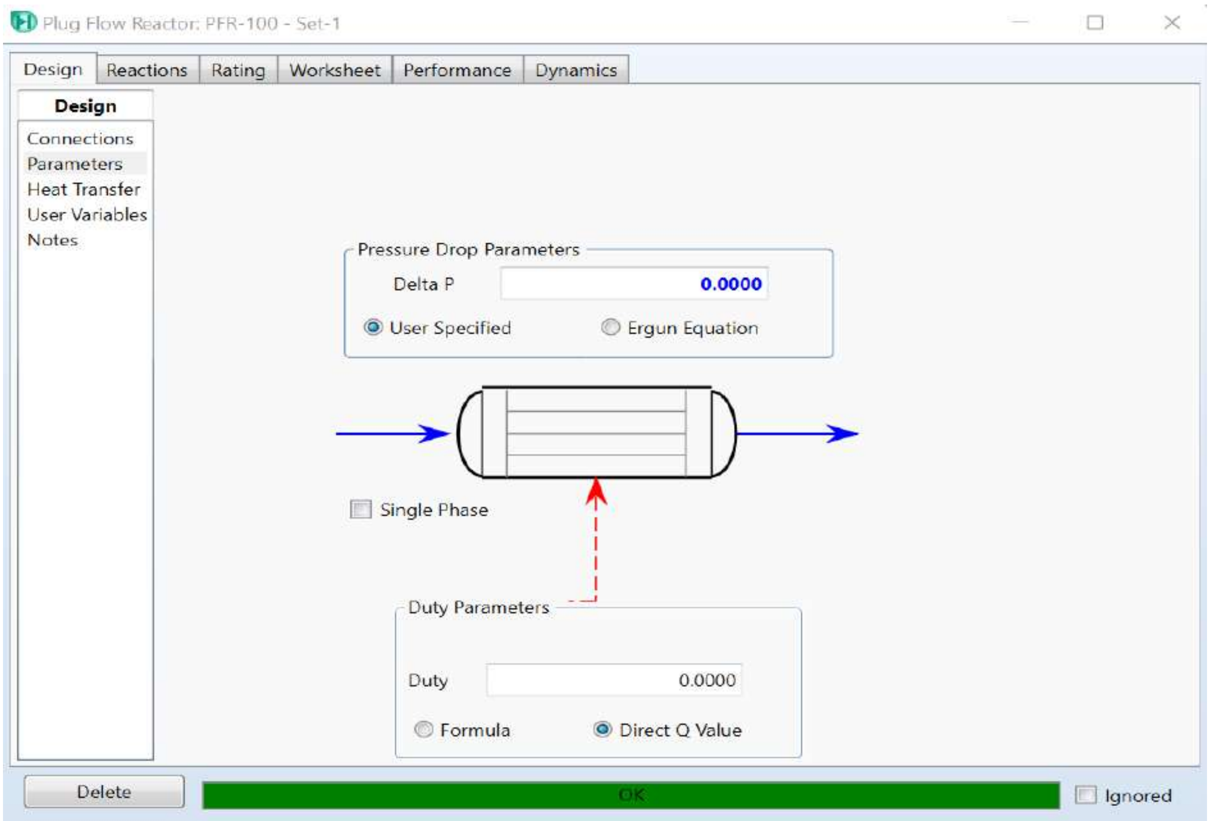
Inlets: feed, <empty>

Outlet: Hydrogen

Energy (Optional):

Fluid Package: Basis-1

9.1.6 Parameters of Reactor



Pressure Drop Parameters

Delta P: 0.0000

● User Specified ○ Ergun Equation

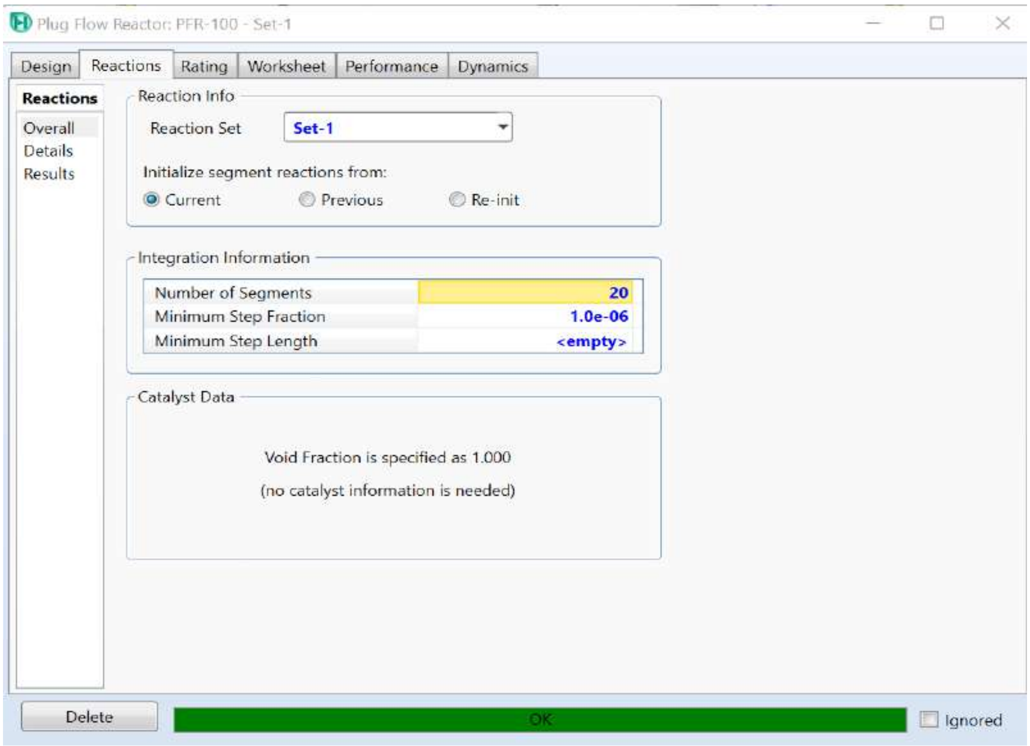
☐ Single Phase

Duty Parameters

Duty: 0.0000

○ Formula ● Direct Q Value

9.1.7 Addition of Reaction Set



Reaction Info

Reaction Set: Set-1

Initialize segment reactions from:

● Current ○ Previous ○ Re-init

Integration Information

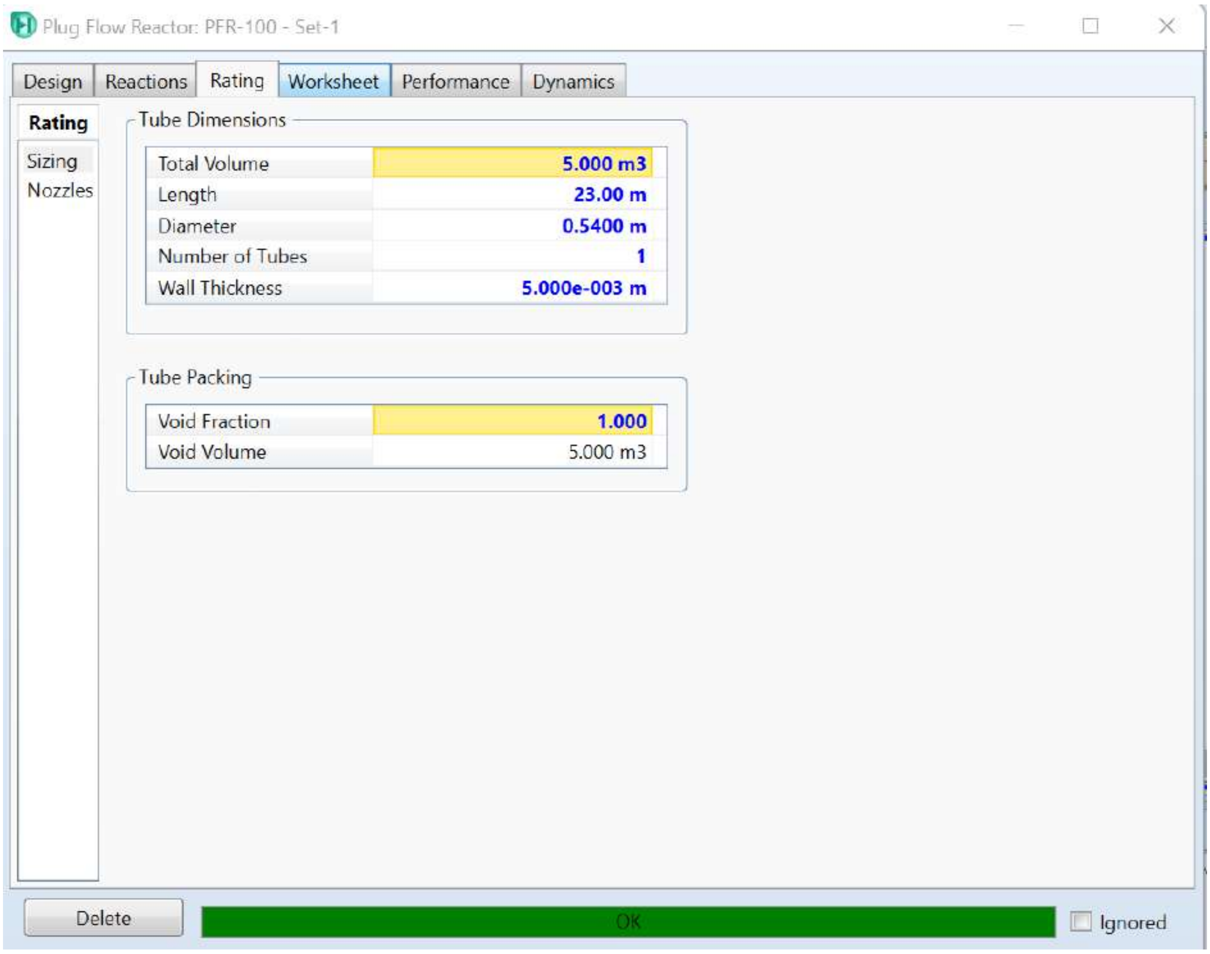
Number of Segments	20
Minimum Step Fraction	1.0e-06
Minimum Step Length	<empty>

Catalyst Data

Void Fraction is specified as 1.000

(no catalyst information is needed)

9.1.8 Rating of Reactor



Tube Dimensions

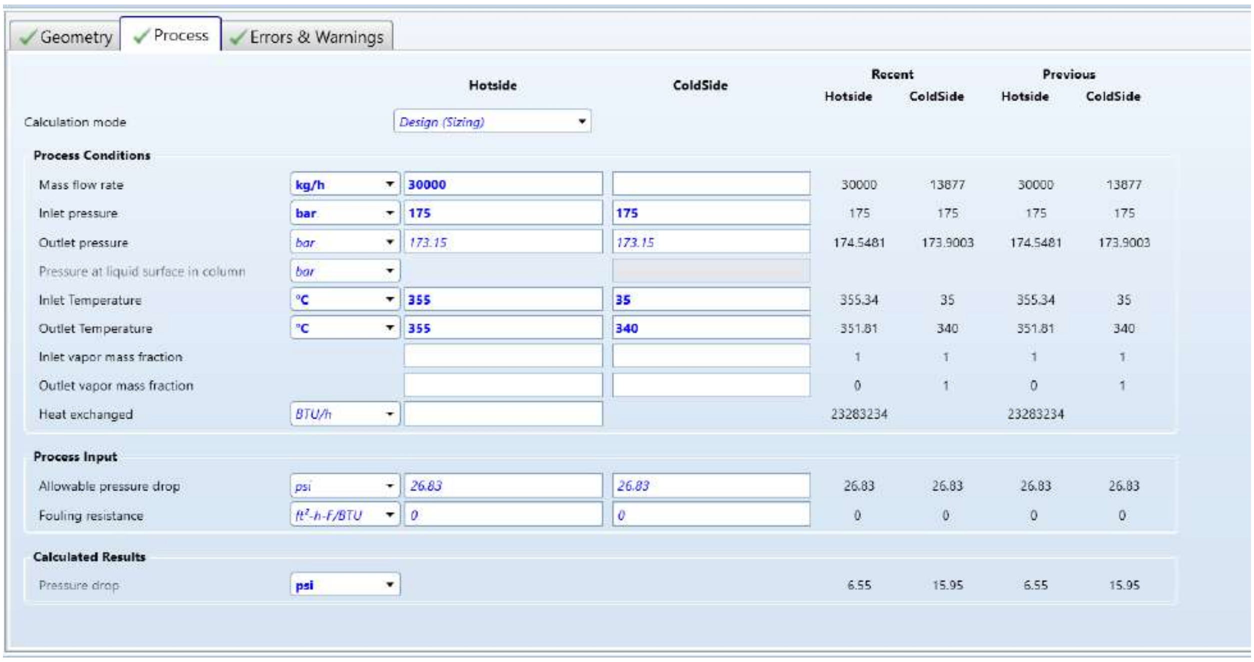
Total Volume	5.000 m3
Length	23.00 m
Diameter	0.5400 m
Number of Tubes	1
Wall Thickness	5.000e-003 m

Tube Packing

Void Fraction	1.000
Void Volume	5.000 m3

9.2 Simulation of Heat Exchanger on Aspen Plus (EDR)

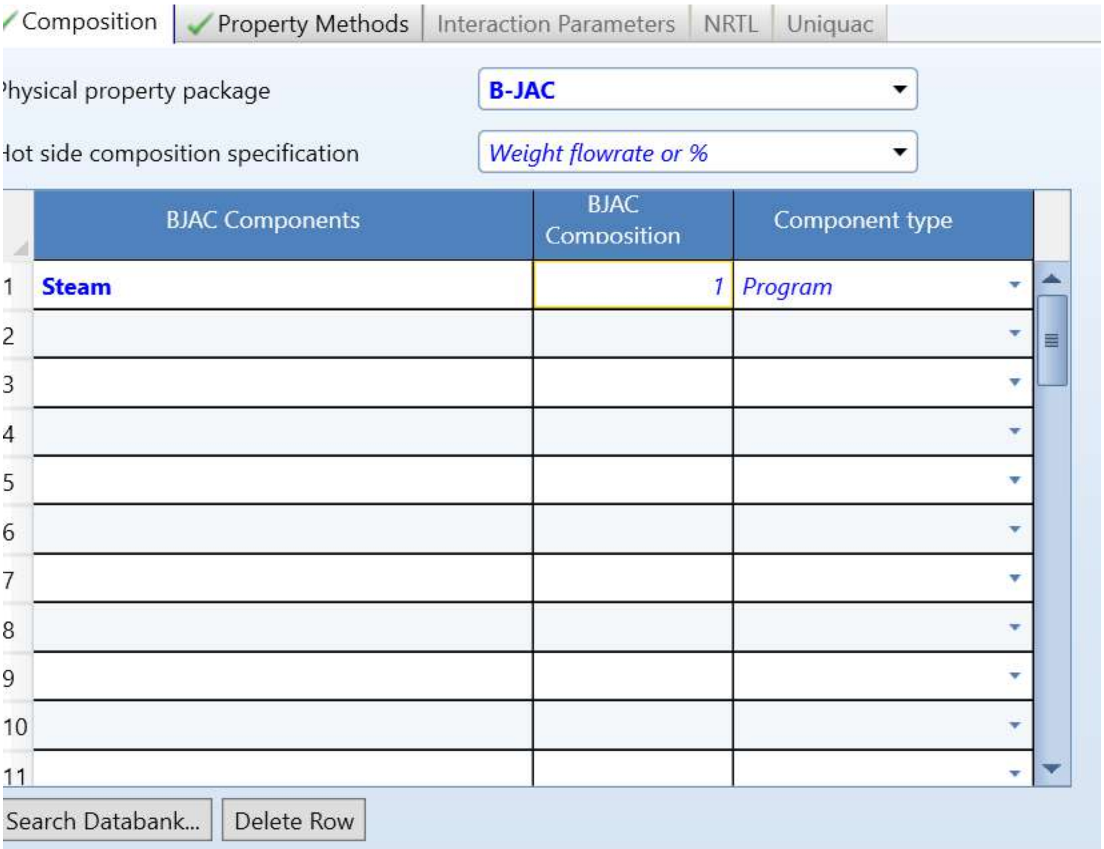
9.2.1 Process Conditions



Calculation mode: Design (Sizing)

	Unit	Hotside	ColdSide	Recent Hotside	Recent ColdSide	Previous Hotside	Previous ColdSide
Process Conditions							
Mass flow rate	kg/h	30000		30000	13877	30000	13877
Inlet pressure	bar	175	175	175	175	175	175
Outlet pressure	bar	173.15	173.15	174.5481	173.9003	174.5481	173.9003
Pressure at liquid surface in column	bar						
Inlet Temperature	°C	355	35	355.34	35	355.34	35
Outlet Temperature	°C	355	340	351.81	340	351.81	340
Inlet vapor mass fraction				1	1	1	1
Outlet vapor mass fraction				0	1	0	1
Heat exchanged	BTU/h			23283234		23283234	
Process Input							
Allowable pressure drop	psi	26.83	26.83	26.83	26.83	26.83	26.83
Fouling resistance	ft²-h-F/BTU	0	0	0	0	0	0
Calculated Results							
Pressure drop	psi			6.55	15.95	6.55	15.95

9.2.2 Property Method for Steam

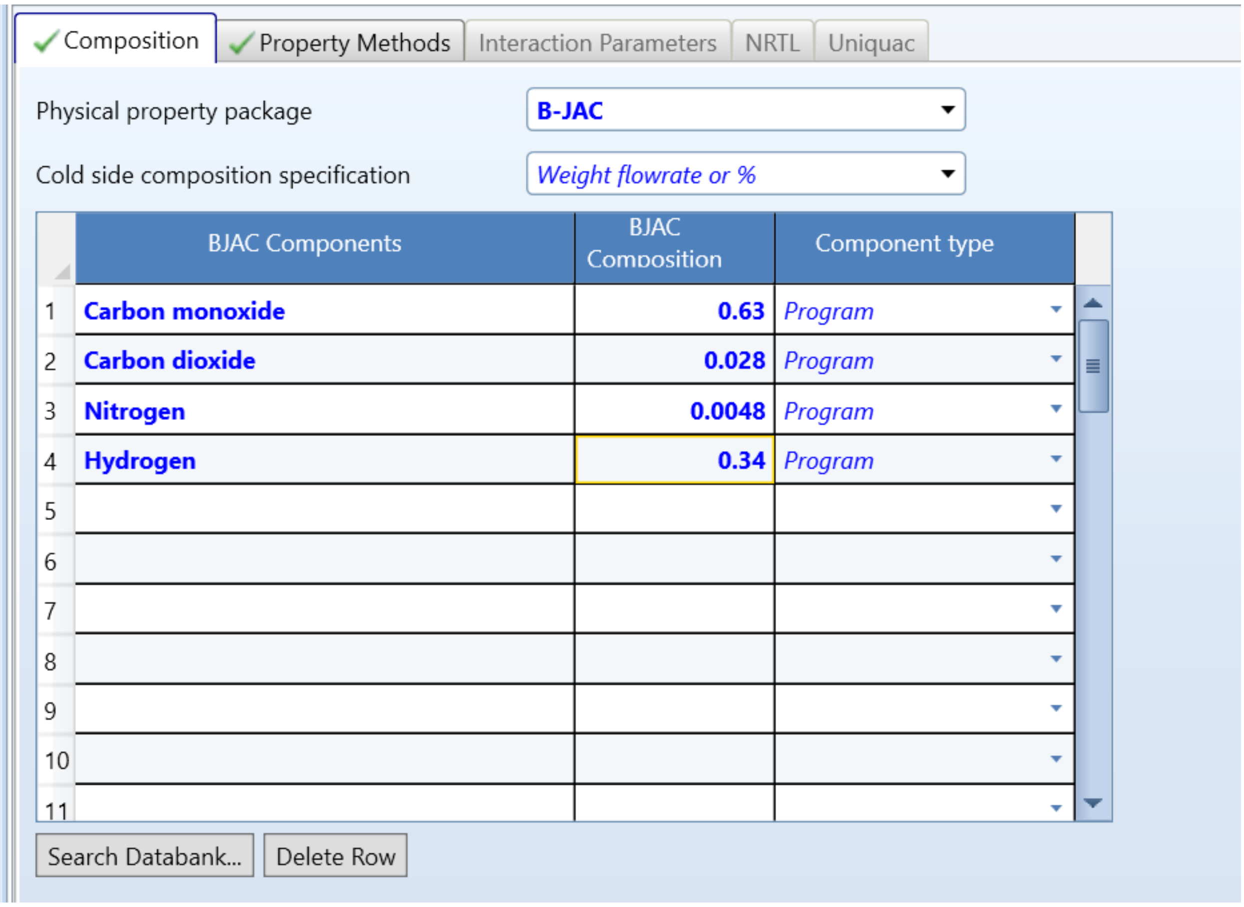


Physical property package: B-JAC

Hot side composition specification: Weight flowrate or %

	BJAC Components	BJAC Composition	Component type
1	Steam	1	Program
2			
3			
4			
5			
6			
7			
8			
9			
10			
11			

9.2.3 Property Method for Gas Mixture

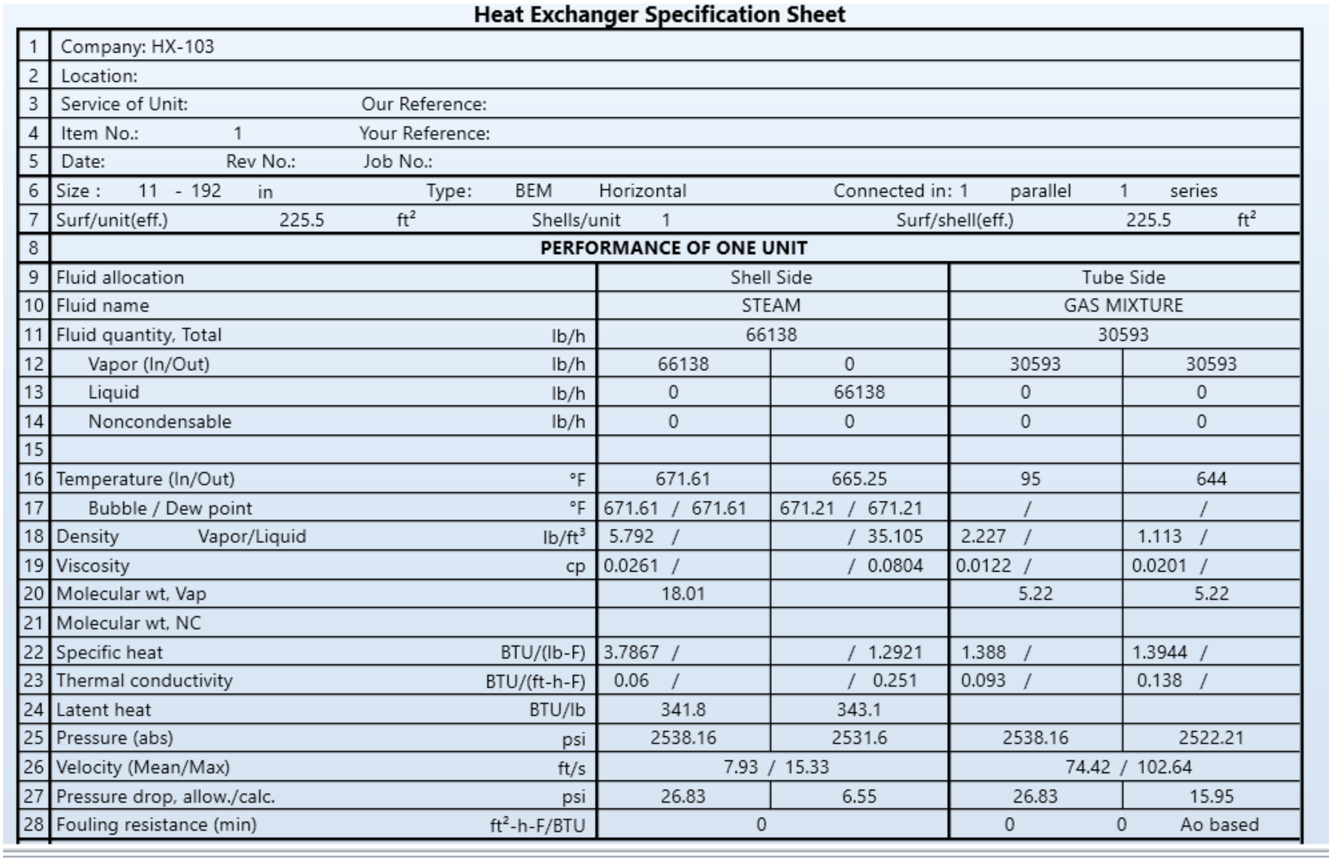


Physical property package: B-JAC

Cold side composition specification: Weight flowrate or %

	BJAC Components	BJAC Composition	Component type
1	Carbon monoxide	0.63	Program
2	Carbon dioxide	0.028	Program
3	Nitrogen	0.0048	Program
4	Hydrogen	0.34	Program
5			
6			
7			
8			
9			
10			
11			

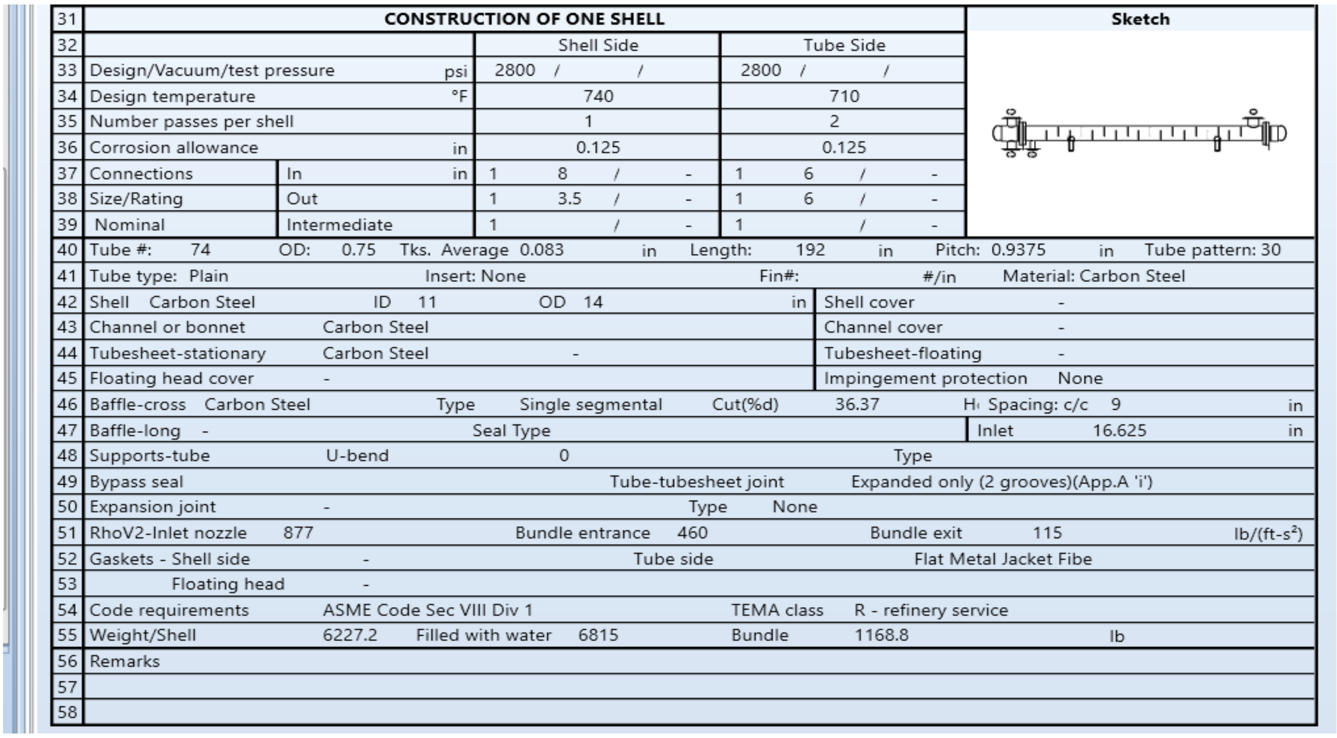
9.2.4 Specification Sheet



Heat Exchanger Specification Sheet

1	Company: HX-103					
2	Location:					
3	Service of Unit: Our Reference:					
4	Item No.: 1 Your Reference:					
5	Date: Rev No.: Job No.:					
6	Size : 11 - 192 in Type: BEM Horizontal Connected in: 1 parallel 1 series					
7	Surf/unit(eff.) 225.5 ft² Shells/unit 1 Surf/shell(eff.) 225.5 ft²					
8	**PERFORMANCE OF ONE UNIT**					
9	Fluid allocation		Shell Side		Tube Side	
10	Fluid name		STEAM		GAS MIXTURE	
11	Fluid quantity, Total	lb/h	66138		30593	
12	Vapor (In/Out)	lb/h	66138	0	30593	30593
13	Liquid	lb/h	0	66138	0	0
14	Noncondensable	lb/h	0	0	0	0
15						
16	Temperature (In/Out)	°F	671.61	665.25	95	644
17	Bubble / Dew point	°F	671.61 / 671.61	671.21 / 671.21	/	/
18	Density Vapor/Liquid	lb/ft³	5.792 /	/ 35.105	2.227 /	1.113 /
19	Viscosity	cp	0.0261 /	/ 0.0804	0.0122 /	0.0201 /
20	Molecular wt, Vap		18.01		5.22	5.22
21	Molecular wt, NC					
22	Specific heat	BTU/(lb-F)	3.7867 /	/ 1.2921	1.388 /	1.3944 /
23	Thermal conductivity	BTU/(ft-h-F)	0.06 /	/ 0.251	0.093 /	0.138 /
24	Latent heat	BTU/lb	341.8	343.1		
25	Pressure (abs)	psi	2538.16	2531.6	2538.16	2522.21
26	Velocity (Mean/Max)	ft/s	7.93 / 15.33		74.42 / 102.64	
27	Pressure drop, allow./calc.	psi	26.83	6.55	26.83	15.95
28	Fouling resistance (min)	ft²-h-F/BTU	0		0	0 Ao based

9.2.5 Specification Sheet



31	CONSTRUCTION OF ONE SHELL					Sketch
32				Shell Side	Tube Side	
33	Design/Vacuum/test pressure		psi	2800 / /	2800 / /	
34	Design temperature		°F	740	710	
35	Number passes per shell			1	2	
36	Corrosion allowance		in	0.125	0.125	
37	Connections	In	in	1 8 / -	1 6 / -	
38	Size/Rating	Out		1 3.5 / -	1 6 / -	
39	Nominal	Intermediate		1 / -	1 / -	
40	Tube #: 74	OD: 0.75	Tks. Average 0.083 in	Length: 192 in	Pitch: 0.9375 in	Tube pattern: 30
41	Tube type: Plain		Insert: None		Fin#: #/in	Material: Carbon Steel
42	Shell Carbon Steel	ID 11	OD 14 in		Shell cover	-
43	Channel or bonnet	Carbon Steel			Channel cover	-
44	Tubesheet-stationary	Carbon Steel	-		Tubesheet-floating	-
45	Floating head cover	-			Impingement protection	None
46	Baffle-cross Carbon Steel	Type	Single segmental	Cut(%d) 36.37	H Spacing: c/c 9	in
47	Baffle-long -		Seal Type		Inlet 16.625	in
48	Supports-tube	U-bend	0		Type	
49	Bypass seal			Tube-tubesheet joint	Expanded only (2 grooves)(App.A 'i')	
50	Expansion joint	-		Type None		
51	RhoV2-Inlet nozzle 877		Bundle entrance 460		Bundle exit 115	lb/(ft-s²)
52	Gaskets - Shell side	-		Tube side	Flat Metal Jacket Fibe	
53	Floating head	-				
54	Code requirements	ASME Code Sec VIII Div 1		TEMA class	R - refinery service	
55	Weight/Shell	6227.2	Filled with water 6815	Bundle	1168.8	lb
56	Remarks					
57						
58						

CHAPTER # 10

INSTRUMENTAION AND PROCESS CONTROL

10 Objective of instrumentation and control

The following are the instrumentation and control's main objective:

i. Process variables to help in understanding the proper operational limits.
ii. To recognize hypothetically dangerous conditions as they develop and to offer alarms and methods for automatic shutdown.
iii. Interlocks and alerts should be available to avoid risky operating procedures.

10.1 Production Rate

To produce the intended design product.

10.2 Product Quality:

To keep the product's composition within a certain range of quality.

10.3 Cost

In line with the other purpose, to operate at the lowest production cost possible. Since these goals are interrelated, they must be taken into account jointly. Measurement is a important requirement for process control, whether the control is implemented manually, spontaneously, or semi-automatically. The dependability, repeatability, and accuracy of the measurement tools used to regulate the level of control that may be acquired.

The objective of an automatic process control is to use the operated variable to maintain the measured variable at its fixed position in spite of interruptions. Instruments are delivered to track the fundamental process variables while the plant is in process. Instruments with automatic alarms will monitor crucial process variables and alert the operation if a risky situation develops.

10.4 Process Instrumentation

Without sufficient instrumentation, no chemical plant can be run. Almost every process requires the checking of flows, pressures, temperatures, and levels in order for the plant operator to see that every component of the plant is operating as it should. It may also be essential to track and display a number of additional quantities that are more pertinent to the specific procedure under consideration. In many cases, sensors play a crucial role in a process's control system. Process instrumentation highly intricate and rely on the functionality and traits of a wide range of various sensors.

10.4.1 Temperature

The most frequent process control actions can be temperature measurement and control. The fundamental rules for measuring temperature are:

- The most basic form of the expansion of a material and temperature, which results in a variation in length, volume, and pressure, is the conventional mercury in glass thermometer.
- Resistance thermometers (RTD) utilize a change in electric resistance with temperature.
- Temperature thermocouples and a change in the contact potential between different metals.
- Temperature, optical, and radiation pyrometers all affect the change in radiant energy.

10.4.2 Pressure

All pressure transducers focus on measuring static pressure, such as the fluid's pressure at rest, while measuring pressure. The most popular the DP cell acts as a pressure transducer. , which is used in combination with any type of output mechanism and a sensing device such an orifice metre. It can be connected to something mechanical, electrical, or pneumatic to transmit signals.

10.4.3 Flow

Almost all industrial processes require the monitoring of flow, and numerous techniques have been developed for this purpose. Similar to measuring pressure, measuring flow typically involves a sensing device connected to a DP cell. Other flow metres may be used for specialised purposes, such as processes where magnetic flow metres don't require an external disturbance in the fluid stream.

10.4.4 Concentration

Understanding the makeup of a process stream is frequently crucial. To ascertain whether a certain product meets the needed specifications or the arrangement of a specific stream is changing, such information may be required. In order to maintain the plant, fluctuation in either will frequently necessitate some sort of management intervention. Typically, a material's characteristic is used to assess concentration, such as electromagnetic wave absorption, refractive index, pH, or component density in chromatography.

10.5 Process Control Terms

In the context of process control, a process variable is a parameter or measurement that characterizes the behavior of a physical process. Process variables can consist of temperature, pressure, flow rate, level, pH, conductivity, and many others.

Process variables are used as inputs to control systems that regulate the behavior of a process. For example, a temperature control system might use a temperature sensor to measure the process variable, and then adjust a heater or cooler to maintain a desired temperature setpoint.

10.5.1 Process Variable

- Pressure
- Flow
- Level
- Temperature
- Density
- Ph (acidity or alkalinity)
- Mass

10.5.2 Set point

A process variable's set point is a value that should be maintained.

10.5.3 Measured variable

The process fluid's state, which must be maintained at the predetermined set point, is the measured variable.

10.5.4 Manipulated variable

Variable that can be changed to keep the switch variable at the correct level.

10.6 Hardware elements of control system

The evaluating instruments or sensors:

These are the tools that are used to measure controlled variables and disturbances.

10.6.1 Transducers

A device that changes changes in a physical quantity—like pressure or brightness—into an electrical signal or the other way around.

10.6.2 Transmission line

The dimension signal is transferred from the computing equipment to the controller using it.

10.6.3 Controller

This gets data from the measuring apparatuses and determines if the data is accurate or not.

10.6.4 The final controller element

A final control element (FCE) is a device that is used to regulate or control a process variable such as temperature, pressure, flow, level, or composition. It is typically the last component in a control loop, and its function is to implement the control output from the controller to adjust the process variable to the desired setpoint.

10.7 Classification of control systems

The following control loops are frequently used to instrument and regulate various plant sections and pieces of equipment.

i. Feed-back control loop
ii. Feed forward control loop
iii. Ratio control loop
iv. Split range control loop
v. Cascade control loop

To support our decision to choose a control loop for a specific piece of equipment, a brief summary of these control schemes is provided here.

10.7.1 Feed Back Control Loop

A feedback control loop is a system in which the output of a process is continuously monitored and compared to a desired or reference value. Based on this comparison, a control action is taken to adjust the input to the process, with the goal of bringing the output closer to the desired value.

10.7.2 Feed Forward Control Loop

A feedforward control loop is a type of control system used in engineering and process control applications to achieve a desired output based on a set of input variables. In a feedforward control loop, the control action is based on a prediction of the future output, which is calculated using a mathematical model of the process being controlled.

10.7.3 Ratio Control

Ratio control is a type of process control in which the flow rate of one fluid or substance is adjusted based on the flow rate of another fluid or substance. The ratio between the two flows is kept constant, which ensures that the desired proportion of the two substances is maintained.

10.7.4 Split Range Loop

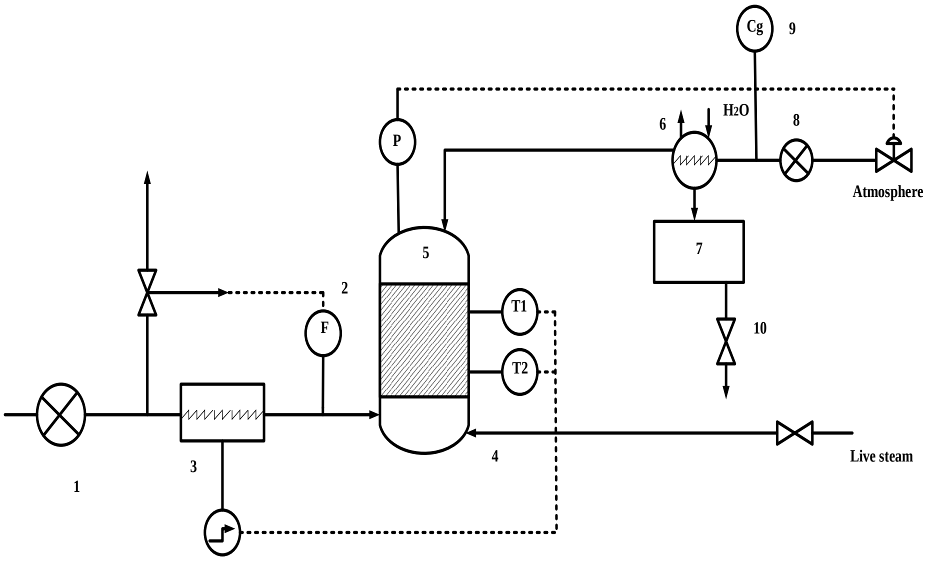
A split range loop is a type of loop in programming that involves dividing a range of values into smaller segments and processing each segment in parallel using multiple threads or processes.

10.7.5 Cascade Control Loop

Cascade control is a control strategy used in process control systems to improve the control performance of a process. The cascade control loop consists of two control loops: an inner loop and an outer loop.

10.8 Feedback Control Loop around Fluidized Bed Gasifier

There are several types of control loops, including feedback, feedforward, and cascade control loops. The right control loop should be chosen based on the needs of the process because each form of control loop has benefits and drawbacks.



1, 2, 3.Temperature control of feed

4. Temperature and pressure control of steam

5. Gasifier

6. Flowrate control of gas

Figure 10.1 Control loop on Fluidized bed Gasifier

- A feedforward control loop uses a measurement of a disturbance variable to adjust the system's input to prevent any changes in the output. This type of control loop is useful when the disturbance variables have a significant effect on the system's output. A feedforward control loop may not be required since disturbance variables do not significantly affect the gasification process in a fluidized bed gasifier.

- A cascade control loop uses multiple feedback control loops to control different variables in a system. This type of control loop is useful when one variable's control affects another variable However, a fluidized bed gasifier's gasification procedure is quite straightforward, and the variables are not strongly interdependent, making a cascade control loop unnecessary.
- Therefore, a feedback control loop is the most suitable control loop for a fluidized bed gasifier for hydrogen production from biomass. The feedback control loop allows the system to continuously adjust the input to maintain the desired output and prevent any safety hazards. Additionally, a feedback control loop can be easily implemented and adjusted, making it an effective and efficient control loop for a fluidized bed gasifier.

10.9 Control Objectives

The main control goal is to keep the reactor temperature within a predetermined range because it has an impact on the rate of the gasification reaction and the calibr of the produced gas.

Manipulated variables

i. The reactor's inlet gas composition and flow rate
ii. The feedstock feeding rate
iii. The rate of air or steam addition to the reactor

Disturbances

- Feed flowrate
- Feed temperature.
- Pressure inside the reactor
- Composition of the feed
- Pressure and temperature of steam

Description

A feedback control loop for a fluidized bed gasifier for hydrogen production from biomass involves continuously measuring the reactor temperature and comparing it to a set point temperature. The control system increases the heat input to the system by altering the fuel feed rate of the cooling water circulating around the reactor if the measured temperature is lower than the set point temperature. If the recorded temperature beats the set point temperature, the control system lowers the fuel feed rate or modifies the cooling water flow rate to reduce the heat input to the system.

A proportional-integral-derivative (PID) controller in the feedback control loop is used to modify the input and maintain the desired output. The PID controller uses this error signal to change the controlled variables in order to get the measured temperature closer to the setpoint temperature. The error signal is calculated by subtracting the measured temperature from the setpoint temperature.

The control system may also include additional feedback loops to control other variables, such as pressure and gas flow rates. These feedback loops work in a similar manner, continuously measuring changing the manipulated variable and the process variable to maintain the desired output.

In summary, the feedback control loop continuously measures the process variable, compares it to the desired setpoint, and adjusts the manipulated variable to maintain the desired output. This control loop is effective in controlling a fluidized bed gasifier for hydrogen production from biomass by maintaining the reactor temperature within a specific range, achieving maximum efficiency, and minimizing safety hazards.

CHAPTER # 11

HAZOP STUDY

11 HAZOP Study

HAZOP stands for Hazard and Operability Study. It is a systematic and structured method used to recognize potential hazards and operability concerns in industrial procedures, and to develop appropriate measures to prevent or mitigate them.

HAZOP studies involve a team of experts from different disciplines, such as engineering, safety, and operations, who analyze the process in detail and systematically identify potential hazards and deviations from the intended design. The team uses a set of guidewords, such as "no," "more," "less," "reverse," "other than," and "part of," to help them identify possible deviations.

11.1 Objectives of HAZOP Study

A HAZOP study's aims can be described as follows:

- To locate (areas in the design that might provide a substantial threat).
- To discover and investigate design aspects that impact the likelihood of a failure.
- There is a dangerous situation taking place.
- To acquaint the research team with the available design information.
- To guarantee that the regions of substantial hazard are studied in a methodical manner
- To find important design information that the team doesn't have access to right now.

11.2 HAZOP Guide Words and Meanings

Table 11.1 Guide words for HAZOP

Guide Words	Meanings
No	Negation of design intent
Less	Quantitative Decrease
More	Quantitative Increase
Part off	Qualitative Increase
As well as	Qualitative Decrease
Reverse	Logical opposite of the intent
Other than	Complete substitution

11.3 Success and Failure of HAZOP

The following elements affect whether the HAZOP is successful or unsuccessful:

- The correctness and completeness of the drawings and other data utilized as the study's foundation were assessed.
- Technical expertise and team insights.
- The team's capacity to apply the Asian approach let them use their imagination to visualise variances, causes, and effects.
- The team's capacity to focus on the more critical threats that are discovered.
- It helps to specify the phrases used because the procedure is systematic.

11.4 Steps to Conduct HAZOP Study

The steps of a HAZOP investigation are as follows:

1. Describe the study's aim, goal, and scope. The goal might be to evaluate a plant that has not yet been built or to assess the risk of an existing unit. The objectives described above can be made more detailed depending on the study's aim and conditions. The physical unit's limits, as well as the range of events and variables studied, define the study's scope. For example, HAZOPs used to be solely focused on fire and explosion endpoints, but now they often contain toxic release, disagreeable odor, and environmental endpoints as well.
2. Choose the HAZOP research team. To enable good group interaction, The team captain needs to be skilled in interpersonal and HAZOP techniques. To shield all sides of design, process and safety, the team should be made up of as many distinct professionals as is practical. The HAZOP approach should be discussed with the team, and the team leader should highlight that main objective of a HAZOP study is to identify dangers; coming up with solutions to problems is a separate effort.
3. The following items are frequently required, :
    - Gather Information
    - Description of the procedure
    - Flowcharts for processes
    - All components, steps, and final goods have chemical, physical, and toxicological qualities.
    - Diagrams of piping and instruments (P&IDs)
    - Specifications for equipment, pipelines, and instruments

- Logic diagrams for process control
- Drawings for the layout
- Operating procedures are a set of rules that govern how things are done.
- Procedures for routine maintenance
- Procedures for dealing with emergencies

4. Carry out the research. The unit is split into study "nodes" using the data obtained, and the procedure shown in Figure 1 is shadowed for each node. Process bulges are places in the process where known and desired values for process parameters (pressure, temperature, composition, and so on) exist. The functioning of several pieces of equipment, such as distillation columns, heat exchanges, and pumps, causes these values to fluctuate between nodes. To assist arrange the node process parameters and control logic data, several forms and work sheets have been designed.
5. The essence of the HAZOP research is recurring cycling through this process, which evaluates how and why each parameter could differ from the planned and the consequences.
6. Prepare a report. The study should reveal as much information as possible concerning events and their consequences. Clearly, if the HAZOP detects a not-too-improbable order of circumstances that might lead to a tragedy, suitable follow-up act is required. Although risk reduction activity is not part of the HAZOP, it may be required as a result of the HAZOP.
7. HAZOP studies take a long time and are costly. Bringing an older plant's P&IDs up to date might be a big technical undertaking. Even yet, when weighed beside the possible damage of life, property, business, and uniform the survival of the company that a catastrophic spill may cause, they are cost effective.

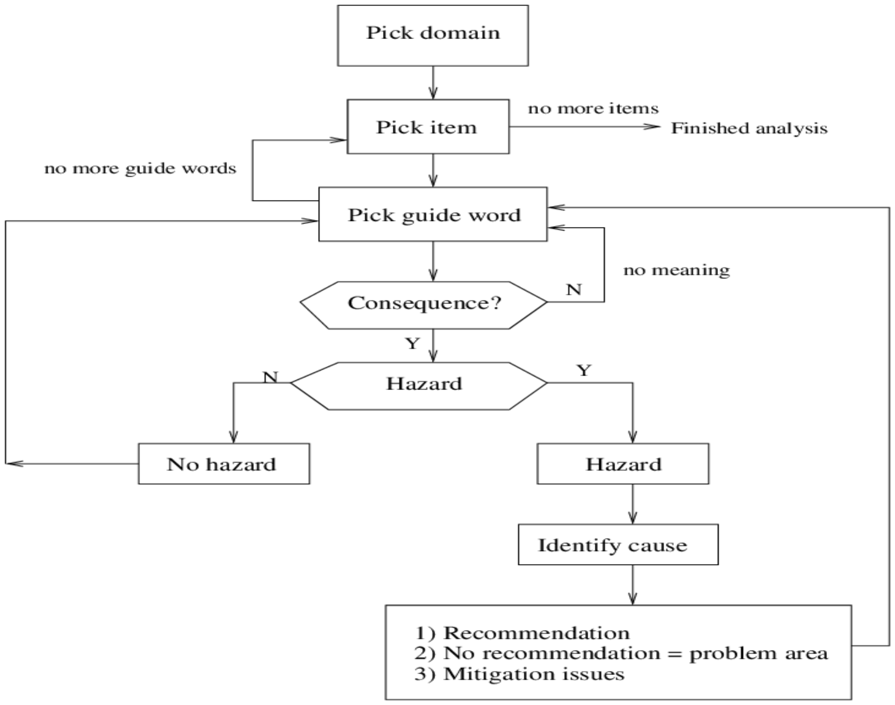


Table 11.2 Steps to conduct HAZOP study

11.5 HAZOP Study on Membrane Reactor (MR-101)

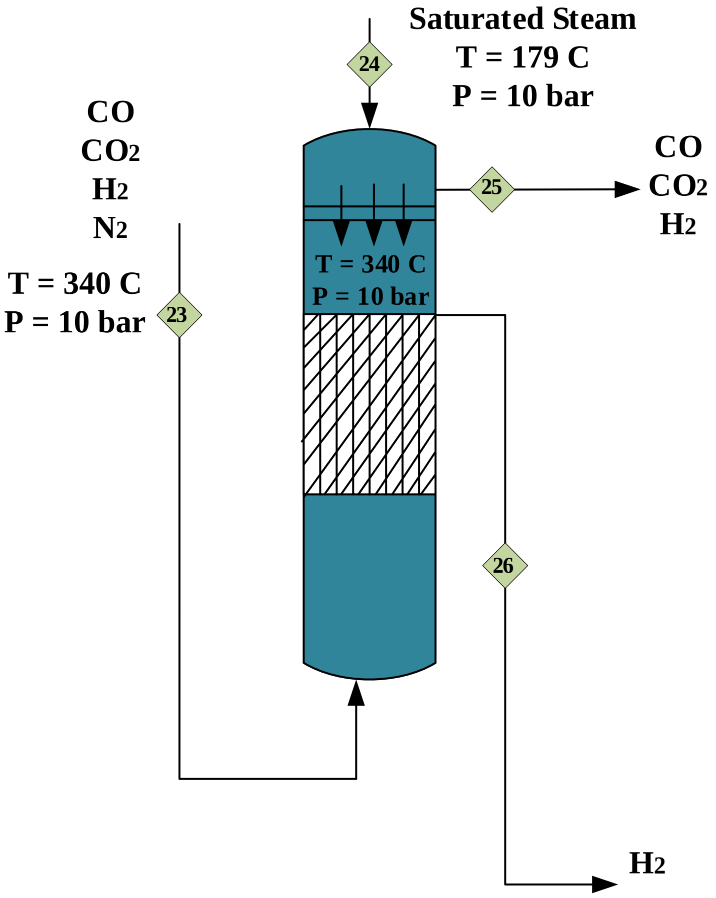


Figure 11.1 Packed Bed Membrane Reactor (MR-101)

Table 11.3 HAZOP on Membrane Reactor

Process Parameters	Guide Words	Possible Causes	Possible Consequences	Action Required
Flow	Low	Pipe is partial plugged/leakage	Decrease of level in reactor (MR-101)	Install check valve
Flow	Reverse	Failure of inlet valve	Fluid flow is reversed	Install check valve
Temperature	Less	Blockage in pipe	Reaction will not start	High temperature alarm
Temperature	More	Failure of valve	Reaction becomes runaway	Low temperature alarm
Temperature	None	Failure of inlet valve to open	Reaction will not start	Install temperature indicator
Pressure	More of	Failure of process fluid valve	Bursting of reaction vessel (MR-101)	Install high pressure alarm

11.6 HAZOP Study on Heat Exchanger (HX-103)

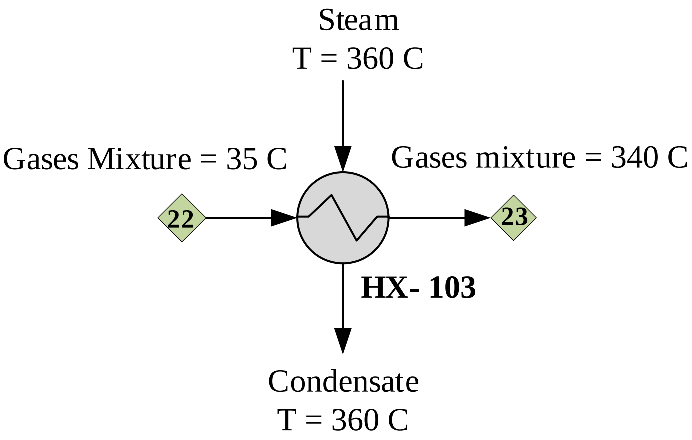


Figure 11.2 Heat Exchanger (HX-103)

Table 11.4 HAZOP on Heat Exchanger (HX-103)

Process Parameter	Guide Word	Deviation	Possible Causes	Possible Consequences	Required Action
Temperature	Less	Less flow of cooling water in heat exchanger (HX-103)	Pipe blockage	Temperature of process fluid remains constant	High temperature alarm
Temperature	More	More flow of cooling water in heat exchanger (HX-103)	Cooling water valve malfunction	Temperature ofprocess fluid decreases	Low temperature alarm
Pressure	More of	More pressure on tube side	Failure of process fluid valve	Bursting of tubesof heat exchanger (HX-103)	Install high pressure alarm
Temperature	None	No cooling water flow in heat exchanger (HX-103)	Failing to open the intake cooling water valve	Process fluid temperature isnot lowered accordingly	Install temperature indicator before and after the process fluid line
Flow	Reverse	Reverse process fluid flow	Failure of process fluid inlet valve	Product off set	Install check valve

CHAPTER # 12

ENVIRONMENTAL IMPACT ASSESSMENT

12 Environmental Impact Assessment

An Environmental Impact Assessment (EIA) is a rigorous and systematic process that thoroughly evaluates the potential environmental impacts of human activities or development projects. It encompasses a comprehensive analysis of the social, economic, and environmental effects of proposed initiatives, providing crucial information to the responsible environmental authority for informed decision-making.

The primary objective of an EIA is to assess both the positive and negative consequences that development proposals may have on the environment. While the emphasis is typically placed on the biophysical aspects, including factors such as air quality, water resources, ecosystems, and biodiversity, it is important to consider the social and economic dimensions as well. Good practice dictates that all these aspects are taken into account during the assessment process.

In summary, an EIA is a systematic and comprehensive approach to assess and analyze the potential impacts of development projects on the environment. It ensures that social, economic, and biophysical factors are thoroughly evaluated, enabling decision-makers to make well-informed choices regarding the proposed initiatives.

12.1 Hydrogen

Hydrogen (H2) is a naturally occurring element, consisting contains only one proton and one electron. Being the supreme prevalent element in the universe, it is essential to many different natural processes. Hydrogen is gaining attention as a promising alternative fuel due to its environmental benefits and potential for decarbonization.

As a clean and versatile energy carrier, hydrogen offers significant advantages to fight climate modification and reduce greenhouse gas discharges. When used as a fuel, hydrogen produces only water vapor as a byproduct, making it emission-free and environmentally friendly. It can be used in various sectors, including transportation, industry, and power generation, as a substitute for fossil fuels.

The production of hydrogen can be achieved through different methods, such as electrolysis, biomass gasification, and steam methane reforming. Each method has its own environmental implications, and it is important to assess the specific impact of hydrogen production processes on the environment.

In conclusion, hydrogen presents a promising pathway towards a cleaner and more sustainable energy system. Its environmental benefits, abundance, and versatility make it an attractive option for reducing greenhouse gas emissions and tackling the problems caused by climate change while fostering energy security and economic expansion.

12.2 Exposure to hydrogen

Exposure to hydrogen gas (H_2) presents certain risks and safety considerations that need to be understood and managed appropriately. While hydrogen is generally considered safe when handled properly, it is important to be aware of the possible risks connected to exposure. Here are some important points surrounding hydrogen exposure. :

1. **Flammability:** Hydrogen is is extremely flammable and can catch fire when concentrated. as low as 4% in air. To prevent the risk of fire or explosions, it is crucial to avoid the accumulation of hydrogen in confined spaces. Proper ventilation systems and leak detection mechanisms should be in place to ensure safe handling and storage of hydrogen.

2. **Rapid Dispersion:** Due to its low molecular weight, hydrogen disperses rapidly in the atmosphere. While this property helps mitigate the risk of hydrogen buildup, it is still important to prevent the presence of ignition sources in areas where hydrogen may be present.

3. **Asphyxiation Hazard:** Hydrogen is colorless, odorless, and tasteless, making it difficult to detect without appropriate monitoring equipment. In high concentrations, hydrogen can displace oxygen in confined spaces, leading to the risk of asphyxiation. Adequate ventilation and monitoring of oxygen levels are crucial when working with hydrogen in enclosed areas.

4. **Cryogenic Hazards:** Liquid hydrogen (LH2) is extremely cold and can cause severe frostbite or cryogenic burns upon direct contact with skin or other materials. Proper personal protective equipment, such as insulated gloves and clothing, should be used when handling LH2.

5. **Hydrogen Embrittlement:** Hydrogen can cause embrittlement in certain metals, leading to potential structural failures. This is of particular concern in high-pressure systems or when hydrogen comes into contact with susceptible materials. Proper material selection and design considerations are necessary to mitigate the risk of hydrogen embrittlement.

6. **Training and Safety Measures:** Adequate training, education, and adherence to safety protocols are essential to minimize risks associated with hydrogen exposure. This includes providing comprehensive training to personnel involved with hydrogen, implementing

appropriate storage and handling procedures, conducting regular inspections and maintenance of equipment, and having emergency response plans in place.

12.2.1 Reactivity Profile

Hydrogen gas (H2) produced from biomass gasification has a low reactivity profile under normal conditions. It is not considered highly reactive or unstable. However, hydrogen can readily react to create potentially dangerous chemicals when combined with oxidizers like fluorine or chlorine.. Care should be taken to prevent the introduction of reactive substances in the vicinity of hydrogen storage and handling areas.

12.2.2 Skin and Eye Irritation

Hydrogen gas does not cause direct irritation to the skin or eyes. However, if released under pressure, it can displace oxygen and lead to oxygen deprivation in enclosed spaces. Oxygen deprivation can have indirect effects on the skin and eyes due to a lack of oxygen supply.

12.2.3 First Aid

In case of accidental exposure or injury, appropriate first aid measures should be followed. For inhalation exposure, affected individuals should be transferred to a fresh air environment. If eye contact occurs, it is important to thoroughly rinse the eyes for at least 15 minutes while custody the eyelids wide. The skin should be washed with soap and water if hydrogen comes into contact with it. When symptoms are severe or continue, medical attention should be sought.

12.2.4 Eyes and Skin Exposure

Direct exposure of hydrogen gas to the eyes or skin does not cause immediate harm or irritation. However, in cases of high-pressure gas release or oxygen displacement, the indirect oxygen deprivation can have an impact on the eyes and skin. It is vital to address oxygen insufficiency as soon as possible by relocating to a well-ventilated environment and, if required, seeking medical attention.

12.2.5 Inhalation

Inhalation of hydrogen gas, especially in high concentrations, can lead to oxygen deprivation. Symptoms of oxygen deficiency include dizziness, breathing difficulties and unconsciousness. Affected individuals should be transferred to a location with fresh air and should seek emergency medical assistance if they have been exposed to significant quantities of hydrogen gas or are experiencing any respiratory discomfort.

12.2.6 Ingestion

Hydrogen gas is not intended for ingestion and should never be consumed. It's crucial to make sure that hydrogen gas is not accidentally released in areas where it could contaminate food or beverages.

12.2.7 Spills and Disposal

In the event of a hydrogen gas spill, it is important to evacuate the immediate area and take appropriate measures to prevent ignition sources. Hydrogen gas, being lighter than air, tends to disperse rapidly. If the gas is released in an outdoor area, it will dissipate and pose minimal risk. However, if the spill occurs indoors or in a confined space, it is crucial to ensure proper ventilation and allow the gas to dissipate safely. Disposal of hydrogen gas is not typically required as it is a naturally occurring element.

12.2.8 Disposal Methods

Since hydrogen gas is a naturally occurring element, disposal methods are not typically necessary. However, any equipment or materials contaminated with hydrogen gas should be properly cleaned and maintained according to standard procedures to ensure safety and prevent potential hazards.

Please note that safety protocols and procedures may vary depending on specific regulations, facility design, and operational conditions. It is important to consult relevant safety guidelines, standards, and local regulations to ensure the safe handling, storage, and disposal of hydrogen gas in the context of biomass gasification plants.

12.3 Handling and Storage

Handling and storage of hydrogen gas at a biomass gasification plant require careful adherence to safety protocols to ensure the safe operation of the facility. Here are key considerations for handling and storage:

1. **Ventilation:** Adequate ventilation is crucial to prevent the accumulation of hydrogen gas in enclosed spaces. The plant should be designed with proper ventilation systems to disperse any potential leaks or releases of hydrogen gas.

2. **Leak Detection Systems:** Implementing reliable leak detection systems is essential to promptly identify and address any hydrogen gas leaks. These systems can include gas sensors, alarms, and automated shut-off mechanisms to ensure the safety of personnel and prevent the escalation of potential hazards.

3. **Ignition Sources:** Strict control measures should be in place to prevent the presence of ignition sources near areas where hydrogen gas is stored or handled. This includes avoiding open flames, sparks, smoking, or any equipment that can generate sparks or static electricity.

4. **Storage Containers:** Hydrogen gas is typically stored in high-pressure cylinders or tanks. These storage containers should be designed, tested, and certified to withstand the pressure of the stored gas. Regular inspections, maintenance, and compliance with applicable regulations are necessary to ensure the integrity of the storage containers.

5. **Segregation:** Hydrogen storage areas should be clearly marked and segregated from other incompatible substances. This prevents potential reactions or hazards if accidental leaks or releases occur.

6. **Training and Education:** Proper training and education should be provided to personnel actively involved in managing and storing hydrogen gas. This includes understanding the properties of hydrogen, safety protocols, the usage of personal protection equipment and emergency response protocols.

7. **Emergency Response Plans:** Comprehensive emergency response plans should be developed and communicated to all relevant personnel. These plans should outline procedures for addressing hydrogen gas leaks, evacuations, first aid measures, and coordination with emergency services.

8. **Personal Protective Equipment (PPE):** When handling hydrogen gas, the proper PPE, such as safety goggles, gloves, and flame-resistant clothing, should be given and used. The special risks and dangers related to handling hydrogen gas should be taken into account when choosing PPE.

9. **Maintenance and Inspections:** Regular maintenance, inspections, and testing of equipment, storage containers, and safety systems should be conducted to ensure their proper functioning and compliance with safety standards.

10. **Regulatory Compliance:** It is essential to adhere to all relevant safety regulations, codes, and standards specific to the handling and storage of hydrogen gas. Compliance with applicable regulations helps ensure the safety of personnel, the facility, and the surrounding environment.

12.4 Exposure control and personal protection

Measures for personal safety and exposure management are crucial to minimize the risks associated with working in a biomass gasification plant where hydrogen gas is present. Here are key considerations for exposure control and personal protection:

1. **Engineering Controls:** Implementing engineering controls is the first line of defense in reducing hydrogen gas exposure. This can include proper ventilation systems, such as local exhaust ventilation, to ensure adequate air circulation and reduce the concentration of hydrogen gas in the working environment.
2. **Administrative Controls:** Establishing administrative controls helps to minimize exposure risks. This includes implementing safe work practices, such as conducting regular risk assessments, providing appropriate training and education to personnel, and enforcing standard operating procedures for handling hydrogen gas.
3. **Personal Protective Equipment (PPE):** The use of appropriate personal protective equipment is essential to protect workers from hydrogen gas exposure. PPE can include safety goggles, face shields, gloves, and flame-resistant clothing. The specific type of PPE required should be determined based on a comprehensive risk assessment of the tasks and potential hazards involved.
4. **Gas Monitoring:** Continuous monitoring of hydrogen gas levels is crucial to detect any leaks or abnormal concentrations. Gas monitoring systems, including fixed gas detectors or portable gas monitors, should be installed in relevant areas of the plant. Regular calibration and maintenance of these monitoring systems are necessary to ensure their accuracy and reliability.
5. **Training and Education:** Providing comprehensive training and education to all personnel working in the biomass gasification plant is essential. This includes raising awareness about the properties and hazards of hydrogen gas, proper handling techniques, emergency response procedures, and the correct use of personal protective equipment.
6. **Emergency Response Preparedness:** Developing and practicing emergency response plans specific to hydrogen gas-related incidents is critical. This includes establishing evacuation procedures, designating assembly points, and ensuring that personnel are familiar with emergency shutdown procedures and the use of firefighting equipment.

7. **Hygiene Practices:** Encouraging good hygiene practices is important to minimize the potential for hydrogen gas exposure. This includes promoting regular handwashing, avoiding touching the face or mouth with contaminated hands, and providing adequate washing facilities for personnel working with hydrogen gas.

8. **Regular Monitoring and Auditing:** Regular monitoring and auditing of exposure control measures are necessary to assess their effectiveness and identify areas for improvement. This can include periodic air monitoring, inspections of PPE usage, and feedback from workers to ensure ongoing compliance with safety protocols.

12.4.1 Personal Equipment for Protection

- **Eye/face protection**

A face protection and safety glasses are necessary. Use eye shelter that has been examined and approved in accordance with legal requirements.

- **Body Protection**

Chemical protection is provided by the entire outfit. Antistatic and flame-resistant protective clothing. The quantity and concentration of the hazardous material present at the worksite must be taken into consideration when choosing the type of protective equipment to be worn.

- **Respiratory protection**

Use a full-face respirator with multifunctional combination respirator cartridges as a fallback for engineering controls when risk assessments show air-purifying respirators are appropriate. If a respirator is your only means of protection, wear a full-face complete air respirator. Utilize respirators and parts that have been examined and approved in accordance with regulatory requirements.

Fire Prevention

There will be no open fires, sparks, or smoke. Ventilation, explosion-proof electrical equipment, and lighting are all included in the closed system. Prevent electrostatic charges from accumulating (e.g., by grounding). Filling, discharging, or handling with compressed air is not recommended.

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APPENDICES

Appendix-A

List of Tables:

Table A.1: Maximum Allowable Stress

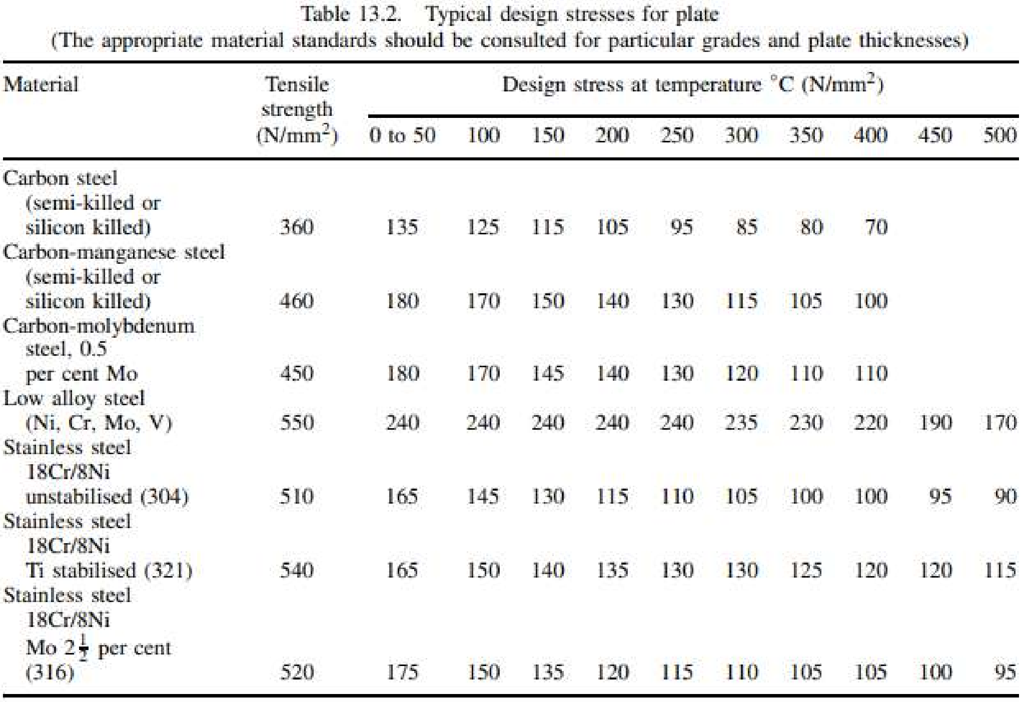
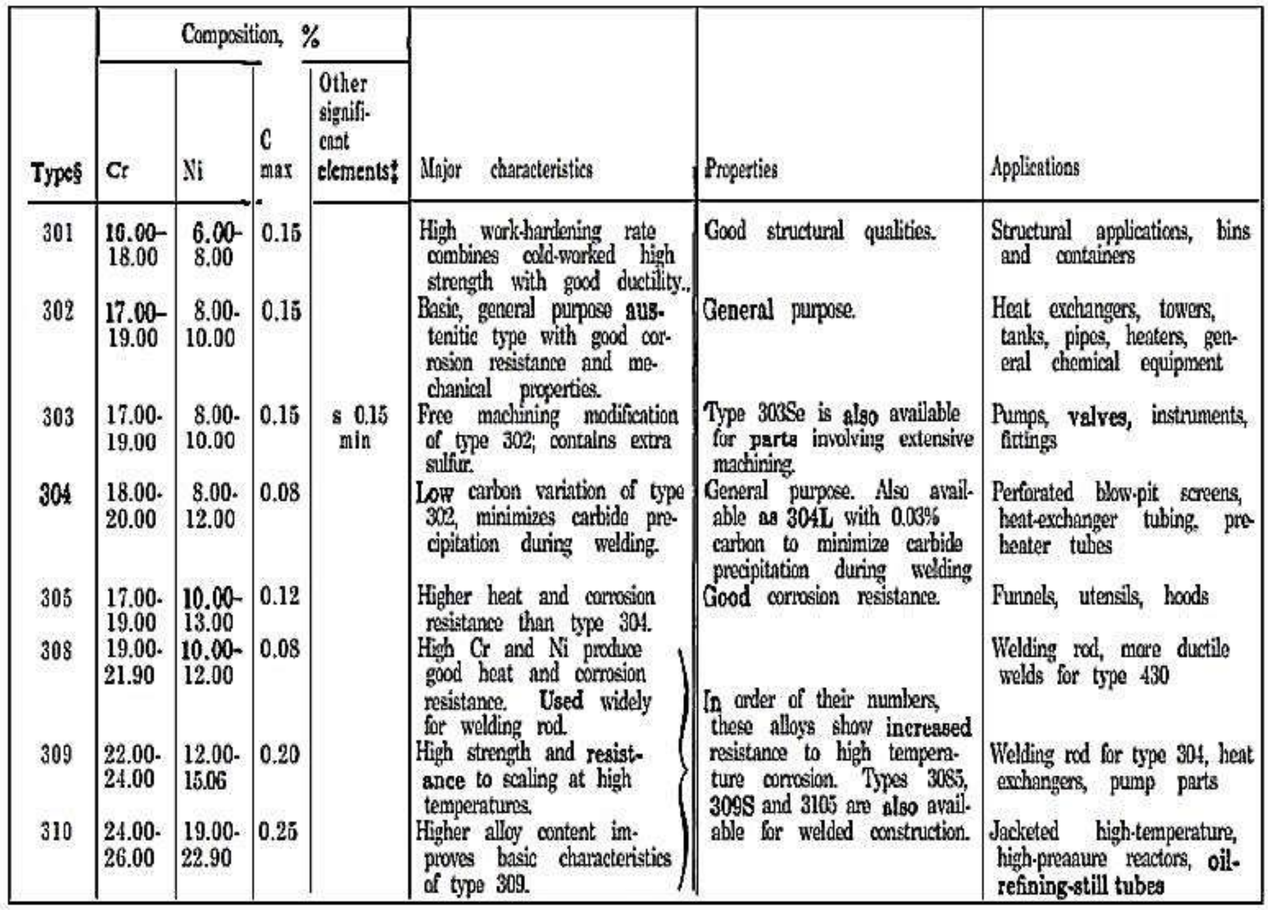


Table 13.2. Typical design stresses for plate
(The appropriate material standards should be consulted for particular grades and plate thicknesses)

Material	Tensile strength (N/mm^2)	Design stress at temperature °C (N/mm^2)									
		0 to 50	100	150	200	250	300	350	400	450	500
Carbon steel (semi-killed or silicon killed)	360	135	125	115	105	95	85	80	70		
Carbon-manganese steel (semi-killed or silicon killed)	460	180	170	150	140	130	115	105	100		
Carbon-molybdenum steel, 0.5 per cent Mo	450	180	170	145	140	130	120	110	110		
Low alloy steel (Ni, Cr, Mo, V)	550	240	240	240	240	240	235	230	220	190	170
Stainless steel 18Cr/8Ni unstabilised (304)	510	165	145	130	115	110	105	100	100	95	90
Stainless steel 18Cr/8Ni Ti stabilised (321)	540	165	150	140	135	130	130	125	120	120	115
Stainless steel 18Cr/8Ni Mo $2\frac{1}{2}$ per cent (316)	520	175	150	135	120	115	110	105	105	100	95

Table A.2 Material of Construction



Type§	Composition, %				Major characteristics	Properties	Applications
	Cr	Ni	C max	Other significant elements‡			
301	16.00–18.00	6.00-8.00	0.15		High work-hardening rate combines cold-worked high strength with good ductility.,	Good structural qualities.	Structural applications, bins and containers
302	17.00–19.00	8.00-10.00	0.15		Basic, general purpose austenitic type with good corrosion resistance and mechanical properties.	General purpose.	Heat exchangers, towers, tanks, pipes, heaters, general chemical equipment
303	17.00-19.00	8.00-10.00	0.15	s 0.15 min	Free machining modification of type 302; contains extra sulfur.	Type 303Se is also available for parts involving extensive machining.	Pumps, valves, instruments, fittings
304	18.00-20.00	8.00-12.00	0.08		Low carbon variation of type 302, minimizes carbide precipitation during welding.	General purpose. Also available as **304L** with 0.03% carbon to minimize carbide precipitation during welding	Perforated blow-pit screens, heat-exchanger tubing, preheater tubes
305	17.00-19.00	10.00-13.00	0.12		Higher heat and corrosion resistance than type 304.	Good corrosion resistance.	Funnels, utensils, hoods
308	19.00-21.90	10.00-12.00	0.08		High Cr and Ni produce good heat and corrosion resistance. Used widely for welding rod.	In order of their numbers, these alloys show increased resistance to high temperature corrosion. Types 3085, 309S and 3105 are also available for welded construction.	Welding rod, more ductile welds for type 430
309	22.00-24.00	12.00-15.06	0.20		High strength and resistance to scaling at high temperatures.		Welding rod for type 304, heat exchangers, pump parts
310	24.00-26.00	19.00-22.90	0.25		Higher alloy content improves basic characteristics of type 309.		Jacketed high-temperature, high-pressure reactors, oil-refining-still tubes

Table A.3 Typical Overall Heat Transfer Coefficients

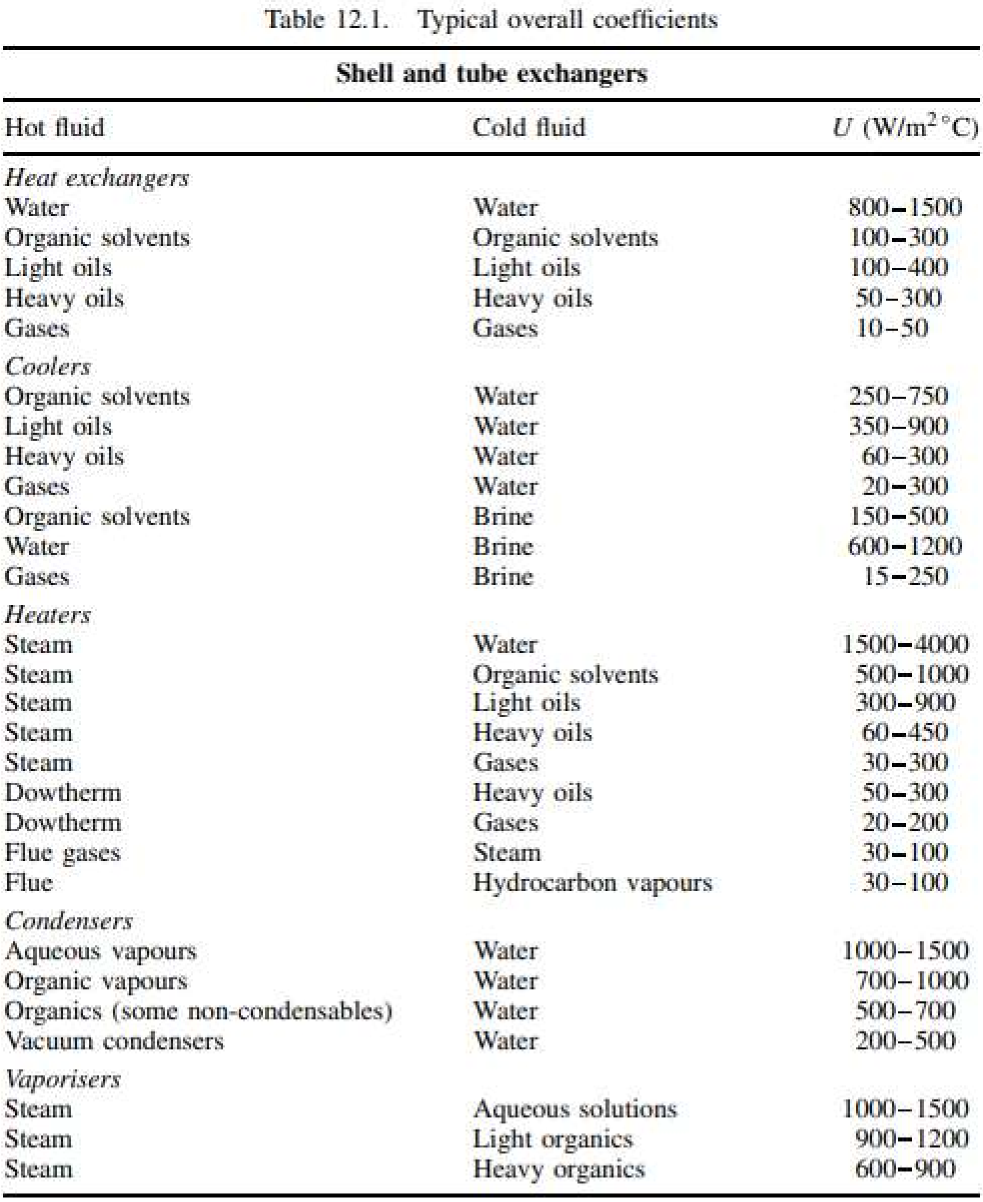


Table 12.1. Typical overall coefficients

Shell and tube exchangers		
Hot fluid	Cold fluid	U (W/m^2°C)
Heat exchangers		
Water	Water	800–1500
Organic solvents	Organic solvents	100–300
Light oils	Light oils	100–400
Heavy oils	Heavy oils	50–300
Gases	Gases	10–50
Coolers		
Organic solvents	Water	250–750
Light oils	Water	350–900
Heavy oils	Water	60–300
Gases	Water	20–300
Organic solvents	Brine	150–500
Water	Brine	600–1200
Gases	Brine	15–250
Heaters		
Steam	Water	1500–4000
Steam	Organic solvents	500–1000
Steam	Light oils	300–900
Steam	Heavy oils	60–450
Steam	Gases	30–300
Dowtherm	Heavy oils	50–300
Dowtherm	Gases	20–200
Flue gases	Steam	30–100
Flue	Hydrocarbon vapours	30–100
Condensers		
Aqueous vapours	Water	1000–1500
Organic vapours	Water	700–1000
Organics (some non-condensables)	Water	500–700
Vacuum condensers	Water	200–500
Vaporisers		
Steam	Aqueous solutions	1000–1500
Steam	Light organics	900–1200
Steam	Heavy organics	600–900

Table A.4 Fouling Factors Typical Values

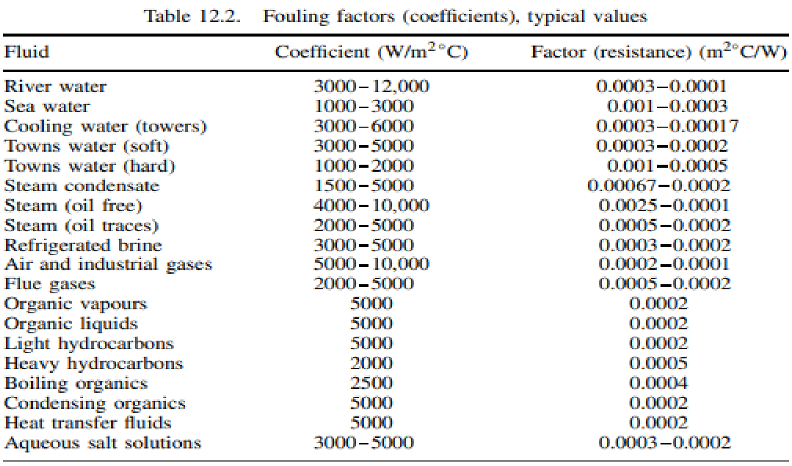


Table 12.2. Fouling factors (coefficients), typical values

Fluid	Coefficient (W/m^2°C)	Factor (resistance) (m^2°C/W)
River water	3000–12,000	0.0003–0.0001
Sea water	1000–3000	0.001–0.0003
Cooling water (towers)	3000–6000	0.0003–0.00017
Towns water (soft)	3000–5000	0.0003–0.0002
Towns water (hard)	1000–2000	0.001–0.0005
Steam condensate	1500–5000	0.00067–0.0002
Steam (oil free)	4000–10,000	0.0025–0.0001
Steam (oil traces)	2000–5000	0.0005–0.0002
Refrigerated brine	3000–5000	0.0003–0.0002
Air and industrial gases	5000–10,000	0.0002–0.0001
Flue gases	2000–5000	0.0005–0.0002
Organic vapours	5000	0.0002
Organic liquids	5000	0.0002
Light hydrocarbons	5000	0.0002
Heavy hydrocarbons	2000	0.0005
Boiling organics	2500	0.0004
Condensing organics	5000	0.0002
Heat transfer fluids	5000	0.0002
Aqueous salt solutions	3000–5000	0.0003–0.0002

Table A.5 Standard dimensions for Tube

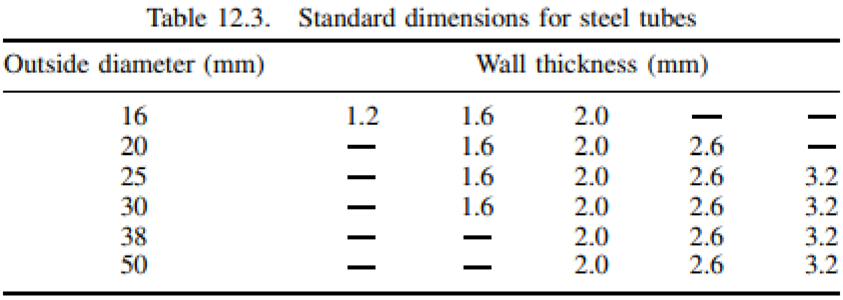
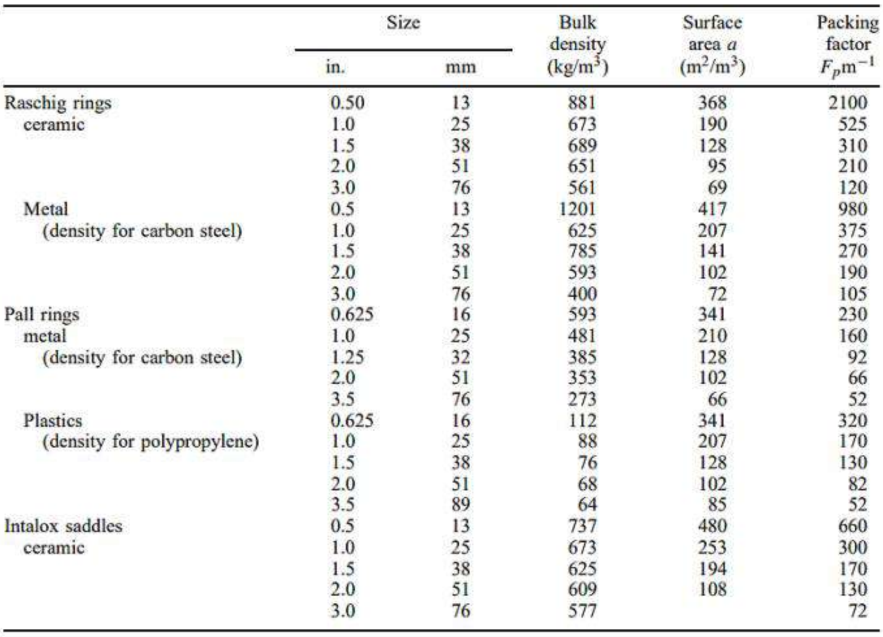


Table 12.3. Standard dimensions for steel tubes

Outside diameter (mm)	Wall thickness (mm)				
16	1.2	1.6	2.0	—	—
20	—	1.6	2.0	2.6	—
25	—	1.6	2.0	2.6	3.2
30	—	1.6	2.0	2.6	3.2
38	—	—	2.0	2.6	3.2
50	—	—	2.0	2.6	3.2

Table A.6 Design data for various packing



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

Table A.7 Packed Tower correlations for packed Tower

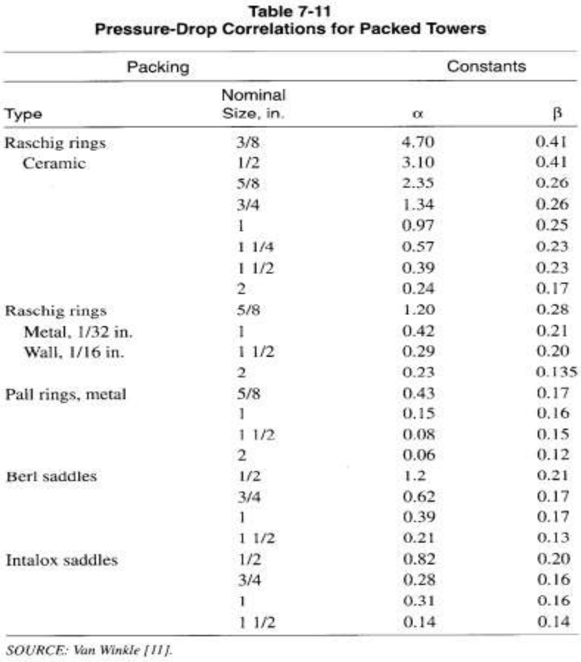


Table 7-11
Pressure-Drop Correlations for Packed Towers

Packing		Constants	
Type	Nominal Size, in.	α	β
Raschig rings Ceramic	3/8	4.70	0.41
	1/2	3.10	0.41
	5/8	2.35	0.26
	3/4	1.34	0.26
	1	0.97	0.25
	1 1/4	0.57	0.23
	1 1/2	0.39	0.23
	2	0.24	0.17
Raschig rings Metal, 1/32 in. Wall, 1/16 in.	5/8	1.20	0.28
	1	0.42	0.21
	1 1/2	0.29	0.20
	2	0.23	0.135
Pall rings, metal	5/8	0.43	0.17
	1	0.15	0.16
	1 1/2	0.08	0.15
	2	0.06	0.12
Berl saddles	1/2	1.2	0.21
	3/4	0.62	0.17
	1	0.39	0.17
	1 1/2	0.21	0.13
Intalox saddles	1/2	0.82	0.20
	3/4	0.28	0.16
	1	0.31	0.16
	1 1/2	0.14	0.14

SOURCE: Van Winkle [11].

Appendix-B

List of Figures

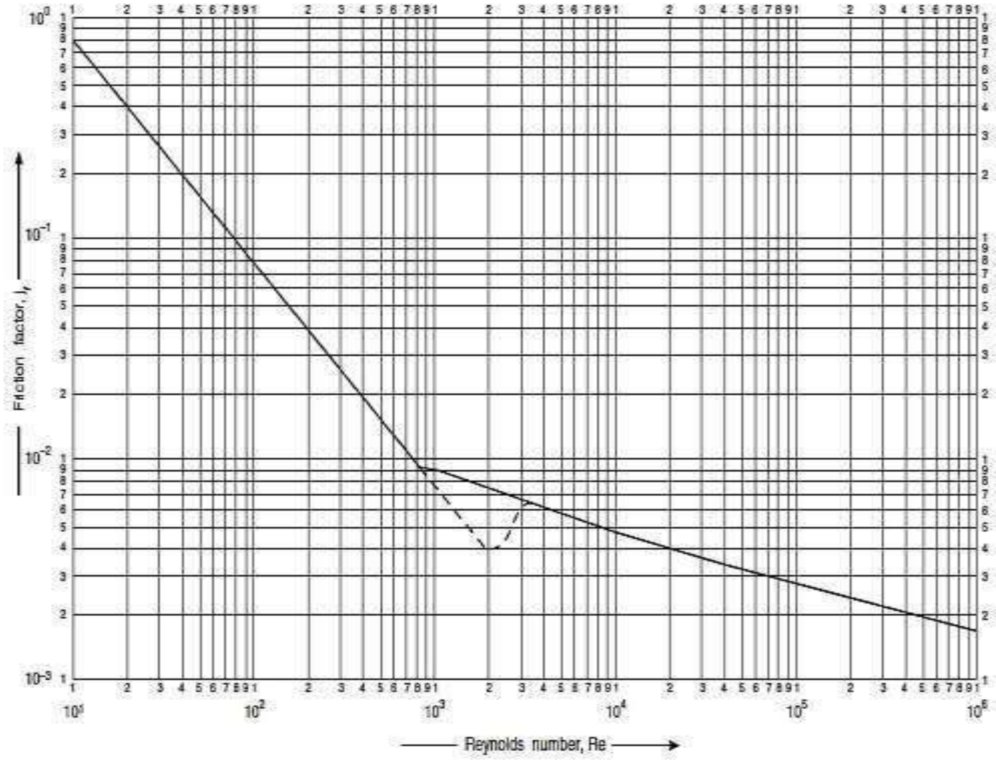


Figure B.1 Tube side friction factor

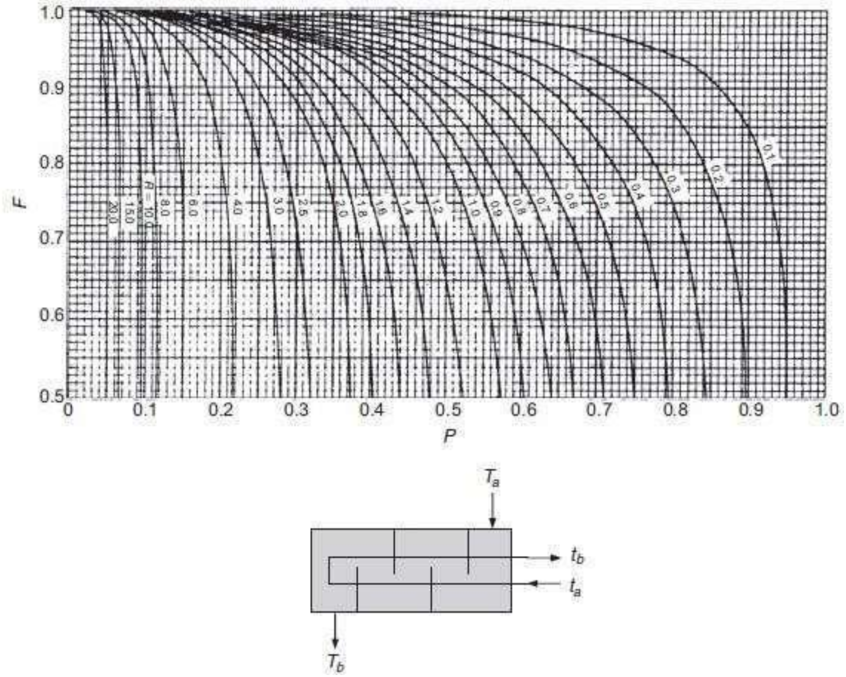


Figure B.2 LMTD Correction Factor

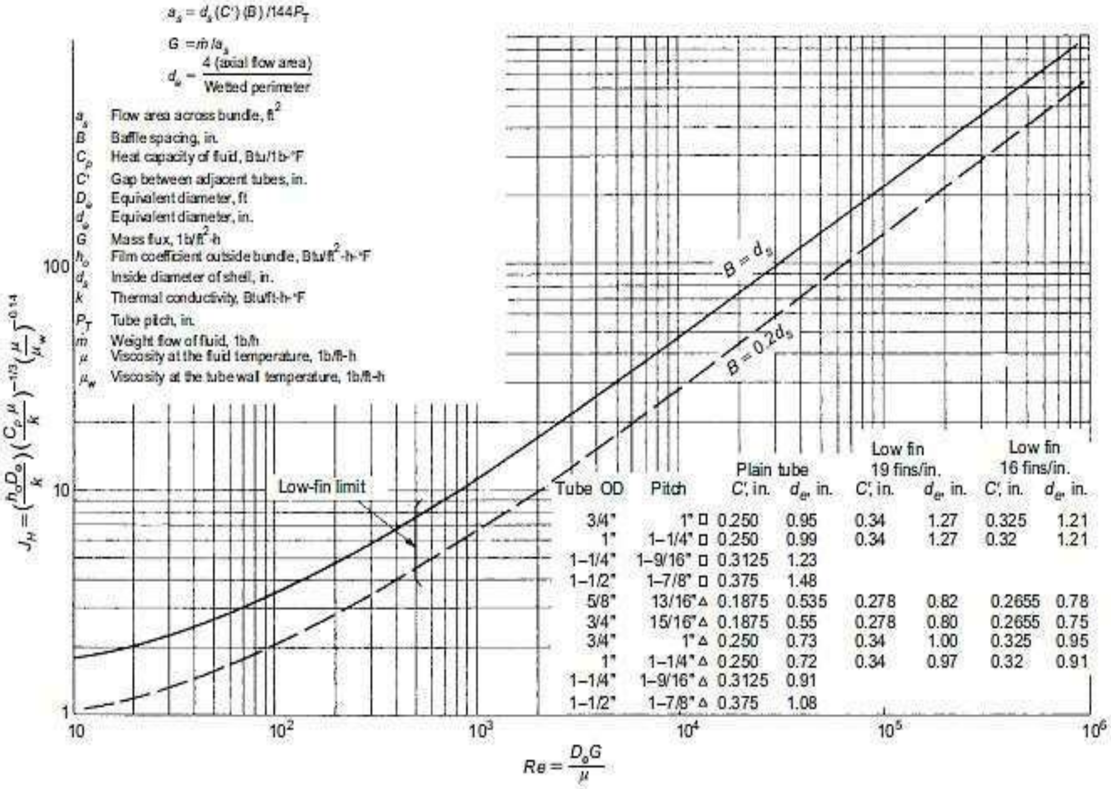


Figure B.3 Correlation for Shell-Side Heat-Transfer Coefficient

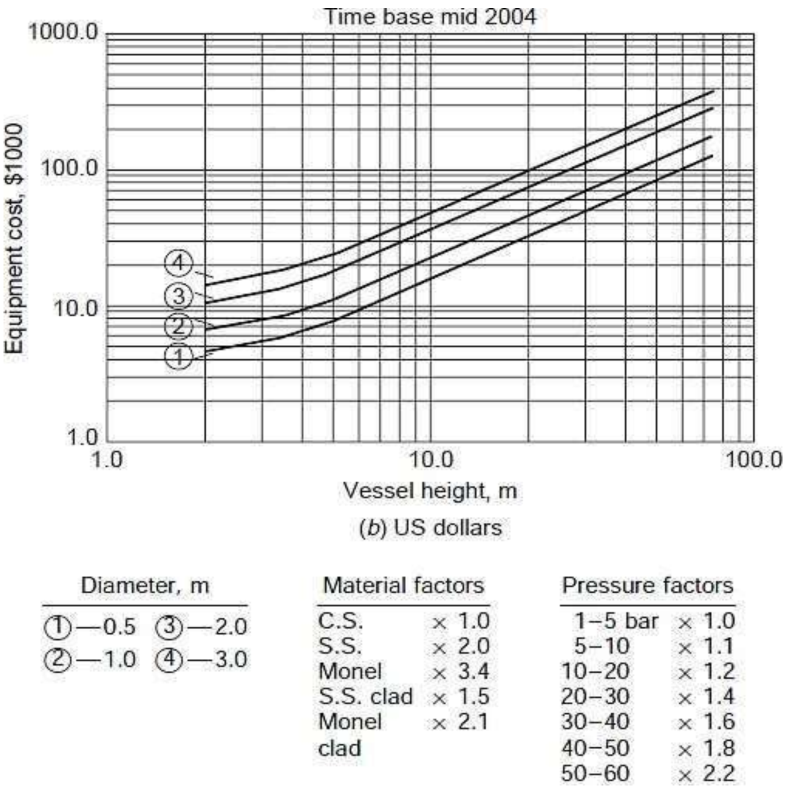
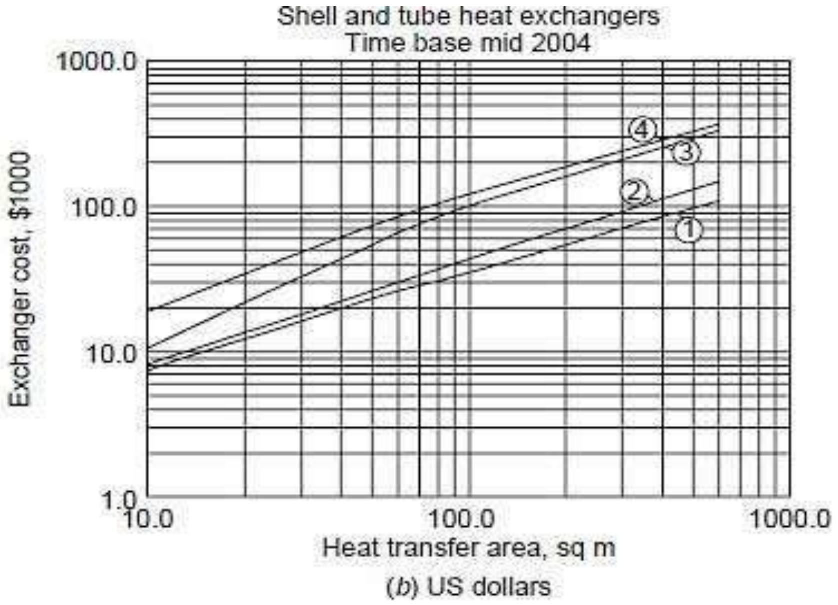


Figure B.4 Cost of Reactor

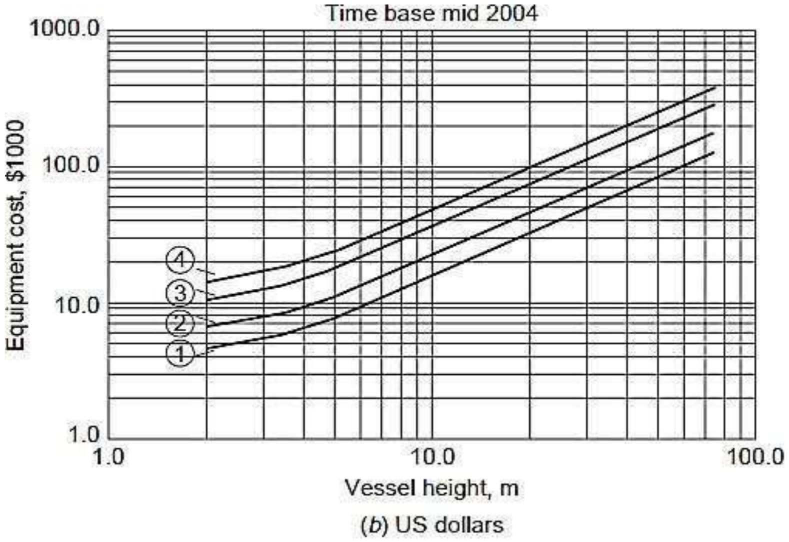


Materials	
Shell	Tubes
① Carbon steel	Carbon steel
② C.S.	Brass
③ C.S.	Stainless steel
④ S.S.	S.S.

Pressure factors	
1–10 bar	× 1.0
10–20	× 1.1
20–30	× 1.25
30–50	× 1.3
50–70	× 1.5

Type factors	
Floating head	× 1.0
Fixed tube sheet	× 0.8
U tube	× 0.85
Kettle	× 1.3

Figure B.5 Cost of Shell and Tube Heat Exchanger



Diameter, m	
①—0.5	③—2.0
②—1.0	④—3.0

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

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

Figure B.6 Cost of Tower

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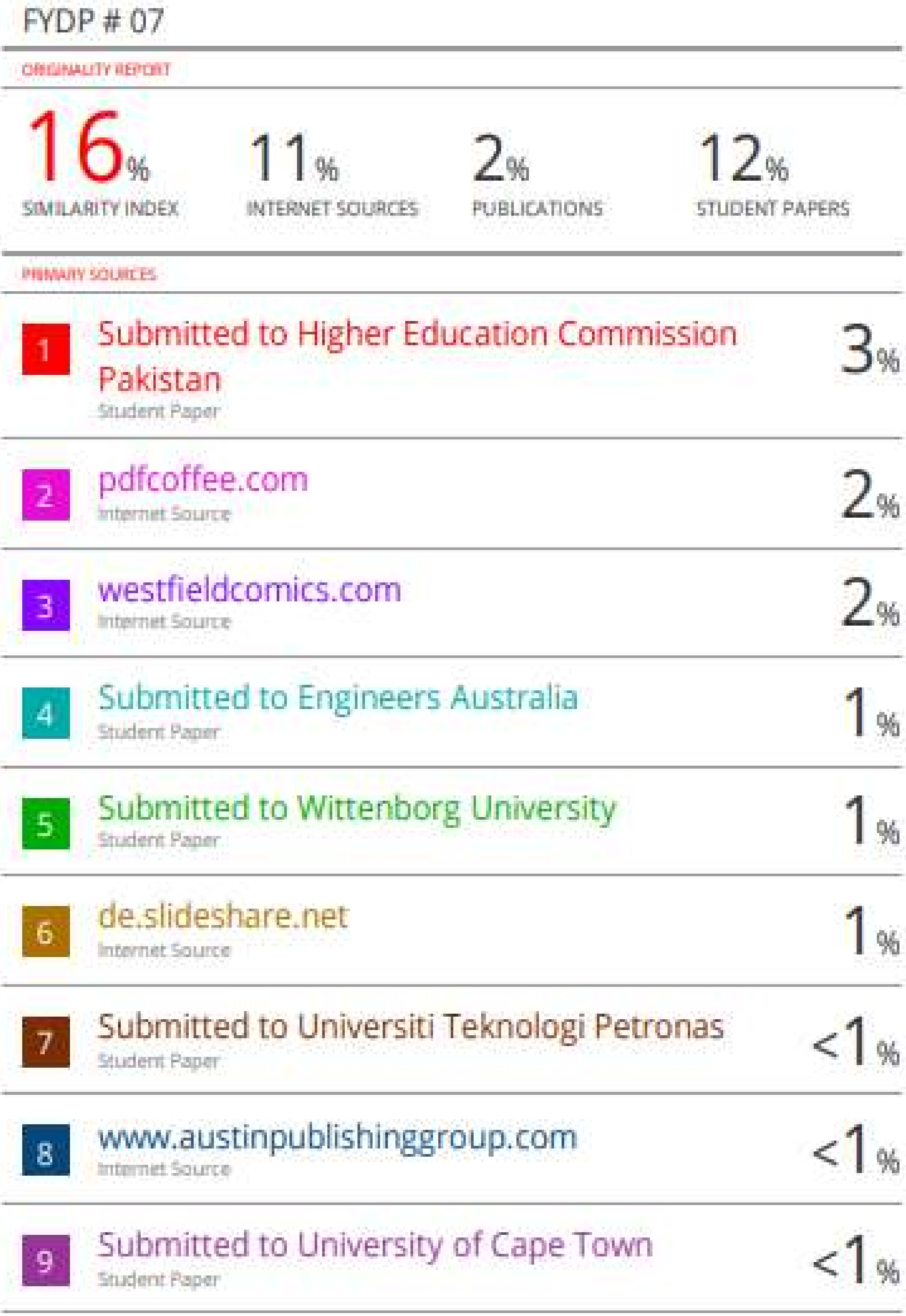

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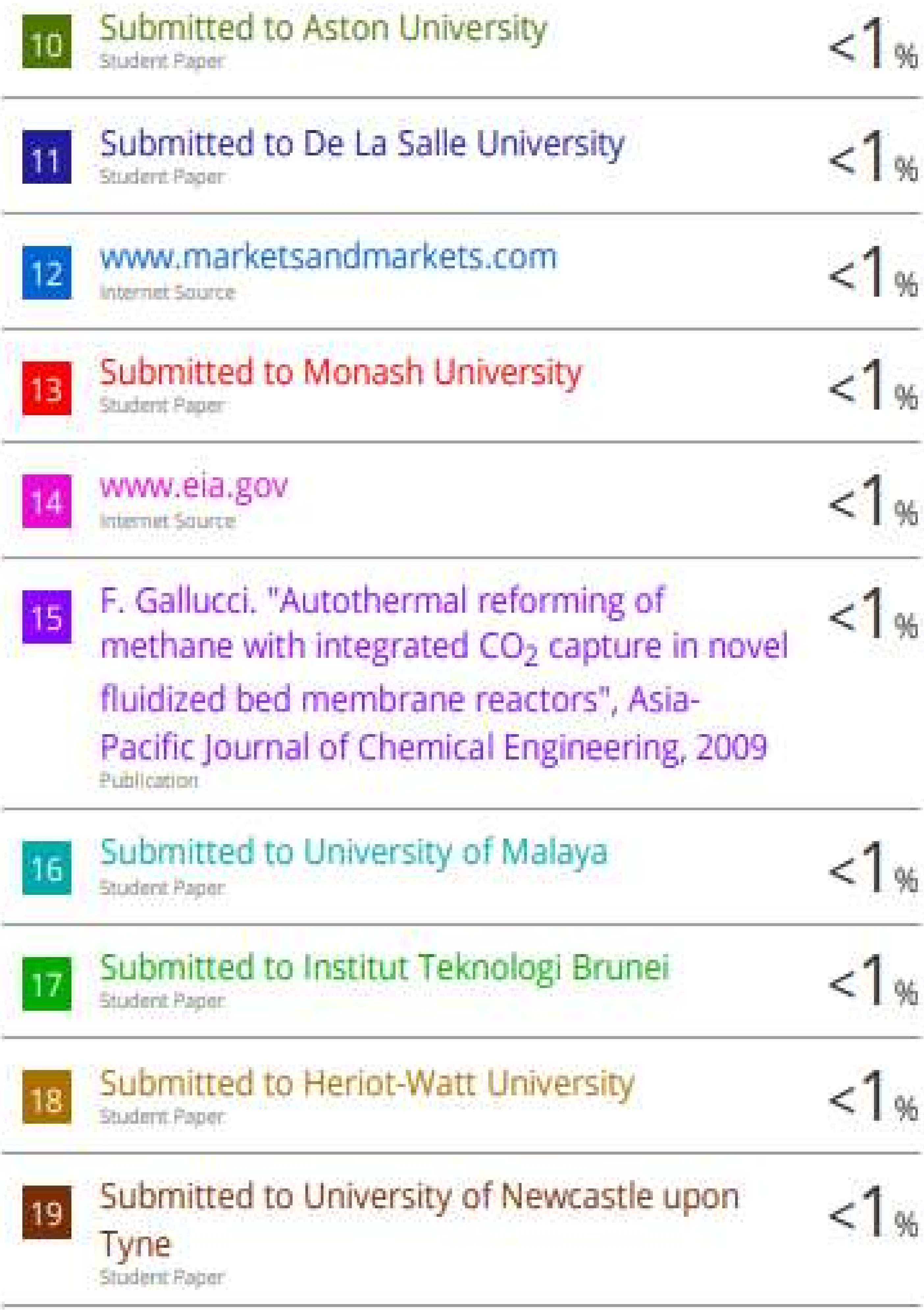

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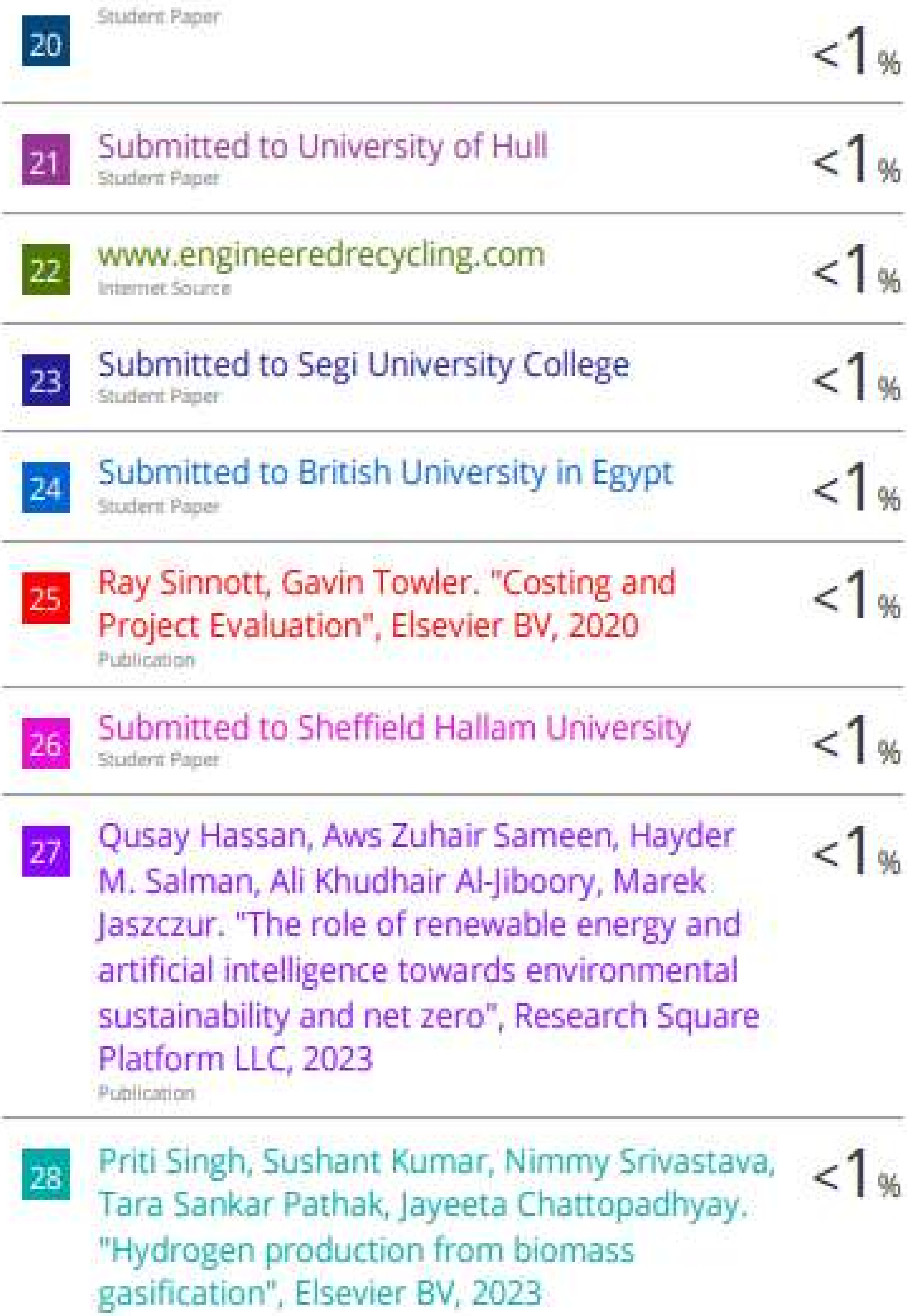

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