ISSN No:-2456-2165

Design of a Plant for the Production of 16,000 Metric Tonnes of Bio-Methanol Per Annum from Wood

BASSEY, Samuel Nathaniel
Chemical Engineering, University of Uyo
Uyo Nigeria

UMOH, Gabriel Tommy
Petroleum Engineering, University of Uyo
Uyo Nigeria

Abstract:- Currently, less than 0.2% of the total methanol production capacity is from renewable sources. In this study, we designed and modelled a methanol production plant. The plant used 25,882.52mt per annum of wood to produce 16,000mt of methanol per annum. Details of the plant including a process flow diagram with a material flow stream table have been discussed. A preliminary control system and the resulting piping and instrumentation diagram were developed. Oron local government area of Akwa Ibom state, Nigeria was chosen as a suitable location for the plant and the plant layout was carefully mapped out taking into consideration the safety measures, environmental influence and the hazard factors involved. Detailed safety analysis was carried out on the plant; the environmental analysis, occupational health and safety analysis, hazard and operability studies and general plant safety have also been discussed. To understand the degree of hazard the plant will pose; the fire and explosive index was calculated for the major equipment and the overall fire and explosive index of 159 was obtained indicating that the degree of hazard is severe. At a total investment cost of 6.3 million USD, the plant realized a net profit of 3.1 million USD.

***Keywords**:- Greenhouse Gas Emissions, Methanol Production, Renewable Feedstock, Wood, Plant Design, Safety Analysis, Economic Viability.*

I. INTRODUCTION

Methanol is one of the most important chemical materials that is produced worldwide, about 90% is used in the chemical industry and the remaining 10% is for energy use. The world's global production capacity of methanol as of 2021 stood at 160 million metric tons and is expected to exceed 256 million metric tons by 2030 [17]. About 38% of the methanol produced is used as a feed in the production of formaldehyde and a further 27% is used in the production of MTBE (methyl tert-butyl ether) and TAME (Tert-Amyl Methyl Ether). It is used in the production of other chemicals and solvents, acetic acid, single-cell protein, and oxygenated compounds as well.

China has over the years emerged as the chief player in the methanol market concerning methanol capacity and demand owing to its rapid economic growth. Reference [2] reported that China represented just 12% of global methanol demand in 2000 while North America and West Europe represented 33% and 22% respectively. By 2020, Chinese methanol consumption had grown to 40% of global demand while North America had fallen to 5% and Europe to 5% (see Fig. 1 for the 2020 global methanol demand by region). Chinese direct blending use of methanol into the country's gasoline pool was estimated at 7 million metric tons and was projected to hit 10 million metric tons by 2026.

Conversely, there are no reliable Fig.s on methanol consumption in Nigeria. Despite prolonged and lingering challenges associated with fuel availability in the country, the demand for methanol as fuel appears to be low. However, as the cost of liquid and gaseous fuel increases and subsequently creates a greater economic burden in the country, the use of an alternative source of energy such as wood or woody biomass is becoming increasingly attractive as one of the largest economic burdens is created by the importation of gasoline [4]. This is evident from the planned design and construction of a $3 billion methanol processing plant on Brass Island in Nigeria's Bayelsa state by the Nigerian National Petroleum Corporation and Brass Fertilizer and Petrochemical Company Limited.

According to [3], the technology of methanol synthesis from natural gas and coal has been practiced widely. Synthetically, methanol is produced from carbon monoxide (CO) and hydrogen (H_2) in a catalyst-filled converter operation at pressures ranging from 1500 to 4,000 pounds per square inch (Ib/in2). Two volumes of hydrogen to one volume of carbon dioxide react to form a crude methanol which is refined. In today's methanol plant, natural gas consisting primarily of methane is steam-reformed catalytically into CO and H_2. A small amount of carbon dioxide is added to the methane to permit part of the hydrogen to form additional CO so that the final gas product contains two volumes of H_2 to one volume of CO.

In congruence with [8] who opined that any carbonaceous material such as coal, lignite, wood, agricultural residue, and garbage can be utilised for synthetic methanol production, recently, studies have been completed on the production of methanol from other sources (see Fig. 2) like municipal waste, agriculture residue/biomass, sewage, captured CO_2, renewable electricity, and wood. These studies have confirmed the technical and economic justification.

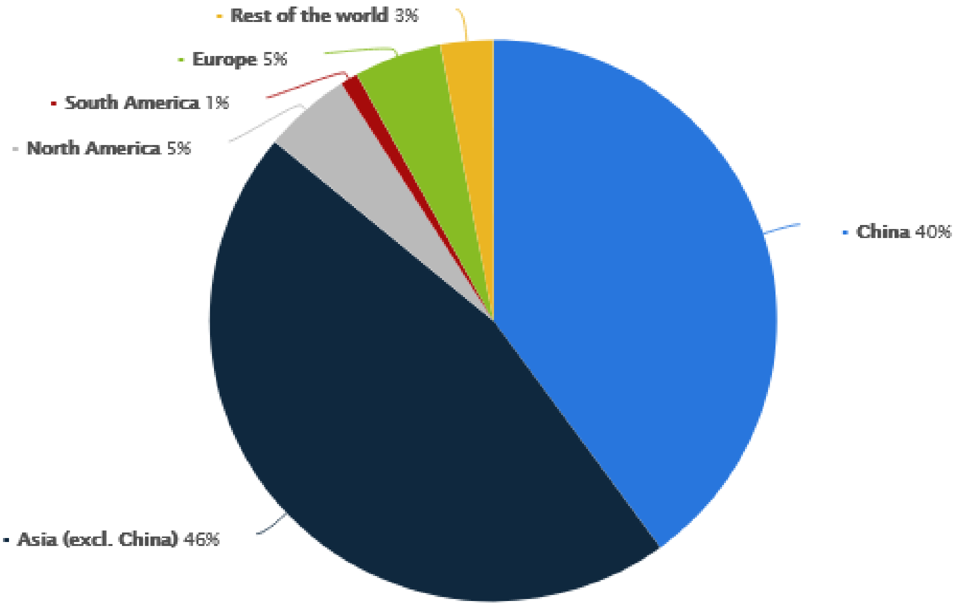

Fig. 1: Distribution of methanol demand worldwide in 2020, by region
Source: [17]

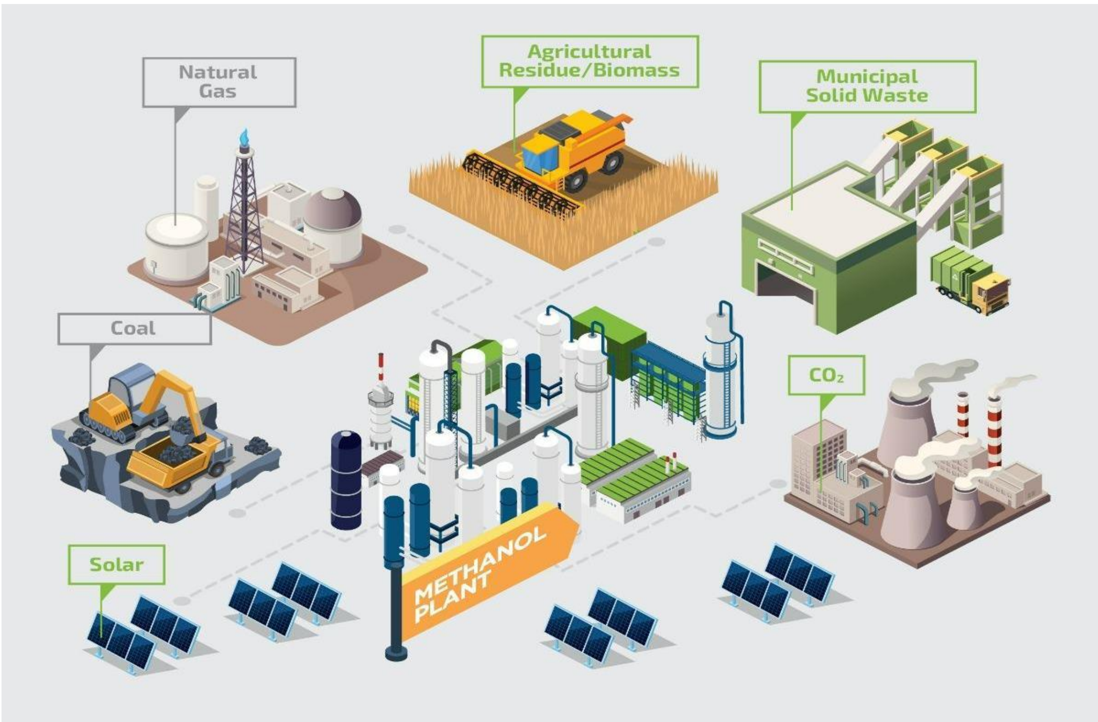

Fig. 2: Feedstock for Methanol Production
(Source: [13])

However, in contrast to natural gas, these raw materials require several additional processing steps to refine the crude gas product (syngas) consisting of two parts of H_2 to one part of CO_2. As a result, the conversion of a carbonaceous material is considerably more energy-intensive than that required by natural gas. Its logistics are considerably greater (solid handling versus pipeline). Additionally, the life-cycle emissions from methanol production and use as noted by [11] stands at 0.3 gigatonnes (Gt) of CO_2 per annum. This is about 10% of total emissions in the chemical sector, analysing this value, it can be deduced that this trend is not sustainable for the environment. With the increasing global interest in energy transition and decarbonisation, there is a need to assess the feasibility of producing bio-methanol to meet global demand. In this paper, the design of a methanol plant capable of producing 16,000 metric tonnes per annum of bio-methanol from a suitable renewable feedstock was developed. The main steps of the methanol production process, including torrefaction, gasification, gas cleansing/conditioning and distillation were described. The economics of the methanol plant, layout and location, safety and environmental considerations have all been analysed and discussed in this study.

II. MATERIALS AND METHODS

A. Process Selection

Various process routes are available for producing methanol from wood, biomass and other woody feedstock. Since their composition is somewhat similar to wood, some of the processes were evaluated to extract valuable insight, crucial to the choice of a process route that will be used in this design. In the following section, process routes by different authors are analysed, evaluated and presented.

B. Process Route by Hokanson and Rowell

Reference [8] detailed a systematic wood-to-methanol production process, commencing with the partial oxidation of wood to generate a crude gas, which was subsequently cleaned, cooled, and compressed. The process involved successive stages of carbon dioxide removal using hot potassium carbonate and monoethanolamine, elimination of nitrogen and hydrocarbons via a cryogenic system, and a water gas shift reaction to obtain the desired hydrogen to carbon-monoxide ratio for methanol synthesis. Methanol was then produced from hydrogen and carbon monoxide using a zinc-chromium catalyst, achieving a high conversion rate. Finally, a refining process separated the produced methanol from higher alcohols like 1-butanol, ethanol, and propanol using a distillation column. This process focused on converting wood to high-purity methanol through a sequence of gas treatment and conversion steps.

C. Process Route by Hamelinck and Faaij

Reference [7] detailed a methanol production process from biomass and woody materials, emphasizing several key steps. The sequence includes pre-treatment, gasification, gas cleaning, gas conditioning, and methanol synthesis. Pre-treatment involves chipping biomass to a specific size and drying to lower moisture levels, requiring varying energy inputs and considering factors like steam and flue gas drying methods. Gasification, using fluidized bed gasifiers, involves indirect firing but produces wet gas with low carbon conversion, necessitating oxygen use for optimum performance. Gas cleaning is pivotal, addressing impurities like tars and organic compounds through hot gas or low-temperature filtration, with considerations for scrubbing and tar removal methods. Gas conditioning incorporates reforming processes to convert methane and light hydrocarbons to CO and H_2 using steam reforming or auto-thermal reforming methods. The water gas shift reaction is employed to increase H_2 production while CO_2 removal processes ensure the desired gas composition for methanol synthesis. Methanol synthesis utilizes adiabatic and isothermal reactors, managing factors such as equilibrium considerations, temperature sensitivity of the catalyst, and gas recycling to optimize conversion at specified temperatures and pressures, with a focus on copper catalyst efficiency amidst potential sulfur and chlorine poisoning.

D. Process Route by Phillips and Colleagues

Reference [14] proposed a multi-step process for methanol production, commencing with feed handling and preparation, followed by gasification using indirect methods to create synthesis gas. Gas cleanup involves removing impurities and acid gases before the synthesis of alcohols. Alcohol synthesis from the cleaned syngas occurs in a fixed bed reactor, ensuring the methanol meets ASTM sales specifications through separation processes. The entire process involves intricate stages of feed treatment, gasification, purification, alcohol synthesis, and final separation, focusing on producing methanol while managing impurities and maintaining quality standards.

Following the investigation of the various process routes, [5] process route for wood-to-methanol production is selected for the production of methanol from wood. This route was selected and modified based on its favourable attributes tailored to meet environmental and economic objectives. The route exhibited qualities such as low downstream processing costs, reduced methane and increased higher hydrocarbon content, lower investment costs, minimal sulfur content, high gasifier efficiency, accessibility to raw materials (like wood chips and sawdust), enhanced synthesis gas conversion, improved energy recovery, ease in construction and installation, and higher concentrations of hydrogen and carbon monoxide. The modification aimed to align the process with specific criteria, emphasizing efficiency, cost-effectiveness, and environmental sustainability.

E. Material Selection

The modelling feedstock of choice is wood. The wood feedstock is made up of sawdust, wood chips, and pellets, with the pellets making up a larger portion of the feed. Table 1 shows the composition of the feedstock as adapted from [1]. The wood is assumed to be obtained from the sawmill and the forest, and transported to the plant by boat through the river and truck through the land. They are stored appropriately in the storage tank. Chemcad developed by chemstation was used to simulate the process. Chemcad is a simulation software used in modelling industrial and chemical processes and it’s among the few software used in solid state simulation, other solid state simulation software like Aspen Plus also has wide usage and application. Fig. 3 shows the process flow diagram (PFD) simulated with Chemcad. The PFD highlights all the equipment and process streams in the production process.

F. Process Description (Simulation)

The process taking place can be placed in 5 steps described as follows:

Feed Preparation: In the simulation software, a modelled wet wood component of size 5" to 1 metre is fed at a rate of 3268kg per hour into the torrefaction unit - D101 which operates at a temperature range of 180 - 200°C. The wet feed has an average moisture content of 30%. With an energy input of 15533 x 10^4 KJ/hr, the wet feed is torrefied to a final moisture content of 2.5% resulting in the final weight of 2346.4kg. This process is essential in improving the energy density and pulverisation of the feedstock. Moisture from the wood escapes (as indicated on stream 4) the unit as steam where it is condensed, collected and stored.

Table 1: Composition of Feedstock

Component	Dry basis (%)	Wet basis (%)	Dry & ash free (%)
Carbon	48.8	34.16	49.24
Oxygen	43.9	30.73	44.30
Hydrogen	6.2	4.34	6.26
Nitrogen	0.17	0.119	0.17
Sulphur	0.02	0.014	0.02
Ash	0.91	0.64	-
Moisture	-	30.00	
	100%	100%	100%

Adapted from [1]

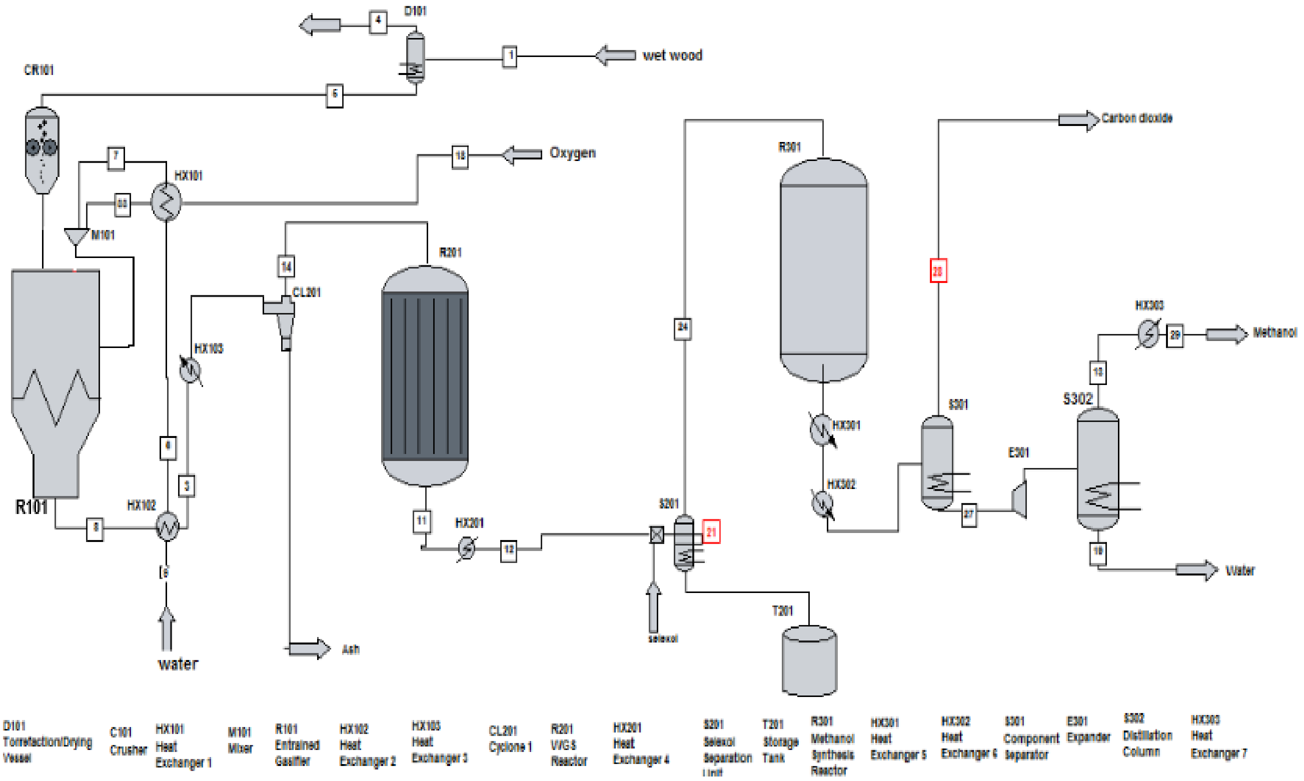

Fig. 3: Proposed Process Flow Sheet generated using Chemcad

The torrefied wood is loaded into the crusher - CR101 which is an electrical-powered primary and secondary crusher that mills the feed to a particle size of approximately 17mm. The crusher operates at a high efficiency and no loss was recorded. A mixer which doubles as a compressor because of labelled M101 is used to mix 100 kg of oxygen at a purity rate of 99.6mole% from seal tanks with 2000 kg of steam. Before this, 100 kg of oxygen is passed through the heat exchanger - HX101 where it is heated by 2000 kg of superheated steam from heat exchanger - HX102. The steam and the hot oxygen gas are fed into the mixer which consists of a compressor chamber, a pump and several valves. The mixer compresses the steam/oxygen mixture to a pressure of 45 bar.

Gasification: 2346.4kg of milled feedstock is introduced at the top of Entrained flow gasifier - R101 modelled as a Gibbs combustor, a component on CHEMCAD, operated at a temperature of 1500°C and a pressure of 45 bar. The feedstock is fed into the gasifier via a lock hopper system and gradually descends through the different chambers. The pressurised oxygen and steam mixture from M1O1 is fed into the gasifier vessel through sidewall-mounted tuyeres. The exit stream from the gasifier is syngas with impurities. The content of the impure gas stream includes hydrogen, carbon monoxide, carbon dioxide, methane, sulphur, nitrogen and silica. The gasifier was modelled to operate at a higher efficiency thus, mass-in was equal to mass-out. This means that 4447kg of the gaseous stream was collected at the exit stream of the gasifier. However, due to the high temperature of the exit stream from the gasifier, the gas needs to be cooled before feeding into the cyclone.

Gas Cleaning and Conditioning: The hot gas stream of 4447 kg with a pressure of 45 bar and a temperature of 1100°C is fed into the heat exchanger HX102 where it is cooled with water to the temperature of 900°C. However, as this superheated gas stream passes through the heat exchanger it heats the water to steam while being cooled simultaneously. The steam is fed into the mixer - M101 after heating the oxygen at HX101. The rationale of this design is to promote conservation and optimisation of energy in the plant. The syngas stream from heat exchanger HX102 is fed

ISSN No:-2456-2165

into the second heat exchanger HX103 which further cools the gas stream to 500°C before feeding it into the guard bed and particle removal system, modelled as cyclone - CL201. This system which operates at 90% efficiency gets rid of the solid impurities present in the gaseous stream and is collected at the bottom of the equipment in the form of ash. The resulting gas stream of 4425 kg contains carbon monoxide, water, carbon dioxide, hydrogen and trace components of methane, nitrogen, sulphur, and silicon dioxide.

The gas stream of 4425 kg is fed into the high-temperature Water-Gas-Shift (WGS) reactor R201 operating at about 588°C and 45 bar along with a conversion rate of 30%. Modelled as an equilibrium reactor on Chemcad, the WGS reactor increases the mole of hydrogen from 108 kmol in the inlet stream to 132 kmol and reduces the moles of carbon monoxide from 78.6 kmol in the inlet stream to 55 kmol. It also increases the moles of carbon dioxide from 14.3 kmol to 37.9 kmol. There is a zero net change in the amount of gas at the inlet and outlet streams of the WGS reactor, thus 4425kg of outlet gaseous stream. This gas is further cooled to a temperature of 200°C by the heat exchanger HX201 before feeding to the acid gas removal unit - the selexol unit which operates at 45 bars. In the methanol synthesis reaction, CO_2 is needed as a promoter in the reaction, therefore only 60% of CO_2 is absorbed in the selexol absorption process unit labelled S201 and sent off to a storage tank. Trace quantities of nitrogen, sulphur and silica are also separated. Out of the 4425 kg inlet stream, 3419 kg of stripped syngas is received at the outlet, the adsorbed gas and other impurities accounts for the remaining mass.

Methanol Synthesis: The 3419 kg of stripped syngas from the selexol adsorption process is fed into the methanol reactor R301 which generates 1999.2kg of methanol and 1077kg of water. In the exit stream of the reactor, about 342 kg of CO_2 and a trace quantity of methane were detected. Since the reaction is exothermic, heat is produced thereby increasing the temperature of the reactor to 1025°C. The product stream from the methanol reactor is passed through a series of two heat exchangers, HX 301 and HX 302 where the temperature is reduced to 55°C. The lower-temperature stream is transported to a component separator S301 operating at a temperature range of 55°C which strips the mixture of all CO_2 and methane components, leaving the product exit stream with only 3077kg of liquid containing methanol and water. This product however is highly pressurised and unsuitable as a feed stream for the distillation column, therefore, to lower the pressure, the liquid is sent to the expander E301 which reduces the pressure to 1 bar.

Distillation: The distillation column S302 distils methanol at 65°C collecting the produce as a distillate in the higher tray. The vapourised methanol is fed into the condenser marked HX303 (Heat exchanger) and pure 1,999kg of liquid bioethanol is collected and stored.

G. Material and Energy Balance

The material and energy balance are presented in Tables 2 and 3 respectively. According to the simulation results, at an annual production time of 8,004 hours per year, 16,000,000kg (16,000 metric tonnes) of methanol would be produced per year. A total feedstock mass of 3,268kg together with 2,100kg of oxygen and steam were fed into the system. The output was 1999.2564kg of methanol and 3368.7436kg of undesired product, balancing the mass in and mass out of the system.

H. Economic Analysis

The Bridge waters method plant economic evaluation was used to determine the total investment cost of the plant. Using Equation 1 which is the appropriate equation for our plant capacity of 16,000mt; less than 60,000 tonnes per annum, the total investment cost required was found to be $1,687,612.41.

$$C = 28000N\ (Q/S)0.3 \qquad (1)$$

Where: N = number of function units
Q = plant capacity
S = mass of product obtained in kg/hr. / mass of reactor feed in kg/hr.

Further computation was done using cost factors obtained from [16] to determine the fixed and variable cost of production of the plant. Table 4 gives a breakdown of the fixed production cost components. The components of the variable production cost are presented in Table 5. Based on the computed fixed and variable production costs, the total capital investment and total annual production cost of $6,339,748.40 and $2,224,063.51 were derived respectively. The annual production coat and annual production rate were used to arrive at a unit production cost of $144/metric tonne. Using the plant's annual production of 16000 metric tonnes/year and the current price of methanol in Europe which is valid from October 2023 to December 2023 is €375 (400 USD) per metric tonne as reported by [12], the plant revenue projections were computed as follows:

Total annual income = annual production × price (2)
Total annual income = 16,000 × 400 = $6,400,000
Gross profit = total income - total production cost
= 6,400,000 – 2,224,063.5
= $4,175,936.5

Taxes and depreciation is 25% of gross profit
= 0.25 × 4,175,936.5
= $1,043,984.13

Net profit = gross profit – taxes and depreciation
= $4,175,936.5 - $1,043,984.13
= $3,131,952.37

Return on investment = net profit/total capital investment x 100 (3)
= 3,131,952.37/6,339,748.40 ×100
= 49.4%

ISSN No:-2456-2165

Payback period = total capital investment/net profit (4)
= 6,339,748.40/3,131,952.37
= 2years

As stated by Aduka *et al.* (2010), Capital cost ($/year) = total equipment cost ($)/economic life(yr.)

Economic life (year) = total equipment cost/working capital cost

Total equipment cost = 30% of total capital
= 0.3 × 6,339,748.40
= $1,901,924.52

Economic life = 1,901,924.52/88,822.653
= 21 years, 5 months

Table 2: Material Balance

No	Component	Type of Equipment	Mass In (kg/hr)		Mass out (kg/hr)	
1	D-101	Torrefaction vessel/dryer	3268.0000	3268.0000	2346.4510 921.5486	3268.0000
2	CR-101	Crusher	2346.4510		2346.4510	
3	HX-101	Heat exchanger 1	100.0000 2000.000	2100.000	100.0000 2100.0000	2100.000
	M-101	Mixer	100.0000 2000.0000	2100.0000	2100.0000	2100.0000
4	R-101	Gasifier	2346.4510 2100.0000	4447.8599	4447.8599	4447.8599
5	HX-102	Heat exchanger 2	4447.8599		4447.8599	
6	HX-103	Heat exchanger 3	4447.8599		4447.8599	
7	CL-101	Cyclone	4447.8599		20.9273	
				4447.8599	4425.5090	4447.8599
8	R-201	Water gas shift reactor	4425.5090		4425.5276	
9	HX-201	Heat exchanger 4	4425.5010		4425.5010	
10	S-201	Selexol separation unit	4425.5277 50.0000	4475.5277	3419.8114 1055.7164	4475.5277
11	R-301	Methanol reactor	3419.8114		3419.8302	
12	HX-301	Heat exchanger 5	3419.8302		3419.8302	
13	HX-302	Heat exchanger 6	3419.8302		3419.8302	
14	S-301	Component separator	3419.8302	3419.8302	342.6957 3077.1348	3419.8302
15	E-301	Expander	3077.1348		3077.1348	
16	S-302	Distillation column	3077.1348	3077.1348	1999.2568 1077.8782	3077.1348
17	HX303	Heat Exchanger	1999.2568		1999.2568	

Table 3: Energy Balance

No	Component	Type of Equipment	Energy In (kJ/hr x 10^3)		Energy out (kg/hr x 10^4)	
1	D-101	Torrefaction vessel/dryer	15533	15533	12253 560	12813
2	CR-101	Crusher	560		560	
3	HX-101	Heat exchanger 1	23186 1.36	23187	23211 26.185	23237
	M-101	Mixer	560 23211 26.185	23800	23745	23745
4	R-101	Gasifier	23745		18220	
5	HX-102	Heat exchanger 2	31750 18220	49970	23186 26793	4.9979
7	CL-101	Cyclone	28600		96.317	
				28600	28504	28600
8	R-201	WGS reactor	28503		28503	
9	HX-201	Heat exchanger 4	28503		32208	
10	S-201	Selexol separation unit	32208 18.814	32226	22560 8855	31420
11	R-301	Methanol reactor	22560		22560	
12	HX-301	Heat exchanger 5	22560		32060	

13	HX-302	Heat exchanger 6	32060		34970	
14	S-301	Component separator	34970	34970	3060 31750	34810
15	E-301	Expander	31750		32030	
16	S-302	Distillation column	32032		14930 16860	31790
17	HX303	Heat Exchanger 7	14930		15100	

Table 4: Fixed Production Cost

Fixed production cost	**Cost ($)**
Maintenance	71,057.40
Operating labour	76,453.37
Supervision	19,113.34
Direct salary overhead	57,340.03
Capital charges	106,587.18
Taxes and insurance	26,646.80
General plant overhead	120,752.09
Purchase of lands/buildings	905,991.06
Laboratory	22,936.011
Direct salary overhead	57,340.028
Total fixed production cost	$1,410,217.31

Table 5: Variable Production Cost

Variable Production cost	Cost ($)
Raw material	352,554.33
Utilities	282,043.46
Miscellaneous	141,021.73
General overhead	38,226.685
Total variable production cost	$ 813,846.20

III. EQUIPMENT SELECTION FOR PROPOSED METHANOL PLANT

The selection of equipment for the manufacturing of methanol described was based on the plant capacity, energy demand for the target production rate, purity of methanol produced, the nature of the process stream, environmental factors, and economic feasibility. In addition to the factors above, the specifications also stemmed from the modelled plant parameters of the equipment. It is however pertinent to know that there may be variation with what is attainable in the industry as equipment modification is a frequent activity.

- **Torrefaction/Drying Unit (High Temperature):** The torrefaction process of wood is carried out in a rotary dryer where the wood is converged along the inside of a rotating inclined cylinder and is heated and dried by direct contact with hot air flowing through the cylinder. However, in this design, the wood is indirectly heated to a very high temperature of 2000C. The dryer consists of a rotating shield made of carbon steel sheets supported on two sets of rollers and driven by a gear and pinion. At the upper end is a hood which is connected through a fan to a stack and a spout which brings in the wet wood from the feed hopper. The fan is placed in the stack and it draws air through the dryer and keeps the dryer under slight vacuum pressure to prevent the generation of excess dust. The dryer diameter is 4 m and has a shell peripheral speed of about 25 metres per minute. The heat used in this model is generated by electricity where high voltage is used to power the heating jacket.
- **Crusher:** The milling equipment specified for the milling of the torrefied wood in the plant is one of Nordberg's HP Series cone crushers, the HP100. This cone crusher comes with an optional IC70C crusher automation system which includes fully automated lubrication and hydraulic circuit controls, hydraulic unit motor starters and electrical cabinets. This automation system automates the process by optimizing and monitoring the operation to achieve the best performance and a remote controller for improved safety and protection.
- **Gasifier:** The gasifier specified for this plant is the KX-600S Gasifier which is an entrained bed gasifier that operates at a very high temperature and pressure to achieve a high carbon conversion efficiency. This equipment is a slagging gasifier which melts the ash from the feedstock to form a slag. The wall of the gasifier is designed to be slagging which means that the wood ash melts in the gasifier and runs down the gasifier walls to the bottom of the gasifier, where it is collected and solidified. The liquid ash acts as an insulator (protective layer) for the gasifier wall from the high temperature of the gasifier. The walls of the shell gasifier are cooled by generating medium-pressure steam.

However, since wood has low ash content, a slay recycle should be installed in the equipment to create a sufficiently high slag flow on the gasifier walls, subsequently increasing the carbon conversion. Alternatively, a fluxing agent can be used to increase the slag flow on the gasifier walls. The internal cooling section of the equipment at the exit section cools the

ISSN No:-2456-2165

produced gas from 1500°C to 1100°C. The maximum size of the gasifier is 5000 tonnes of wood/day.

- **Cyclone Specification:** Cyclone is used to remove particles of a diameter greater than 0.01mm from the synthesis gas stream. A typical cyclone consists of a vertical knock-out drum with mesh pads used to separate solids or liquids from gases. The cyclone consists of a vertical cylinder with a conical bottom, a tangential inlet near the top and an outlet for dust collection at the bottom of the cone. The inlet is rectangular; the outlet pipe is extended into the cylinder to prevent the short-circuiting of air from inlet to outlet. For a given air flow rate and inlet velocity, a moderate increase in cyclone diameter and length improves the collection efficiency because the increase in surface area offsets the decreased centrifugal force. Since an entrained gasifier is used where little char is produced, only one cyclone is used at high efficiency.
- **Water Gas Shift (WGS) Reactor:** The equipment needed for this process is the multi-stage, fixed-bed adiabatic reactor containing shift catalysts supported on a ceramic substrate. These catalysts (Nickel and Iron) are packed in the bed to promote the reaction. The wall of the reactor is stainless steel which is the most commonly used engineering material for medium to high temperature processes to prevent corrosion.
- **Methanol Reactor:** The methanol synthesis reactor is simulated as a typical reactor operating at a moderate temperature in a gas-liquid phase. The material for the methanol reactor was chosen to be carbon steel. Since the process streams at this stage are only gases, corrosion is not believed to be a problem. Due to the temperature conditions at about 250°C, metal dusting does not come into consideration. This leads to a construction material of carbon steel, which is the least expensive material.
- **Mixer and Compressor:** In this plant setup, there are two compressors. The first is modelled as a mixer -M101 which consists of a compressor chamber, a pump and several valves used to pressurize the oxygen and steam stream before introducing the mixture into the gasifier, while the second is a compressor used to compress the $CO2$ into its storage tank. The compression equipment specified for the first compression process is the Atlas Copco GT-Series integrally geared centrifugal compressors with a compression capacity of up to 205 bars.
- **Expander:** The methanol/water stream is expanded by a polytropic expander operating at a constant temperature. The outlet pressure of the expander is 1 bar with an efficiency of 0.9. The actual power of the expanded was -2.12859 x 10 KJ/hr with a Cp/Cu value of 1.36193. Due to low-temperature conditions, the material of construction is basic carbon steel.
- **Separators:** The separator was used to separate the condensed liquid from the unreacted syngas stream. The separator is equipped with demisters to ensure good separation and to decrease equipment costs. The separator has a minimum diameter and height of 1.0m, the height of the vessel outlet above the gas inlet is sufficient to allow for disengagement of the liquid drops. The liquid level is proportional to the hold-up time which is 10 minutes. The construction material of the separator is carbon steel with nickel alloy clad. The nickel–alloy clad is added due to the water content in the actual process streams. Nickel exhibits high corrosion resistance to most alkalis increases toughness and improves low-temperature properties and corrosion resistance of the material (Peters, 2005)
- **Heat Exchangers:** Heat exchanges were modelled by using the duty and the logarithmic mean temperature difference from chemCAD. Appropriate heat transfer co-efficiencies were found and to be heat transfer areas were calculated. Heat exchanges which experienced sharp temperature drops or rises were split into multiple heat exchange calculation purposes. There are two shell and tube heat exchangers; the first is used at the feed point of the gasifier while the second is used at the end. The heat exchanger is networked in a way that ensures maximum heat recovery. The heat exchangers were constructed with a shell of carbon steel and tubes of nickel alloy, due to the seawater used for cooling. Nonferrous metals, like nickel, are often employed in heat exchangers when water is one of the fluids. To reduce costs, the water may be pressed through the more expensive tubes and the shell side of the exchanger can be constructed of steel (Peters, 2003).

IV. THE PROCESS AND INSTRUMENTATION DIAGRAM (PID)

The Process and Instrumentation Diagram (PID) for the plant is shown in Fig. 4. The PID shows all the piping arrangement, pipe diameter, type of pipe used, the control devices, the material of construction of all the equipment, the nature of the insulator etc.

V. PROCESS CONTROL

The process control in the production of methanol from wood involves various objectives, with safety being the primary concern. The control objectives are prioritized as follows: safety, environment, equipment protection, smooth operation, and monitoring/diagnosis. Control variables such as temperature, pressure, and flow are critical in the process engineering of methanol production. Instruments, either in automatic control loops or for manual monitoring, play a role in ensuring key process variables are maintained.

The control systems include pressure control, where gases are compressed into a storage tank, and flow control, utilizing bypass controls for compressors and pumps. Ratio control is employed to maintain specific ratios of oxygen and steam in the gasifier, while cascade control is used in the water-gas shift reactor to compensate for short-term temperature variations. Reactor conditions and product variables are continuously monitored, with the reactor operator adjusting control set points to maintain product specifications.

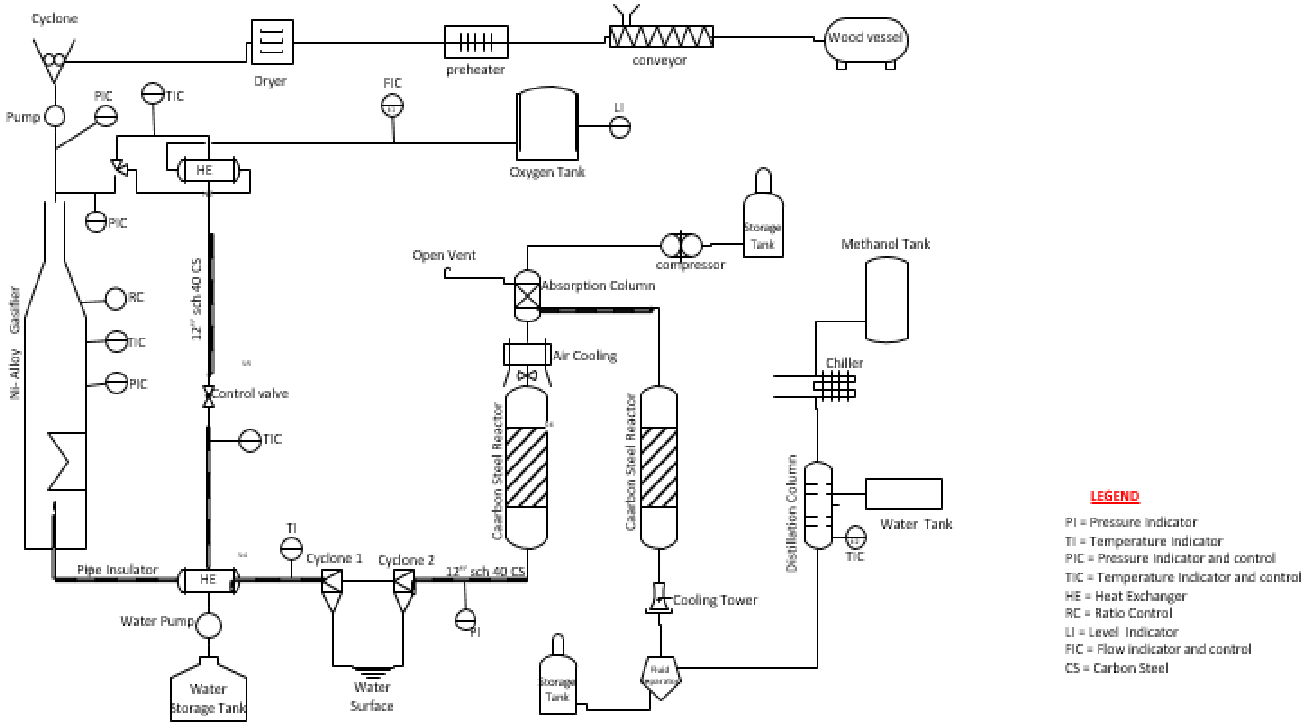

Fig. 4: Process and Instrumentation Diagram for the Overall Plant

Heat exchangers are employed to control process stream temperatures by varying the flow of the cooling or heating medium. Safety measures include alarms on equipment to alert operators of hazardous deviations, safety trips in pumps and reactors to avert potential hazards, and interlocks to prevent operators from deviating from required sequences. Overall, the control mechanism is designed to ensure the safe and efficient operation of the plant, considering environmental impact, equipment protection, and smooth operation.

VI. PLANT LOCATION AND LAYOUT

The design of a methanol production plant, aiming for an annual capacity of 16,000 metric tonnes, involves careful consideration of location and layout factors that significantly impact capacity attainment, profitability, operability, safety, and potential future expansion. The proposed plat layout is presented in Fig. 5. The chosen location is Oron Local Government Area, Akwa Ibom State, Nigeria, determined by various factors:

- **Marketing Area:** The plant is strategically located near the industrial hub of Akwa Ibom State, benefiting from proximity to potential buyers and reducing transportation costs for methanol-consuming industries in the region.
- **Raw Material Supply:** Oron is surrounded by areas with abundant forest resources, particularly wood used in methanol production, ensuring a sustainable and local supply of the required feedstock.
- **Transport Facilities:** Oron has a developing sea dock, a major advantage for material transportation. The site also boasts good road connectivity and is near the Akwa Ibom International Airport.
- **Availability of Labour:** The region's population ensures the availability of manual labour and skilled workers required for the plant's operations.
- **Availability of Utilities:** The plant is strategically located near the Ibaka River, providing the required cooling water for methanol production. Electricity needs will be met by the Port Harcourt Electricity Distribution Company.
- **Availability of Suitable Land:** The selected site offers ample undeveloped land for the plant's current and future expansion. The land characteristics, being flat and well-drained, are suitable for plant siting.
- **Environmental Impact and Effluent Disposal:** Effluent disposal will adhere to local regulations. Measures are taken to minimize CO2 emissions, including capturing and recycling CO2 from various process streams. The plant considers environmental impact during its modelling and simulation.
- **Local Community Considerations:** The Oron community is characterized as peaceful and supportive of industrial development. Adequate facilities for plant personnel, such as schools, banks, hospitals, hotels, and recreational centres, contribute to the overall suitability of the location.

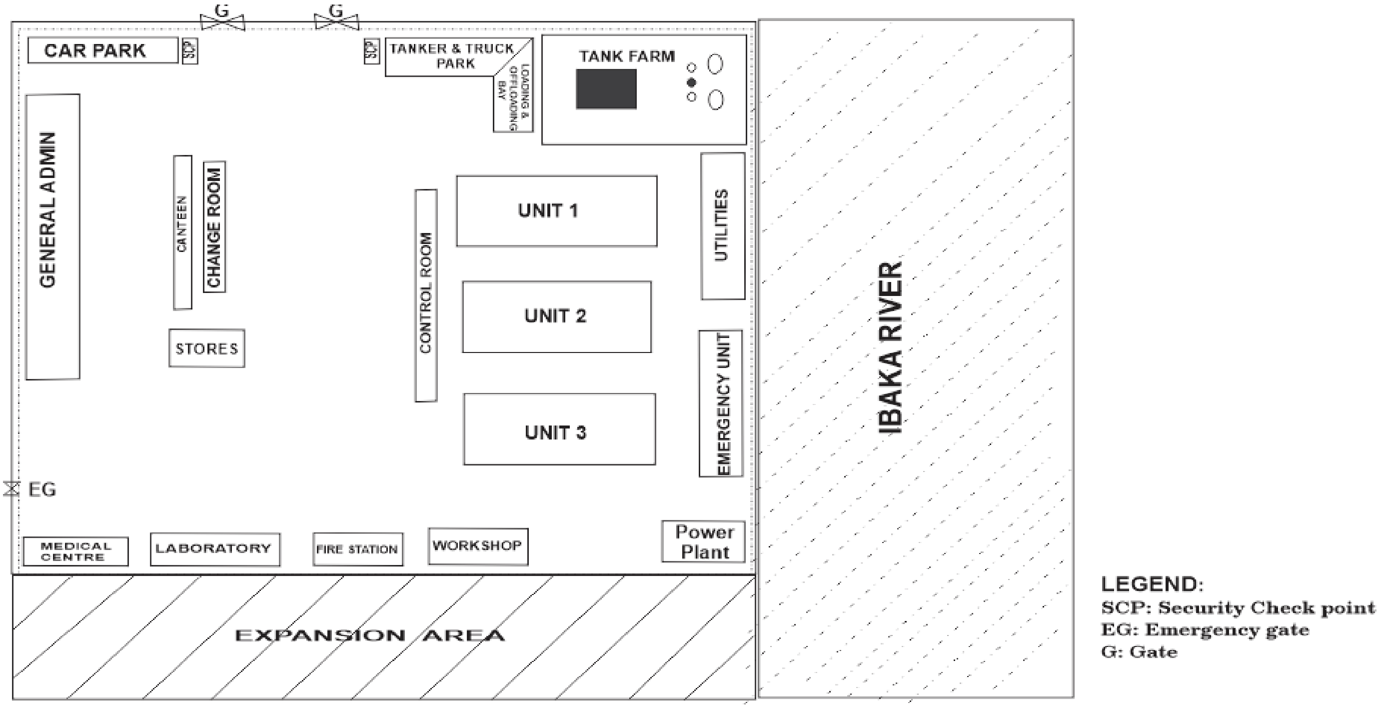

Fig. 5: Plant Layout

VII. PLANT SAFETY AND ENVIRONMENTAL CONSIDERATION

Environmental considerations in the design of the methanol production plant are comprehensive and address various aspects of sustainability and impact on the surroundings. The key factors and measures considered are:

- **Effluent Emission and Waste Management:** Effluent and waste management are crucial aspects to ensure compliance with environmental standards. The plant minimizes waste through efficient processing, reprocessing off-specification products, and integrating the plant to minimize effluent gas emissions. High control systems, alarms, indicators, and interlocks are implemented to reduce mis-operations [16].
- **Noise:** Although noise can be a nuisance [15], the plant, located in a sparsely populated area, mitigates noise-related issues using earth berms and tree screens. Silencers are installed in noisy equipment, and plant operators wear ear protection to minimize the impact of noise.
- **Smells:** Pungent odours from materials in the plant are contained in confined and airtight areas, and the odours are treated to protect the health of workers.
- **Air Quality:** Air quality is closely regulated by the Environmental Protection Agency (EPA) to ensure safety for workers and the general public. The plant takes measures to minimize the release of inert gases, while emissions from equipment using fuel are vented following environmental guidelines.
- **Chemical Toxicity:** Methanol exposure risks are considered, with measures in place to protect workers. While methanol is readily degraded in the environment, exposure risks include reproductive defects in rats, and human exposure can lead to various health issues [9]. Regulatory concentrations for human exposure to methanol are strictly adhered to, as defined by OSHA [6].
- **Potential Safety Problems:** Methanol's environmental impact is assessed, revealing its low toxicity to aquatic and terrestrial organisms. Degradation processes in various environmental media ensure that adverse effects are unlikely, except in the case of a spill [10]. The design incorporates measures to manage and prevent potential safety problems associated with methanol.

A. Plant Safety

The safety considerations for the methanol production plant are detailed and focused on mitigating potential hazards associated with toxic gases, flammable materials, and various operational aspects. Key points include:

➢ *Toxic Gases and Flammable Materials:*

- The presence of toxic gases like carbon monoxide, carbon dioxide, hydrogen sulfide, and flammable materials such as methanol necessitates stringent safety measures.
- Monitoring fugitive emissions is crucial due to the colourless and odourless nature of these gases.
- Methanol and methane pose fire and explosive hazards, requiring careful handling in well-ventilated, confined areas. Workers use respirators, gloves, and protective equipment in high-methanol concentration areas.

➢ *Safety Rules and Regulations:*

- Adherence to safety rules and regulations is emphasized, including good housekeeping, personal hygiene, personal protective equipment usage, regular medical check-ups, routine equipment maintenance, and periodic worker training.
- Visible warning signs and posters are displayed around hazardous equipment to enhance safety awareness.

➢ *General Safety and Fire Protective Measures:*

- Basic safety and fire protective measures are implemented, covering aspects such as adequate water supplies for firefighting, correct structural design, pressure-relief devices, corrosion-resistant materials, and compliance with national codes and standards.
- Additional measures include fail-safe instrumentations, provision for emergency vehicle access and personnel evacuation, drainage for spills and firefighting water, insulation of hot surfaces, and the proper design and location of control rooms.

➢ *Safety Indices (Dow Fire and Explosion Index):*

- The Dow Fire and Explosion Index is utilized for hazard classification, evaluating loss, and identifying units with the greatest impact on fire or explosion.
- The analysis identifies three critical units: feed preparation (gasification), gas conditioning (Water Gas Shift Reaction), and methanol synthesis. These units are assessed based on material factors, resulting in hazard factors and Fire and Explosion Index values.
- The overall Fire and Explosion Index for the plant is calculated as 159.67, indicating a severe level of hazard due to the presence of toxic gases, high operating temperature, and pressure.

➢ *Radius and Area of Exposure:*

- The radius of exposure is determined for each critical unit, indicating the distance within which equipment may be exposed to potential incidents.
- The area of exposure is calculated for each unit, defining the theoretical area within which equipment may be exposed to incidents.

B. HAZOP Analysis

The Hazard and Operability Study (HAZOP) analysis was conducted on the gasification unit and the methanol synthesis unit due to their severe and heavy hazard degrees, respectively, as indicated by the Fire and Explosion Index (F&EI). The primary focus of the HAZOP analysis was on potential hazards arising from deviations from the intended design conditions [15]. The key findings from the HAZOP analysis performed on the gasification unit and the methanol synthesis unit are presented in Tables 6 and 7 respectively.

Table 6: HAZOP Analysis on Gasification Unit

Guide words	Deviation	Possible causes	Consequences	Action required
No or Not	Flow of torrefied wood	(1) Pneumatic feeder is not working	a) No feed in the gasifier only superheated steam and oxygen b) Loss of heat energy and pressure build-up	(a) Check whether the pneumatic feeder is on or off (b) Check for fault in the feeder (c) Install backup feeding unit
	Oxygen flow	(2) No oxygen in the oxygen storage tank (3) Oxygen storage tank valve is closed (4) Faulty oxygen supply line (5) Blockage of oxygen pipe	c) Gasifier flame will stop burning d) Build-up of torrefied wood in the gasifier	(d) Install a level metre on the oxygen storage tank to indicate the volume of oxygen in the tank at all time (e) Check the tank value (f) Routine check and maintenance of oxygen supply line
	Steam flow	(6) Blocked steam supply line (7) Same as oxygen (2), (3), (4)	Incomplete combustion of wood Wood deposit in the gasifier	(g) Check for obstruction in the steam supply line
More	Pressure Temperature Flow	(1) Failure in control system (2) Faulty mixer (3) Faulty temperature control system (4) Faulty flow/level control system	a) Rupture of reactor b) Loss in production c) Sever reactor damage d) Reduced efficiency e) Loss in production	(a) Installation and maintenance of pressure indicator and control system (b) Installation of blast wall (c) Installation of alarm system to signal sudden rise in pressure (d) Installation of emergency shut – down protocol (e) Maintenance of temperature control system (f) Installation of emergency cooling system (g) Installation of alarm system to signal sudden temperature increase

				(h) Maintenance of control system
Less	Pressure Temperature Flow	(3) Leakage in piping system Same as (5) Same as (6)	f) Loss in production g) Reduced efficiency	(i) Routing check for leakage

Table 7: HAZOP Analysis on Methanol synthesis unit

Guide words	Deviation	Possible causes	Consequences	Action required
Part of	Flow of CO_2	1. Low efficiency of the selexol absorption system 2. Depletion of dimethoxy polyglycol on the absorption tray	a. Decrease in efficiency of the synthesis unit b. Increase in energy demand c. Loss in production	a) Maintenance and routine check-up of the absorption column
Reverse	Ratio of H_2:CO	3. Using an inadequate catalyst which are as an inhibitor in the W.G.S reactor 4. Poor monitoring of the reaction condition of the W.G.S reaction 5. Thermal runaway	d. Disproportionate increase in the quantity in the quantity of CO e. Decrease in the H_2:CO ratio f. Incomplete reaction g. Decrease in the production target for the plant	b) Maintaining the optimum reaction condition of the W.G.S c) Using adequate and proven catalyst for the production
Less	Flow Temperature Pressure	6. Leakage in pipe 7. Poor insulation of piping 8. System	h. Low production rate	d) Routine check-up and periodic maintenance of the piping system
More	Temperature Pressure	9. Overall poor performance of the heat exchanger system 10. Poor monitoring of the reactor condition 11. Deviation from the set value 12. Poor temperature / pressure control system	i. Thermal runaway j. Low production rate k. Rupture of the reactor l. Large scale hazard	e) Routine maintenance of the heat exchange f) Maintenance of optimum g) Reaction condition

VIII. CONCLUSION

Biomethanol can be produced from wood via gasification. Technically, all necessary reactors exist and the feasibility of the process has been proven in practice. The 16,000 metric tonnes of methanol plant based on entrained flow gasification of torrefied wood achieved wood-to-methanol efficiency of 85%. It was shown that CO_2 emissions can be reduced to about 10% of the input carbon in the torrefied wood by using CO_2 capture and storage together with certain plant design changes.

The main purpose of this plant design work was for the production of 16,000 metric tonnes of methanol from wood. The design is standard and can deliver efficient, reliable and quality methanol of commercial value. The design of the plant being carried out indicates that it is technically feasible to construct the plant because the equipment is available, the process is feasible and the process conditions attainable. While some of this equipment and its associated units can easily be fabricated and constructed, others have to be purchased and fully installed at the plant site. They are also easy to maintain and repair. The constant power supply is required for the plant to perform optimally.

REFERENCES

[1]. J. Ahrenfeldt, U. Henriksen, T. Jensen, B. Gøbel and L. Wiese, “Validation of a continuous combined heat and power (CHP) operation of a two-stage biomass gasifier,” Energy & Fuels, Vol. 20, No. 6, pp. 2672-2680, 2006.
[2]. M. Alvarado, “The changing face of the global methanol industry,” IHS Chemical Bulletin, 2017. Extracted from https://www.methanol.org/wpcontent/uploads/2016/07/IHS-ChemicalBulletin-Issue3-Alvarado-Jun16.pdf
[3]. S. C. Bhattacharya and J. C. “Agarwal. methanol synthesis from natural gas: an economic and technical assessment. Chemical Engineering Progress, Vol. 78, No. 7, pp. 42-47, 1982.
[4]. P. K. Chatterjee, “Biofuels: an alternative to fossil fuels,” Academic Press, 2009.
[5]. M. Clausen, P. Kristensen & P. Jensen, “Wood-to-methanol: a promising biomass conversion technology,” Chemical Engineering and Technology, Vol. 34, No. 4, pp. 595-604, 2011.

[6]. Environmental Protection Agency- EPA, “Methanol” Fact Sheet. 2006
[7]. C. N. Hamelinck and A. C. Faaij, “Production of methanol from biomass,” Journal of Power Sources, Vol. 111, No. 1, pp.1-22, 2002.
[8]. A. E. Hokanson and R. M. Rowell “Methanol from wood waste: a technical and economic study,” Forest Products Laboratory Forest Service U. S. Department of Agriculture USDA. Forest Service General Technical Report FPL 12. 1977.
[9]. Y. Hu and E. Ruckenstein, “Binary MgO-based solid solution catalysis,” Catalysis Reviews. Vol. 44, pp. 423-453, 2002.
[10]. IPSC INCHEM, “environmental health criteria 196– methanol” http://www.inchem.org/documents/ehc/ehc/ehc196.htm. World Health Organization. Geneva. 1997.
[11]. IRENA and Methanol Institute, Innovation outlook: renewable methanol, International Renewable Energy Agency, Abu Dhabi, 2021.
[12]. Methanex. Pricing, Methanex posts regional contract methanol prices for Europe, North America, Asia and China. Methanex Corporation. 2023 https://www.methanex.com/about-methanol/pricing/
[13]. Methanol Institute. About Methanol. Available Online at: https://www.methanol.org/about-methanol/ [Accessed 08 11 2023].
[14]. S. Phillips, J. Tarud, M. Biddy, & A. Dutta, “Gasoline from wood via integrated gasification, synthesis, and methanol-to-gasoline technologies. National Renewable Energy Laboratory, 2011.
[15]. R. Sinnott, and G. Towler, Chemical engineering design: (5th ed.). Elsevier. 2009.
[16]. R. K Sinnott, Chemical Engineering Design, Vol. 6. Coulson and Richardson’s series. Jordan Hill, Oxford OX2 8DP 30 Corporate Drive, MA 01803 Elsevier Butterworth-Heinemann Linacre House, 2005.
[17]. Statistica, “Distribution of methanol demand worldwide in 2020, by region. 2023,” Available Online at: https://www.statista.com/statistics/1323612/distribution-of-methanol-demand-worldwide-by-region/ [Accessed 08 11 2023].