Heat Integration Study of Biomass Gasification Plant for Hydrogen Production

by

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CERTIFICATION OF APPROVAL

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Approved by,

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JULY 2010

CERTIFICATION OF ORIGINALITY

This is to certify that I am responsible for the work submitted in this project, that the original work is my own except as specified in the references and acknowledgements, and that the original work contained herein have not been undertaken or done by unspecified sources or persons.

MUHAMMAD FITRI AZIZ BIN ADDENAN

ABSTRACT

Hydrogen is found to be the most important source of sustainable, renewable and clean of energy. As the world is facing global warming crisis and environmental problem due to usage of fossil fuels as major energy source, the potential of hydrogen as an alternative source of energy is highly regarded. This project aims to develop process simulation of selected flowsheet by using Aspen Plus software. Heat integration development has been applied by using Pinch Analysis technique and carried out in Process Integration Software (STAR). The temperature difference is set at 10. The minimum hot utility required is 0.1642 kW while the minimum cold utility required is 0.05456 kW. Maximum heat recovery from the process is 0.8413 kW. By obtaining problem table algorithm, the pinch temperature is at 628.54^{o}C. Three heat exchangers are proposed to be used result from heat exchanger network development. Calculation of energy saving show around 72% of hot utility and 88% of cold utility can be saved by doing heat integration technique.

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CHAPTER 1

INTRODUCTION

1.1 Background of Study

1.1.1 Hydrogen

Hydrogen is considered as a promising fuel for the twenty-first century, due to its factor as environmental-friendly character. Production of hydrogen from renewable biomass has a lot of advantages compared to that of fossil fuels. Currently hydrogen is mostly extracted from natural gas and has been commercially used in various industries as stated before (Nath *et al.*, 2003). An average 90% of hydrogen is formed by steam reformation of naphtha or natural gas (Nath *et al.*, 2003). Natural gas is known as non-renewable fossil fuel. Hydrogen can be generated from natural gas an approximately 80% efficiency. Steam-methane reforming to produce hydrogen which is widely used in United States is a process in which high-temperature steam around 700°C–1000°C is used to produce hydrogen from a methane source from natural gas (Padro *et al.*, 1999). Today, a lot of research has been carried out on developing of hydrogen from renewable sources.

According to Nath *et al.* (2003) reducing the demand on fossil fuels remains a concern throughout the world. Renewable source of energy such as wind, geothermal and solar hold promise as clean source of energy but face significant difficulties before they become economically viable. Hence, generating hydrogen from biomass may be more viable, renewable, efficient and potentially carbon neutral option. Biomass as energy source is characterized in the form of both flow and stock. The amount of global forest is estimated at 700 billion tons and acts as storage of carbon dioxide. Available energy flow from forest is huge and is estimated to be 5 billion tons in petroleum equivalent. The resources can become major source of energy by appropriate ways of handling.

1.1.2 Source of Biomass in Malaysia

Malaysia as a developed nation by 2020 has focused in development of renewable energy under National Energy Policy which is the main objective is to provide adequate and secure energy supply with high efficient utilisation and ensure minimum impacts on the environmental (Mokhtar, 2002). Oil reserves in Malaysia are expected to be limited in another 30-40 years and will be net oil importer from 2040 (Hassan *et al.*, 2005). Therefore biomass is looking to be the main sources of energy based on high resources obtain from agricultural or industrial process in Malaysia (Hassan *et al.*, 2005). The potential of biomass energy resources are (Hashim, 2005):

1) Oil palm residues
2) Wood residues
3) Paddy residues
4) Sugar cane residues
5) Municipal solid wastes

Figure 1.1 shows the types of biomass resources from residues listed above.

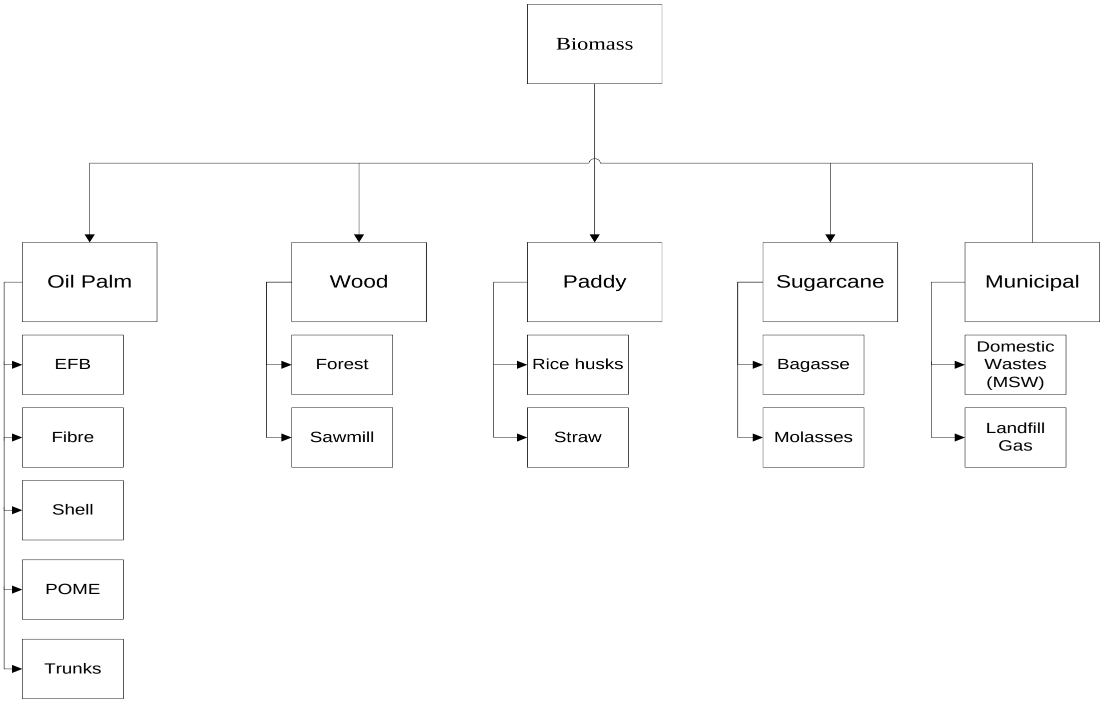


Figure 1.1: Biomass resources in Malaysia (Hashim, 2005).

The main portion of biomass in Malaysia comes from the palm oil industries which consist of Empty Fruit Bunch (EFB), fibre, shell and Palm Oil Mill Effluent (POME). Biomass production in 2003 recorded 14 million tonnes from EFB which is the higher among other resources (Hassan *et al.,* 2005). Therefore, EFB has the potential to become one of the main resources of biomass in Malaysia to supply energy.

1.1.3 Hydrogen to Biomass

Ni *et al.* (2006) stated that the available energy production from biomass can be categorized in two general processes which are; thermochemical and biological processes.

1) Thermochemical process
    i) Combustion

       Combustion is the direct burning of biomass in the air to convert biomass chemical energy into heat and electricity. The energy efficiency is low and pollutant by-product emission. According to Ni *et.al,* it is not preferable.
    ii) Liquefaction

       Biomass is heated in 525-600 K in water under a pressure of 5-20 MPa in the absence of air. The difficulty to achieve operating condition and low hydrogen production is the disadvantages of this process.
    iii) Fast pyrolysis

       It is high temperature process where biomass is heated rapidly in the absence of air to form vapor and condensed to dark brown mobile bio-liquid. Water gas shift reaction can be applied to increase hydrogen production. The products of fast pyrolysis can be found in all gas, liquid and solid phases. Biomass pyrolysis is a competitive method of hydrogen production from biomass.
    iv) Biomass gasification

       Biomass can be gasified at high temperature (above 1000K) and aims to produce gaseous product through steam reforming and water shift reaction.

Formation of tar and ash as a problems need to be resolve. High conversion efficiency makes biomass gasification as preferable alternative.

2) Biological processes
    i) Direct biophotolysis
       Direct biophotolysis of hydrogen production is a biological process using microalgae photosynthetic systems to convert solar energy into chemical energy in the form of hydrogen.
    ii) Indirect biophotolysis
       In a typical indirect biophotolysis, Cyanobacteria are used to produce hydrogen. Indirect biophotolysis is still under active research and development
    iii) Biological water-gas shift reaction
       Using of microorganism to shifted the water-gas shift reaction towards hydrogen production.
    iv) Photo-fermentation
       Photosynthetic bacteria that have capacity to produce hydrogen through the action of using nitrogenise using solar energy and organics acids or biomass in the process. Not competitive method for hydrogen production.
    v) Dark-fermentation
       Fermentation by anaerobic bacteria as well as some microalgaes, such as green algae on carbohydrate-rich substrates, can produce hydrogen at 30 -C to 80 -C especially in a dark condition.

Two main processes to produce hydrogen from biomass are pyrolysis and gasification. Throughout the research for this project, hydrogen production from catalytic steam gasification has show more efficient and economically viable than all gasification processes. Hydrogen yield can be improved by using CO_2 sorbent (Inayat *et al.*, 2009). Palm oil plant consumes atmospheric CO2 during growth which results in small net CO2 impact compared from the usage of fossil fuel (Elam *et al.*, 2004). The applications of hydrogen mostly used in refinery, fertilizer, chemical, food and aerospace industries.

Gasification of biomass to produce hydrogen is economically viable and will become competitive with the conventional natural gas reforming method. Therefore, it is under development for large scale processing plant. According to Hassan *et al.*,(2005) in Malaysia, the government has continued the efforts to promote renewable energy and energy efficient as its progress towards Vision 2020. Figure 1.2 shows the total energy requirement in Malaysia.

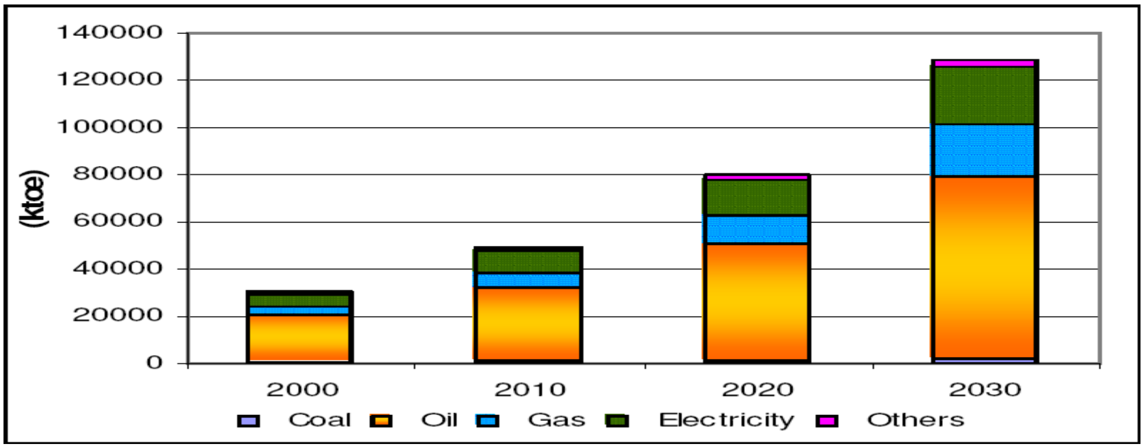


Figure 1.2: Total final energy demand in Malaysia (ktoe)

Source: Preliminary Energy Outlook, Pusat Tenaga Malaysia (PTM)

Figure 2 show the energy requirement up until 2030 in Malaysia. It show the energy requirement would still rely heavily on fossil fuel therefore, it is time to embark on other renewable source of energy especially gas as it growth fastest compared to others. Thus, this project shows its significance as hydrogen is recognized as one of the most promising energy carriers in the future.

1.1.4 Heat Integration

Gasification is an energy intensive process. To make the process more cost competitive in terms of energy usage, heat integration can be applied to recover and reuse as much heat possible. Many researches had been carried out. For example the integrated gasification combined cycle which is originally developed for fossil fuels, is been used as promising ways of opportunities for achieving higher efficiencies for combined heat and power plant from biomass waste (Sadhukan *et al.,* 2009). However, gasification of biomass as mentioned before produce tar and char which need to be remove to obtain clean and low environmental impact of gas. Therefore, the low heating value of the gas generated from biomass gasification imposes major barriers for gasification plant for power plants to be implemented (Sadhukan *et al.,* 2009). Intensive studies had been carried out to analyze and control such problem from biomass gasification plant and several integration strategies in view to maximize heat recovery. The process integration strategy for combined heat power plant is based on using agricultural wastes which is straws.

Steinwall (1997) proposed some other study is possibilities of integrating the gasification of biomass with evaporative gas turbine cycles. The analysis study on heat integration makes it possible to use low level of heat to evaporate the water in order to improve the efficiency of plant proposed.

1.2 Problem Statement

1.2.1 Problem Identification

Current proposed method to produce Hydrogen via biomass gasification is an endothermic reaction that requires a lot of energy. Hence, is aimed to develop an energy efficient and self-sustained system to produce Hydrogen from biomass result by developing a heat integrated gasification system.

Biomass basically derived from agricultural waste can be used to generate electricity and produce heat. The producing of hydrogen from biomass gasification provides sustainable and clean source of energy. It is widely used to generate electricity. It can be produce by fermentation process which is slow process. The preferable way is by steam gasification when biomass is gasified at high temperature (above 1000K). Gaseous product can be produce through steam reforming and water shift reaction.

Development of renewable energy as a green, friendly and no harm to the environment will result to getting pure sustainable energy and save our mother earth. Therefore, the production of hydrogen as one of the sustainable energy system and clean fuel from biomass gasification needs to be carried out in an energy efficient manner.

Research and analysis on process design need to be carried out to develop energy efficient and heat integrated flowsheet design for hydrogen production from biomass using pinch analysis.

1.2.2 Significant of Project

Research analysis is carried out to study and find possible ways to improve plant efficiency in term of energy consumption. Plant simulation is developed in process simulator from proposed plant design. Development of heat integrated in biomass gasification plant is followed up as to obtain the result from analysis apply. Besides, by determine the heat exchanger networks for energy recovery for the process, it can be used to minimize the annualized cost of the equipment plus the annual cost of utilities.

1.3 Objective and Scope of Study

1.3.1 Objectives

The objectives of this project are:

1) To study on methods to improve the efficiency of a biomass gasification plant in terms of energy consumption as recovery.
2) To identify hot and cold streams and generate composite curves for a selected flowsheet for biomass gasification plant.
3) To determine hot and cold utilities needed by the process and obtain maximum energy recovery in the biomass gasification plant using pinch analysis.
4) To design possible heat exchanger network and propose modified design in process simulator.
5) To evaluate the cost saving that can be achieved via the heat integrated flowsheet.

1.3.2 Scopes of Study

As outlined by the objectives above, developing a heat integrated flow sheet of biomass gasification plant for Hydrogen production is the main focus throughout the project time. This can be achieved by using specialized software. Understanding and study each process in biomass gasification plant, evaluation of processing options, and developing process simulation in a selected process simulator are activities to be carried out prior to heat integration analysis.

Scopes of study related to literature review carried out throughout the project consists of information and analysis on hydrogen production from biomass gasification plant and heat integration in plant.

CHAPTER 2

LITERATURE REVIEW AND THEORY

Literature research analysis and study had been carried out based on hydrogen plant/production from biomass gasification process and heat integration study on gasification plants.

Several articles have reviewed for the production of hydrogen from biomass. Ni *et al.* (2006) have listed the possible ways to produce hydrogen from biomass by thermochemical and biological process. The thermochemical pyrolysis and gasification hydrogen production method are economically viable and will become competitive with the conventional natural gas reforming method. Dark fermentation can be improved for commercial use in the future. According to Nath *et al.* (2003) there are different technologies presently being practiced to produce hydrogen economically but it is too early to predict which one will be successful. Holladay *et al.* (2009) briefly described all the process technologies for hydrogen production including both resources from fossil fuel and renewable energy. Reforming and gasification from biomass is stated as the most mature technology.

2.1 Gasification of Biomass into Hydrogen

As mentioned before, hydrogen production from biomass catalytic gasification by using steam as indirect gasification agent is preferred because it is favor of more hydrogen and economical than other conventional gasifying agents (Gonzalez *et al.*, 2008). Pfeifer *et al.* (2004) is using Ni-Olivine catalyst in dual fluidized bed with wood pellets as a source of biomass waste in attempt to produced hydrogen rich gas. Nikoo *et al.* (2008) has run simulation by using ASPEN PLUS process simulator for fludized bed reactor for biomass gasification process. The effect of temperature, steam to biomass ratio and particle size of biomass on the product gas had been studied (Nikoo *et al.,* 2008). Shen *et al.* (2008) proposed process simulation on biomass gasification using interconnected fluidized beds in process simulator. Heat required for gasification process has obtained from second fluidized bed that acts as a combustor. All the analysis can be used to have good understanding on factors that affected hydrogen yield from biomass gasification plant.

2.2 Flowsheet Design Considerations and Heat Integration Studies

Study on biomass gasification flowsheet had been carried out. Spath *et al.* (2005) in their detailed report used two fluidized bed reactor for gasifier and char combustor using indirect gasification model by steam produced in steam cycle. Two designs of flowsheet had been studied which different in the tar reformer. The tar reformer in the current design is a bubbling fluidized bed reactor with 1% per day catalyst replacement. In the goal design, there is a tar reformer/catalyst regenerator system and because the conversion of methane is higher for this case, the steam methane reformer can be eliminated from the process design. Heat integration and energy recovery are important due to high temperature of operation. Pinch analysis was performed to analyze the energy network of the biomass gasification curves for hot and cold stream. First, the temperature and enthalpy for hot and cold streams are determined before constructing composite curves. The minimum approach temperature is 50^{o}F. These two curves (hot and cold streams) are shifted so that they touch at pinch point. Grand composite curves follow by heat exchanger network diagram can be constructed afterwards. 57 MMkg/yr of hydrogen had been produced by using indirectly heated gasifier and steam as gasification medium. This approach can be used as reference as the gasification agent use is the same.

Sadhukan *et al.* (2009) had proposed flowsheet of combined heat and power from biomass waste plant. The objective is to design heat integrated, cost effective and cleaner combined heat power (CHP) generation plant from biomass. The gasification process had been carried out by using two separated fluidized bed reactor which are gasification reactor and combustion reactor. Heat of gasification to burn char produced is obtain by combustion reactor. Main focus on heat integrated development for heat recovery from two main boilers, syngas cooler and heat recovery steam generators (HRSG). Syngas cooler produced high pressure superheated steam at 65 bar and at 65^{o}C while HRSG at 5 bar and 250^{o}C. One of the strategies to improve heat recovery in this design is by cooling the syngas below its dew point (60-70^{o}C) via high pressure superheated steam generation (650^{o}C). It is an energy efficient way to recover high temperature heat into superheated steam. This approach can be applied in process design flowsheet for biomass gasification for hydrogen production plant. The exit temperature of the gases from the boilers is predicted based upon maximum heat recovery using composite curve analysis and a minimum temperature approach between hot gas and cold water-steam. Excess heat from steam gasification is rejected to cooling water used for district heating. Figure 2.1 show the flowsheet design on process simulator for CHP generation plant from biomass waste.

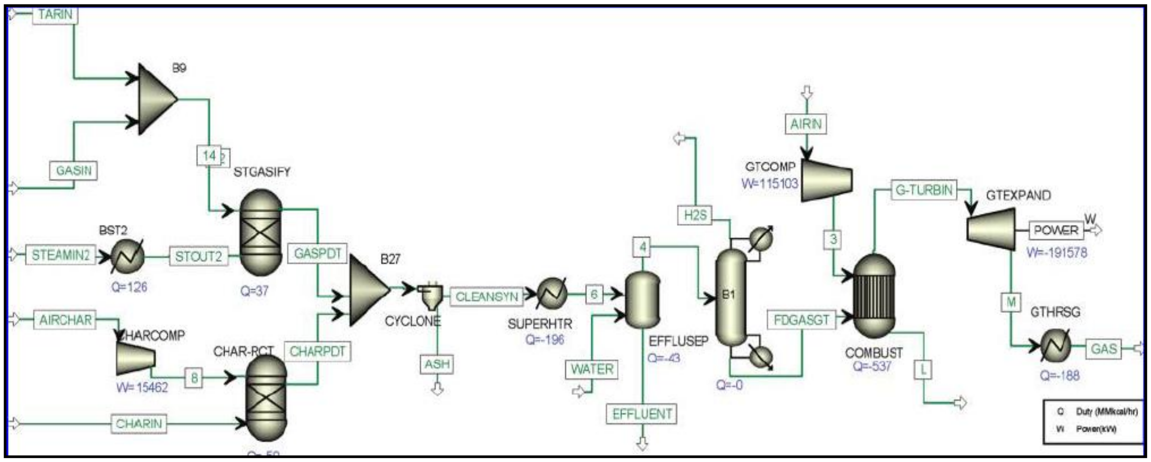


Figure 2.1: Simulation of the biomass CHP flowsheet presented: without anyCO_2 removal and with the flue gas from the char combustor added with the syngas from the steam gasifier. The main process modules are the following: steam gasification (STGASIFY), char combustor (CHAR-RCT), cyclone separator for removing ash (CYCLONE), syngas cooler (SUPERHTR), effluent recovery (EFFLUSEP), gas turbine combustor and expander (COMBUST and GTEXPAND, respectively), and HRSG (GTHRSG). In addition, there are two air compressors for the char combustor and gas turbine, respectively (Sadhukan *et al.*, 2009)

This paper has been main reference for this project as the flowsheet design proposed above does not have major difference by comparing to our proposed design flowsheet. A few strategy applied to increase plant efficiency by improving amount of energy recovery can be great applications in biomass gasification for hydrogen production plant.

2.3 Heat integration in power plant cycle

Jurado *et al.* (2003) have come out with usage of sub-product by olive tree in Spain to be used for biomass gasification. In modelling of combined power cycle plant, gas turbine is coupling with heat recovery steam generator (HRSG). The idea given is to improve overall system efficiency by linking together these two different thermal cycles. A heat recovery boiler has been used to provide steam for a steam turbine by received high temperature exhaust of gas turbines. Steinwall (1997) look to integrating the biomass gasification by using evaporative gas turbines cycle (EvGT). There are possible design had been considered. By using steam dryer, steam needed is produce by cooling down the gas from the gasifier. The product gas from gasifier is cooling down from 920^{o}C to about 400^{o}C. There also possibilities to use flue gas dryer functions as heat carriers and energy sources. Flue gas have the temperature of 140^{o}C cooling down to 55^{o}C for the vapour to begins condensed. This study has shown the possibilities for integrating heat in biomass gasification process design. Pavlas *et al.* (2010) have analysed an industrial case study for application of heat pump in energy system for biomass gasification in a wood processing plant. A large amount of heat has been generated from heat pump (HP) therefore, it is been utilized to improve energy management of the plant.

CHAPTER 3

METHODOLOGY

3.1 Project Methodology and Activities

After obtaining the final flowsheet design for biomass gasification plant, the first step is to understand each process involved in producing hydrogen from biomass. The discussion had been carried out for any changes in process flowsheet design development stage. Then, the simulation is developed in process simulator referring to the selected process flow diagram. Aspen Plus is recommended to be used as it supports the reactions that assume to take place in the gasifier. As an alternative, Aspen Hysys can be used as process simulator if the simulation did not work out successfully in the Plus. Operating conditions and some assumption are obtained from a prior work by Inayat *et al.* (2010). The process flowsheet is then developed in Aspen Plus.

Data from the process simulation will be extracting in order to generate a composite curve which is temperature vs. enthalpy plot to set the energy targets of the process. Temperature and enthalpy are extracted from the Aspen Plus simulation model.

Smith (2005) explains on how to construct composite curve. Composite curve are drawn as temperature vs. enthalpy with the slope as specific heat value (CP). Composite curve for hot stream are created by combining all hot streams in the same temperature interval. The CP value for the combined stream is the summation of CP for each individual stream within the same temperature interval. Similarly, the composite curve for cold streams is obtained the same way. The composite curve of hot and cold stream is then constructed in the same plot. Shift the curves near or away from each other until the set minimum temperature difference between the curves is achieved. The overlap between the curves represents the amount of heat that can be recovered. Hot utility must be supplied for the cold composite curve that extends beyond the start of the hot composite curve. Meanwhile, cold utility must be supplied for the hot composite curve that extends beyond the start of the cold composite curve. The value of minimum hot utility requirement, minimum cold utility requirement and location of pinch point also can be obtained from composite curve.

Maximum energy recovery obtained by using pinch analysis will allow the design of the possible heat exchanger network (HEN). The HEN design will used to propose a modified flowsheet design. Process Heat Integration (SPRINT) software will be used for this process. This software provides the accessibility to generate composite curves, construct pinch analysis and design heat exchanger networks.

Then, Grand Composite Curve (GCC) will be generating by using STAR software. The purpose is to obtain saturation temperature (T_{sat}) which will be used to determine the utility needed for the plant. Different pressure used in the process is determine by referring to saturation temperature obtain from GCC. Steam and cooling water are possible utility system in the plant. Utility system development is the final step in process development of heat integrated process for biomass gasification plant. Throughout the project, the literature review is constantly been used as a reference in order to obtain related information. The methodology used is summarized in Figure 3.1.

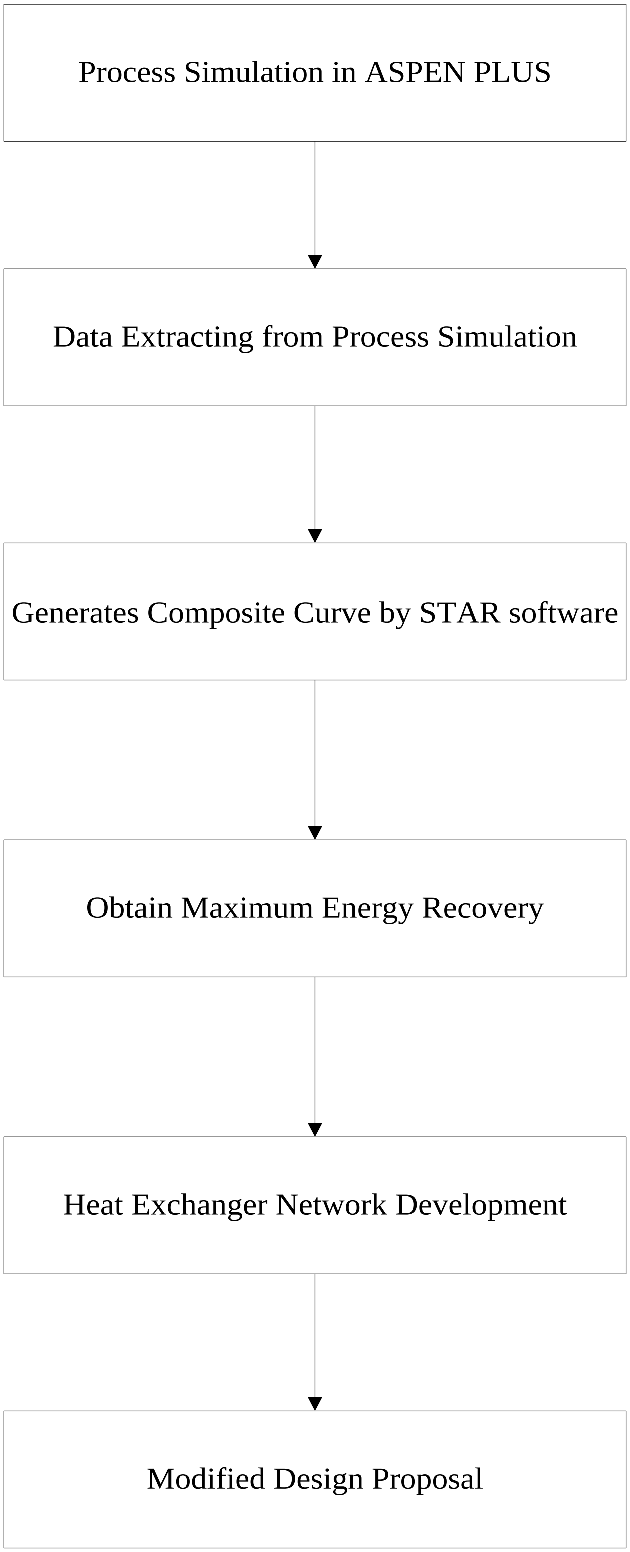


Figure 3.1: Flowchart summarizing the project methodology

3.2 Approach

Pinch Technology Method is used to determine the energy requirement from the process and the amount of energy recovery. Methodology used is aims to calculate the amount of energy for the process by constructing composite curves to set energy target or develop the problem table algorithm and heat cascade diagram. Composite curves are useful in providing the conceptual understanding of the process but the problem table algorithm is a more convenient calculation tool.

The term Pinch Analysis is been used correspond to application of the tools and algorithms of Pinch Technology related in industrial process. The application of First and Second Law of Thermodynamics determine the direction of Pinch Analysis application. Heat energy only flows in the direction of hot to cold. This prohibits the temperature crossovers of the hot and cold stream profiles through the exchanger unit. There is two main important things in dealing with transfer of heat between hot and cold stream which are, heat load and temperature. The minimum heat load between the two streams is selected when comparing their value while in a heat exchanger unit a hot stream cannot be cooled below cold stream supply temperature nor a cold stream can be heated to temperature more than hot stream supply temperature.

3.2.1 Pinch Analysis

From the description, development of heat integrated biomass gasification plant need to be carried out by identifying hot and cold streams involved in the process. Pinch Analysis Method has been used to indentify energy cost and Heat Exchanger Network capital cost targets for a process and recognizing the pinch point. The steps involves in Pinch Analysis is as followed:

1) Identification of the Hot, Cold and Utility Streams in the Process
2) Thermal Data Extraction for Process & Utility Streams
3) Selection of Initial DT_{min} value

4) Construction of Composite Curves and Grand Composite Curve and Grand Composite Curves
5) Estimation of Minimum Energy Cost Targets
6) Estimation of Heat Exchanger Network (HEN) Capital Cost Targets
7) Estimation of Optimum DT_{min} Value by Energy-Capital Trade Off
8) Estimation of Practical Targets for HEN Design
9) Design of Heat Exchanger Network

The calculation of pinch analysis can be carried out by using manual calculation (Microsoft Office Excel) or by using Process Integration Software (SPRINT). From both of this method, Q_{Hmin} (minimum hot utility requirement) and Q_{Cmin} (minimum cold utility requirement) and location of pinch point will discovered.

By identify hot and cold stream data from process flowsheet diagram (PFD), the data can be extracted into STAR software to determined Problem Table Algorithm, Composite Curves and Grand Composite Curves. The steps involve generating a composite curves and a grand composite curve is simplified below as show in Figure 3.2.

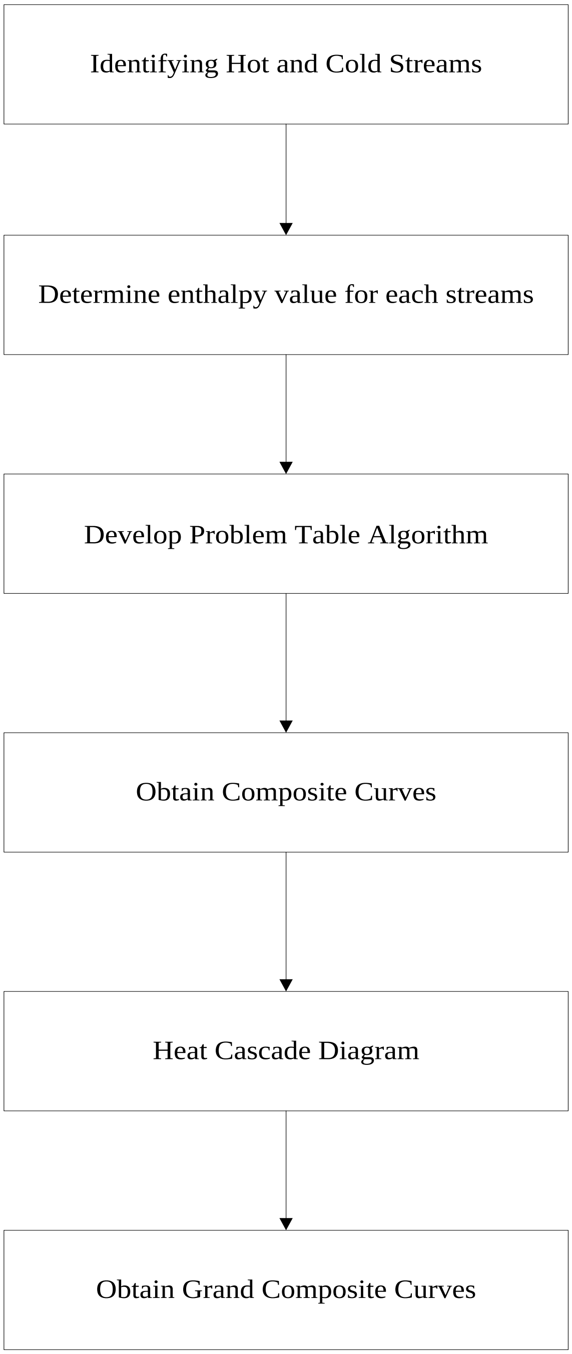


Figure 3.2: Steps to generate composite curves and grand composite curves

3.2.2 Design of Heat Exchanger Network (HEN)

The next step in developing heat integrated biomass gasification flowsheet for hydrogen production plant is by constructing the heat exchanger network design. Grid diagram shown earlier is divided at the pinch into above and below pinch sections. Then, the network is designed by following feasible matching rules between hot and cold stream. The heat load required for each stream must be satisfied by taking the minimum heat duty between the stream and determine the temperature at point of heat exchange occur. If the heat exchanging between the streams is not enough to reach the desired temperature, heater or cooler is installed to provide additional energy requirement. High amount of energy recovered and reused increases plant efficiency in term of energy consumption.

To design a feasible heat exchanger network, the following rule must be obeyed:

1. The rule of thumb (Smith, 2005):

Do not transfer heat across the pinch

i) Above pinch:

- CPH ⩽ CPC
- Do not use cold utility
- Cold stream require residual heating duty
- Can use hot utility for cold stream

ii) Below pinch:

- CPC ⩽ CPH
- Do not use hot utility
- Cold streams must be heated (residual cooling duty)
- Can use only cold utility for hot streams

3.3 Assumptions

The biomass considered in this project for Hydrogen production via the steam gasification process is char (C).

3.4 Gantt Chart

Table 3.1: Project Gantt Chart

No.	Detail/ Week	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	Literature review	■	■	■	■	■	■	■	■	■	■	■	■	■	■
2	Process simulation	■	■	■	■	■									
3	Data extraction						■	■							
4	Composite curves construction							■							
5	Pinch analysis								■						
6	Heat exchanger networks development								■	■	■				
7	Generate Grand Composite Curves										■				
8	Modified design proposal											■			
9	Dissertation writing												■		
10	Oral Presentation													■	
11	Dissertation Finalized (Hardbound)														■

CHAPTER 4

RESULT AND DISCUSSION

Figure 4.1 shows the process flow diagram for the biomass gasification for hydrogen production process.

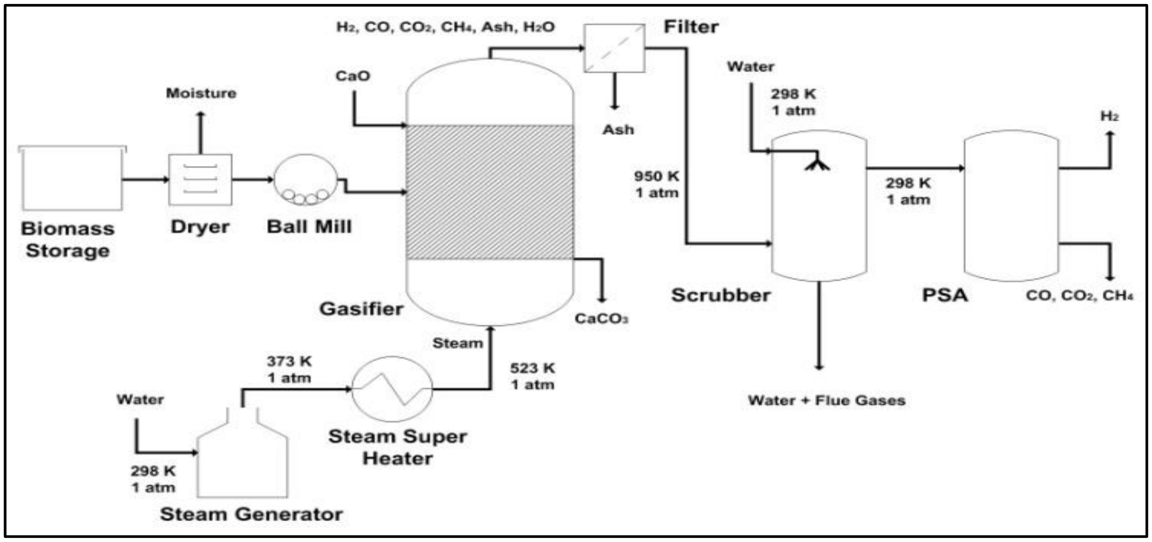


Figure 4.1: Process Flow Diagram (Inayat *et al.*, 2010).

4.1 Process Flow Diagram Description

Based on Figure 4.1, water has been heated from room temperature (298K) until superheated condition (523K) under atmospheric pressure. Dry biomass enters the gasifier along with sorbent, CaO as a catalyst. Both are under room temperature and atmospheric pressure. Heat is supply to the gasifier in order to increase the temperature up to 1073K with enthalpy energy value of 8681 kJ/hr (Inayat *et al.,* 2010). Mixture of gas exit the gasifier is contains H_2O, H_2, CO, CO_2, CH_4 and ash will go through filter where ash will be filtered as an unwanted components. The remaining components in the gas mixture will enter scrubber unit to remove most of the water and flue gas. The temperature need to be reduced from around 1004K to 298K by supplying 1521 kJ/hr of energy (Inayat *et al.*, 2010). Mixture of gas exits the scrubber unit to enter adsorption unit where H_2 has been produced as a product (Inayat *et al.*, 2010).

4.2 Process simulation in Aspen Plus

Based on process design attached, simulation of the plant has been carried out by using Aspen Plus process simulator. The result from this process simulation will be compared with mass balance calculation from the previous work. The gasification process is integrated with CO2 adsorption steps and there are six major reactions are assumed to occur in the gasifier (Inayat *et al.*, 2010). The list of reactions is listed in Table 4.1.

Table 4.1: Reactions involved in gasifier (Inayat *et al.*, 2010).

No	Name	Reaction
1	Char gasification	$C + H_2O \longrightarrow H_2 + CO$ (R1)
2	Methanation	$C + 2H_2 \longrightarrow CH_4$ (R2)
3	Boudouard	$C + CO_2 \longrightarrow 2CO$ (R3)
4	Methane reforming	$CH_4+H_2O \longrightarrow CO+3H_2$ (R4)
5	Water gas shift	$CO+H_2O \longleftrightarrow CO_2+H_2$ (R5)
6	Carbonation	$CO_2+CaO \longrightarrow CaCO_3$ (R6)

The kinetics parameters used for the reaction is listed as in Table 4.2.

Table 4.2: Kinetics constant used in biomass gasification modelling in ASPEN PLUS.

Reaction	Kinetic Constant	Reference
R1	$2.0 \times 10^{5} \exp(-6000/T)$	Corella *et al.*, (2005)
R2	$2.345 \times 10^{-11} \exp(-13670/T)$	De Suza-santos (2004)
R3	$1.19 \times 10^{-3} \exp(-16840/T)$	De Suza-santos (2004)
R4	$3 \times 10^{5} \exp(-15000/T)$	Corella *et al.*, (2005), liu *et al.*,(2003)
R5	$10^{6} \exp(-6370/T)$	Corella *et al.*, (2005)
R6	$1.67 \times 10^{-3} \exp(-29/T)$	Lee *et al.*,(2005)

The operating conditions selected are as follows (Inayat *et al.*, 2010).

- Biomass (char) feed rate: 72 g/hr
- Temperature range: 800 to 1300 K
- Steam/biomass ratio range: 1 to 5
- Sorbent/biomass ratio: 1.0

Biomass is assumed as char to simplify the simulation. It is also assumed that the biomass has 10% moisture content which is an acceptable assumption used for tropical based biomass sources (Inayat *et al.*, 2010). Tar formation in the gasification process is negligible (Nikoo *et al.*, 2008; Shen *et al.*, 2008), isothermal condition and constant volume and pressure (Nikoo *et al.*, 2008; Shen *et al.*, 2008; Chejne *et al.*, 2002; Choi *et al.*, 2001; Zhang *et al.*, 2009)

4.2.1 Process simulation in Aspen Plus: Biomass (Pure Char)

A process simulation of a basic process flowsheet is carried out using the Aspen Plus package software. Aspen is a standard process flowsheet simulation tool, which is suitable to simulate gasification based process site (Sadhukan *et al.*, 2009). From the process simulation, the mass and energy balance for the flowsheet had been established. Then, data extraction had been carried out from the energy related data from the heat source and sinks processes and stream in order to apply heat integration approach afterwards.

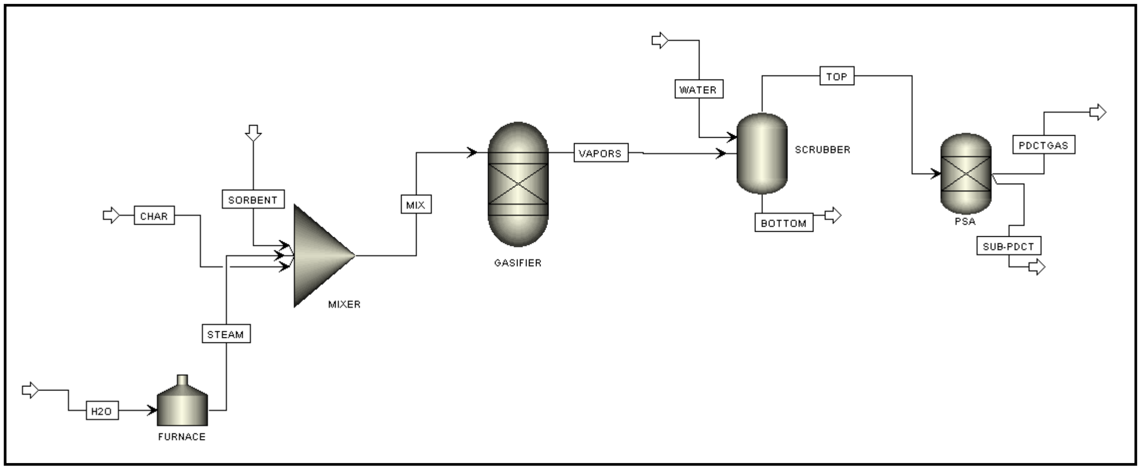


Figure 4.2: Simulation of the biomass gasification flowsheet, assuming biomass as char.

Table 4.3: Stream table from process simulation

Mole Flow kgmol/hr	PDCTGAS	BOTTOM	CHAR	H2O	MIX	SORBENT	STEAM	SUB-PDCT	VAPORS	WATER	TOP
C	0	0	0.00599	0	0.00599	0	0	0	1.66E-25	0	0
H_2O	0	2.70E-05	0	1.20E-02	1.20E-02	0	1.20E-02	1.56E-02	4.40E-03	1.11E-02	0
CO	0	7.75E-08	0	0	0	0	0	0.00448	0.00448	0	0.00448
H_2	0.00744	2.38E-08	0	0	0	0	0	7.51E-05	0.00751	0	0.00751
CH_4	0	2.39E-12	0	0	0	0	0	8.33E-08	8.33E-08	0	8.33E-08
CO_2	0	6.70E-08	0	0	0	0	0	0.00152	0.00152	0	0.00152
CaO	0	1.28E-03	0	0	0.00128	0.00128	0	0	0.00128	0	4.15E-35
$CaCO_3$	0	0	0	0	0	0	0	0	9.76E-23	0	0
Total Flow kgmol/hr	0.00744	0.001311	0.00599	0.01199	0.01927	0.00128	0.01199	0.02162	0.01927	0.0111	0.29
Total Flow kg/hr	0.01499	0.07249	0.005991	0.01199	0.01941	0.001284	0.01199	0.021621933	0.0192684	0.0111	0.02906
Total Flow cuft/hr	10.77	0.032157	0.00113	0.00767	0.01111	0.0007711	18.17	31.32	72.57	0.00711	42.09
Temperature ^{o}C	226.85	226.85	24.85	24.85	623.54	24.85	249.85	226.85	1026.85	24.85	226.85
Pressure psi	14.7	14.7	14.7	14.7	14.7	14.7	14.7	14.7	14.7	14.7	14.7
Enthalpy Btu/hr	41.47	20.13	-0.0072	-3246.7	-3433	-772.87	-2660.1	-4459.94	-1378.15	-3006.21	-3006.17

From the data stream show in the Table 4.3, the production of H_2 has been highlighted. The final product of H_2 is obtained at mass flow rate of 0.01499 kg/hr by using 72 g/hr of char as a source of biomass at the end of process. However, water is carried out from scrubber and did not completely remove. Remaining amount of water has been separated at Pressure Swing Adsorption (PSA) column along with other subproduct which is CO, H_2, CH_4 and CO_2.

Simulation of the process flowsheet in Aspen Plus is shown in Figure 7 with char as biomass had been used in the process. The fluidized bed gasifier for all six reactions is modelled as RGibbs reactor. By controlling the temperature, pressure and steam to biomass ratio entered the gasifier, the product composition of Hydrogen can be easily manipulated. The RGibbs reactor is chosen to be used in the process as it is representing an overall process gasification process in the case of biomass. This option is thermodynamically more preferable exothermic reactions over endothermic reactions (Sadhukan *et al.*, 2009). Besides, by using RGibbs reactor no cracking or reforming reaction is taken into account and the elements presented in the process are treated as pure components (C, H, O, N and S) if input feed composition are taken as ultimate analysis (Sadhukan *et al.,* 2009). Then, an oxidations reaction is selected over steam gasification (cracking and reforming reactions). Water gas reactions and methanation which is exothermic is using oxygen present in biomass analysis even though the reactions were carried out in the absence of oxygen (Sadhukan *et al.*, 2009).

In this simulation all the reactions is taken place in one gasifier to deal with gas and char. Pavlas *et al.*, (2010) had done heat integrated for heat pumping for biomass gasification process from the flowsheet contain fluidized bed reactor as a reactor.

Undesired contaminants presented in the process required separation process to take place. According to Pavlas *et al.*,(2010) wet scrubbing is one of the technique available for the removal of undesired contaminants which is apply in this process flowsheet where water is been used as feed entering the scrubber along with other components. Water is considered as the cooling /scrubbing medium.

For this process simulation, furnace has been used to generate steam require at temperature of 523K. Steam generated also can possibly used to supply require amount of energy to be considered in heat integrated section.

4.3 Heat Integration Study

Heat integration was carried out to recover the maximum amount of energy and minimize the usage of utilities system. The approach to achieve this objective is by using Pinch Analysis. As mention in the Chapter 3 (Methodology), the first step is to identify the hot and cold streams in the process flowsheet carried out in Aspen. The data extraction is show in Table 4.4.

Table 4.4: Hot and cold streams

Stream Name	Supply Temp. (^oC)	Target Temp. (^oC)	Δ H (kW)	CP (kW/K)
H1	1026.85	226.85	0.89102	1.11E-03
C1	623.54	1026.85	0.6022	1.49E-02
C2	24.85	249.85	0.1719	7.64E-04
C3	24.85	623.544	0.2265	3.78E-04

By referring to process flowsheet;
H1: VAPORS and TOP streams
C1: MIX and VAPORS streams
C2: H2O and STEAM streams
C3: SORBENT and MIX streams

Star software package is been used to construct composite curves and grand composite curve based on the data show above. An initial delta T_{min} is taken as 10^oC that will give optimum value of minimum hot and cold utility needed after several trials using other value (20^oC, 30^oC and 40^oC). The result of composite curve and problem table algorithm is shown in Figure 4.3 and 4.4 below.

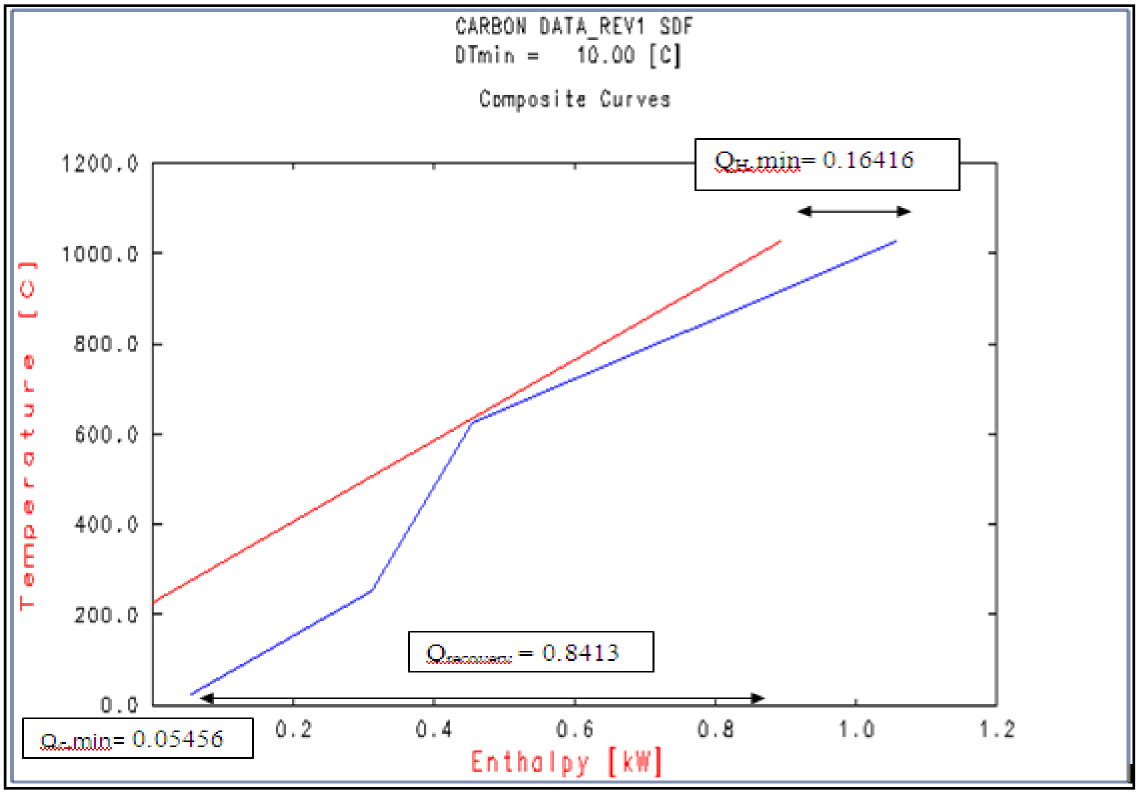


Figure 4.3: Composite curve construction.

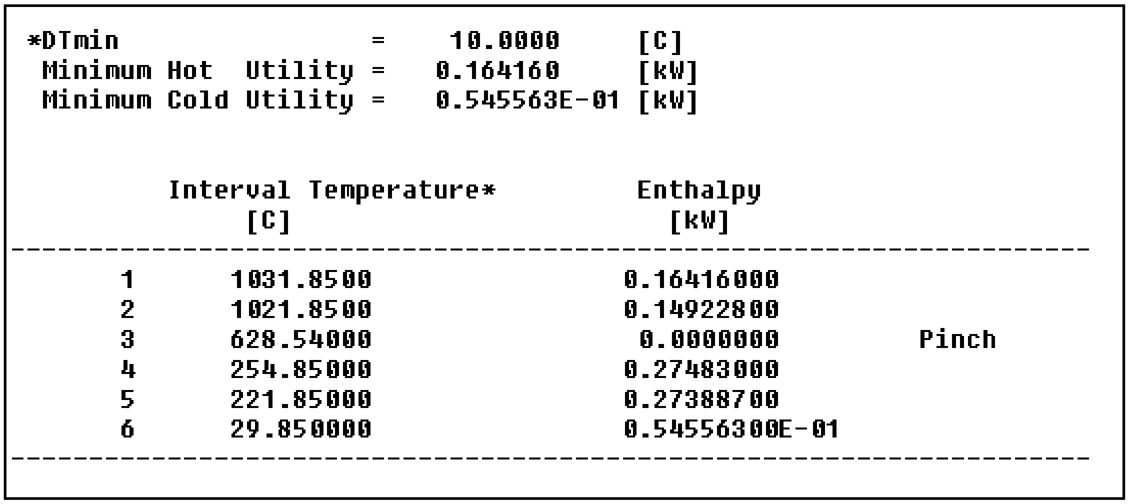
From the figure it is show;

i) Minimum hot utility requirement (Q_{Hmin}): 0.16416 kW

ii) Minimum cold utility requirement (Q_{Cmin}): 0.05456 kW

iii) Maximum heat recovery ($Q_{recovery}$) : 0.8413 kW

Composite curves provide information on how much hot and cold utility required in this process. The red line represent hot stream meanwhile the blue line acts as cold stream. From the figure, 0.16416 kW of hot utility and 0.05456 kW of cold utility need to be supply to the process. Maximum heat of recovery is recorded as 0.8413 kW means amount of heat potentially been transferred between streams. Temperature difference used in this process is set at 10^{o}C. Amount of utility required show in composite curves will be compared with the amount obtain when heat exchanger network diagram completely constructed.



```
*DTmin                  =    10.0000     [C]
 Minimum Hot  Utility =   0.164160     [kW]
 Minimum Cold Utility =   0.545563E-01 [kW]


         Interval Temperature*         Enthalpy
              [C]                        [kW]
---------------------------------------------------------------------
      1      1031.8500              0.16416000
      2      1021.8500              0.14922800
      3      628.54000               0.0000000         Pinch
      4      254.85000              0.27483000
      5      221.85000              0.27388700
      6      29.850000              0.54556300E-01
---------------------------------------------------------------------
```

Figure 4.4: Problem Table Algorithm

Problem Table Algorithm show:

i) Minimum hot utility (Q_{Hmin}) : 0.16416 kW

ii) Minimum cold utility (Q_{Cmin}) : 0.05456 kW

iii) Pinch temperature (Tp_{inch}) : 628.54^{o}C

Problem table algorithm provides important information in Pinch Analysis method which is Pinch Temperature. From the Figure 4.4, pinch temperature is at 628.54^{o}C which the heat flow goes zero. Pinch temperature will be used to determine above and below pinch temperature in order to construct heat exchanger network in the next step. Thus, the actual hot and cold stream temperatures are 633.54^{o}C and 623.54^{o}C. At pinch temperature,

Grand Composite Curve (GCC) is show by Figure 4.5 which obtains by plotting problem table cascade. The temperature plotted here is shifted temperature (T*) and not actual temperature. GCC helps to identify the possible level(s) of utility to be introduced to avoid induction of it at an extreme point. Besides, it also enables utility selection and quantification if the option of utilities is fixed. The profile of GCC represents the residual heating and cooling demands after recovering heat within the shifted temperature intervals in the problem table algorithm. GCC provide information on how to manipulate available utilities and select the least expensive ones to supply and remove heat without inventing a heat exchanger network.

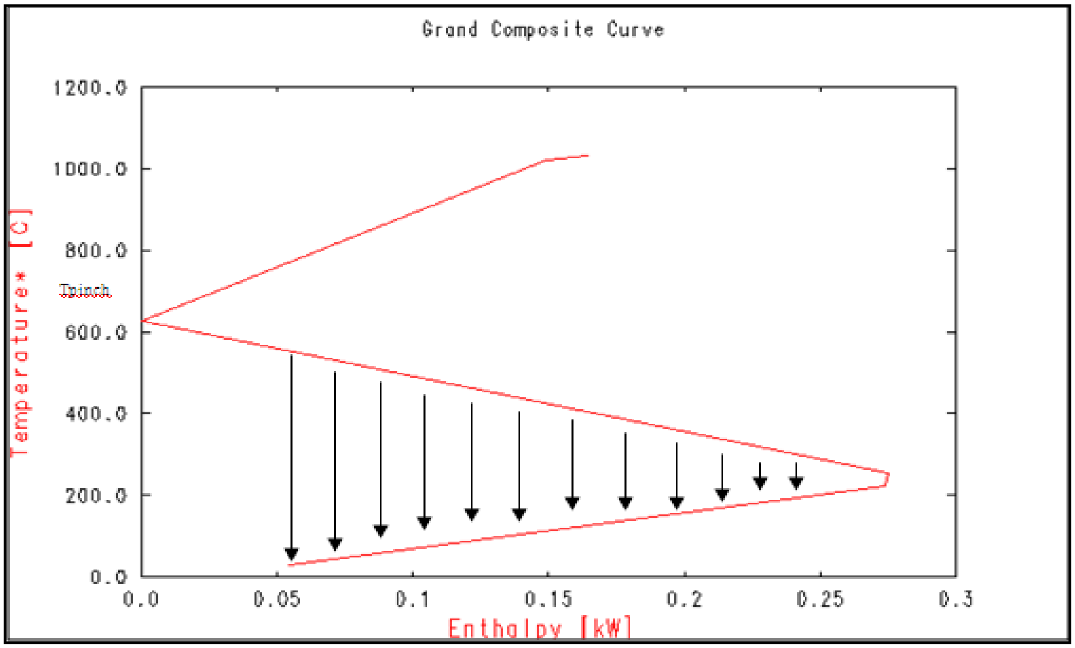


Figure 4.5: Grand Composite Curve

Above the pinch temperature is the section of heat sink while below the pinch temperature is heat source or generated during the process. Process to process heat transfer is happen below pinch temperature. The arrow area in Figure 11 is known as pockets; represent area of additional process-to-process heat transfer. As all the heat generated is covered by the heat sink, and therefore no cooling water is needed for the process. It leaves the process to use steam as utility to supply more heat to the process. Possible alternative is by using Very High Pressure (VHP) steam or flue gas as utility. However, the process is happen at very high temperature which exceeds the saturation temperature for very high pressure (VHP) steam to be used as utility. Therefore, the better option is by use of flue gas generated from the furnace at theoretical flame temperature (2000^{o}C) which is burn in air without loss or gain of heat, and then it is cooled to pinch temperature. Usage of flue gas in the process is shows in Figure 4.6.

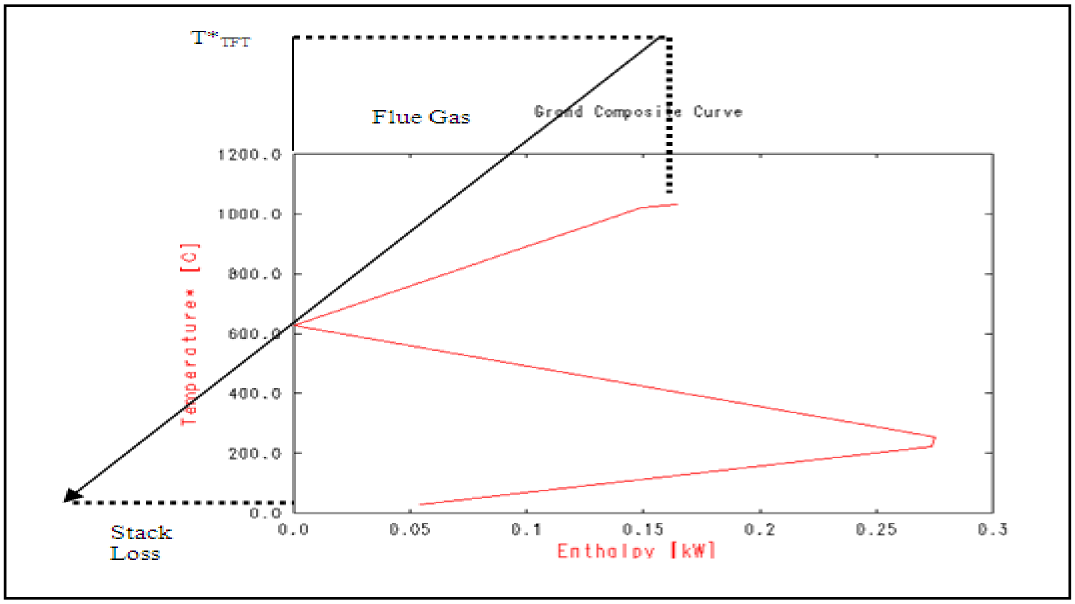


Figure 4.6: Grand composite curve with flue gas.

4.4 Design of Heat Exchanger Network

As mention in Chapter 3, heat exchanger network development is a further step after completing heat integration part. The result is divided between above pinch, below pinch and combined pinch. The result is shown in Figure 4.7, 4.8 and 4.9.

i) Above pinch design

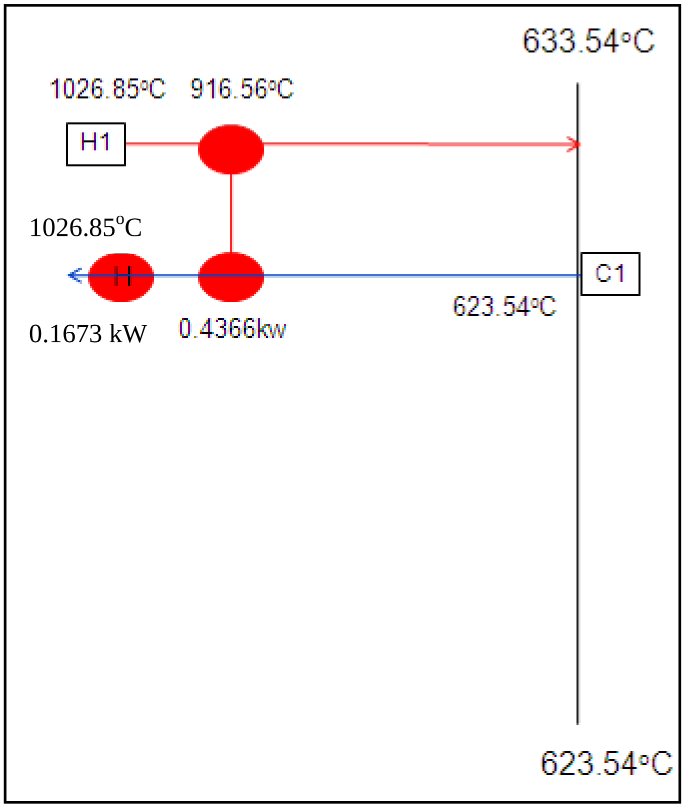


Figure 4.7: Above pinch design

The calculation is as follow:

Table 4.5: Calculation for above pinch

Stream	$\Delta T(^oC)$	Cp(kW/K)	$\Delta H(kW)=Cp* \Delta T$
H1	393.31	0.00111	0.4366
C1	403.31	0.00149	0.6009

ii) Below pinch

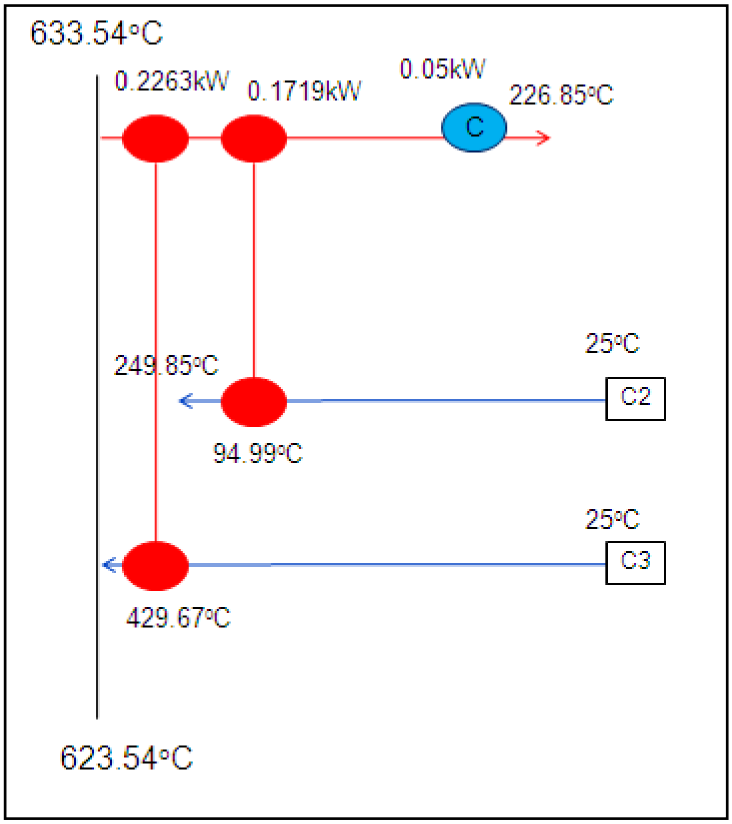


Figure 4.8: Below pinch design

Table 4.6: Calculation for below pinch

Stream	ΔT(°C)	Cp(kW/K)	ΔH(kW)=Cp* ΔT
H1	406.69	0.00111	0.4514
C2	225	0.000764	0.1719
C3	598.69	0.000378	0.2263

iii) Complete heat exchanger network design

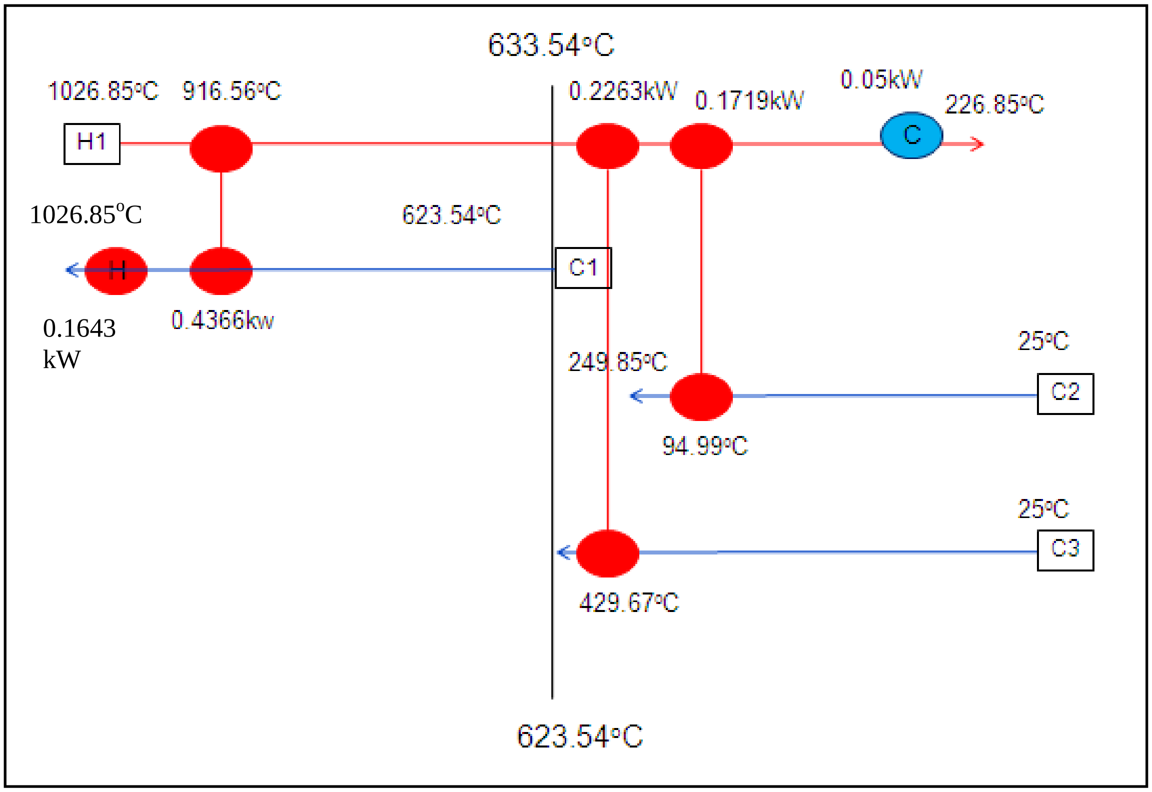


Figure 4.9: Complete heat exchanger network design

Complete heat exchanger network design proposed is based on manual calculation is due to limitation in time to determine suitable utility option for the process which result limitation to be carried out in SPRINT software. From Figure 4.9, one heater and one cooler is proposed to be used in the process supported by three heat exchangers to minimize the utility requirement. From the analysis, the minimum hot utility requirement for the process is 0.1643 kW which is comparable with the amount obtain from composite curve generated in STAR software. Meanwhile the minimum amount of cold utility required is obtain at 0.05 kW which is also similar with the amount of cold utility generated before in STAR software. With all the required information is available, the modified design of process flowsheet can be carried out in process simulator (Aspen Plus).

4.5 Energy Saving

Total energy required before heat integration

i) Hot utility

$$\Delta H = CP\Delta T$$
$$= 0.00149(1026.85 - 623.54)$$
$$= 0.6009\ kW$$

ii) Cold utility

$$\Delta H = CP\Delta T$$
$$= 0.00111(633.54 - 226.85)$$
$$= 0.4514\ kW$$

Total energy required after heat integration

i) Hot utility $= 0.1673\ kW$

ii) Cold utility $= 0.0532 kW$

Percentage of energy saving

i) Hot utility

$$\frac{(0.6009 - 0.1673)}{0.6009} \times 100\% = 72.16\%$$

ii) Cold utility

$$\frac{(0.4514 - 0.0532)}{0.4514} \times 100\% = 88.2\%$$

From the calculation, 72.16% of energy saving from hot utility and 88.2% from cold utility managed to be saved by development of heat exchanger network. These high percentage values show the efficiency of plant flowsheet.

4.6 Modified Design of Process Flowsheet

A process simulation of modified design of process flowsheet is consisting of three heat exchangers, one heater and one cooler by referring to heat exchanger network development constructed in previous section. Figure 5.0 show the result of modified design of process flowsheet.

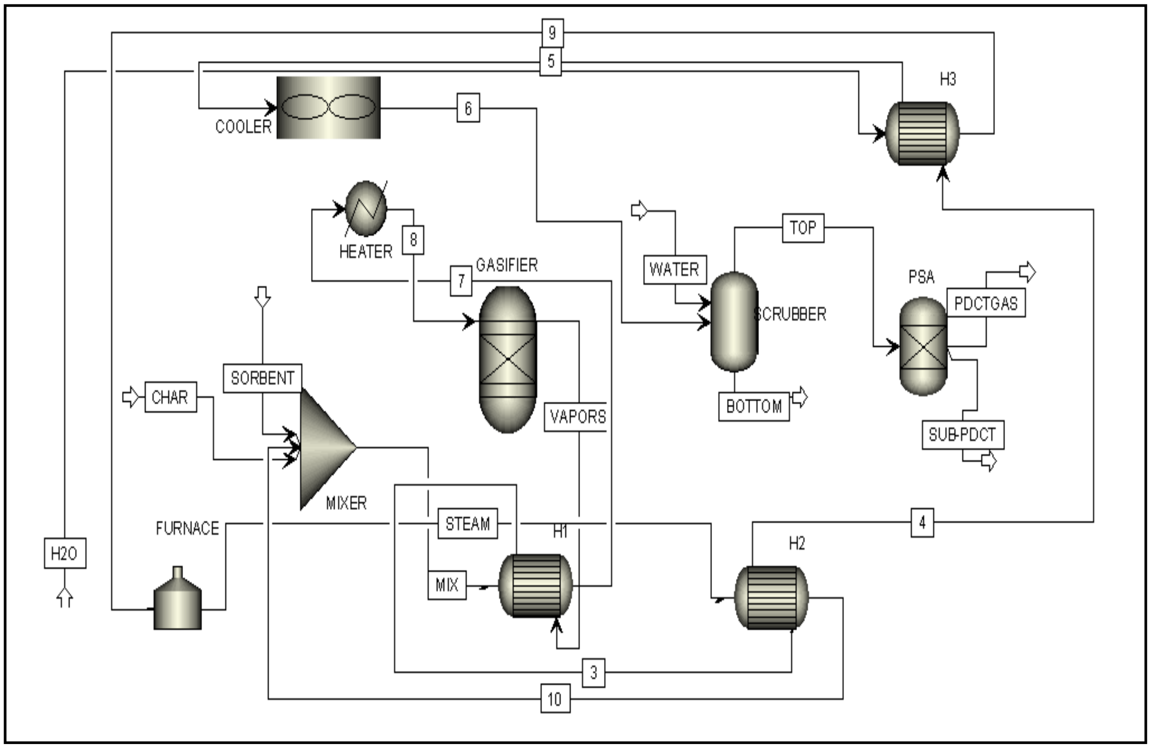


Figure 5.0: Modified Design of Process Flowsheet

Table 4.7: Stream table from process simulation

Mole Flow kgmol/hr	PDCTGAS	BOTTOM	CHAR	H2O	MIX	SORBENT	STEAM	SUB-PDCT	VAPORS	WATER
C	0	0	0.00599	0	0.00599	0	0	0	1.66E-25	0
H_2O	0	2.70E-05	0	1.20E-02	1.20E-02	0	1.20E-02	1.56E-02	4.40E-03	1.11E-02
CO	0	7.75E-08	0	0	0	0	0	0.00448	0.00448	0
H_2	0.00744	2.38E-08	0	0	0	0	0	7.51E-05	0.00751	0
CH_4	0	2.39E-12	0	0	0	0	0	8.33E-08	8.33E-08	0
CO_2	0	6.70E-08	0	0	0	0	0	0.00152	0.00152	0
CaO	0	1.28E-03	0	0	0.00128	0.00128	0	0	0.00128	0
$CaCO_3$	0	0	0	0	0	0	0	0	9.76E-23	0
Total Flow kgmol/hr	0.00744	0.00131	0.00599	0.01199	0.01927	0.00128	0.01199	0.02162	0.01927	0.0111
Total Flow kg/hr	0.01499	0.07249	0.005991	0.01199	0.01941	0.001284	0.01199	0.021621933	0.0192684	0.0111
Temperature ^{o}C	226.85	226.85	24.85	24.85	623.54	24.85	249.85	226.85	1026.85	24.85
Pressure psi	14.7	14.7	14.7	14.7	14.7	14.7	14.7	14.7	14.7	14.7

Mole Flow kgmol/hr	TOP	3	4	5	6	7	8	9	10
C	0	1.66E-25	1.66E-25	1.66E-25	1.66E-25	0.00599	0.00599	0	0
H_2O	0	4.40E-03	4.40E-03	4.40E-03	4.40E-03	1.20E-02	1.20E-02	1.20E-02	1.20E-02
CO	0.00448	0.00448	0.00448	0.00448	0.00448	0	0	0	0
H_2	0.00751	0.00751	0.00751	0.00751	0.00751	0	0	0	0
CH_4	8.33E-08	8.33E-08	8.33E-08	8.33E-08	8.33E-08	0	0	0	0
CO_2	0.00152	0.00152	0.00152	0.00152	0.00152	0	0	0	0
CaO	4.15E-35	0.00128	0.00128	0.00128	0.00128	0.00128	0.00128	0	0
$CaCO_3$	0	9.76E-23	9.76E-23	9.76E-23	9.76E-23	0	0	0	0
Total Flow kgmol/hr	0.29	0.01927	0.01927	0.01927	0.01927	0.01927	0.01927	0.01199	0.01199
Total Flow kg/hr	0.02906	0.0192684	0.0192684	0.0192684	0.0192684	0.01941	0.01941	0.01199	0.01199
Temperature ^{o}C	226.85	916.56	423.67	310.42	226.85	916.56	1026.85	94.99	25
Pressure psi	14.7	14.7	14.7	14.7	14.7	14.7	14.7	14.7	14.7

Type of heat exchanger been used in process design is shell and tube heat exchanger with counter current flow. Three heat exchangers have been used along with one heater and one cooler to supply the minimum utility.

H1 represents the first heat exchanger and operated at 0.4366 kW of heat duty which is to supply heat to the cold stream to reach 916.56^{o}C of temperature. The cold stream outlet will enter the heater installed to receive 0.167 kW amount of heat in order for the stream to reach its target temperature at 1026.85^{o}C. The outlet stream of heater then enters the gasifier for the reaction to happen.

H2 acts as second heat exchanger and transfer an amount of 0.226 kW of energy to cold stream represents by steam to reach 623.54^{o}C. The energy is supply by excessive heat from H1 outlet at temperature of 429.3^{o}C. Hot stream discharge from H2 continue to enter H3 acts as third heat exchanger where the heat transfer occur with cold stream from H2O stream. Amount of heat transfer is approximately at 0.1719 kW. Cooler installed in the process manages to reduce the temperature to 226.85^{o}C before entering the scrubber as feed stream to be further separated. The mass flow rate of hydrogen at the end of the process is 0.01499 kg/hr.

CHAPTER 5

CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

Throughout the project, the research had been carried out to gather all information and knowledge on heat integrated biomass gasification plant for hydrogen production. Heat integration development has been applied by using Pinch Analysis technique. The temperature difference is set at 10. The minimum hot utility required is 0.1642 kW while the minimum cold utility required is 0.05456 kW. Maximum heat recovery from the process is 0.8413 kW. By obtaining problem table algorithm, the pinch temperature is at 628.54^{o}C. Three heat exchangers are proposed to be used result from heat exchanger network development. Calculation of energy saving show around 72% of hot utility and 88% of cold utility can be saved by doing heat integration technique. Overall, all the objectives successfully achieved.

5.2 Recommendations

Further studies are recommended on this project to improve the results obtain from the simulation and heat integration method. First, the flowsheet design can be developed for specific biomass for example empty fruit bunch (EFB). Besides, the actual experimental kinetic data on the specific biomass can be used in order to obtain more accurate simulation result. More detailed economic analysis can be performed to evaluate the result of heat integration development on the process plant.

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